

UNIVERSITÄT ZU LÜBECK INSTITUT FÜR TELEMATIK

# HIGH PERFORMANCE COMMUNICATION IN STREAM-BASED MULTICHANNEL WIRELESS SENSOR NETWORKS

DISSERTATION

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# HIGH PERFORMANCE COMMUNICATION IN STREAM-BASED MULTICHANNEL WIRELESS SENSOR NETWORKS

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# DEDICATION

To the Brave Martyrs & Heroes of Army Public School (APS), Peshawar, Pakistan.

A Huge Tribute to the Everlasting Sacrifice in the Way of Education!

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# KURZFASSUNG

Tatsächlich kann das 21. Jahrhundert als Informationszeitalter angesehen werden, das die Welt mit der Einführung von Informations- und Kommunikationstechnologien revolutioniert und modernisiert hat. Im Zeitalter der Information leistet die drahtlose Hochleistungskommunikation einen enormen Beitrag zur Weiterentwicklung und Digitalisierung der herkömmlichen Kommunikationsinfrastruktur. Zu diesem Zweck wurde eine Vielzahl neuer drahtloser Technologien wie IEEE 802.11, 3G/4G, WiMax, ZibBee usw. erfunden, die die Welt mit zahlreichen aufregenden Funktionen revolutioniert haben.

In ähnlicher Weise stellen drahtlose Sensornetzwerke (WSNs) eine wachsende drahtlose Netzwerktechnologie dar, die eine zentrale Rolle bei der Erfassung, Überwachung und automatischen Überwachung der Umgebung spielen kann. Aufgrund ihrer selbstorganisierenden und unabhängigen Natur können WSNs die Beobachtung einer Region von Interesse automatisieren. In der Folge können Sensornetzwerke die Arbeitsteilung von Menschen sicherstellen und weiter zur Digitalisierung des Globus beitragen. Aus diesem Grund können WSNs als potenzieller Akteur für den sozioökonomischen und technologischen Fortschritt der Welt angesehen werden.

Herkömmlicherweise erfolgte die drahtlose Kommunikation einkanalig und die Kanalzuweisung wurde statisch durchgeführt. Da diese Sensornetzwerke auf einem einzelnen Frequenzkanal basieren, können sie unter verschiedenen Herausforderungen leiden, wie z. B. Durchsatzverlust, Verzögerung, Überlast und Sendewiederholungs-Overhead. Mit der Weiterentwicklung der Technologie wurden Multichannel Wireless Sensor Networks (MWSNs) eingeführt, die die Möglichkeit bieten, parallele Kommunikation zur Verbesserung des Netzwerkdurchsatzes, der Verzögerung, des Paketverlustverhältnisses usw. bereitzustellen. Auf diese Weise können MWSNs als geeignete Kandidaten für die Gewährleistung einer zuverlässigen und effizienten Echtzeitkommunikation in verzögerungsempfindlichen Anwendungen wie Multimedia- oder Streambasierten Sensornetzwerken angesehen werden. Letztendlich können MWSNs eine Hochleistungskommunikation in geschäftskritischen WSNs sicherstellen.

Obwohl eine Vielzahl von Funkkanälen im nicht lizenzierten Bereich für Industrie, Wissenschaft und Medizin (ISM) verfügbar ist, ist die Auswahl eines geeigneten Kommunikationskanals unter den verfügbaren Funkfrequenzen (gemäß den Anwendungsanforderungen) in MWSNs in der Tat eine anspruchsvolle Aufgabe. Da das Umschalten eines drahtlosen Kanals in Bezug auf Verzögerung und Energieverbrauch kostspielig ist, ist es eine herausfordernde Aufgabe,

#### KURZFASSUNG

über das Umschalten eines Kanals mit Bedacht zu entscheiden, wobei die Anwendungsanforderungen von WSNs berücksichtigt werden. Außerdem können zu häufige Kanalwechsel zu Datenverlusten bei Anwendungen mit hoher Datenrate wie Multimedia- und Stream-basierten Sensornetzwerken führen. Darüber hinaus ist es eine echte Herausforderung, geeignete Mechanismen für die Zuweisung und Weiterleitung von JOINT-Kanälen zu entwickeln, um die Dienstgüte (Quality of Service, QoS) zu verbessern und damit eine hohe Leistung in MWSNS sicherzustellen.

Um die oben genannten Herausforderungen zu bewältigen, liefert diese Dissertation eine Vielzahl von Algorithmen, deren Zweck es ist, den geeigneten Kanal für die drahtlose Kommunikation auszuwählen und ihn zur Weiterleitung der Überwachungsinformationen an mehrere Senkenknoten zu verwenden, um eine hohe Leistung in geschäftskritischen MWSNs zu erzielen. Zu diesem Zweck werden zwei Mehrkanal-MAC-Protokolle, d. H. Ext-NEAMCBTC und MAGIC, entwickelt, um den geeigneten Kommunikationskanal in normalen bzw. verrauschten (mit einem gewissen Grad an Stabilität) Mehrkanalumgebungen auszuwählen. Anschließend wird ein QoS-fähiges Mehrkanal-Mehrfachsenken-Routing-Protokoll mit dem Titel QCM2R vorgeschlagen, das für eine End-to-End-Kommunikation mit hoher Leistung in streambasierten MWSNs geeignet ist. Die Simulationen von MAC-Protokollen werden in MATLAB durchgeführt, während das Routing-Protokoll in NS-2 implementiert ist. Die Ergebnisse zeigen, dass unsere entwickelten Protokolle hinsichtlich der Leistung besser sind als die existierenden Protokolle.

Darüber hinaus werden in dieser Dissertation die Vorkenntnisse, Anwendungsbereiche, Probleme und Herausforderungen der Mehrkanaltechnologie auf MACund Routing-Ebenen ausführlich erörtert. Zum Abschluss der Arbeit werden zahlreiche zukünftige Forschungsrichtungen auf den entsprechenden Ebenen skizziert.

# ABSTRACT

Indeed 21<sup>st</sup> century can be regarded as information era which has revolutionized and modernized the world with the implementation of information and communication technologies. In the prevailing information era, high performance wireless communication has an enormous contribution in further advancing and digitizing the conventional communication infrastructure. To do so, a variety of new wireless technologies are invented such as IEEE 802.11, 3G/4G, WiMax, ZibBee and suchlike, that have revolutionized the world with numerous exciting features.

In the similar line, Wireless Sensor Networks (WSNs) is a growing wireless network technology that may play a pivotal role in sensing, surveillance and automatic monitoring of the surroundings. Due to self organizing and independent nature, WSNs may automate the observation of a region of interest. Subsequently, sensor networks may ensure division of labor of human beings and may further contribute to digitize the globe. That is why, WSNs may be regarded as a potential player for bringing socio-economic and technological advancement of the world.

Conventionally, wireless communication was single channel based and channel assignment was performed in a static manner. Being based on single frequency channel, these sensor networks may suffer from various challenges such as throughput loss, delay, congestion and retransmissions overhead. With the advancement of technology, Multichannel Wireless Sensor Networks (MWSNs) were introduced, having the ability to provide parallel communication for improving network throughput, delay, packet loss ratio and so on. In this way, MWSNs may be regarded as suitable candidate for ensuring real-time, reliable and efficient communication in delay sensitive applications such as multimedia or stream-based sensor networks. Eventually, MWSNs may make sure high performance communication in mission critical WSNs.

Although a variety of wireless channels are available in the unlicensed Industrial, Scientific and Medical band (ISM), however selecting an appropriate communication channel among the available wireless frequencies (as per application requirements) is indeed a demanding assignment in MWSNs. Since switching a wireless channel is costly in terms of delay and energy consumption, therefore, it is a challenging task to judiciously decide about channel switching, keeping in view the application requirements of WSNs. Besides that, too frequent channel switchings may induce data loss in high data rate applications such as multimedia and stream-based sensor networks. Furthermore, devising appropriate mechanism for JOINT channel assignment and routing for improving Quality ABSTRACT

of Service (QoS) and thereby ensuring high performance in MWSNS is a real challenge.

To handle the above mentioned challenges, this dissertation contributes a variety of algorithms whose purpose is to select the appropriate channel for wireless communication and to employ it for routing the surveillance information to multiple sink nodes for achieving high performance in mission critical MWSNs. For this purpose, two multichannel MAC protocols i.e. Ext-NEAMCBTC and MAGIC are devised for selecting the appropriate communication channel in normal and noisy (with some degree of stability) multichannel environments respectively. Afterward, a QoS-aware multichannel multi-sink routing protocol is proposed entitled as QCM2R that is suitable for high performance end-to-end routing in stream based MWSNs. The simulations of MAC protocols are performed in MATLAB whereas the routing protocol is implemented in NS-2 and its graphs are constructed in MATLAB. The results shows that our devised protocols are superior in performance than the existing counterparts.

Furthermore, this dissertation discusses in-detail the preliminaries, application areas, issues/challenges of multichannel technology at MAC and Routing layers. The thesis is concluded by outlining numerous future research directions at the corresponding layers.

# LIST OF FIGURES

1.1	Surveillance using a multichannel/multipath WSN [4]	2
3.1 3.2 3.3 3.4 3.5 3.6 3.7 3.8 3.9 3.10	Classification of Multichannel MAC Protocols in WSNs Unicast and Broadcast Communication in MuChMAC Protocol [221] Frequency Hopping in Y-MAC Protocol [154] Operation of in QoS-MAC Protocol [133] Data Communication in EM-MAC Protocol [192] Timeslot and Frequency Assignment in HYMAC Protocol [179] Transmission slot in MMSN Protocol [213] Channel Assignment to Clusters in DTFMM Protocol [89] Network Segmentation in HMC-MAC Protocol [129] Channel Assignment in MASN Protocol [167]	38 41 44 45 47 53 57 59 60 69
4.1	Significance of Survey	73
4.2	Taxonomy of Multichannel Routing Protocols in WSNs	90
4.3 4.4	Hierarchical Model of Nodes redrawn from DRM-MAC Protocol [147] Demonstration of Random Walks based Approach depicted from	94
1. 1	OR+SCP Protocol [164]	97
4.5	Data Aggregation based Routing in ICADAR Protocol [96] using Two	
1.0	Channels	98
4.6	Demonstration of Opportunistic Module with 4 Channels and 2 Radio Interfaces sketched from MMOCR Protocol [151]	99
4.7	Vertex Coloring in QoS-aware Protocol [140] for Assigning Latin	
	Square Symbols to Nodes	101
4.8	Graphical Illustration of channel assignment procedure depicted	102
4.9	from Distributed-CA Protocol [117]	103
1.7	· · ·	105
		107
4.11	Multipath/multichannel data transmission in QS-LEERA-MS Proto-	114
	col [19]	114
5.1	Diagrammatic representation of Channel Rank Measurement (CRM)	
5.2	0 0	122 125
5.2 5.3	0	125
5.4		120
5.5		131
5.6	Channel quality (and stability) assessment for NEC.	133

5.7	Channel quality (and stability) assessment for NEWMAC	134
5.8	Channel quality (and stability) assessment for NEAMCBTC	135
5.9	Channel quality (and stability) assessment for Ext-NEAMCBTC	136
5.10	Channel abnormal behavior tracking and healing.	137
5.11	Channel switching energy overhead. Case I: the channel switching	
	energy consumption of the compared techniques shows that Ext-	
	NEAMCBTC and random selfish (in the above scenario) are the best	
	due to no switching energy overhead, while the EM-MAC-based	
	approach behaves the worst among all	139
5.12	Channel switching energy overhead. Case II: the channel switching	
	energy consumption of the compared techniques shows that Ext-	
	NEAMCBTC is superior while random selfish (in the above scenario)	
	performs worse than the NEWMAC approach. Random channel	
	selection gives varying behavior to the random selfish approach	139
5.13	Channel switching delay overhead. Case I: the channel switching	
	delay measurement of discussed algorithms where Ext-NEAMCBTC	
	and random selfish (in the above scenario) are behaving the best	
	owing to no switching delay overhead, whereas the EM-MAC-based	1 4 1
F 1 4	approach behaves the worst due to frequent channel hopping	141
5.14	Channel switching delay overhead. Case II: the channel switching	
	delay measurement of discussed algorithms where Ext-NEAMCBTC	
	behaves the best while random selfish (in the above scenario) behaves worse than NEWMAC technique. The varying behavior of random	
	selfish approach is due to random channel selection.	141
	senish approach is due to random channel selection.	111
6.1	Current confidence interval at a particular channel quality level	
	considers only immediate past confidence interval at that channel	
	quality level	156
6.2	Confidence interval based channel selection probability calculation	
	(based on intermediate channel quality level in Fig. 1)	159
6.3	Change in channel quality levels Part(A). is showing the change in	
	channel quality from Intermediate to Good level, Part(B). is repre-	
6.4	senting the channel quality change from Bad to Good level	160
< <b>-</b>	Channel switching and toggling behavior	163
6.5	Channel switching and toggling behavior	
6.5 6.6	Channel switching and toggling behavior	163
	Channel switching and toggling behavior	163 165
6.6	Channel switching and toggling behavior	163
	Channel switching and toggling behavior	163 165
6.6	Channel switching and toggling behavior Flowchart of the proposed channel prediction architecture Generalized diagram of channel transitions from one state to the other state. For simplicity, only the transitions <i>from/to</i> state 1 are depicted here. The quality thresholds are based on Table 6.3 The quality levels (states) involved in transition of channels 1, 2, 3 and 4 are depicted in Sub-Figures ( <b>a</b> ), ( <b>b</b> ), ( <b>c</b> ) and ( <b>d</b> ) respectively. For	163 165
6.6	Channel switching and toggling behavior Flowchart of the proposed channel prediction architecture Generalized diagram of channel transitions from one state to the other state. For simplicity, only the transitions <i>from/to</i> state 1 are depicted here. The quality thresholds are based on Table 6.3 The quality levels (states) involved in transition of channels 1, 2, 3 and 4 are depicted in Sub-Figures ( <b>a</b> ), ( <b>b</b> ), ( <b>c</b> ) and ( <b>d</b> ) respectively. For simplicity, the transitions <i>from/to</i> only two states of each channel are	163 165
6.6	Channel switching and toggling behavior $\dots \dots \dots \dots \dots \dots$ Flowchart of the proposed channel prediction architecture $\dots \dots$ Generalized diagram of channel transitions from one state to the other state. For simplicity, only the transitions <i>from/to</i> state 1 are depicted here. The quality thresholds are based on Table 6.3. $\dots$ The quality levels (states) involved in transition of channels 1, 2, 3 and 4 are depicted in Sub-Figures ( <b>a</b> ), ( <b>b</b> ), ( <b>c</b> ) and ( <b>d</b> ) respectively. For simplicity, the transitions <i>from/to</i> only two states of each channel are depicted here i.e. ( <b>a</b> ) from states 1 & 7 of channel 1; ( <b>b</b> ) from states 1	163 165
6.6	Channel switching and toggling behavior Flowchart of the proposed channel prediction architecture Generalized diagram of channel transitions from one state to the other state. For simplicity, only the transitions <i>from/to</i> state 1 are depicted here. The quality thresholds are based on Table 6.3 The quality levels (states) involved in transition of channels 1, 2, 3 and 4 are depicted in Sub-Figures ( <b>a</b> ), ( <b>b</b> ), ( <b>c</b> ) and ( <b>d</b> ) respectively. For simplicity, the transitions <i>from/to</i> only two states of each channel are depicted here i.e. ( <b>a</b> ) from states 1 & 7 of channel 1; ( <b>b</b> ) from states 1 & 6 of channel 2; ( <b>c</b> ) from states 1 & 9 of channel 3; ( <b>d</b> ) from states 2	163 165 167
6.6	Channel switching and toggling behavior	163 165
6.6 6.7	Channel switching and toggling behavior Flowchart of the proposed channel prediction architecture Generalized diagram of channel transitions from one state to the other state. For simplicity, only the transitions <i>from/to</i> state 1 are depicted here. The quality thresholds are based on Table 6.3 The quality levels (states) involved in transition of channels 1, 2, 3 and 4 are depicted in Sub-Figures ( <b>a</b> ), ( <b>b</b> ), ( <b>c</b> ) and ( <b>d</b> ) respectively. For simplicity, the transitions <i>from/to</i> only two states of each channel are depicted here i.e. ( <b>a</b> ) from states 1 & 7 of channel 1; ( <b>b</b> ) from states 1 & 6 of channel 2; ( <b>c</b> ) from states 1 & 9 of channel 3; ( <b>d</b> ) from states 2 & 6 of channel 4	163 165 167 168
<ul><li>6.6</li><li>6.7</li><li>6.8</li><li>6.9</li></ul>	Channel switching and toggling behavior	163 165 167 168 168

7.1	SAP Message Broadcast from Sink 1 (aka Destination 1)	190
7.2	Hello Messages Broadcasts for Updating hop count, Residual Energy	
	and Path Reservation Status of Sensor Nodes	192
7.3	RREQ Broadcasts at Source for Sink 1 (aka Destination 1)	195
7.4	Preferred intermediate neighbor rebroadcasts RREQ for Sink 1 (aka	
	Destination 1)	196
7.5	End-to-end reverse path establishment at the arrival of RREQ Broad-	
	cast at Sink 1 (aka Destination 1)	197
7.6	RREP Unicasts from Sink 1 (aka Destination 1) to Source and simul-	
	taneous execution of BCCS Mechanism at each on-path node	198
7.7	PS transmission (periodically) from Sink 1 & 2 (aka Destinations 1 &	
	2) to Source node	199
7.8	Path Setup Module (PSM) of QCM2R: depicting Algorithms regard-	
	ing Sink Advertisement Packet (SAP), Next Hop Selection (NHS),	
	Route Request message ( <i>RREQ</i> ) and Route Reply message ( <i>RREP</i> ).	200
7.9	Path Setup Module (PSM) of QCM2R: depicting Algorithms regard-	
	ing Best Common Channel Selection (BCCS).	203
7.10	Preferred Path Selection Module (PPSM) of QCM2R: depicting Algo-	
	rithms for Path Statistics ( <i>PS</i> ) calculation, Path Calculation Metric	
	( <i>PCM</i> ) and Preferred Sink Calculation ( <i>PSC</i> )	204
7.11	Channel Tuning Module ( <i>PSM</i> ) of QCM2R: depicting Algorithms	
	regarding Refresh Path Channel Request (RPCREQ), Refresh Path	
	Channel Reply ( <i>RPCREP</i> ) and Channel Tune Signal ( <i>CTSIG</i> )	206
7.12	Network Lifetime of QCM2R and multi-REBTAM.	212
7.13	Network Lifetime of QCM2R for One, Two and Three Source and	
	Two Sinks (Destinations).	213
7.14	Network Reliability of QCM2R and multi-REBTAM	214
7.15	Network Reliability of QCM2R for One, Two and Three Source and	
	Two Sinks (Destinations).	215
7.16	Network End-to-End Delay of QCM2R and multi-REBTAM	216
7.17	Network End-to-End Delay of QCM2R for One, Two and Three	
	Source and Two Sinks (Destinations)	217
7.18	Network Throughput of QCM2R and multi-REBTAM	218
7.19	Network Throughput of QCM2R for One, Two and Three Source and	
	Two Sinks (Destinations)	219

# LIST OF TABLES

3.1	Review of channel related strategies of multichannel MAC protocols for WSNs	25
3.1	(Continued)	26
3.2	Evaluation of generic features of multichannel MAC protocols for	
	WSNs	29
3.2	(Continued)	30
3.3	Anatomization of design challenges of multichannel MAC protocols for WSNs	34
3.3	(Continued)	34
3.4	Supplementary attributes of highly robust multichannel MAC proto-	55
	cols for WSNs	50
3.5	Supplementary attributes of medium robust multichannel MAC pro-	64
3.5	tocols for WSNs	64 67
3.6	Supplementary attributes of least robust multichannel MAC proto-	07
0.0	cols for WSNs	67
4.1	Review of Existing Surveys on Multichannel WSNs	75
4.2	Comparison of the General Characteristics of Multichannel Routing	
	Protocols for WSNs	80
4.2	(Continued)	81
4.3	Comparison of Channel Access Mechanism of Multichannel Routing Protocols for WSNs	86
4.3	Continued	87
4.4	Miscellaneous Characteristics of Multichannel Routing Protocols for	07
	WSNs	111
4.4	(Continued)	112
4.4	(Continued)	113
5.1	Demarcation link types. LQI, link quality indicator.	118
5.2	Summary of related protocols reviewed. ETX, expected number of	
	transmissions.	121
5.3	Channel rank measurement metric.	123
5.4	$\beta$ - <i>tracker</i> based channel quality level $Q(ch)$ assignment with $q_1 = 0.3$ ,	129
5.5	$q_2 = 0.2, q_3 = 0.1$ $\beta$ -tracker-based channel decision making.	129
5.5 5.6	Simulation parameters.	129
5.0		152

#### LIST OF TABLES

5.7	Feasibility of the proposed schemes for stream-based communication in multichannel WSNs. CQA; CQTA, channel quality-tracking assessment;						
	CSA, channel stability assessment.	138					
6.1	Listing of Symbols with Description	145					
6.2	Review of channel assignment methodology, quality and stability						
	analysis of multichannel MAC protocols for WSNs	149					
6.2	(Continued)	150					
6.3	Channel quality levels	162					
7.1	Overview of QCM2R Control Packets	193					
7.2	Energy Levels during <i>NHS</i>	201					
	Overview of Simulation Parameters						

# CONTENTS

DEDIC	ATION	V
Ackno	OWLEDGMENT	vii
Kurzf	ASSUNG	ix
Abstr	ACT	xi
List o	F FIGURES	xiii
List o	f TABLES	xvii
Conte	NTS	xix
1 INT 1.1 1.2 1.3 1.4 1.5 1.6	RODUCTION: A BRIEF OVERVIEWBackground	1 3 4 4 5 5 6 7 7 8 9 10
2 SAI 2.1 2.2	IENT GUIDELINES FOR LITERATURE REVIEWIntroduction	13 13 13 14 14 14 15 15 15

		2.2.7	Novelty of Research	15		
3	Mu	ULTICHANNEL TECHNOLOGY OVERVIEW: AT MAC LAYER 17				
	3.1	Introd	uction	17		
	3.2	Related	d Contributions and Analysis	18		
	3.3	Applic	cations of Multichannel WSNs—With reference to Emerging			
		Smart	Technologies	20		
		3.3.1	Smart Cities — Air-Drones Communication	20		
		3.3.2	Smart Grid Framework	21		
		3.3.3	Smart Homes	21		
		3.3.4	Smart Transportation Networks	22		
		3.3.5	Smart Healthcare Applications	22		
	3.4	Design	Issues of Multichannel MAC Protocols for WSNs	23		
		3.4.1	Dynamic Power-management Issue	23		
		3.4.2	Node Deafness Issue	23		
		3.4.3	Multichannel Hidden-terminal Issue	24		
		3.4.4	Communication Impedance Issue	27		
		3.4.5	Frequent Channel-switching Issue	27		
		3.4.6	Redundancy Avoidance Issue	28		
		3.4.7	Transmission-power Control Issue	31		
		3.4.8	Single-sink-bottleneck Handling Issue	31		
		3.4.9	Load Balancing Issue	32		
		3.4.10	Security Threat Issue	33		
		3.4.11	Interference Avoidance Issue	36		
		3.4.12	Clock Drift Issue	36		
			Control Design Inefficiency Issue	36		
	3.5		Protocols for Multichannel MWSNs	39		
		3.5.1	Highly-Robust Protocols	40		
		3.5.2	Medium-Robust Protocols	51		
		3.5.3	Least-Robust Protocols	66		
		0.0.0		00		
4			ANNEL TECHNOLOGY OVERVIEW: AT NETWORK			
	LAY			71		
			uction	71		
	4.2	0	cance of Survey	73		
	4.3		ations of Multichannel Routing Protocols for WSNs	76		
		4.3.1	Disaster Management	76		
		4.3.2	Combat/Surveillance Operations	77		
		4.3.3	Industrial Exploration	77		
		4.3.4	Moving Phenomenon Tracking	77		
		4.3.5	Air-Vehicles On-board Communication	78		
	4.4		and Challenges of Multichannel Routing Protocols for WSNs $$ .	78		
		4.4.1	Network Architecture Design	79		
		4.4.2	Energy Efficiency	79		
		4.4.3	Network Service Quality Issues	82		
		4.4.4	Load Balancing	84		
		4.4.5	Data Fusion and Aggregation	84		
		4.4.6	Network Scalability Issue	85		

#### CONTENTS

		4.4.7	Broadcast Issue	85
		4.4.8	Fault Tolerance	85
		4.4.9	Miscellaneous Issues	88
	4.5	JOINT	Channel Assignment and Routing (JCAR) at Network Layer	89
		4.5.1	Single Path Multichannel Routing Protocols for WSNs	91
		4.5.2	Multi Path Multichannel Routing Protocols for WSNs	100
	4.6	DISJO	INT Channel Assignment and Routing (DCAR) at Network Layer	104
		4.6.1	Single Path Multichannel Routing Protocols for WSNs	104
		4.6.2	Multi Path Multichannel Routing Protocols for WSNs	109
5			QUALITY AND STABILITY ESTIMATION: FOR LONG	
	ANI	SHO	RT-TERM STABLE FREQUENCIES	117
	5.1	Introd	uction	117
	5.2		d Work and Motivation	119
	5.3		n Model	121
	5.4		el Rank Measurement	122
	5.5	Superv	vised Machine Learning-Based Prediction Algorithms	123
		5.5.1	Normal Equation-Based Prediction	123
		5.5.2	Normal Equation-Based Channel Quality Prediction Algorithm	125
		5.5.3	Normal Equation-Based Weighted Moving Average Channel	
			Quality Prediction Algorithm	126
		5.5.4	Normal Equation-Based Aggregate Maturity Criteria with Beta	
			Tracking Based Channel Weight Prediction Algorithm	127
	5.6		mance Evaluation	131
		5.6.1	Channel Quality and Stability Assessment Using the Proposed	
			Machine Learning-Based Algorithms	132
		5.6.2	Measurement of Channel Switching Overhead	138
6			QUALITY AND STABILITY ESTIMATION: FOR SHORT	-
	TER		BLE FREQUENCIES	143
	6.1		uction	143
	6.2	Literat	ture Review and Motivation	144
		6.2.1	Primus-Inter-Pares based multichannel MAC protocols	146
		6.2.2	Deterministic based multichannel MAC protocols	147
	6.3	Propos	sed System Model and Problem Statement	153
		6.3.1	Proposed System Model	153
		6.3.2	Problem Statement	154
	6.4	Propo		
		ach fo	r Grading Immediate Channels for Stream-based Multichannel	
		Wirele	ess Sensor Networks	155
		6.4.1	Channel Residence Probability Estimation	155
		6.4.2	Channel Quality Tracking	161
		6.4.3	Average-past Confidence Interval Boosting	161
		6.4.4	Channel Quality Smoothing	162
		6.4.5	Channel Toggling Probability Calculation	162
		6.4.6	Special Cases	166
	6.5		mance Evaluation	166
		6.5.1	Simulation Framework	166

#### CONTENTS

		6.5.2	Simulation Results and Discussion	170
7	Qo	S-AWA	RE CROSS-LAYERED MULTICHANNEL MULTISINK	
	Rou	UTING		177
	7.1	Introd	uction	177
	7.2	Literat	ture Review and Motivation	179
		7.2.1	JOINT Channel Assignment & Routing based Approaches	179
		7.2.2	Multisink Routing Protocols	184
		7.2.3	Motivation	188
	7.3	Propo	sed Network Model	188
	7.4	Propo	sed QoS-aware Cross-layered Multichannel Multisink Routing	
		Protoc	ol for Stream-based WSNs	191
		7.4.1	QCM2R: A Brief Operational Overview	191
		7.4.2	QCM2R: A Compendious Modular Overview	194
	7.5	Perfor	mance Evaluation	211
		7.5.1	Network Lifetime	211
		7.5.2	Network Reliability	213
		7.5.3	Network End-to-End Delay	215
		7.5.4	Network Throughput	219
8	Co	NCLUS	SION AND FUTURE RESEARCH	221
	8.1	Conclu	usion: A Synopsis of Contributions	221
	8.2	Open	Research Directions: An Overview of Recommendations	223
		8.2.1	Based on MAC based Review [3]	223
		8.2.2	Based on Routing based Survey [6]	226
Lı	ST O	f Pubi	LICATIONS	231
	Arti	cles fror	n trade Journals	231
Bi	BLIO	GRAP	НҮ	233
	Diss	ertation	s and specialist Books	233
	Arti	cles fror	n trade Journals	233
	Con	ference	Articles	241
	Othe	ers		252

# CHAPTER **1**

# INTRODUCTION: A BRIEF OVERVIEW

## 1.1 BACKGROUND

Wireless sensor networks are composed of tiny sensing devices which are equipped with small memory, processor, sensing unit, battery and a transceiver for data exchange [4]. These tiny devices are deployed in a challenging terrain either in a planned manner or dropped from the air [139] and may self-organize themselves in ad-hoc manner [11] [20]. In this way, they may perform division of labor and may help human beings in environmental monitoring in an efficient manner. Doing so, WSNs may accomplish a variety of duties such as dealing with natural calamities [118], defending against sniper attacks [182], accomplishing structural observation [198], performing target tracking [205], monitoring environment [83], oceans [15] and patients remotely in the disaster regions [60] [136], health-care [86] [14] such as telemedicine prescription [42], combat/surveillance operations, industrial exploration [6] and so on.

Traditionally, energy conservation (network lifetime maximization) was considered the primary design goal in WSNs [27] [6] whereas throughput, delay and bandwidth utilization were regarded as the secondary design objectives [27]. However, the sensitivity of a variety of applications towards low-bandwidth and high-delay has motivated researchers to focus on secondary design objectives as well e.g. structural health monitoring applications [23] may sample at a high rate for identifying structural damages in buildings and therefore, require more bandwidth. Similarly, the researchers have realized that Wireless Multimedia Sensor Networks (WMSNs) [37] [63] [12]-based applications (such as near-shore video monitoring [41]) could perform appropriately, if the inherent sensing network fulfills bandwidth and delay requirements of real-time delay-sensitive multimedia data. Likewise, stream based data communication can be efficiently performed when the data stream is transmitted on a channel exhibiting good quality and stability.

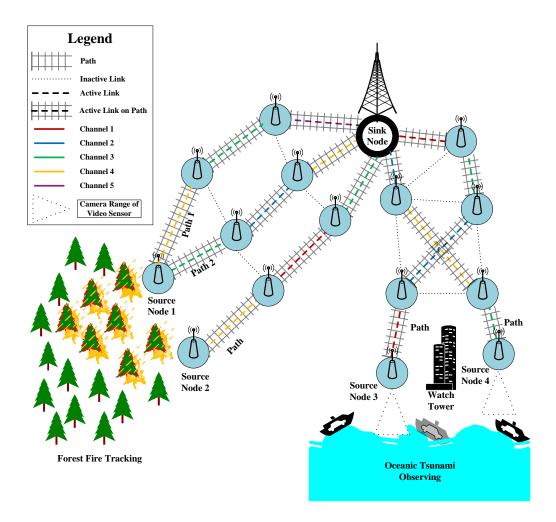


Figure 1.1: Surveillance using a multichannel/multipath WSN [4]

Statically assigning a single channel for communication cannot meet the above objectives because 2.4 GHz based Industrial, Scientific and Medical band (ISM) is already over-crowded due to the existence of various technologies such as ZigBee/ IEEE 802.15.4, Wi-Fi/ IEEE 802.11, Bluetooth, Car-Alarms, Microwave-Ovens and Wireless-Microphones [241]. Due to the fact that these neighboring technologies affect each other communication, the chances of efficient communication in IEEE 802.15.4 based WSNs (having wireless channel statically assigned) are further diminished. For dealing effectively with the above mentioned issues, the researchers have realized the utilization of multichannel technology in WSNs and henceforth Multichannel Wireless Sensor Networks (MWSNs) are emerged.

Multichannel technology can be used in a variety of applications of WSNs such as moving phenomenon (e.g. forest fire and water currents) tracking [139], air-vehicles on-board communication [109], cooperative mobile robot-based applications [175], multimedia communication [161] [89] [133] [19], smart cities [3], disaster management, surveillance operations, industrial exploration and air-vehicles on-board communication [6]. Furthermore, employing multichannel methodology in the emerging smart technologies may bring further efficiency and robustness in their operations. Besides that, a detailed description of various applications of WSNs is outlined in Sections 3.3 and 4.3.

Until now, a brief overview of multichannel WSNs is provided. In Section 1.2, we would briefly explain 2.4 GHz standards and exploiting a particular frequency band using multichannel radios. The Section 1.3 provides a general overview of architectural framework employed in this thesis. In Section 1.4, we would delineate the scope and problems definition of this dissertation. The Section 1.5 discusses various novel contributions of this thesis. In Section 1.6, we would explain the overall structure of this dissertation in a brief manner.

# 1.2 A BRIEF OVERVIEW OF 2.4 GHZ BASED WIRE-LESS STANDARDS

ISM band comprise of numerous *unlicensed* frequency bands (of the overall radio frequency spectrum) that are reserved by International Telecommunication Union (ITU) for providing *free-of-cost* communication internationally to ISM applications. The 2.4 GHz ISM band is the one among those frequency bands that has a bandwidth of 100 MHz. The reason for its popularity is due to providing *free-of-cost* communication to various *day-to-day* applications across the globe such as walkie-talkies, security cameras, wireless phones and microwave oven etc. A variety of standards operate in the unlicensed 2.4 GHz ISM band. The main standards include ZigBee/ IEEE 802.15.4, Wi-Fi/ IEEE 802.11, Bluetooth/ IEEE 802.15.1 and Wireless USB. Among them, ZigBee Bluetooth and Wireless USB are the Private Area Network (PAN) technologies [246] while Wi-Fi is a Local Area Network (LAN) technology. The PAN technologies may communicate in the infrastructure-less or small-infrastructure oriented mode.

Among them, ZigBee is based on Direct Sequence Spread Spectrum (DSSS), built over IEEE 802.15.4 and supports low-power, self-organized and multihop communication in WSNs and IoT based applications [218]. The ZigBee devices at 2.4 GHz ISM band may use 16 channels or communication and may transmit at a distance of 100 meters Line of Sight (LoS) using a data rate of 250 kbit/s [260]. Bluetooth employs Frequency Hopping Spread Spectrum (FHSS) for transmitting data over short distances in 2.402-2.480 GHz ISM band. It divides the assigned bandwidth into 79 channels (1MHz each) which are hopped 800 times/sec using Adaptive Frequency Hopping mechanism (AFH) [220]. Additionally, the Bluetooth Basic Rate/Enhanced Data Rate (BR/EDR) ranges 1 Mb/s-3 Mb/s [249]. Wireless USB is another technology operating in 2.4 GHz ISM band and provides high bandwidth communication using 79 channels (1MHz each). Being frequency agile, it uses fixed channel for communication as long as the link quality is good, otherwise shifts the channel dynamically [218]. This technology may be employed for WSNs [218].

Wireless Fidelity (WiFi) is a technology operating very frequently in 2.4/5.8 GHz ISM band [257]. Among the WiFi standards, IEEE 802.11b and 802.11g operate in 2.4 GHz ISM band, whereas 802.11n operates in both 2.4/5 GHz ISM bands [235]. Both IEEE 802.11b and 802.11g comprise of 14 wireless channels whereby each channels has a bandwidth of 22 MHz [218]. The separation

between all the channels is 5 MHz except the last *channel 14* which is 12 MHz apart from *channel 13*. The IEEE 802.11b is DSSS based with an indoor and outdoor range of 35m and 140m respectively whereas 802.11g is Orthogonal Frequency Division Multiplexing (OFDM) based with an indoor and outdoor range of 38m and 140m respectively [235]. In addition to that, the maximum achievable data rate of IEEE 802.11b and 802.11g are 11 Mbit/s and 54 Mbit/s respectively [235].

## 1.2.1 EXPLOITING A 2.4 GHZ BASED FREQUENCY BAND

A multichannel WSN is a network of sensor nodes occupying multichannel enabled transceivers. Unlike the conventional transceivers, a multichannel transceiver may tune to any of the available frequencies in the allowed frequency spectrum in a static, hybrid or dynamic manner (as explained in Section 1.3.3). The motivation behind using multichannel radios is many folded. i.e.

- Spectrum Efficiency: Each unlicensed wireless technology is allocated a specific frequency band in the 2.4 GHz band e.g. ZigBee/ IEEE 802.15.4 operates in 2.4–2.4835 GHz band [241] while Wi-Fi/ IEEE 802.11 bandwidth is 2.402–2.494[235]. The efficient communication in the given bandwidth may be feasible using multichannel radios. It is because a multichannel radio is able to switch to any of the available channels in the 2.4 GHz ISM band. Therefore, employing multichannel radios for communication may bring about efficiency in spectrum usage.
- Spectrum Variability: Due to time-variant nature of wireless frequencies, the wireless channels may exhibit varying response at different instants of time. Employing multichannel radios may enable WSNs to tune to better channels at different epochs. Communicating on better quality stable channels is efficient and cost effective solution for high data rate applications such a multimedia and stream based communication.
- Spectrum Maneuverability: Multichannel radios are indispensable for opportunistically or intelligently using the available spectrum. Consequently, high performance, reliability and robustness may be achieved.

# 1.3 A GENERAL OVERVIEW OF SYSTEM ARCHITEC-TURAL FRAMEWORK

Based on a brief discussion, this section delineates some general features of the proposed system architecture, as outlined below.

## 1.3.1 INFRASTRUCTURE-BASED VS INFRASTRUCTURE-LESS WIRELESS NETWORKS

The wireless networks can be broadly categorized into two main categories i.e. *infrastructure-based* and *infrastructure-less*. The *infrastructure-based* wireless networks contain a central entity called access point with whom the nodes in the range are directly linked. They are capable of making centralized decisions

and henceforth they are more optimized. Being infrastructure-based, they may suffer from network establishment and administration costs. A common example of such networks are the cellular networks. The *infrastructure-less* wireless networks operate in the ad-hoc or peer-to-peer mode. In this type of networks, the intelligence is distributed across the network which enables nodes to communicate with each other and take some local decisions too. Henceforth, they are more reactive than optimized. Being infrastructure-less, these networks don't suffer from network setup and management costs [258]. *In this thesis, we have considered infrastructure-less sensor networks*.

## 1.3.2 CENTRALIZED VS DISTRIBUTED MULTICHANNEL WSNS

WSNs are established on-the-fly and are a type of ad-hoc networks [258]. Therefore they are infrastructure-less by nature. Following the similar lines, the multichannel WSNs are also ad-hoc natured and operate in the infrastructureless mode. However based on the channel access mechanism, the multichannel WSNs may be categorized into two types i.e. *centralized* and *distributed* MWSNs. In case of *centralized* MWSNs, the channel assignment decisions are executed by a central entity which is normally the data gathering point or sink node. Doing so, these networks may suffer from huge control overhead (by sending channel related information to sink node), round-trip delay (by sending/receiving information to/from sink node), throughput loss (by dedicating a huge bandwidth for control purpose), energy overhead (due to sending a lot of control packets) and so on. However, the benefit is optimized channel decisions at the sink node.

On the other hand, the *distributed* MWSNs may perform channel decisions locally. Therefore they do not suffer from additional control overhead and the associated delay, throughput loss and energy overhead that the *centralized* MWSNs may experience. Additionally, distributed channel decisions are more reactive (to environmental changes) and less optimized than the *centralized* MWSNs. *In this thesis, we have employed distributed MWSNs where each multichannel radio is capable of determining local preferred channels for communication as elaborated in Chapter 5 and Chapter 6. Furthermore in Chapter 7, we have discussed a novel orthogonality criteria for peer to peer best channel assignment (based on local preferred channels of adjoining on-path nodes). Besides that, Chapter 7 also discusses a distributed next-hop selection mechanism for establishing end-to-end QoS path(s).* 

## 1.3.3 FIXED VS HYBRID VS DYNAMIC CHANNEL ALLOCA-TION

The channel assignment may be fixed, hybrid and dynamic in nature. The static channel assignment is suitable for high data rate and delay-sensitive applications with the traffic pattern known in advance [81] [3]. Such a prior knowledge of data configuration is helpful in assigning the wireless channels to multichannel radios either permanently (for network lifetime) or very sporadically (for accommodating the network aging) [81]. Therefore it may suffer from none or negligible channel switching overhead. Being unable to handle the evolving traffic patterns, this scheme is unsuitable for interference and jamming oriented environment [81]. The dynamic channel assignment requires to switch

channel before each transmission [81]. The channel switching causes some delay [81] [44] whereas frequent channel switching may induce data loss in case of high data rate applications [174]. Consequently, this scheme experiences high switching delays and thereby not suitable for the delay-sensitive applications [81]. However, the dynamic channel assignment approach is more resilient to channel/traffic variations and interference than the hybrid channel assignment scheme.

The hybrid channel assignment requires to switch channels periodically or in an event-based manner [81]. Therefore in comparison to dynamic channel assignment, it suffers from lesser channel switching overheads (in terms of delay and energy consumption). On the other hand, it may handle traffic variations and interference in a better manner than fixed channel assignment techniques. Therefore, to the best of our understanding, hybrid channel assignment approaches are more suitable for delay sensitive and high data rate applications with unknown traffic pattern. *Since we are dealing with stream based communication having high data rate and is delay sensitive, therefore, we have considered hybrid channel assignment in this thesis.* 

# 1.4 SCOPE AND PROBLEM DEFINITION

The scope of this thesis is two folded i.e. (i)- determining the local preferred channels for communication (ii)- finding the optimal paths and channels (between source and sinks) for routing the data streams from the region of interest to the preferable sink.

A large number of MWSNs use single radio for communication [6]. If wireless radio is *half-duplex* and transmitting/receiving channels of sensor node are different, then single radio based sensor networks may experience channel switching overhead (in terms of switching delay & energy consumption). In case of high data rate applications (such as multimedia/stream-based), the frequent channel switchings may induce data loss [174] that may adversely affect network performance. For decreasing frequent channel switchings, it is more efficient and cost-effective to aim for stream-based channel assignment rather than per-packet based frequency allocation [20, 91]. However, stream based channel assignment may suffer from performance degradation in case the quality of a channel is frequently degraded during the transmission of data stream. Eventually, it is crucial to measure average channel response (in terms of channel quality & stability assessment) before reserving a channel for stream-based communication. However, as per literature reviewed in [6], normally multichannel protocols do not employ any scheme for channel quality assessment before allocating a wireless channel for communication.

The channel quality and stability estimation criteria is helpful in determining the best channel for stream-based communication. In this respect, channel status may be determined based on the quality and stability analysis of the received data packets and classifies wireless channels into good, intermediate and bad categories. Among them, good and intermediate quality channels are feasible for communication. The stability of a channel is the measure of time duration during which a wireless channel maintains a particular quality level. It is a determinant factor in deciding the suitability of a channel for accommodating a data stream. Therefore, a channel unable to maintain its quality during the transmission of data stream may cause channel switching. Additionally, frequent channel switching during data stream transmission may induce delay, energy consumption and data loss.

It is a challenging activity to find optimal end-to-end paths between source and sink nodes in MWSNs. For this purpose, there must be some efficient mechanism of network discovery, so that the multichannel sensor nodes may conserve energy and undergo less delay. Although, a variety of metrics are available for next-hop selection, however such a node may be selected as next-hop node which has both sufficient energy and less distance from sink for avoiding energy holes creation and enabling fast data delivery. Each end-to-end multi-hop path has a variety of links, therefore the channel assignment may be performed in a manner for avoiding interference. For this purpose, channel assignment may follow either top-down approach (where the link near sink is assigned channel first and so on till the source node is reached) or bottom-up strategy (which allocates channels to sensor nodes from source towards sink). For avoiding congestion in the neighborhood of sink and countering single point of failure issue, multi-sink strategy is a reasonable solution. A multi-sink WSNs may require a mechanism for selecting the best sink (path) for stream-based communication. However, when quality of a selected path decreases than a threshold value, then fresh channel decision may be taken for ensuring QoS and load balancing in streambased MWSNs.

# 1.5 NOVEL CONTRIBUTIONS

In the following sections, we will discuss the proposed technical and review contributions in this thesis. Furthermore, we will also summarize the research methodology in this dissertation. It is worth mentioning here that this thesis is based on six novel contributions, among them four are already published whereas two are submitted in the renowned impact factor journals. More precisely, our first & fourth contribution is published in the *MDPI Sensors* Journal while second & third contribution is published in *Elsevier Journal of Network and Computer Applications*. Moreover, our fifth and sixth contributions are under review and submitted respectively in the reputed journals of high impact factor. Below, we will outline a brief summary of our contributions in this thesis.

## **1.5.1 PROPOSED REVIEW CONTRIBUTIONS**

1. The first contribution of this dissertation is our novel *General Survey Design Framework (GSDF)*. It is important to underline that our GSDF is helpful for writing and evaluating WSNs related surveys specifically at network layer (as discussed in [2]) and generally at the other layers of communication protocol stack. Being inspired from the features of GSDF, the second and third contributions of this dissertation have mostly considered GSDF in their design too.

- 2. The second contribution of this dissertation is our MAC based survey for MWSNs [3]. In this review article, we have discussed a variety of design issues and challenges of multichannel technology at MAC layer. On the basis of those design issues, we have evaluated the robustness of a large number of multichannel MAC protocols for WSNs. The survey also discusses the usage of multichannel methodology in the emerging smart technologies of WSNs such as air-drones communication, smart grids, smart homes, smart vehicular networks and smart health care applications. The survey highlights a variety of future research issues and challenges for further brainstorming in this area of research.
- 3. The third contribution of this dissertation is the extensive survey of multichannel routing protocols for WSNs [6]. The review discusses the applications of multichannel technology in disaster management, surveillance operations, industrial exploration, moving phenomenon tracking and air-vehicles on-board communication. Besides that, our survey outlines a novel taxonomy which classifies the contemporary single/multi-path and single/multiradio multichannel routing protocols into JOINT and DISJOINT channel assignment & routing based categories. Besides that, our review summarized the operation of multichannel routing protocols for WSNs and outlines their pros & cons too. Furthermore, our survey also discusses numerous future research directions of multichannel routing technology in WSNs.

### **1.5.2 PROPOSED TECHNICAL SOLUTIONS**

- The fourth contribution of this thesis is the Ext-NEAMCBTC algorithm [4] which may predict the best among the local preferred channels at a particular epoch based on channel quality and stability assessment criteria. Furthermore, the best channel may be used for stream-based communication in WSNs. The Ext-NEAMCBTC algorithm [4] has the ability to effectively handle the instantaneous major distortions occurring infrequently, however affecting the prediction capability of memory based protocols [4]. Besides that, it has the ability to avoid the unstable (jammed) channel. The Ext-NEAMCBTC algorithm [4] is designed for a multichannel environment where some channels maintain good, intermediate and bad quality while others exhibit a hybrid(noisy) behavior. Among these channels, some demonstrate long-term stability while others denote short-term stable behavior.
- 2. The fifth contribution of this dissertation is the MAGIC algorithm [1]. The MAGIC algorithm has the ability to select the best channel (among local preferred channels) at a particular epoch in a noisy environment, where all channels indicate short-term stable behavior. The quality assessment of available channels is determined based on channel quality and stability assessment of corresponding frequencies at a particular epoch. The protocol implements a *dynamic channel blacklisting* methodology which steadily decreases the selection probability of a channel exhibiting bad quality until the channel is completely *blacklisted (jammed)* for the communication session. Moreover, if a channel exhibits good behavior for an extended period of time, then its stability behavior may be *improved dynamically*. The protocol may

avoid switching to jammed channel or may leave frequency where jamming occurs.

The sixth contribution of this dissertation is the QCM2R algorithm [5]. The 3. QCM2R algorithm is a multichannel multi-hop multi-sink routing protocol that may determine end-to-end routes on-demand for sending surveillance information to sink nodes. During the course of path establishment, a nodeenergy and hop-count based metric is employed for selecting the optimal routes between source and sink nodes. Due to assigning (and on-demand refreshing) the best channels to individual links under channel orthogonality criteria, the protocol avoids interference and achieves reliability in MWSNs. Maintaining channel orthogonality criteria helps in possibly avoiding frequency reuse in two-hop neighborhood and achieving load balancing among communication channels. The protocol may adopt load balancing between the communication paths which enables source node to decide the best sink based on path statistics messages coming from the available sink nodes, for performing stream-based communication in MWSNs. Such a load balancing mechanism may avoid congestion and may ensure reliability/energy efficiency in MWSNs.

## 1.5.3 RESEARCH METHODOLOGY

In the beginning of our research, we have performed an extensive literature review of both renowned and fresh multichannel MAC and routing approaches. The main reason behind it was to understand the technology and to identify various open issues and challenges. After finishing this phase, we have decided to write state-of-the-art surveys regarding multichannel MAC and Routing protocols for WSNs. Before writing good quality surveys, it was very important to learn about the methodology of writing a good survey. However, we realized the unavailability of a research article that may clearly outline the design requirements of writing a good survey for WSNs. To bridge this gap, we devised a General Survey Design Framework and decided to publish it in future. In the meantime, we have completed our multichannel routing related survey (by mainly considering the proposed GSDF) and submitted it for possible publication. Afterwards, we have evaluated the design of numerous routing-related surveys under the proposed GSDF and subsequently submitted a review of routing-related surveys for WSNs. Afterwards, we have also completed a multichannel MAC survey for WSNs (by chiefly taking into account the suggested GSDF) and submitted it for possible publication.

The extensive literature review has helped us a lot in understanding the multichannel technology in WSNs and properly outlining our problem statement. Eventually, we ascertained that no multichannel MAC protocol is devised till now that may perform channel quality and stability assessment for high data rate communication in WSNs. Therefore to bridge this gap, we have devised Ext-NEAMCBTC algorithm [4] that has the ability to select the best quality stable channel (among the local preferred channels) at a particular epoch for stream based communication in MWSNs. For analyzing the performance of our protocol, we have extensively compared it with the related techniques. For the CHAPTER 1. INTRODUCTION: A BRIEF OVERVIEW

purpose of achieving more robustness, we have devised MAGIC algorithm that has the ability to perform stream based communication in a more challenging and noisy multichannel environment where the wireless channels are stable only for short time intervals. Both Ext-NEAMCBTC [4] and MAGIC algorithms are simulated in MATLAB [242] environment. Moreover, the simulation result show that the proposed protocols are superior in performance than the related techniques.

Finally, we have focused on the design of our multichannel multi-hop multi-sink routing algorithm entitled as QCM2R protocol. Since ns-2 [252] is a widely accepted network based simulator and provides a more realistic network environment, therefore we have decided to simulate QCM2R protocol in ns-2.31 [253]. The normal ns-2.31 [253] is single channel based, therefore we have patched it with CRCN Multichannel Patch [225] for ensuring multichannel capability for WSNs. Afterwards, we have implemented the proposed QCM2R protocol in multichannel enabled ns-2.31 [253] and extensively compared it with the competitor protocol. It is clear from the simulation results that the proposed QCM2R protocol clearly outperforms the opponent technique.

# 1.6 THESIS STRUCTURE

This thesis is composed of eight chapters. After this chapter, the Chapter 2 discusses a novel general survey design framework. The proposed GSDF may serve as a guiding schema for writing and evaluating the review articles at different layers of Open Systems Interconnection model (OSI model). Our literature review in Chapter 3 and Chapter 4 is mainly based on the proposed GSDF.

In Chapter 3, the use of multichannel methodology in various smart technologies is delineated. The chapter discusses MAC layer based design issues and challenges of multichannel technology. It also provides relevant tables where the important properties of multichannel MAC protocols are outlined. Additionally, most of the literature in this chapter is based on our second contribution [3].

The Chapter 4 comprehensively discusses multichannel routing in WSNs. It discusses the applications and design issues of multichannel routing in WSNs and proposes a novel taxonomy for categorizing multichannel routing protocols into JOINT and DISJOINT channel assignment and routing based categories. The literature of this chapter is mostly based on our third contribution [6].

The Chapter 5 elaborates the design and implementation of Ext-NEAMCBTC algorithm [4]. The Ext-NEAMCBTC algorithm [4] is suitable for selecting the best channel (among local preferred frequencies) at a particular epoch based on channel quality and stability estimation criteria. Furthermore, Ext-NEAMCBTC algorithm [4] considers both long and short-term stable frequencies.

In Chapter 6, the design and implementation of MAGIC algorithm [1] is delineated. The MAGIC algorithm has the ability to select the best channel (among local preferred frequencies) at a specific instant for performing stream based communication in WSNs. It also considers both channel quality and stability for performing stream based communication in WSNs. The MAGIC algorithm is designed for a noisy multichannel environment consisting of short-term stable frequencies.

The Chapter 7 elaborates the design and implementation of QCM2R protocol [5]. The QCM2R approach is a reactive multichannel multihop multi-sink routing protocol whose purpose is to send the data stream (surveillance based) to best sink using the best channels for communication. The protocol also maintains load balancing between the available sink nodes.

Finally, the Chapter 8 concludes the overall work and outlines numerous future research directions of multichannel technology based on our review articles [6] [3].

# CHAPTER **2**

# SALIENT GUIDELINES FOR LITERATURE REVIEW

# 2.1 INTRODUCTION

A concrete design framework establishes guidelines for writing a research manuscript. Such guidelines may provide coherence, organization, and consistency in the research outcome and may serve as a tool for evaluating the related manuscript. Due to methodical approach, it may also assist in drawing logical conclusions for further technological advancements in the concerned area of research. However, to the best of our knowledge, we have not found any such design framework for writing and evaluating a review manuscript for WSNs. For this purpose, we have proposed a novel general survey design framework [2]. The GSDF has devised a methodological framework that has guided us to design mutichannel MAC [3] and mutichannel Routing [6] based review articles, as discussed in Chapter 3 and Chapter 4 respectively. From now onward, we would discuss the salient features of our proposed GSDF [2].

# 2.2 GENERAL SURVEY DESIGN FRAMEWORK — A PERSPECTIVE UNDER SURVEY DESIGN REQUI-REMENTS

Writing a good survey paper is quite a challenging task. It requires both in-depth knowledge and critical analysis for classifying the related research into comprehensible categories. Subsequently, meaningful conclusions can be drawn for future research and development. A good survey paper should fulfill some basic design requirements. These design requirements may provide a platform for comparing relevant reviews and organizing the review literature into intelligible categories. However to the best of our knowledge, we have not found any review article that is clearly outlining such a design framework for analyzing the survey articles for WSNs. To bridge this gap, a *general survey design framework* is devised in [2] that may analytically evaluate the soundness of survey articles for WSNs. The key design requirements of GSDF are outlined below:

## 2.2.1 COMPREHENSIBLE LITERATURE REVIEW

Literature review has the pivotal role in the design of every survey. It may inform about the ongoing and published research and brings about novelty in further investigation. However, surveying literature properly is a time consuming activity and therefore, a large number of MAC/routing-related surveys for WSNs lack in Comprehensible Literature Review (CLR). Particularly, for providing a comprehensible literature review of routing-related surveys for WSNs, an effort is made in [2] to present a critical review of surveys emphasizing either completely or partially on routing in WSNs. It may provide an *in-depth resource* of literature for researchers who are interested in writing review articles in the corresponding areas of routing in WSNs. Subsequently, it may develop survey literature regarding different areas of routing in WSNs in future.

## 2.2.2 FIELDS OF APPLICATION

By clearly outlining the relevant Fields of Application (FoA), data-delivery models and implementation scenarios, a survey may capture the curiosity of both beginners and expert readers. Eventually, it may increase the *readability* of a survey and may develop *interest* among readers for further research and development. The motivated readers may do more brainstorming for dealing with advanced real-world problems and for bringing forth technological innovations and advancements. Therefore, a good MAC/routing survey should properly address and explain the real-world applications of a field of research. Due to the role of this design parameter in mushrooming technology, it should be considered in MAC/routing surveys design framework.

## 2.2.3 DESIGN ORIENTED CHALLENGES

The design oriented challenges of a research field describe the design issues, requirements and characteristics that a researcher may seriously consider while investigating in that particular field of research. On the one hand, they may cautious the researchers to be meticulous in addressing those challenges. On the other hand, they may motivate the researchers to propose novel techniques for addressing the undone issues and thereby contribute in technological advancements. In short, clearly outlining the design issue and challenges of a particular field of research in WSNs may not only improve understanding of researchers about that field, but also stimulate them for novel contributions in that area of research. Therefore, including Design Oriented Challenges (DOC) in MAC/routing survey design model has a very critical role in the design completeness of the corresponding survey.

2.2. GENERAL SURVEY DESIGN FRAMEWORK — A PERSPECTIVE UNDER SURVEY DESIGN REQUI-REMENTS

#### 2.2.4 PROPER COMPARISON APPROACH

On the basis of proper analytical and experimental comparison, the MAC/routing protocols may be differentiated into good, better and the best categories. The best algorithms may be used as a benchmark for future comparison with the newly devised techniques. Following this guideline, a MAC/routing survey may also provide a reliable and scientific mechanism for analytically and experimentally evaluating the relevant protocols. In this respect, a variety of parameters are used by various MAC/routing surveys for comparing the corresponding protocols. These parameters include energy efficiency, delay, reliability, throughput, jitter, mobility, scalability, architecture, data aggregation, security, multi-path, multichannel approach and so on. However, there are some inherent challenges in analytically and experimentally categorizing the corresponding surveyed protocols such as simulation set-up, operational framework and non-comparison of protocols with *widely-acceptable* techniques [73]. The analytical and experimental comparisons may enlighten the researchers to devise new protocols for handling the unattended issues, therefore Proper Comparison Approach (PCA) may be given due place in survey design framework.

#### 2.2.5 PROTOCOL DESIGN ARCHITECTURE

As outlined earlier in Section 2.2.4 that it is very hard to compare the available protocols due to variability in their simulation set-up, operational framework and comparison approaches. As a solution to this issue, a MAC/routing survey should model clear-cut and acceptable framework(s) for devising, simulating and comparing the relevant protocol(s) in the corresponding areas of WSNs. Such model(s) may bring organization in designing new MAC/routing protocols and may serve as a platform of easy comparison and evaluation of relevant techniques in future. Since Protocol Design Architecture (PDA) may address the daunting issue of variability in the design of corresponding protocols in terms of simulation set-up, operational framework and comparison with non *state-of-the-art* approaches, therefore it should be given prime importance in GSDF.

#### 2.2.6 FUTURE DIRECTIONS AND TRENDS

Properly outlining Future Directions and Trends (FDT) may provide on-hand knowledge of hot areas of research and open issues that require further investigation, brainstorming and development. A strong focus on this section of GSDF may result into flourishing novel MAC/routing techniques and up-to-date surveys that may address the pending research challenges. Since this aspect of survey design framework serves as a driving force for future research and development, therefore it should be included in GSDF.

#### 2.2.7 NOVELTY OF RESEARCH

Instead of just rearranging the surveyed protocols, a novel MAC/routing survey should provide a new approach and methodology of outlining and categorizing the surveyed literature. It describes the *pros-and-cons* of discussed routing

#### CHAPTER 2. SALIENT GUIDELINES FOR LITERATURE REVIEW

protocols that may unearth new issues and challenges. Therefore, categorizing the routing protocols in the perspective of a new taxonomy plays an important role in increasing the knowledge resource and bringing forth new ideas and challenges for future research and development. In short, Novelty of Research (NoR) is the measure of innovativeness, uniqueness and modernity or conversely repetitive-nature of a routing survey. That is why, it may also be included in the survey design framework.

# CHAPTER **3**

# MULTICHANNEL TECHNOLOGY OVERVIEW: AT MAC LAYER

## 3.1 INTRODUCTION

The bandwidth and delay requirements are very challenging to be accomplished appropriately using the traditional single channel approaches. This is due to the fact that the single channel approaches do not allow parallel transmissions and may suffer from interference in one-hop and two-hop neighborhoods. To address this issue, multichannel techniques are proposed which increase network throughput by affording parallel transmissions (through allocating dissimilar frequencies to adjoining nodes) [44] [81], avoiding interference (by allocating orthogonal channels to interfering nodes), minimizing delay (by performing fresh data delivery) [81] and extenuating interference, jamming and congestion (by providing more robust channels for communication) [81]. Therefore, multichannel techniques provide high performance to WSNs and outperform the single-channel approaches [197]. Additionally, the availability of radio chips such as CC2420 [88] and CC2520 [101] have practically assisted in materializing multichannel technology in WSNs. At current, numerous multichannel techniques are devised for WSNs which may handle various issues such as jamming [192] [4], interference [200] and help in reliable data transmission [240].

It is evident from the above discussion that the multichannel methodology provides robustness and Quality of Service (QoS) in terms of throughput, delay, reliability, and energy efficiency across a sensor network. These QoS-based metrics can be ascertained by carefully considering the underlying MAC-oriented design issues discussed in Section 3.4. In other words, if MAC-based design issues are contemplated exhaustively, they may result in achieving QoS in WSNs. It is due to the fact that MAC-based design issues are significant in locally ensuring some appropriate level of data rate, reliability, energy efficiency, jitter and delay which may contribute to enhancing *end-to-end* QoS in WSNs.

The aim of this chapter is to review the existing multichannel MAC protocols for WSNs so that the soundness of their design and *pros* & *cons* are highlighted. For this purpose, we have divided our research effort into four main categories. *It is important to mention here that the literature discussed in this chapter is mainly taken from our multichannel MAC based review article [3]*. Furthermore, the leading contributions of this chapter are outlined below:

- An overview of the implementation of multichannel methodology in the *emerging smart technologies* of WSNs is discussed/proposed.
- A variety of design issues which may impact the functionality of multichannel MAC protocols and may help in achieving QoS at MAC layer are elaborated.
- A large number of multichannel MAC protocols (31 in total) is evaluated in the light of the design issues outlined. Afterwards-based upon *aggregateof-the-design-issues* addressed by each multichannel MAC protocol, they are classified into Highly, Medium and Least-Robust categories. Furthermore, the operation of each multichannel MAC protocol is evaluated along with relevant pros & cons.

The upcoming portion of this chapter is organized as follows. In Section 3.2, the significance of this survey is put forth. Section 3.3 presents a brief overview of the emerging smart applications of MWSNs. In Section 3.4, the design issues of multichannel MAC protocols for WSNs are presented. Section 3.5 classifies multichannel MAC protocols into different groups and discusses their functionality along with pros & cons in a detailed manner. Besides that, the chapter is supported by relevant tables and diagrams for providing more clarity about the characteristics and operation of multichannel MAC protocols in WSNs. The channel related features, general attributes and design challenges of the surveyed multichannel MAC protocols are described in Tables 3.1, 3.2 and 3.3 respectively. Whereas, miscellaneous features are outlined in Tables 3.4, 3.5 and 3.6.

## 3.2 RELATED CONTRIBUTIONS AND ANALYSIS

As of today, a number of MWSNs-related surveys have been published, including [44], [31], [29], [243], [81] and [13]. All of them predominantly discuss multichannel protocols performing channel assignment at MAC layer. Below we will provide a brief summary of the above-stated reviews and afterward highlight those points that manifest the significance of our survey.

The review in [44] explores the challenges of multichannel technology and elaborates channel assignment mechanisms in wireless ad hoc networks. The survey investigates main technological differences between wireless ad hoc and sensor networks. Additionally, it differentiates multichannel protocols on the basis of coordination approaches, communication models and implementation mechanisms. Furthermore, it briefly summarizes the functionality of multichannel protocols along with their pros & cons. In the end, some future research directions are outlined.

The survey in [31] discusses various attributes of WSNs at MAC layer and challenges of multichannel MAC protocols for WSNs. Additionally, it summarizes the operational characteristics and limitations of underlying multichannel MAC protocols and compares them on the basis of a few design issues. The authors outline future research directions in a brief manner. Likewise in [29], the authors inspect and compare various multichannel protocols and outline their pros & cons. In the end, various open issues are presented. The review in [243] discusses various challenges of multichannel networks. The authors analyze various concepts such as channel assignment mechanisms, network capacity, interference, topology control, power/traffic-aware approaches and multi-radio challenges along with some examples from the published literature.

The authors in [81] scrutinize the characteristics and challenges of multichannel approaches in WSNs. The survey analyzes channel assignment strategies in WSNs with reference to cellular and mesh networks. The survey also elaborates a network framework/model and categorizes a few multichannel protocols for WSNs using the classification framework. In the end, a variety of future research directions is put forth. In [13], the authors have put forth a new classification framework which extends the previous studies (i.e. [44] [31] [81]) by considering those aspects that are relevant to the interaction of MAC with the lower and upper layers of the communication protocol stack. Afterward, various MAC protocols are discussed under the proposed classification framework. The review also outlines some multichannel issues and future research directions.

To the best of our understanding, our review is *unique* and *more comprehensive* than the already published survey studies, with the following distinctive characteristics:

- Our survey comprehensively discusses/proposes the *emerging state-of-the-art smart applications* of MWSNs as elaborated in Section 3.3, which are however not considered in the already published survey literature. Furthermore, properly describing the application areas is helpful in proliferating any technology, according to *General Survey Design Framework* proposed in [2].
- Our survey provides an *in-depth* discussion of a variety of design issues of multichannel MAC protocols for WSNs as elaborated in Section 3.4. The design issues are discussed in a manner that their role in determining QoS in multichannel MAC protocols for WSNs is properly highlighted. It may also help the protocol designers in deeply understanding those challenges and properly considering them for devising novel QoS oriented multichannel MAC protocols for WSNs. To the best of our understanding, this survey discusses those design issues in a more exhaustive manner than the already published review literature.
- Our survey analyzes the *robustness* of 31 multichannel MAC protocols on the basis of 13 design criteria outlined in Table 3.3. The *classification metric* for measuring *robustness* is *grand sum-of-the-design-issues* addressed by a multichannel MAC protocol for WSNs. Consequently, multichannel MAC

protocols are classified into *Highly, Medium* and *Least-Robust* categories, addressing a total of '9 or more', '5 to 8', and '4 or less' design issues in a respective manner. Besides that, the protocols belonging to each main category are sub-categorized on the basis of the *channel access mechanism* into *Time Division Multiple Access (TDMA), Carrier Sense Multiple Access (CSMA), Composite* and *Other-Novel* categories. To the best of our knowledge, such an evaluation of multichannel MAC protocols has not been considered in the already published studies.

• The survey synthesizes the operation of each multichannel MAC protocol along with relevant pros & cons in a more detailed manner than the already published relevant studies. Additionally, it also outlines future research directions in a detailed manner, so that the researchers may brainstorm on for further maturing multichannel technology for WSNs.

# 3.3 APPLICATIONS OF MULTICHANNEL WSNS— WITH REFERENCE TO EMERGING SMART TECH-NOLOGIES

Contrary to the single channel approach, the multichannel methodology improves performance *in-terms-of* network capacity, throughput, delivery ratio, latency, robustness [81]. Therefore, it may be employed in a variety of applications (discussed comprehensively in [6]) such as disaster management, combat/surveil-lance operations, industrial exploration, moving phenomenon tracking [139], air-vehicles on-board communication [109], cooperative mobile robot-based applications [175] and multimedia communication in WSNs [161] [89] [133] [19]. Besides that, multichannel WSNs may be employed in a *smart city environment* where numerous multichannel WSNs may be employed for environmental monitoring regarding temperature, pressure, roadside illumination, traffic monitoring, city surveillance and so on in the various metropolitan areas.

Below, some of the hot areas are discussed where multichannel WSNs technology may be employed for serving mankind.

#### 3.3.1 SMART CITIES — AIR-DRONES COMMUNICATION

With the first test of drone taxis in Dubai [230] by the German company Volocopter, Dubai is on the way for becoming the smartest city of the world by 2030, with a goal of performing one-quarter of the transportation using autonomous vehicles [230]. However, establishing autonomous air-drones transportation is a challenging job because, unlike the ground-based transportation where the roads are properly built, the air-drones-based transportation has to deal with real-time path calculations towards a destination, all around the journey. Such path calculations may be performed effectively if air drones are communicating in real-time with the main navigation management system. However, when such communication is intercepted due to jamming or interference in the communication channel, then air-drones may suffer from path loss and even collision with the neighboring air-vehicles and tall buildings. This issue may be handled

# 3.3. Applications of multichannel wsns—with reference to emerging smart technologies

by employing multichannel technology in the air-drones communication system that may assist them in maintaining an active connection with the control center using the best among the available communication channels (e.g. as devised in [4]) and thereby making secure air navigation possible. Furthermore, in case, the main air navigation system is compromised by adversaries/miscreants, then MWSNs may establish a backup cooperative navigation system which may enable air-drones to perform effective communication with the surrounding air-vehicles in the communication range. Consequently, air vehicles may avert the danger of collision with each other and assist each other effectively in air navigation through cooperative communication. In addition to that, MWSNs are able to perform on-board air-drones communication and help in reducing cabling-cost and ensuring fuel-efficiency & cheap transportation.

#### 3.3.2 SMART GRID FRAMEWORK

The electric grid refers to the intermediate infrastructure between power generation plants and households (consumers). Broadly, the SGF is comprised of transmission lines, towers, transformers, switches and local grid stations. The traditional electric grids were designed to fulfill only the electricity demand of customers and therefore-based on unidirectional power transmission only. However with the advancement of technology, a novel economic, green and more robust electric grid model came forward, termed as *Smart Grid Framework (SGF)*. The SGF enables a two-way interaction between power plants and customers. On the one hand, it enables powerhouses to fulfill the electricity demand of consumers and inform them about the peak and off-peak hours, so that the customers may manage their savings, whereas, on the other hand, the SGF may estimate region-wise power demand of customers and may also locate the sites of power breakdown too. Such information is sent by the SGF to power houses, so that the expert systems at power generation plants may perform appropriate power management activities accordingly.

Since wired sensors may suffer from severe cabling-related issues such as installation, maintenance and troubleshooting of cables, WSNs are more promising solutions for power-metering (at customer premises) and power outage detection (at intermediate locations). Since traditional WSNs are single channel-based, they may suffer more from electromagnetism and interference from the surrounding electric stations. Such electromagnetic perturbations may attenuate and distort wireless communication, so it will be better to use MWSNs for power metering and power-breakdown sensing in smart grid environments. Such MWSNs may be programmed to dynamically select the best and most stable channels for communication.

#### 3.3.3 SMART HOMES

The multichannel methodology may be used in smart homes [123] by allocating different frequencies to the sensing units, so that they may not interfere with each other's communication. Furthermore, the data collected by sensing units is sent to a coordinator node which passes it further on to the host controller for performing appropriate actions and ensuring good PDR [123].

In case of smart grid environments, smart homes are required to perform various operations simultaneously e.g. when a smart home receives a *peak hour* signal from SGF, then it may either (i) reschedule/postpone some services (such as dish-washing, clothes-drying, electric-car-charging) to *off-peak hours* or (ii) adjust some indispensable/continuous services (e.g. dimming the light bulbs, lowering down room-heating/cooling equipment and so on). For ensuring parallel communication and avoiding interference/data collision, the indispensable/continuous services may be assigned to orthogonal/non-overlapping channels which may result in reliable high-performance communication across MWSNs.

#### 3.3.4 SMART TRANSPORTATION NETWORKS

Vehicular Ad-hoc Networks (VANETs) provide vehicle-to-vehicle communication which may ensure safety on the roads. For this purpose, a variety of sensors may be deployed on-board and also in critical locations along the roadside for ensuring safety and security. Using the sensed information, a connected car may apply emergency brakes in case of an accident, reroute the vehicle in case of congestion ahead or sideline the vehicle after getting signals about the arrival of ambulances, fire-brigades and police vehicles. Normally a vehicle may travel through a diversified environment such as congested-urban areas, remote-rural communities and elevated-hilly localities where the performance of various channels is adversely influenced by overcrowding, un-reachability or altitude of the terrain. Thus, single channel WSNs may show varying communication behavior in the above circumstances and consequently are risky to be used. A promising solution is to use MWSNs where a variety of communication channels are available. Furthermore, channel quality and stability-based approaches such as Ext-NEAMCBTC [4] may be used for selecting the best quality stable channel (among the available channels) at a particular epoch for providing secure and reliable communication onboard vehicles. Finally, employing the MWSNs may increase the communication resilience of Vision Oriented Artificially Intelligent (VOAI) systems that may be deployed in vehicles for detecting fugitives or missing persons.

#### 3.3.5 SMART HEALTHCARE APPLICATIONS

One of the promising applications of MWSNs is in healthcare applications. Normally Wireless Body Area Networks (WBANs) use single channel for communication and therefore may experience malfunctioning, e.g., if a patient comes close to an interference source. If the condition of a patient is critical, then such an exposure may result in more adverse consequences. A safer and more favorable solution is to employ MWSNs for body area communication. Such multichannel WBANs would be more resilient and reliable for monitoring the patients' health and sending critical information to a remote center for analysis. Therefore, in case of an emergency, the patient may be given fast first aid.

It is clear from the above discussion that there lies a great potential in employing multichannel technology in WSNs and more innovative solutions for the unattended applications are still to come.

# 3.4 DESIGN ISSUES OF MULTICHANNEL MAC PRO-TOCOLS FOR WSNS

Multichannel MAC protocols for WSNs may experience a variety of issues. These issues, once considered carefully in the design of multichannel MAC protocols, may facilitate the protocol designers in proposing novel solutions which may provide the desired QoS (at MAC Layer) in terms of energy efficiency, throughput, delay, and jitter. The aggregate of these design issues may serve as a valuable metric for evaluating the robustness of a multichannel MAC protocol for WSNs as discussed in Section 3.5. Below we will discuss the crucial among these issues for achieving QoS at MAC layer.

#### 3.4.1 DYNAMIC POWER-MANAGEMENT ISSUE

Contrary to continuous power consumption in always-on MWSNs, dynamic power management allows multichannel sensor nodes to switch between various operational modes (such as active, passive and idle). Such transitions may help in countering the Idle Listening Issue (ILI) which may deplete 50-100% of the energy required by a sensor node for receiving data [95] and thereby ensuring energy conservation. The dynamic power management is executed through fixed or dynamic sleep/wake-up strategies.

During fixed sleep/wake-up strategy, multichannel sensor nodes exhibit static sleep/wake-up schedules that may require synchronization between sensor nodes [203]. Although a fixed duty cycling strategy is simple to implement and may conserve more energy than the always-on strategy, however it may suffer from the *sleep delay issue*. Moreover, the fixed sleep/wake-up strategy is unsuitable for handling bursty/sporadic traffic patterns and inconsistent traffic loads. The dynamic sleep/wake-up strategy follows flexible sleep/wake-up schedules which may be adjusted according to the intensity/rate of data traffic [128]. It is more energy efficient and practical than the fixed sleep/wake-up strategy because sensor nodes remain in sleep mode when there is no data to transmit or receive. Possibly, it is more suitable for sensor networks dealing with a bursty or sporadic traffic pattern. Managing dynamic sleep/wake-up schedules is a complex mechanism requiring dynamic synchronization between sensor nodes and is really a challenging issue to be coped with.

Therefore, it is the responsibility of the multichannel MAC protocol designer to consider the most suitable duty cycling strategy depending on application requirements so that Dynamic Power-management Issue (DPI) may be addressed efficaciously in MWSNs.

#### 3.4.2 NODE DEAFNESS ISSUE

The multichannel Node Deafness Issue (NDI) is caused when a sender node sends packets to a receiver node but the receiver does not listen to them as it resides on a different channel [127]. As a result, the sender tries to retransmit data packets again and again before going to a long timeout which may cause additional bandwidth consumption, data loss and unreliability in WSNs. It may

#### CHAPTER 3. MULTICHANNEL TECHNOLOGY OVERVIEW: AT MAC LAYER

also induce retransmission overhead (in terms of additional energy consumption and delay) which is not suitable for accommodating multimedia communication in WSNs.

The NDI is effectively handled in TDMA-based clustering approaches because the cluster members (CMs) wake-up on their assigned timeslot and channel for sending data to the Cluster Head (CH). However, in case of CSMA/CAbased approaches, a channel coordination mechanism may help to handle this issue [92]. Further on, sensor nodes with a single half-duplex transceiver and employing a sender/receiver-based multichannel assignment methodology may more readily suffer from the node deafness issue. This is due to the fact that, when an incoming node on a channel attempts to perform data communication with a sender or receiver node which has recently switched the same channel, then this may result in data loss. To avoid this issue, the incoming node has to make sure before sending a frame that the intended counterpart is also listening on the same channel.

Contrary to the multichannel *node deafness issue* is the multichannel *node overhearing issue* where a sensor node may overhear those packets which are intended for the other nodes [95]. However, the multichannel approach, having the ability to distribute traffic load among various orthogonal channels, naturally reduces the impact of overhearing in multichannel WSNs. Consequently, energy wastage and data loss due to overhearing can be reduced accordingly.

#### 3.4.3 MULTICHANNEL HIDDEN-TERMINAL ISSUE

A two-hop interfering node which occupies the same channel as a sender node, but resides outside the communication range of the sender node may induce the *single channel hidden terminal problem*. The single-channel hidden terminal problem may be handled by assigning non-interfering channels to two-hop interfering neighbors [102]. However, multichannel protocols may suffer from the Multichannel Hidden-terminal Issue (MHI). In this case, an incoming node to a channel may attempt to use that channel for transmitting/receiving its packets because it is unaware of any channel reservation (e.g. through Request to Send/Clear to Send (RTS/CTS) mechanism) performed earlier by the neighboring nodes already occupying that channel. Consequently, data collision and loss may occur, causing additional delay and energy overhead due to data retransmissions. The solution may be to inform the incoming node (to a new channel) about channel occupancy and reservation so that it may be refrained from transmission during the channel reservation period which may help in handling the *multichannel hidden-terminal problem* [92].

Approaches such as the even distribution of channels in a neighborhood [213], priority-based channel assignment in a locality [102] and the TDMA-based approach [45] may handle the hidden-terminal issue. Additionally, statically assigning orthogonal channels to interfering nodes may help to deter the MHI. Likewise, node coloring-based techniques such as *Latin Rectangular*-based channel hopping [94] may also assist in handling the MHI.

Protocols	Transceiver H/W	Channel Allo	cation Model	Channel Alloca	ation Orientation	Channel Allocation Type			
	Transcerver n/w	Centralized	Distributed	Sender-based	Receiver-based	Static	Hybrid	Dynamic	
MMSN [213]	Single radio		$\checkmark$		$\checkmark$		$\checkmark$		
MCMAC [122]	Single radio		$\checkmark$			$\checkmark$			
Multiple-Channel LMAC [238]	Single radio		$\checkmark$				$\checkmark$		
CMAC [127]	Multi radio		$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$		
MCPE [139]			$\checkmark$			$\checkmark$			
TFMAC [152]	Single radio		$\checkmark$		$\checkmark$		$\checkmark$		
HYMAC [179]		$\checkmark$				$\checkmark$			
ACMAC [72]	Single radio		$\checkmark$	$\checkmark$			$\checkmark$		
CTATO [158]			$\checkmark$		$\checkmark$		$\checkmark$		
PMMAC [159]	Single radio		$\checkmark$		$\checkmark$		$\checkmark$		
COM-MAC [161]	Single radio CMs/ Multi radio CHs		$\checkmark$				$\checkmark$		
Y-MAC [154]			$\checkmark$					$\checkmark$	
QoS-MAC [133]			$\checkmark$			$\checkmark$			
SMC MAC [68]	Single radio		$\checkmark$		$\checkmark$		$\checkmark$		
MuChMAC [221]	Single radio		$\checkmark$		$\checkmark$			$\checkmark$	
RMCA [208]			$\checkmark$		$\checkmark$		$\checkmark$		
MC-LMAC [45]	Single radio		$\checkmark$	$\checkmark$			$\checkmark$		

Table 3.1: Review of channel related strategies of multichannel MAC protocols for WSNs

Protocols	Transceiver H/W	Channel Allo	ocation Model	Channel Alloca	tion Orientation	Channel Allocation Type			
TIOLOCOIS		Centralized	Distributed	Sender-based	Receiver-based	Static	Hybrid	Dynamic	
EM-MAC [192]	Single radio		$\checkmark$		$\checkmark$			$\checkmark$	
MASN [167]		$\checkmark$				$\checkmark$			
IMMAC [102]	Single radio		$\checkmark$		$\checkmark$		$\checkmark$		
MCCT [104]			$\checkmark$			$\checkmark$			
DTFMM [89]	Single radio		$\checkmark$			$\checkmark$			
Enhanced HMC-MAC [129]	Single radio		$\checkmark$		$\checkmark$	$\checkmark$			
GTCF [178]	Single radio		$\checkmark$		$\checkmark$		$\checkmark$		
MinMax [71]	Single radio		$\checkmark$	$\checkmark$		$\checkmark$			
MCAS-MAC [56]	Single radio		$\checkmark$		$\checkmark$		$\checkmark$		
RC-MAC [43]	Single radio		$\checkmark$				$\checkmark$		
PWMMAC [180]	Single radio		$\checkmark$		$\checkmark$			$\checkmark$	
SLA [103]			$\checkmark$	$\checkmark$			$\checkmark$		
LRCH [94]	Single radio		$\checkmark$					$\checkmark$	
Ext-NEAMCBTC [4]	Multi radio		$\checkmark$		$\checkmark$		$\checkmark$		

#### 3.4.4 COMMUNICATION IMPEDANCE ISSUE

Statically assigning the available channels to sensor nodes may cause the Communication Impedance Issue (CII) which may hinder the direct interaction among neighboring nodes, occupying different channels for communication. Eventually, network partitioning may occur [45] [6] which inhibits the direct communication between adjoining sensor nodes and promulgates the establishment of longer alternate routes between source and sink nodes. Consequently, additional delay and energy consumption may be caused which is unsuitable for delay-sensitive applications such as multimedia. The CII may be handled by employing hybrid/dynamic channel assignment strategies, however, these approaches may suffer from channel switching overheads (in terms of switching delay and energy consumption). Furthermore, frequent channel switchings may cause data loss and extra power consumption in high data rate applications [174] [4]. Therefore, the designer of a multichannel MAC protocol should carefully consider these issues on a per-application-requirement basis for fulfilling the desired tasks in a cost-effective manner.

#### 3.4.5 FREQUENT CHANNEL-SWITCHING ISSUE

Channel switching may require additional overhead in the form of channel switching delays and energy consumption [174]. Single channel WSNs cannot switch channels and do not suffer from channel switching overhead. On the other hand, multichannel WSNs may show a varying degree of channel switching behavior subject to the underlying channel assignment strategy (e.g. static, dynamic or hybrid).

In case of static channel assignment, multichannel WSNs do not suffer from any channel switching overhead because the channel assignment may be fixed or sporadic in nature [81]. Therefore, it is more suitable for delay-sensitive and high data rate applications with the traffic pattern known in advance [81]. In case of dynamic and hybrid channel assignment, multichannel WSNs may suffer from varying degree of (Frequent Channel-switching Issue (FCI) which is more intense in dynamic than hybrid channel assignment-based MWSNs. This is because dynamic channel assignment requires (both sender and receiver nodes) to switch channel before each transmission [81] whereas hybrid channel assignment requires (either sender or receiver node in case of receiver-oriented or sender-oriented channel assignment respectively) to switch channels periodically or in an event-based manner [81]. Additionally, the dynamic channel assignment based approaches are more resilient in handling channel/traffic variations and interference than the hybrid channel assignment scheme. On the one hand, hybrid channel assignment schemes suffer from smaller channel switching overheads (in terms of delay and energy consumption) compared to dynamic channel assignment approaches. On the other hand, hybrid channel allocation techniques may handle traffic variations and interference in a better manner than static channel assignment techniques. Therefore, to the best of our understanding, hybrid channel assignment approaches are more suitable for delay sensitive and high data rate applications with unknown traffic pattern.

Conclusively, it is up to the MAC protocol designer to select an appropriate channel assignment strategy under the given constraints such as channel variations, traffic behavior, interference, throughput, and delay. Moreover, it is very important to maintain a balance between the channel usage and the switching time, so that the sensor network may maintain an equilibrium between channel starvation and frequent channel switching overhead that is required for achieving fairness in multichannel WSNs [102]. However, the accurate measure of channel fairness is still an open issue and requires further investigation. Another vital aspect regarding FCI is the hardware constraint due to half-duplex transceiver of sensor nodes. Therefore, when the sending and the receiving channels of a sensor node are different, then the transmitter would have to switch frequently between sending and receiving frequencies for performing data transmission and reception, eventually FCI may occur.

#### 3.4.6 REDUNDANCY AVOIDANCE ISSUE

The Redundancy Avoidance Issue (RAI) is significant in MWSNs. It is because, on the one hand, redundancy increases fault tolerance and reliability in WSNs [26], while on the other hand, it escalates the network budget by sending duplicate packets on the sensor network. Multichannel WSNs may employ either:

- Within-channel Redundancy: this may involve sending duplicate packets on the same channel using single/multiple path(s) as observed in conventional single-channel WSNs. Consequently, reliability is ensured at the cost of an increased data rate.

- *Between-channels Redundancy:* this may involve sending duplicate packets on multiple channels using single/multiple path(s). Such a redundancy may further enhance reliability, however, data duplication overhead would also be increased enormously which requires additional bandwidth accordingly. Possibly, the chances of packet loss and energy consumption would be increased too, if channel switching is performed frequently [174] [4].

Redundancy may be avoided by applying data suppression or aggregation techniques where either before transmission, the sensor node may suppress the irrelevant data from the sensed information or after reception, the sensor node may aggregate the data belonging to the same event while coming from various sensors. Such data processing (suppression/aggregation) involves purging the redundant information locally at sensor nodes which may lower down the data transmission rate. Consequently, energy efficiency is ensured because data transmission is more costly than data processing [69] [250]. For example, a general-purpose processor with 100 Million Instructions Per Second per Watt (MIPS/W) power may execute 3 million instructions using 3 joules of energy while, with the same amount of energy, it may send only 1kb of data over a distance of 100 meters [65]. However, data processing at a sensor node increases the waiting delay (in a queue) and associated energy consumption overhead which may add to overall end-to-end delay and energy consumption in MWSNs.

Protocols	Network	Network	Broadcast	Traffic	Callisian / Congression	Sink	
Protocols	Design	Scalability	Support	Differentiation	Collision/ Congestion Handling	Single	Multi
MMSN [213]	2 tier		$\checkmark$		$\checkmark$		$\checkmark$
MCMAC [122]	3 tier		$\checkmark$	$\checkmark$			$\checkmark$
Multiple-Channel LMAC [238]	2 tier	$\checkmark$	~		$\checkmark$	$\checkmark$	
CMAC [127]	2 tier				$\checkmark$	$\checkmark$	
MCPE [139]	2 tier	$\checkmark$	$\checkmark$		$\checkmark$	<ul> <li>✓</li> </ul>	
TFMAC [152]			$\checkmark$		$\checkmark$		
HYMAC [179]	2 tier	$\checkmark$			$\checkmark$	<ul> <li>✓</li> </ul>	
ACMAC [72]					$\checkmark$	<ul> <li>✓</li> </ul>	
CTATO [158]	3 tier	$\checkmark$	$\checkmark$		$\checkmark$		$\checkmark$
PMMAC [159]	2 tier	$\checkmark$	~		$\checkmark$	<ul> <li>✓</li> </ul>	
COM-MAC [161]	3 tier		$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	
Y-MAC [154]	2 tier	$\checkmark$	~		$\checkmark$	<ul> <li>✓</li> </ul>	
QoS-MAC [133]	3 tier		<ul> <li>✓</li> </ul>	$\checkmark$		<ul> <li>✓</li> </ul>	
SMC MAC [68]			$\checkmark$				
MuChMAC [221]	2 tier		$\checkmark$			$\checkmark$	
RMCA [208]	2 tier	$\checkmark$	<ul> <li>✓</li> </ul>		$\checkmark$	$\checkmark$	
MC-LMAC [45]	2 tier		$\checkmark$		$\checkmark$	$\checkmark$	$\checkmark$

Table 3.2: Evaluation of generic features of multichannel MAC protocols for WSNs

Protocols	Network	Network	Broadcast	Traffic	Collision/Congestion	Sink	
Frotocols	Design	Scalability	Support	Differentiation	Collision/ Congestion Handling	Single	Multi
EM-MAC [192]	2 tier	$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	
MASN [167]	3 tier				$\checkmark$	$\checkmark$	
IMMAC [102]	2 tier		$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
MCCT [104]	3 tier	$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	
DTFMM [89]	3 tier		$\checkmark$		$\checkmark$	$\checkmark$	
Enhanced HMC-MAC [129]	2 tier	$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	
GTCF [178]		$\checkmark$				$\checkmark$	
MinMax [71]			$\checkmark$		$\checkmark$	$\checkmark$	
MCAS-MAC [56]	2 tier	$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	$\checkmark$
RC-MAC [43]	2 tier	$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	
PWMMAC [180]	2 tier	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$		
SLA [103]	2 tier	$\checkmark$			$\checkmark$	$\checkmark$	
LRCH [94]	2 tier		$\checkmark$		$\checkmark$	$\checkmark$	
Ext-NEAMCBTC [4]	2 tier	$\checkmark$	$\checkmark$		✓	$\checkmark$	$\checkmark$

Table 3.2: (Continued...)

For achieving the desired system performance, it is a challenging task to decide between data redundancy and data suppression/aggregation. To sum-up, if fault tolerance and reliability is the ultimate aim, then system redundancy should be enhanced. Otherwise, data aggregation/suppression should be performed for providing energy efficiency, even though at the cost of increased delay.

#### 3.4.7 TRANSMISSION-POWER CONTROL ISSUE

Although transmission power control is a physical layer phenomenon, it has, due to its role in network connectivity, a strong relation to both MAC and network layer [99]. Eventually, Transmission-power Control Issue (TCI) is very challenging to handle in MWSNs. A decrease in transmission power decreases the communication and interference range of sensor nodes. Consequently, network interference is decreased too and energy efficiency is ensured, however latency is also increased because more hops are required to build an end-to-end path between source and destination. On the other hand, increase in transmission power levels may increase the number of communication links. It may help to select the optimal routes with low end-to-end delays [164], however at the cost of more energy consumption. It may also improve link quality [165] because higher transmission power enhances the Signal to Noise Ratio and reduces packet retransmissions [165].

In case of single-channel sensor networks, increase in transmission power may lead to network performance degradation because interference regions of sensor nodes may overlap with each other [88]. In case of multichannel WSNs, there is less likelihood of such overlap because sensor nodes in a neighborhood are tuned on orthogonal channels. However, in the matter of mobile multichannel sensor networks, the nodes may freely move from one region to the other. Therefore, there is a greater chance of overlap of interference regions of sensor nodes which may cause disruption of communication in a neighborhood.

Furthermore, employing higher power for communication on a channel may affect low power transmission(s) on the same channel in a neighborhood and consequently may cause more packet delivery delays [88]. Likewise, employing adaptive power control-based multichannel methodology may soon encourage power competition among neighboring sensor nodes which may induce additional packet delivery delays and energy consumption. Furthermore, efficient use of power level under stored energy and required bandwidth is an open research issue. Therefore, MAC protocol designers must consider these challenges before devising any new multichannel MAC protocol, which otherwise may cause severe data collision, packet loss, delay and retransmission overhead.

#### 3.4.8 SINGLE-SINK-BOTTLENECK HANDLING ISSUE

Sensor nodes sense data from their surroundings and send them towards a sink node. Normally, the load around the sink is very high and results in interference [102] and congestion. The situation becomes even worse in case of contention-oriented protocols because neighboring nodes of the sink may compete for winning the network resources and may contribute to congestion.

Eventually, it may further overload the network and may enhance single-sinkbottleneck issue. Employing the multichannel technology for data delivery to a single sink may reduce the Single-sink-bottleneck Handling Issue (SHI) in contention-oriented MWSNs. However, in case of dense networks, the multichannel approach may also suffer from congestion and collision due to reuse of overlapping/adjacent channels around the sink node. The alternative solution is to employ either the multi-sink methodology or some novel TDMA-based mechanism in MWSNs.

#### 3.4.9 LOAD BALANCING ISSUE

Multichannel sensor nodes send data on different channels (using one or more paths), therefore the traffic load on those channels is not fixed and varies over time. If it is not possible to stabilize the traffic load, a load imbalance may occur. Consequently, data collision/congestion, data loss, and unreliable communication are precipitated. Since dynamic channel assignment requires channel switching before each transmission [81], it may be more effective to perform load balancing than hybrid channel assignment where channel switching is performed either periodically or based on events [81]. The multichannel MAC protocol may adjust the traffic load dynamically and deal with the Load Balancing Issue (LBI) in the following three ways:

- *Channel Load Management:* The channel reassignment policy allows a sensor node to shift to a less busy channel dynamically, if the traffic load on the current channel is higher than a threshold level, as discussed in IMMAC [102]. However, if such a shifting is done frequently, then it may induce channel switching overhead, otherwise channel starvation may be caused [102] due to an indefinitely long residence of a sensor node on the same channel. Since this approach involves continuous monitoring of traffic load on all the available channels in a two-hop neighborhood, it may suffer from additional control overhead and energy consumption.

- *Traffic Prioritization:* The sensor nodes prioritize data packets on the basis of different criteria such as delivery models (e.g. event-based or query-based), QoS criteria (e.g. remaining/traversed hop count or delay deadline) and traffic type (e.g. real-time or non real-time) [140] [19]. Treating data packets of different preferences according to their QoS requirements may help to perform load balancing and to achieve the desired performance in MWSNs. The available channels may be classified into different categories by employing some *state-of-the-art* mechanism such as the one devised in [4]. Afterward, the traffic may be distributed among those channels as per the QoS requirements of traffic and the quality level of channels.

- *Resource Allocation:* Properly allocating the resources according to traffic type and priority may help to balance load and getting high performance in multichannel WSNs. The resource allocation is performed by:

• Adopting an efficient queuing and scheduling mechanism whereby traffic of privileged nature is assigned more memory and processing time than low priority traffic, e.g., in [19], more queues (memory) are assigned to real-time

traffic. However, reserving more memory for the high priority class may cause a waste of memory in case less traffic is available for the corresponding high priority class.

- Adopting a bandwidth readjustment policy whereby the bandwidth of realtime traffic may be adjusted dynamically by a node on the path in a manner that end-to-end delay of time-critical data is reduced while QoS requirements of non real-time traffic are met simultaneously [140].
- Adopting a flexible Contention Window (CW) size and Inter-Frame Space (IFS) oriented policy whereby the traffic of high priority may be assigned small CW size and IFS which may help in acquiring the medium more quickly. Added up with the dynamic Back-off Exponent (BE), associated with different priority classes, may further help to provide service differentiation [54].
- Allocating a flexible time slot assignment policy whereby traffic with high priority is assigned more consecutive time slots. This may increase the data exchange period (between sender and receiver nodes on a channel) which may indemnify for the channel switching delay in MWSNs [44].
- Employing rate adaption mechanism, predefined rate assignment methodology or data priority approach [87] for handling congestion in MWSNs. The rate adaption mechanism involves sending backpressure messages to sensor nodes, so that they may perform data rate adjustment using Additive Increase Multiplicative Decrease (AIMD) algorithm [87]. The predefined rate assignment methodology informs sensor nodes to use pre-established weights when congested [87]. Likewise, data priority approach may allow multichannel sensor nodes to handle the traffic of high and low priority in a separate manner.

In general, traffic load balancing may help to avoid data loss and retransmission overheads. Therefore, it is the responsibility of the MAC protocol designer to consider the traffic type, traffic requirements and QoS constraints for handling the issues regarding load balancing and bandwidth adjustment in multichannel WSNs which is still a brainstorming issue for consideration.

#### 3.4.10 SECURITY THREAT ISSUE

Wireless sensor networks are deployed in a challenging environment where they may work autonomously. Therefore they are vulnerable to security threats which necessitates the effective handling of the Security Threat Issue (STI). An important security threat is the *jamming attack* which can devastate network performance. However, such jamming attacks may be handled by employing appropriate multichannel approaches. EM-MAC [192], e.g., uses a dynamic channel selection mechanism which may cope with jamming attacks and may increase the reliability of WSNs. Likewise, Ext-NEAMCBTC [4] may avoid jammed channels for performing stream-based communication in MWSNs. Employing security resilience in multichannel WSNs may require additional data processing capabilities and control overhead which may also consume additional bandwidth in MWSNs. Therefore, a MAC protocol designer should consider such security-related issues before designing multichannel MAC protocols for WSNs.

	Design issues/problems addressed by multichannel WSNs													
Protocols	DPI	NDI	MHI	CII	FCI	RAI	TCI	SHI	LBI	STI	IAI	CDI	DCO	
MMSN [213]			$\checkmark$	$\checkmark$	$\checkmark$				$\checkmark$			$\checkmark$	$\checkmark$	
MCMAC [122]	$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$				$\checkmark$		$\checkmark$	$\checkmark$	$\checkmark$	
Multiple-Channel LMAC [238]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$						$\checkmark$	$\checkmark$		
CMAC [127]	$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$							$\checkmark$	$\checkmark$	
MCPE [139]	$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$			$\checkmark$		$\checkmark$	
TFMAC [152]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$							$\checkmark$		$\checkmark$	
HYMAC [179]	$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$						$\checkmark$		$\checkmark$	
ACMAC [72]		$\checkmark$		$\checkmark$	$\checkmark$						$\checkmark$			
CTATO [158]		$\checkmark$		$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$				$\checkmark$	
PMMAC [159]		$\checkmark$		$\checkmark$					$\checkmark$		$\checkmark$		$\checkmark$	
COM-MAC [161]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$		$\checkmark$	
Y-MAC [154]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$					$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	
QoS-MAC [133]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$				$\checkmark$		$\checkmark$	$\checkmark$	$\checkmark$	
SMC MAC [68]		$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$									
MuChMAC [221]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$			$\checkmark$							
RMCA [208]		$\checkmark$		$\checkmark$	$\checkmark$					$\checkmark$	$\checkmark$		$\checkmark$	
MC-LMAC [45]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$			$\checkmark$			$\checkmark$	$\checkmark$	$\checkmark$	

Table 3.3: Anatomization of design challenges of multichannel MAC protocols for WSNs

Protocols	Design issues/problems addressed by multichannel WSNs												
Protocols	DPI	NDI	MHI	CII	FCI	RAI	TCI	SHI	LBI	STI	IAI	CDI	DCO
EM-MAC [192]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$				$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
MASN [167]		$\checkmark$	$\checkmark$								$\checkmark$		
IMMAC [102]			$\checkmark$	$\checkmark$	$\checkmark$				$\checkmark$		$\checkmark$		$\checkmark$
MCCT [104]	$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$			$\checkmark$			$\checkmark$	$\checkmark$	
DTFMM [89]	$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$		$\checkmark$		
Enhanced HMC-MAC [129]	$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	
GTCF [178]		$\checkmark$		$\checkmark$	$\checkmark$					$\checkmark$	$\checkmark$		$\checkmark$
MinMax [71]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$			$\checkmark$			$\checkmark$		$\checkmark$
MCAS-MAC [56]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	$\checkmark$
RC-MAC [43]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	$\checkmark$
PWMMAC [180]	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$
SLA [103]		$\checkmark$		$\checkmark$	$\checkmark$					$\checkmark$	$\checkmark$		$\checkmark$
LRCH [94]		$\checkmark$	$\checkmark$	$\checkmark$				$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$
Ext-NEAMCBTC [4]		$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$

Table 3.3: (Continued...)

#### 3.4.11 INTERFERENCE AVOIDANCE ISSUE

Due to parallel communication on similar or contiguous frequencies, the sensor nodes in interference range may suffer from data collision, throughput loss and retransmissions overhead which may cause additional delay and energy consumption. Henceforth, there is a need to properly address the Interference Avoidance Issue (IAI) for achieving high performance in MWSNs. The network interference may be either internal or external. In case of internal interference, the sensor nodes in the interference range may suffer from either intra-channel interference (due to concurrent transmissions on the same channel in a neighborhood) or inter-channel interference (because of simultaneous transmissions on adjacent/overlapping channels in a neighborhood). In case of external interference, the wireless communication in MWSNs is interfered due to the usage of similar or overlapping frequencies by an external network in the neighborhood. The example is co-channel interference which may be caused in IEEE 802.15.4, either due to surrounding ZigBee networks, Wi-Fi [233] [148] or Bluetooth networks.

#### 3.4.12 CLOCK DRIFT ISSUE

Idle listening can be dealt with by employing a low-duty-cycle approach. However, maintaining duty cycles effectively is not an easy task and requires tight synchronization between sensor nodes. In case of small duty-cycled WSNs, monitoring tight synchronization between sensor nodes becomes a very challenging and strenuous job. If synchronization among sensor nodes is disturbed, then it may cause the clock jitter commonly known as the Clock Drift Issue (CDI). Normally, the clock drift problem in MWSNs is caused due to a variety of reasons, e.g.

 Different vendors produce sensors of different quality. The crystal clocks of inexpensive sensor nodes are imprecise [154] and therefore suffer from clock drifts of 30-100 ppm (parts per million) [185].

 Environmental factors such as temperature and moisture may induce clockdrift problems [135].

In case of single radio dynamic multichannel WSNs, a strict coordination is required between sender and receiver nodes for keeping them on the common channel and performing data communication. Some authors have assumed fixed clock drifts in their proposed protocols while others (e.g. MC-LMAC [45]) have given different solutions for dealing with clock drift issue. Handling the clock drift issue in an effective manner may minimize synchronization errors in MWSNs and require further brainstorming.

## 3.4.13 CONTROL DESIGN INEFFICIENCY ISSUE

Since control information consumes additional bandwidth and energy, sensor nodes should send/receive as little control information as possible. Outlined below are some design challenges that may cause Control Design Inefficiency Issue (CDII) in WSNs e.g.

#### 3.4.13.1 DEDICATED CONTROL-CHANNEL OVERHEAD

The dedicated control channel reserves a portion of wireless bandwidth for sending/receiving the control information. Although it is simple to implement, it has some reservations, too. In IEEE 802.15.4, e.g., when one of the sixteen channels is dedicated to control traffic, then it may waste 6% of the overall bandwidth [104]. Likewise, it may induce performance degradation in case of heavy load, interference and jamming on the control channel [192]. Apart from that, a dedicated control channel may suffer from the Denial-of-Service attacks (DoS), where an intruder may flood the system (more specifically the dedicated control channel in this case) with useless messages in an attempt to overburden it, so that it may not accommodate genuine traffic [227] [228]. Although some techniques such as EM-MAC [192] are presented as an alternate solution which decreases the control overhead by working asynchronously and not using any control channel, however still more research is required to devise novel and efficient solutions for adequately handling Dedicated Control-channel Overhead (DCO) in MWSNs.

#### 3.4.13.2 CONTROL PACKETS OVERHEAD

Control packets may help in the neighbor discovery and point-to-point link establishment. However, control information increases the volume of network traffic and the associated control overheads. Too much control information in a MWSN may increase bandwidth loss, collision/congestion rate and extra energy consumption. The Control Packets Overhead (CPO) is measured on the basis of a variety of factors such as:

- *Packet Header Length (PHL):* The packet header contains information for parsing the payload. Any unnecessary control information in the packet header may not only increase the header length, but also requires additional energy for transmitting, receiving and processing the extra control information.

- *Control-to-Data Traffic Ratio (CDTR):* The control-to-data traffic ratio is a measure of control overhead in multichannel WSNs. The impact of control overhead on the overall traffic volume may be neutralized, in-case the size of data packets is large enough. The standard IEEE 802.11, e.g., employs data packets of size 1500 bytes [167] and therefore can assimilate RTS/CTS-based control packets overhead effectively. However, data packet size in IEEE 802.15.4 is 100 bytes (approx) [167], therefore it is not feasible to assimilate RTS/CTS-based control packets overhead in IEEE 802.15.4-based sensor networks.

- Data Acknowledgment Mechanism (DAM): Since wireless channels are unreliable by nature, data communication on those channels may be affected by various factors such as environmental noise, electrical interference from surrounding devices and radio interference from the surrounding networks (operating in a similar frequency band). These factors may attenuate and distort wireless communication which may cause unsuccessful delivery of information to the des-



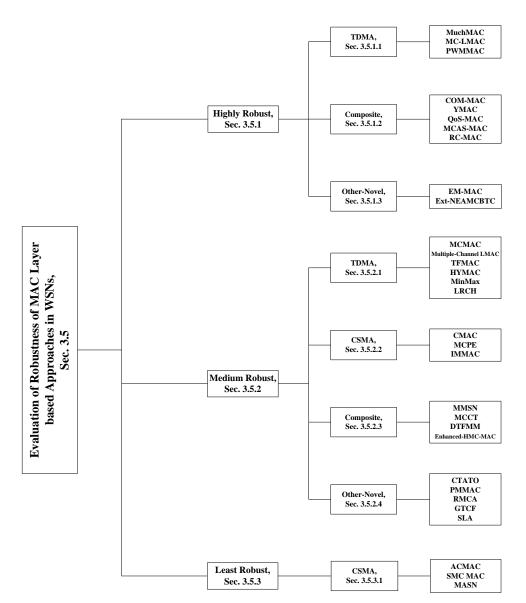


Figure 3.1: Classification of Multichannel MAC Protocols in WSNs

tination. Consequently, network reliability is decreased. One of the mechanisms for ensuring reliability is to employ a data acknowledgment mechanism at MAC layer where successful delivery of data is acknowledged by the receiver node. Although, it may help to figure out lost or erroneous information which may then be retrieved later on. However, such data acknowledgments may require additional bandwidth and energy consumption. Still, there are some MWSNs applications (such as multimedia based) where the use of DAM mechanism is not feasible because retransmitting the lost packets is more costly keeping in view the retransmission delay and associated overheads. Therefore, it is the liability of the MAC protocol designer to contemplate the QoS requirement of the targeted applications before considering any Acknowledgment (ACK) policy for multichannel WSNs.

# 3.5 MAC PROTOCOLS FOR MULTICHANNEL MWSNS

Multichannel methodology hs been explored for more than a decade, still more research is needed for cultivating the real benefits of this promising technology. Due to special features of multichannel technology such as parallel communication, high capacity and robustness against interference/jamming [81], the multichannel methodology may provide high performance in WSNs [6]. Consequently, the QoS of MWSNs may be improved in terms of energy conservation, delay/jitter, reliability and throughput. However, ensuring QoS in multichannel MAC protocols is a challenging task, too, and requires a careful handling of a number of design issues as discussed in Section 4.4.

On the basis of *grand-total-of-the-design-issues* addressed by various multichannel MAC protocols in Table 3.3, they may be classified into the three categories namely *Highly*, *Medium* and *Least-Robust* as depicted in Figure 3.1. Again, it is important to mention here that *Highly*, *Medium* and *Least-Robust* multichannel MAC protocols address a sum total of '9 or more', '5 to 8', and '4 or less' design issues respectively. Furthermore the protocols belonging to each main category are sub-categorized into TDMA-based, CSMA-based, Composite-based (TDMA+CSMA) and Other-Novel categories. Additionally, the functionality of protocols belonging to each category is briefly discussed along with relevant *pros* & cons. Besides that, each main category is also supported with concluding *remarks* which critically summarize multichannel MAC protocols belonging to that category.

Here below, a brief overview of the above-mentioned sub-categories of our classification (i.e. TDMA-based, CSMA-based, Composite-based (TDMA+CSMA) and Other-Novel) is presented.

In case of TDMA-based (contention-free) medium access, multichannel sensor nodes are assigned timeslots on different channels using a TDMA-based scheduling mechanism. Such a scheduling approach enables sensor nodes to wake-up/sleep at their assigned timeslot/channel and maintains natural duty cycles which may support energy conservation and collision avoidance. However, the process of selecting frame size, time slot and channel may result in increasing the overall network delay. Such a delay is acuter in case of the centralized channel and schedule assignment where the central entity requires knowledge of connectivity and interference graphs, for assigning non-interfering channels and appropriate wake-up/sleep schedules to sensor nodes. The centralized approach may require sensor nodes to maintain tight synchronization between each other. On the other hand, distributed channel and schedule assignment requires local connectivity knowledge only, but extensive message passing is carried out across the network for maintaining network-wide synchronization [80]. This may result in additional bandwidth and energy consumption. To sum-up, the TDMA-based approach fabricates natural communication clusters [95] [203] in which it is not simple to change the frame length and time slots dynamically in response to the change in the number of nodes [95] [203]. Therefore it may suffer from both scalability issues [95] [203] and the bandwidth underutilization problem.

- The *contention-based* medium access employs a carrier sense multiple access scheme (such as CSMA/CA), which motivates sensor nodes to contend with each other for accessing the frequency channel. Upon winning the channel, the concerned nodes communicate with each other for a specific interval, whereas the remaining nodes may contend for the other available channels for performing data communication [147]. Although the CSMA-based approach provides quick medium access, its continuous channel monitoring makes it an unsuitable candidate for sensor networks [80]. Moreover, in case of high data rate multichannel multimedia applications, frequent medium access may overburden the already saturated medium which may induce more congestion/collision and thereby retransmission overhead in terms of additional delay and energy consumption.
- In order to get the benefits of both worlds (i.e. TDMA and CSMA-based approaches), some techniques may utilize both approaches for getting high performance in multichannel WSNs and are designated as *Composite approaches*. However, it is also a fact that such techniques may suffer from the inherent issues of both contention-based and contention-free medium access approaches. Therefore, still there is need to do more research for devising novel robust solutions which may effectively handle high data rate time-critical applications in both small and large sized wireless networks.
- The *Other-Novel* approaches include those which do not strictly follow contention based or contention-free mechanisms in their channel access mechanism. EM-MAC [192], e.g., employs a *pseudo-random generator*-based approach where a node may independently predict wake-up time and frequencies for ensuring communication in MWSNs.

#### 3.5.1 HIGHLY-ROBUST PROTOCOLS

The highly-robust protocols are those which may handle the majority of the QoS issues discussed in Section 4.4. More specifically, such protocols may address '9 *or more*' QoS issues outlined in Table 3.3. Highly-robust protocols may be further categorized into TDMA, Composite and Other-Novel categories. Furthermore, the functionality of protocols belonging to each category is briefly discussed along with their *pros and cons*.

#### 3.5.1.1 TDMA-BASED (CONTENTION-FREE MEDIUM ACCESS)

As evident from the classification diagram in Figure 3.1, the multichannel MAC protocols belonging to this category are enlisted below:

– *Multi-Channel MAC (MuChMAC):* In [221], a distributed receiver-oriented schedule-based multichannel MAC protocol is proposed which uses both independent and common hopping for data communication in WSNs. The operating time is divided into slots whereby each slot is associated with an operating frequency used for unicasting or broadcasting. In case of unicast transmission, a sender calculates the lower limit of the next awake period (slot) of a receiver. Afterward, using both slot number and node ID, a pseudo-random generator determines the operating frequency of the receiver for the corresponding slot

and sends preamble messages on it. Upon waking up, the corresponding receiver responds with an ACK message followed by data communication between the two parties as depicted in Figure 3.2(a), redrawn from [221]. In case of broadcast transmission, a node sends data messages slot-by-slot on corresponding channels that does not require any acknowledgments as shown in Figure 3.2(b), redrawn from [221]. The schedule-based communication requires synchronization between sender and receiver nodes that may be maintained by time-stamping the arriving and departing control packets (such as preamble and ACK messages) for handling clock-offsets. In case of high-density networks, there is a likelihood that multiple nodes may occupy the same slot and channel. For addressing this issue and optimizing parallel transmission, a timeslot is further divided into sub-slots with a guard interval between them, so that more nodes may be able to transmit during a timeslot which may help in load balancing. For reducing latency and increasing data rate, a node may transmit on more subslots by spending additional power. However if any data loss occurs, then the transmission power level may be reduced to handle data loss.

*Pros and Cons:* The protocol handles a number of issues as described in Table 3.3. The frequency hopping technique handles interference passively and decreases control overhead enormously. Since a sensor node may also hop to interfered channels, frequency hopping may not handle interference in an active manner. The protocol suffers from recurrent channel switching overhead on a slot-by-slot basis which may add to end-to-end delay and additional energy consumption. Since a node transmits its power level in the packet header, the packet header size increases, too. The received power levels from neighboring nodes are maintained in a neighbor table which may increase both energy and memory overhead. The adaptive power transmission is robust, however increases the corresponding hardware cost, too. The protocol does not provide any recovery procedure, if sender/receiver nodes do not wake at the same time (due to clock drifts and synchronization issues). Sending preamble messages (for knowing the receiver wake-up time) and associated ACKs may increase the control overhead in the energy constrained WSNs.

- *Multi-Channel Lightweight MAC protocol (MC-LMAC):* In [45], a scheduled sender-oriented multichannel protocol is proposed which may accommodate high rate communication in WSNs. After network initialization, the sink broadcasts control messages for maintaining synchronization among sensor nodes. On reception of control messages, each node broadcasts them again. Each control

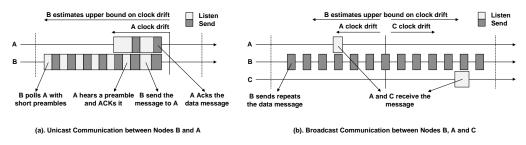


Figure 3.2: Unicast and Broadcast Communication in MuChMAC Protocol [221]

message contains an Occupied Slot Vector (OSV) of the corresponding sender that informs about the used slots on available channels in the one-hop neighborhood of the sender. Upon reception of an  $OSV_{sen}$ , the receiver merges it with indigenous  $OSV_{rec}$ . In this way, the receiver node gets knowledge of occupied/vacant timeslots on available channels in the two-hop neighborhood. Each communication timeslot consists of Common Frequency Period (CFP) and Split Phase Period (SPP). During CFP, a sender node awakes on the common control channel and sends a request to the intended receiver which has shifted to sender channel at the end of CFP. During SPP, data communication takes place between sender and the intended receiver node. Since all the receivers are continuously listening during CFP, they may consume additional power.

*Pros and Cons:* The protocol tackles a number of issues discussed in Table 3.3. It can support broadcasts on the common control channel during a common frequency period. Due to the multichannel approach, the schedule length per channel of MC-LMAC is decreased, however, latency is still higher than the counterparts (such as MMSN). The reason is that for TDMA-based scheduling a node has to wait for its assigned timeslot for data transmission. Since there is one OSV per channel, increasing/decreasing channels would result in corresponding increase/decrease in OSVs and thereby analogous consumption of energy and memory. When during the same CFP, two neighbors address a common receiver, then a conflict may appear which can cause data delivery issues. An increase in the number of channels may result in increasing control overhead because more control information will be sent before data transfer. The protocol exhibits reliable communication by sending acknowledgments (after successful packet delivery) and retransmitting erroneous data packets (due to external interference). However, it may increase control packets overhead, too.

– Predictive Wake-up Multi-Channel MAC (PWMMAC): In [180], an asynchronous duty-cycled multichannel MAC protocol is proposed that may improve system performance by predicting channel and adaptive wake-up schedules in WSNs. Each node maintains a preferred Channel list ( $C_{list}$ ), consisting of non-congested channels, having the Channel Usage ( $C_u$ ) Metric lower than a certain Channel Threshold value ( $C_{th}$ ). The preferred channel list would be empty when the available channels are congested (with  $C_u$  above  $C_{th}$ ). In this case, the channel with least  $C_u$  is inserted into  $C_{list}$ . Each node dynamically adjusts its duty cycle on the basis of the traffic load which is determined upon the availability of channel(s) in  $C_{list}$ . When  $C_{list}$  contains only one channel, this would indicate high traffic load in the neighborhood. Consequently, the duty cycle is increased which likely decreases collision and latency. On the other hand, when more channels are available in  $C_{list}$ , this would indicate less traffic load in the vicinity. Accordingly, the duty cycle is reduced and energy efficiency is ensured.

After receiving the channel prediction parameters of the receiver, a sender may employ the Linear Congruential Generator (LCG) for generating the receiver's channel. When a receiver node is ready for receiving data on a channel, then it sends a wake-up beacon to the sender along with its  $C_{list}$ . Subsequently, the sender (having data for a receiver) communicates with the receiver on its channel. On the basis of  $C_{list}$  of the sender and receiver nodes, the sender may compute the Channel Common List ( $C_{co}$ ) the sender follows for shifting to the relevant receiver's channel. However, if  $C_{list}$  is empty, then the sender node may continue on the already agreed channel performs data communication with the receiver. By using traffic load-based modified LCG, the sender predicts the wake-up slot of the receiver. The sender wakes up a bit earlier on the predicted receiver channel and timeslot for sending data to the receiver which is ACKed by the receiver node. When the receiver sends a wake-up beacon to the sender and subsequently does not receive any data, then the receiver considers this data to be lost due to collision and therefore increments  $C_u$ . Likewise when the sender does not get any ACK after sending the data, it assumes a collision on the channel and increments  $C_u$ . Finally, when  $C_u$  surpasses  $C_{th}$ , then the channel will be categorized as heavily loaded and is expelled from  $C_{list}$ .

*Pros and Cons:* The protocol handles a variety of issues outlined in Table 3.3. It decreases packet delivery delay and exhibits 100% delivery ratio. On the basis of common channels of both sender and receiver node, the sender may calculate  $C_{co}$ . However, the protocol does not discuss any mechanism of sharing  $C_{co}$  of the sender with the receiver node. This may affect selecting and switching to the common channel between sender and receiver nodes because the receiver has no knowledge about  $C_{co}$  of the sender node which may cause the node deafness issue. Even though sending an ACK for each data packet may help to ensure reliability, it may still increase the control overhead.

#### 3.5.1.2 COMPOSITE-BASED

On the basis of the taxonomy drawn in Figure 3.1, the following multichannel MAC protocols are included in this section.

- Cluster-based On-demand Multichannel MAC (COM-MAC): In [161], a traffic and QoS-aware cluster-based multichannel MAC protocol is proposed which provides contention-free medium access. The protocol executes its operation in three steps. During the first step, each cluster head either uses a contentionbased protocol for assigning the available channels to cluster members or employs a contention-free (TDMA/FDMA) protocol for allocating timeslots to CMs on the available channels. Afterward, the CMs may send data Request messages (REQ) on those channels. The REQ messages inform the CHs about data size, priority and acceptable delay of the sensed data. Moreover, the selection of a contention-based/contention-free protocol depends upon the traffic rate and channel reliability of the sensor network. In the second step, a scheduling session is initiated in which the REQ messages are grouped on the basis of their priorities. The REQ messages belonging to highest priority group (with minimum time to transmit) are entertained first and so on. Consequently, the CH may determine the timeslot and channel schedules of CMs which are broadcasted afterward on the already assigned control channels. On accepting the schedule, the third step of data transmission is executed where each CM awakes on its assigned timeslot and channel for sending the data followed by an ACK from the corresponding CH. If no ACK is obtained, then the corresponding packet would be considered lost and marked accordingly by the related CM. Eventually, an implicit selective Automatic Repeat reQuest (ARQ) supported by the hybrid

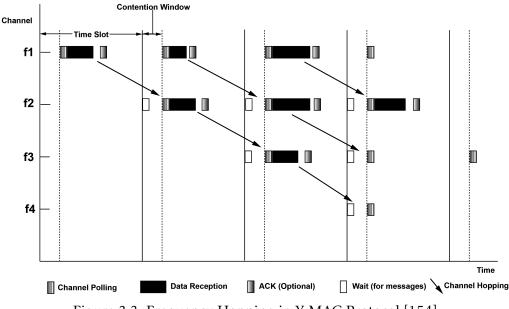


Figure 3.3: Frequency Hopping in Y-MAC Protocol [154]

MAC protocol is used for finding the unused portion of the spectrum on the available channels and lost packets are resent using an energy-efficient MAC protocol (such as S-MAC).

*Pros and Cons:* The protocol handles a number of issues outlined in Table 3.3. However, it may suffer from some issues, too. The single sink bottleneck issue, e.g., may be caused in case more CHs compete for the medium near the sink node. By sending ACK messages following a successful data delivery, the protocol may achieve reliability at the cost of control overhead. The control overhead is also increased when a CH repeatedly broadcasts scheduling information on control channels. In case of a smaller data rate, the TDMA-based scheduling mechanism does not result in better channel utilization and may cause synchronization errors such as clock drifts. Furthermore, nodes having no data to send in the beginning of an interval are not treated differently.

– Energy-efficient Multichannel-MAC Protocol for Dense WSNs (Y-MAC): In [154], a dynamic multichannel MAC protocol is proposed where the sink node periodically broadcasts control messages for maintaining connectivity in the sensor network. Each control message contains the timing information which informs the receiver about the time left to the next super frame period of the sender and may synchronize the corresponding nodes. The control message also contains a Slot Allocation Vector (SAV) which has the timeslot information of a sender and its one-hop neighbors. After receiving  $SAV_{sender}$ , the receiver node merges it with its own  $SAV_{receiver}$  and thereby gets knowledge of occupied timeslots in the two-hop neighborhood. Each sender node always contend s for the medium before broadcasting or unicasting on the base channel. During the contention interval, the node interested in sending data to a particular receiver waits for a random backoff interval for accessing the medium. Afterward, it performs a Clear Channel Assessment (CCA) and then sends a preamble message, so that 3.5. MAC PROTOCOLS FOR MULTICHANNEL MWSNS

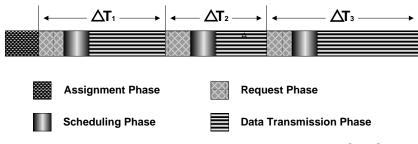


Figure 3.4: Operation of in QoS-MAC Protocol [133]

the contending senders may not interrupt it during data communication with the receiver. If the traffic load is lighter, then the sender node may execute a unicast transmission on the receiver timeslot at the base channel only. However, in case of heavy traffic load, the receiver hops channel-by-channel (followed by the sender) using a *hopping sequence generation algorithm* as depicted in Figure 3.3, redrawn from [154]. However, every time the sender has to compete for a timeslot, the likelihood of re-wining the timeslot is lowered for maintaining fairness among all sensor nodes.

*Pros and Cons:* As outlined in Table 3.3 this protocol handles a lot of issues. The frequency hopping approach helps to achieve robustness against interference, energy efficiency and high performance in MWSNs. However, it suffers from frequent channel switching overhead which causes data loss and extra power consumption in high data rate applications [174] [4]. Due to the contention interval in each timeslot, the protocol may suffer from the single-sink bottleneck issue in case of heavy traffic load. Since each node starts its communication at the base channel, any interference/jamming problem with the base channel may seriously affect the performance of the protocol. The protocol does not provide any appropriate mechanism for handling the queues of contention loser nodes which may overflow due to additional data.

- Quality-of-Service MAC (QoS-MAC): In [133], a cross-layer clustered multichannel MAC protocol is presented where each cluster head dynamically assigns time slots and channels to cluster members based on their QoS requirements. During the network initialization phase, each CH assigns the available N-1 channels to CMs, whereas the remaining channel (with less-bandwidth) is reserved for future use. If the number of channels is less/equal to the number of CMs, then each CM may be assigned a separate channel. Otherwise, CMs share the channel(s) using the adaptive contention window algorithm [74] for improving network performance. When a CM is interested in sending data to its CH, then it sends request messages with QoS parameters (such as data type, affordable delay, and size) to the corresponding CH. In response, the CH broadcasts TDMAbased scheduling messages for active CMs on N-1 channels under the request prioritization and associated QoS constraints received earlier from the relevant CMs. Afterward, data transmission takes place on the assigned timeslot/channel and data messages are acknowledged by the CH if requested in REQ messages. The length of the data transmission phase may vary in accordance with the data size as shown in Figure 3.4, redrawn from [133]. Additionally, the dedicated

reserved channel of low-bandwidth may be used to transmit the REQ messages of recently activated nodes, so that they may also get a schedule for data transmission. However, if the channel/time slot is not available, then such requests are transmitted again in the next interval.

*Pros and Cons:* The protocol handles a variety of issues outlined above in Table 3.3. However it may suffer from some issues, too. The single-sink-bottleneck handling issue, e.g., may occur when many clusters are present around the sink node and compete with each other for performing inter-cluster communication. Since the CH classifies data among different priority queues based on their QoS requirements, maintaining these queues requires additional energy and memory which in turn may induce more delay and high throughput. Additionally, the reserved channel is costly to maintain when no passive nodes are present during the scheduling phase.

– MCAS-MAC: MultiChannel Asynchronous Scheduled MAC protocol: In [56], an asynchronous scheduled-based multichannel MAC protocol is proposed for high data rate dense WSNs which permits back-to-back data transmissions. During the initialization phase, an incoming node may perform channel polling on all channels and listens to HELLO messages of neighbor nodes. The HELLO messages provide knowledge about the home channel and wake-up/hello intervals of the corresponding neighbor nodes. This knowledge is helpful for selecting the least-used home channel and a unique wake-up schedule in a neighborhood. The wake-up schedule is advertised using HELLO messages, so that neighbor nodes may update themselves about it. When a node is interested in sending data to a receiver node, it switches to the receiver's home channel for sending data during the receiver's wake-up timeslot. After data transmission, the sender returns its home channel and sleeps afterward. The channels and wake-up offset-intervals are not fixed, but updated with the new least-used channels and wake-up schedules. Before sending the first HELLO message, the node may wait for a random backoff interval, so that any newly-joined neighbor may avoid getting the same schedule. However, in case of any conflict, the node loses the current contention interval and retries definite attempts for finding the new schedule. Mobility is supported by performing neighbor discovery in a repeated manner on each channel, so as to receive the HELLO message of neighboring nodes and also sending scheduling information to neighbors using HELLO messages in a separate manner.

*Pros and Cons:* The protocol may handle a number of issues outlined in Table 3.3. It may exhibit better PDR in high data rate dense networks. Due to employing different wake-up periods for nearby communicating nodes, the sender node has to wait for the receiver node's wake-up in order to perform data transmission which may induce long delivery delays. The protocol exhibits an insufficient broadcasting mechanism because home channels and wake-up offset-intervals of neighboring nodes are different. Therefore the sender has to specifically broadcast the packet to each neighbor node. The protocol frequently requires neighbor table management which consumes memory and energy.

- *Receiver Centric-MAC protocol (RC-MAC):* In this paper [43], a receiver-oriented multichannel MAC protocol is proposed which combines duty-cycling and

receiver-oriented scheduling for achieving high throughput and fairness in multichannel WSNs. Initially, each node randomly broadcasts a beacon on the common channel which helps the receiving node to determine the beacon-offset with the corresponding sending node. The beacons are broadcasted repeatedly, so that the beacon-offset may be updated periodically for estimating the wake-up timeslots of corresponding neighbors. Consequently, the sender (child node) may wake up prior to the receiver (parent node) and sends data to it on the common channel. Such a duty cycle approach is executed in case of WSNs with lower data rate. However, when the data rate is high due to the occurrence of an event, then both sender and receiver nodes change to fully active mode. Subsequently, sensor nodes at alternate levels may simultaneously perform data transmission or data reception on corresponding data forwarding or data gathering channels respectively. The channel assignment is receiver-centric whereas the selection of channels is made in a manner that interference-free channels may be assigned to each parent-children set. After each successful data delivery, the receiver node broadcasts an ACK message containing the ID of the next sender node. If the corresponding sender is already scheduled, then it transmits its data after a Short Inter-Frame Space (SIFS) interval. Otherwise, the unscheduled neighbors contend for the medium after a backoff interval and the winner node sends its data to the parent node. This way, data travels step-by-step and finally reaches the sink node.

*Pros and Cons:* The protocol handles a number of issues addressed in Table 3.3, nevertheless it may experience some issues, too. Although e.g., it may provide high throughput and less delay in case of heavy traffic load, it may still suffer from the energy efficiency issue which may cause an early death of the network. During duty-cycle mode, all the communication takes place on the default common channel which may be risky in terms of security threats such as jamming. The protocol may suffer from control packet overhead because it periodically broadcasts beacon packets. Since each data packet is responded with an ACK, the control overhead would increase, too. Maintaining beacon-offset tables of one-hop neighboring nodes is costly in terms of energy and memory.

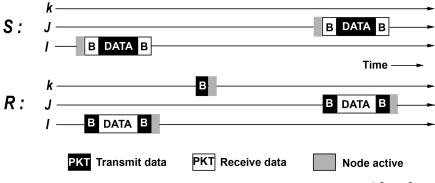


Figure 3.5: Data Communication in EM-MAC Protocol [192]

CHAPTER 3. MULTICHANNEL TECHNOLOGY OVERVIEW: AT MAC LAYER

#### 3.5.1.3 OTHER-NOVEL

The protocols belonging to this category (see again the classification diagram in Figure 3.1) are discussed below:

- Energy-efficient Multichannel MAC (EM-MAC): In [192], an energy-efficient receiver-oriented multichannel MAC protocol is put forth which is asynchronous in nature. The sender awakes on the channel/timeslot of the receiver, using the prediction state information (PSI) of the receiver, and sends data to this receiver as shown in Figure 3.5, redrawn from [192]. Each node maintains a local channel quality measure called Channel Badness Metric (CBM) which ranges between 0 to  $C_{bad}$ . A channel is designated as blacklisted if its CBM value is above  $C_{bad}$  and consequently, a receiver refrains from visiting this channel for a blacklist interval  $T_{black}$ . For informing a sender node about all blacklisted (congested/interfered) channels, the receiver sends a two-byte blacklist bitmap to the sender in a beacon message which may help to avoid those channels. When a sender is unable to connect to a receiver in the second attempt, then it follows an exponential chase algorithm and doubles its Wake-up Advance Time (WAT) until either it finds the receiver on a particular channel and resets WAT to the original value for the anticipated data packets or its WAT reaches a threshold value. The threshold value signals the unreachability of the receiver and then quits the search process.

*Pros and Cons:* The protocol resolves a lot of issues as described in Table 3.3. It may handle collision, jamming attacks and external interference due to IEEE 802.11 networks. It achieves low duty cycles, less delivery delay and 100% packet delivery ratio. The protocol may suffer from frequent channel switching overhead that causes channel switching delay and energy consumption. Such switching overhead may cause data loss and additional energy consumption in case of high data rate applications such as multimedia and stream-based communications. Additionally, sending two-byte blacklist packet before each data messages is costly energy-wise and increases control overhead. Furthermore, the receiver's search procedure may cause delay and energy consumption.

- Extended-Normal Equation-based Aggregate Maturity Criteria with Beta Tracking-based Channel weight prediction (Ext-NEAMCBTC) algorithm: In the Ext-NEAMCBTC algorithm [4], a novel channel prediction approach is devised which considers both quality and stability for estimating the best among all available channels for performing stream-based communication in MWSNs. The underlying idea behind the channel quality and stability estimation criterion is to enable sensor nodes to distributedly select the best channel from the available channel pool that minimizes channel switching delays, energy consumption (and thereby associated data loss) to the lowest ebb, for providing reliable communication in stream-based MWSNs. In the beginning, a data set is created (based on the standard deviation (std) of the Received Signal Strength Indicator (RSSI) and average the (avg) of Link Quality Indicator (LQI) and the associated Channel Rank Measurement (CRM) metric) which is used to train a normal-equationbased channel quality predictor. Consequently, the predictor would be able to perform instantaneous Channel Rank Estimation  $(CRE)_{t,NEAMCBTC}^{i}$  on the basis of instantaneous values of  $std(RSSI_t^i)$  and  $avg(LQI_t^i)$  of received packets on a

channel *i*. Afterward, an exponential smoothing-based approach is used which predicts the final quality  $\phi_{t,NEAMCBTC}^i$  of each channel by summing up the instantaneous quality  $(CRE)_{t,NEAMCBTC}^i$  and the past quality  $\phi_{t-1,NEAMCBTC}^i$ . Added up with the general stability criterion  $\psi_t^i$ , results into estimating the overall quality  $\xi_{t,Ext-NEAMCBTC}^i$  of any channel *i* at a particular epoch. The simulation results indicate that the Ext-NEAMCBTC algorithm has the ability to perform both channel quality and stability estimation in a better manner than its counterparts.

*Pros and Cons:* The protocol handles a variety of issues described in Table 3.3. It is robust to avoid those channels which have either poor quality or instability because of interference, noise, and jamming in the surrounding environment. However, it does not outline any mechanism for handling the transmission-power control issue.

#### 3.5.1.4 CONCLUDING REMARKS FOR HIGHLY-ROBUST PROTOCOLS

This section comprehensively discusses three TDMA, five Composite and two Other-Novel protocols, whereas no CSMA-based protocol is observed in this category. The protocols belonging to this category perform channel assignment in a distributed manner and therefore may dynamically respond to external stimuli. However, distributed channel allocation requires extensive message passing across the WSNs for maintaining network-wide synchronization and therefore consumes additional bandwidth and energy.

Among the protocols belonging to this category, only QoS-MAC [133] performs a static channel assignment. Consequently, it would be more suitable to accommodate constant traffic patterns and rather not varying traffic models or interference/jamming at runtime. Since static channel assignment-based protocols are not suffering from any channel switching overhead, they are more suitable to accommodate high data rate and delay-sensitive applications.

The dynamic channel assignment is exhibited by four protocols including two TDMA-based (i.e. MuChMAC [221] and PWMMAC [180]), one Composite (i.e. Y-MAC [154]) and one Other-Novel protocol (i.e. EM-MAC [192]). The dynamic channel assignment is helpful in handling channel/traffic variations, network interference, and communication impedance issues. However, it causes severe channel switching overheads that may induce additional channel switching delays, energy consumption and even data loss in high data rate applications. Furthermore, based on the design issues oriented analysis in Table 3.3, MuCh-MAC [221] is more robust than the remaining protocols in this category, followed by EM-MAC [192], PWMMAC [180] and Y-MAC [154].

The hybrid channel assignment is exhibited by TDMA-based MC-LMAC [45], Composite-based COM-MAC [161], MCAS-MAC [56], RC-MAC [43] and Other-Novel-based Ext-NEAMCBTC [4]. Since a hybrid channel assignment may handle channel/traffic variations, network interference, and communication impedance and may experience only small channel switching overheads, it is a suitable candidate for delay-sensitive high data rate applications which are dealing with varying traffic patterns. It is clear from Table 3.3 that

Ta	able 3.4: Supp	lementary a	ttributes of highly robu	ist multichannel MAC protoco	ls for WSNs		
Drate colo	Terrellerer	NT - 4		Communication artitle	Comparison Tool		
Protocols	Topology	Network Density	Focal Point	Comparison with	Testbed	Simulator	
COM-MAC [161]	Cluster	Medium	High data-rate & reliable communication	M-TDMA		NS-2 [252]	
Y-MAC [154]		Small	Energy & performance improvement under diversified load	LPL [39], Crankshaft [232]	RETOS O.S. [119] on TMoteSky motes		
QoS-MAC [133]	Cluster	Large	Energy, throughput & reliability enhancement	COM-MAC [161], M-TDMA		C++ based	
MuChMAC [221]	Tree	Small	Network throughput enhancement	X-MAC [113]	Sentilla JCreate Motes		
MC-LMAC [45]	Tree	Large	Throughput optimiz- ation using parallel transmission	MMSN [213], Clustered LMAC, Single-Channel CSMA		Glomosim [209]	
EM-MAC [192]	Tree	Small	Energy efficiency and interference/ jamming avoidance	Y-MAC [154], X-MAC [113], McMAC [183], PW-MAC [191] RI-MAC [190], WiseMAC [146]	MICAz motes		
MCAS-MAC [56]	Chain/Grid	Small to large	Improved PDR and delivery delay	BMAC, SMAC and AS-MAC		RaPTEX [57]	
RC-MAC [43]	Tree	Small to large	High throughput, energy efficiency and fairness	X-MAC [113], Z-MAC [176], Funneling-MAC [105], RI-MAC [190]	TelosB motes	NS-2 [252]	
PWMMAC [180]	Clique/ Grid/ Random	Small to Medium	Energy, delay & delivery ratio improvement	SA-RI-MAC [145], RI-MAC [190], PW-SAMAC [180]		NS-2 [252]	
Ext-NEAMCBTC [4]	Chain	Small to large	Channel quality & stability estimation	EM-MAC [192] based approach		MATLAB [242]	

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Large: Nodes > 70, Medium: 20 < Nodes <=70, Small: Nodes <= 20

Ext-NEAMCBTC [4] outperforms its counterparts in this category, followed by RC-MAC [43] and COM-MAC [161], MC-LMAC [45].

#### 3.5.2 MEDIUM-ROBUST PROTOCOLS

The medium-robust protocols are those which may handle a considerable number of QoS issues delineated in Section 4.4. More specifically, they may address QoS issues in the range of '5 to 8' as outlined in Table 3.3. Below we will classify these protocols into TDMA, CSMA, Composite and Other-Novel categories. Furthermore, this section elaborates the operation of such protocols along with their *pros and cons*.

#### 3.5.2.1 TDMA-BASED (CONTENTION-FREE MEDIUM ACCESS)

On the basis of the taxonomy drawn in Figure 3.1, the following multichannel MAC protocols are included in this section.

- Multi-Channel MAC (MCMAC): In [122], a cluster-based multichannel MAC protocol is put forth in which clusters are established based on LEACH scheme [143]. Here, a data communication cycle consists of four stages. During the first stage, synchronous beacons are sent by each cluster head on the control channel for correcting the wake-up clocks of sensor nodes, thus handling clock drift issue. In the second stage, each cluster member is assigned a time slot in a schedule whose length is equal to the number of nodes in the cluster. The CMs interested in sending a unicast/broadcast request of specific priority may send the control packet on the assigned timeslot on the control channel. The priority-based traffic and resource allocation may help to handle the load balancing issue. During the third stage, each CH announces the channel schedules on the control channel for the requesting CMs and assigns channels one-by-one to the corresponding CMs (sender and receiver nodes in a cluster) for performing data communication. In case all the available channels are assigned to CMs, the pending requests wait in the channel priority queue for a channel released early which may increase the data delivery delay accordingly. During the final step, the corresponding nodes may wake up to perform unicast communication. In case of broadcast communication, the concerned CH relays broadcast messages to all CHs during the contact-time of inter-cluster communication. Afterward, each CH may send the broadcast messages in its cluster in the next scheduled phase.

*Pros and Cons:* The protocol may handle a variety of issues outlined in Table 3.3. However, it may suffer from a variety of QoS issues such as latency. This is the case because the schedule length is not only dependent on the number of nodes in a cluster but also increases with the total number of clusters used and duration of the inter-cluster communication. The delay may further increase due to waiting time in the priority queue. Although duty cycling provides energy efficiency, it also requires tight synchronization and is challenging to observe in a practical scenario.

– *Multiple Channel LMAC:* In [238], a multichannel extension of the traditional single-channel LMAC protocol is proposed. Initially, the nodes are assigned timeslots one-by-one (on the base channel) in a manner that all nodes occupy

a unique time slot in their two-hop neighborhood. An incoming slot-less node performs energy-hungry scanning of available frequencies for searching the network connection points termed as bridge nodes. Each bridge node manages a timeslot vector that may provide knowledge of occupied/free timeslots on a specific channel in a neighborhood. A sensor node may select the best among the available bridge nodes by employing some QoS criteria. When the corresponding bridge node is not sending any data, it transmits a channel negotiation control message. Afterward, the interested slot-less nodes contend for the medium and the winner node responds with a request message (containing channel information) to the corresponding bridge node. If the requested timeslot/channel is available without any conflict in the neighborhood, then it is assigned to the slot-less node. Furthermore, in case of any future conflict, the agreement between the bridge and sensor node is abandoned, so that the sensor node restarts timeslot/channel search procedure again.

*Pros and Cons:* The protocols may handle the idle listening, multichannel hidden terminal, communication impedance, frequent channel switching, interference avoidance and congestion handling issues. However, it does not support broadcasts. Moreover, storing and processing time slot vectors and the occupied/free matrix is energy-consuming. Maintaining synchronization would be a challenging task in dense WSNs.

- Time Frequency MAC (TFMAC): In [152], a multi-frequency extension of a traditional TDMA-based protocol is proposed. Here, the frame is composed of a contention-oriented control slot followed by contention-less timeslots. The control slot is used for transmitting control messages (on the base channel) for network maintenance, whereas timeslots are used for data communication on the available frequencies. The information regarding each timeslot is stored in a data structure called *timetable* consisting of slot number, slot type (*transmission*, reception, idle) and associated frequency. The protocol works in two phases. In the first phase, the frequency assignment, each node randomly selects a receiving frequency and broadcasts it in its two-hop neighborhood. In the second phase, the transmission slot assignment, a node may set up its timetable for executing data transmission in a non-conflicting manner. Here a node broadcasts a timetable request message on its control slot (on the default frequency) which is reciprocated by *active* neighbor nodes through sending their timetables on transmission time slots (on the same frequency). However, in order to get the timetable of *passive* nodes, a node may unicast the timetable request on its control slot which is responded with the timetable by the corresponding *passive* node(s) in the same control slot. Afterward, such a time slot is selected for transmission on a particular frequency that is idle in the timetable of the sender and neighboring receiver nodes on the same receiving frequency. The selected timeslot/frequency pairs are broadcasted in transmission-slot-announcement messages on the control channel while neighboring active & passive nodes update their timetables accordingly.

*Pros and Cons:* The protocol may address issues described in Table 3.3. However, it implements a complex timeslot/channel selection mechanism and suffers from broadcast control overhead. Additionally, the protocol requires synchronization

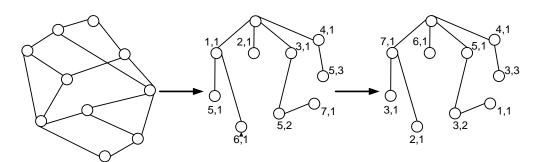


Figure 3.6: Timeslot and Frequency Assignment in HYMAC Protocol [179]

among nodes, but it put forths no mechanism to deal with the clock drift issue which may cause synchronization errors. When two or more nodes in the same area (with common neighbors) initiate the transmission slot selection procedure simultaneously, then they may choose the same timeslot/channel. Hence, they may suffer from collision during the data transmission phase in their common neighborhood.

- HYbrid MAC (HYMAC): In HYMAC [179], a schedule-based multichannel protocol is proposed where the communication cycle is composed of contentionoriented and schedule-based timeslots. The contention-oriented slots are used for sending HELLO messages (of scheduled/unscheduled nodes) while schedule-based slots are reserved for data transmission (of scheduled nodes). Upon receiving a HELLO message, a sensor node updates its one-hop neighbor list and re-broadcasts the HELLO message along with an updated neighbor list until the HELLO message reaches the Base Station (BS). Afterward, the BS executes a Breadth First Search algorithm (BFS) and constructs a tree for assigning a default timeslot/frequency pair to each node in a level-by-level manner. At each level, the interfering nodes are located and assigned different timeslots (if they are siblings) or otherwise different frequencies. Additionally, the default timeslot is also incremented level by level. Finally, for giving the highest timeslot to the BS, the timeslots are reversed in a manner as shown in Figure 3.6, redrawn from [179]. Such a timeslot/frequency assignment helps to aggregate and disseminate data packets in a single communication cycle.

*Pros and Cons:* The protocol may handle a variety of issues outlined in Table 3.3. However, it does not employ any mechanism for handling the synchronization and clock drift issue. Moreover, being centralized, the protocol may suffer from scalability issues in case new nodes are interested in joining the network. Sending the neighbor list in HELLO message would increase the control packet size, especially when the neighborhood is dense. The protocol may also result in too many broadcasts which may cause collisions in the network. Since the number of timeslots has a direct relation to delivery latency [154], an increase in the TDMA-based communication cycle may increase the delivery latency of WSNs.

– *Minimize the Maximum interference (MinMax) algorithm:* In [71], a distributed link-scheduling and interference avoidance-based algorithm is proposed the purpose of which is to minimize the maximum interference observed by any

communication link in WSNs. The protocol works in two phases. In the first phase, a link-oriented-conflict-graph is constructed where each node is assigned a random channel which is broadcasted by the corresponding node in its neighborhood along with its ID. Afterward, each node computes its local conflict on the allocated channel and broadcasts it in its neighborhood. Upon receiving the local conflict(s) of neighboring node(s) (i.e. neighbor conflict(s)), each node again calculates its *local conflict* on all available channels whereby the channel(s) having a neighbor conflict that is greater than the local conflict is left altogether for the ongoing round. Afterward, the node switches to the channel with the least *local conflict* which thereupon is broadcasted in the neighborhood. The process is repeated until convergence is achieved (whereby it is not possible for a node to decrease further its *local conflict*) and the corresponding channel is used by a sensor node for the forthcoming communication. In the second phase, the remaining link conflicts are resolved by employing a link-scheduling algorithm which provides a conflict-free schedule to links in WSNs. For this purpose, a schedule-conflict graph is devised and timeslots are assigned in a manner that the smallest unique timeslot is assigned to a node in a neighborhood in each round so that the TDMA frame length is minimized and consequently timeslots are not wasted.

*Pros and Cons:* The protocol handles a number of issues outlined in Table 3.3. Due to channel assignment and scheduling algorithms, it may suffer from fewer conflicts and less delay than the GBCA algorithm [207]. However, there are still some issues which may seriously affect the performance of the MinMax protocol. The convergence time of the protocol, e.g., may increase when the number of interfering links increases. In case of dense networks, it may seriously affect network performance and energy efficiency. Being TDMA-based, the protocol requires time synchronization between sender and receiver nodes for performing successful data delivery. Any loss of synchronization may cause the clock drift issue and consequently data loss and retransmissions overhead.

– Latin Rectangular-based Channel Hopping (LRCH) and Enhanced-LRCH: In [94], the authors discuss Latin Rectangular (LR)-based multichannel scheduling algorithms for handling interference in WSNs. A Latin Rectangular is a rectangular matrix where each row and each column contains a distinct symbol. Furthermore, each row of the LR represents a specific *channel-hopping sequence* (or color) while each column corresponds to a timeslot indicating the *hopping frequency*. Each node follows a color selection policy in which each color is calculated locally based on the node ID. Afterward, the sensor node hops to the available channels *one-by-one* in the associated timeslots. Due to assigning consecutive frequencies to adjacent timeslots, the LRCH protocol may avoid internal interference, however, it may suffer from external interference from the surrounding Wi-Fi devices. To handle this issue, an enhanced-LRCH protocol is devised which is based on an interleaving channel hopping protocol. Here, the available channels are consecutively arranged into two groups, namely the white and the black group. Afterward, LR is scheduled-based on an interleaving channel hopping protocol which assigns white-group channels to each odd timeslot and black-group channels to each even timeslot. In this way, the adjacent timeslots are assigned to non-adjacent channels using an interleaving approach which

may help to counter both internal and external interference (such as from Wi-Fi devices in the range).

*Pros and Cons:* The protocol addresses a variety of issues outlined in Table 3.3 and exhibits good performance in terms of delay. It employs an LR-based approach of node coloring in a neighborhood which may help to handle interference. However, in case of a limited number of available channels or a heavily dense neighborhood, it may be difficult to avoid interference due to the scarcity of available colors. Consequently, the schedules of the sensor nodes may overlap with one another which may result in interference. Furthermore, additional energy and memory are required for maintaining LRs the size of which depends on the number of available channels and nodes in a neighborhood.

#### 3.5.2.2 CSMA-BASED (CONTENTION-BASED MEDIUM ACCESS)

As evident from the classification diagram in Figure 3.1, the multichannel MAC protocols belonging to this category are enlisted below:

- CMAC-Multichannel Energy Efficient MAC for WSNs: In [127], a distributed multichannel MAC protocol is proposed where each node has two transceivers, namely a Low Rate (LR) and a Maximum Rate (MR) transceiver. The LR transceiver is always ON, usually residing on the default channel of a sensor node, and executing low power channel scanning/negotiation tasks. The MR transceiver is awakened on-demand for performing data transmission/reception-related activities and also consumes more energy than the LR transceiver. Therefore, the LR handles the node-deafness issue while the MR deals with the idle-listening issue. Before performing data transmission, the LR of the sender node jumps to the default channel of the receiver node and sends a data request message after a Distributed Inter Frame Space (DIFS) and a back-off interval. This may help in handling the corresponding transmission conflicts among the contesting nodes. Upon receiving the REQ message, the receiver responds after the SIFS interval by sending either a Confirm (CON) or a WAIT message which may also represent the respective *idle* or *busy* state of the receiver. When a CON message is sent by the receiver, then the MRs of both sender and receiver nodes are turned to the default channel of the sender node for performing data communication. When data transmission is over, then the MR of both sender and receiver nodes are shifted to the default channel of the receiver, and the receiver sends an ACK message to the sender. When a WAIT message is sent by the receiver, then it also enqueues simultaneously the received REQ message for avoiding the REQ retransmission overhead. However, enqueuing a large number of REQ messages may cause node buffer overflow and congestion overhead.

*Pros and Cons:* The protocol may handle the idle listening, node deafness, overhearing, communication impedance, frequent channel switching, clock drift and dedicated control-channel overhead issues. However, introducing SIFS/DIFS intervals and channel handshaking of both LR and MR on the sending/receiving channel may cause additional delay and energy overhead. The channel handshaking mechanism is very costly and causes control overhead, in case the the size of transmitted data is small. Additionally, the protocol requires special CHAPTER 3. MULTICHANNEL TECHNOLOGY OVERVIEW: AT MAC LAYER

half-duplex transceivers which are not available on many widespread sensor platforms.

- Multichannel Clustering for Power Efficiency (MCPE) in sensor networks: In MCPE [139], a cluster tree-based multichannel protocol is proposed aiming at tracking moving phenomena such as forest fires. Based on a granularity level, it divides the temperature range into various sub-ranges where adjoining sub-ranges are assigned to non-adjacent frequencies for countering interference. Such a distributed frequency assignment helps to establish natural clusters the number of which depends on the pre-assigned granularity level. After the deployment of sensor nodes in the fire region, each node senses the temperature and tunes itself to the corresponding frequency. Subsequently, a cluster head is elected among the nodes on a particular frequency using some protocol. The cluster members follow a virtual sensing approach where they wake up periodically for sensing the medium and sleep in case some other CM is already sensing that event. The CHs relay the sensed data to the sink node on the contention-based control channel. Each CH remains active during its clusterheadship. However after some interval, it delegates its duties to the most energetic and closely-located CM. Such a division of labor decreases the duty cycle of CHs and avoids the energy holes issue in WSNs. Due to the spreading phenomenon, if a node senses a temperature which belongs to a new temperature range, then it changes its frequency channel accordingly and joins the new cluster and data plane. Subsequently, the corresponding CH transmits information about new the new CM to the sink, so that it may update the global network image. If in the new clustering frequency no CH is found, then a node may announce itself as CH and afterwards broadcasts control messages for neighbor discovery.

*Pros and Cons:* The protocol deals with a variety of issues described in Table 3.3. It employs a virtual sensing approach for handling data redundancy and conserving energy, bandwidth and data aggregation latency. However, the virtual sensing approach may induce unreliability in MWSNs. Being based on a static channel assignment, the protocol may suffer from the communication impedance issue. The protocol employs a contention-oriented common control channel which, in case of heavy traffic load, may further add to contention near the sink node and thus causes the single-sink-bottleneck issue. Since the protocol is based on too many assumptions and is not compared against any well known approach, it is very challenging to judge the actual performance of the protocol.

– Interference-aware Multichannel MAC (IMMAC): In [102], a receiver-oriented multichannel protocol is proposed. Initially, the nodes broadcast NEIGHBOR messages for exchanging their IDs in their two-hop neighborhood. Afterwards the node with the highest ID in the two-hop neighborhood initiates a channel assignment process where channels are assigned to sensor nodes in the order of priority (from high to low). After being assigned a receiving channel, a sensor node broadcasts a SLOT message, so that the two-hop neighbors may update their local Channel Assignment Table (CAT) accordingly. A node may execute both broadcast and unicast transmissions on the assigned channels. Broadcasting involves copying a packet and sending it on all channels one-by-

one which distributes the network load at the cost of added delay. Each node adopts a channel scheduling policy the purpose of which is to fairly entertain the data for all channels residing in the scheduler FIFO queues. The protocol dynamically adjusts the traffic load on the channels. Therefore, when the load on a channel increases to more than a threshold value, a sensor node is shifted to a less crowded channel which may help to handle network congestion. For avoiding any conflicts on the receiver's channel, the interested sender firstly checks the *Network Allocation Vector (NAV)* for the status (e.g. idle or busy) of the receiver's channel. If the channel is found busy, it retries after a back-off period and thereby avoids collision.

*Pros and Cons:* The protocol handles a variety of issues as described in Table 3.3, but it may suffer from a number of challenges, too. The protocol does not, e.g., require synchronization due to always *ON* quiescent channel, however it may suffer from a daunting idle-listening issue. Because it is following a receiver-oriented channel assignment, the sender may not hear any information on its quiescent receiving channel, when it is sending data to the receiver on the receiver's channel. As a result, it may suffer from the node deafness issue. Although properly maintaining queues increases the network throughput, it also increases the delay, energy consumption and may cause congestion due to queue overflow.

#### 3.5.2.3 COMPOSITE-BASED

As per the classification diagram in Figure 3.1, the MAC protocols belonging to this category are outlined below:

- Multi-frequency Media access control for Sensor networks (MMSN): In [213], a receiver-oriented hybrid protocol is proposed where, on the basis of the application type, receivers are assigned channels by employing one of the four channel assignment techniques such as exclusive, even-selection, eavesdropping and implicit-consensus. The protocol follows a slotted CSMA approach which is based on time-synchronized medium access where synchronization (and the clock drift issue) may be handled by following the time synchronization as outlined in [169]. Consequently, nodes may be aligned during medium access for broadcasting and unicasting. Due to slotted CSMA, the network may ex-

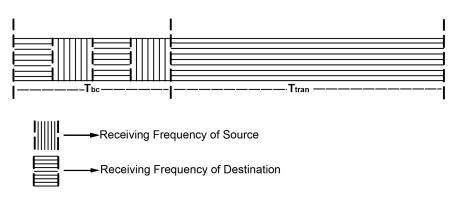


Figure 3.7: Transmission slot in MMSN Protocol [213]

perience jitter, too. A timeslot consists of a broadcast contention period  $(T_{bc})$  and a transmission period  $(T_{tran})$  as shown in Figure 3.7, redrawn from [213]. If a node has won a broadcast frequency during  $T_{bc}$ , then all the other nodes will get broadcast packets during  $T_{tran}$ . Otherwise, all the nodes will perform toggle snooping and pry on both sending and receiving frequencies for data communication. Once a unicast packet is sensed on the receiving frequency, the node stops toggle snooping for receiving the data packets which helps in handling the node deafness issue.

*Pros and Cons:* The protocol assures QoS by addressing a variety of issues as outlined in Table 3.3. However, it may suffer from some challenges, too. Employing, e.g., a broadcast mechanism for getting two-hop knowledge may result in control overhead (due to neighborhood information management). The frequency hopping between broadcast and unicast frequencies (per timeslot and per message) may induce additional delay and energy consumption. Data loss may occur when a node Y switches to the receiver channel of a node Z for packet transmission, while in the meantime another node X attempts to send data to node Y on its receiving channel and thereby induces the node deafness issue. The protocol may face trouble to entertain any newly arriving nodes as frequency assignment is performed after the network initialization. With high node density, the network throughput would decrease because of increased collision/congestion over the shared frequencies in the two-hop neighborhood.

- Multi Channel Cluster Tree (MCCT): In [104], a clustered multichannel MAC protocol is proposed which is based on IEEE 802.15.4-based slotted CSMA/CA. The neighbor discovery is performed by a Cluster Coordinator (CC) through randomly sending HELLO messages per Beacon Interval (BI) during its inactive super-frame interval on the Common Control Channel (CCC). Each HELLO message has neighborhood information which is stored by the receiving node in its neighbor table. It may update a node about the slots/channels used in the twohop neighborhood and making appropriate slot/channel decisions for avoiding collision and interference. The neighbor table information also helps a node in selecting the best among the available CCs. Afterward, the unassociated node may shift to the cluster channel for executing an IEEE 802.15.4-based association procedure during the active super-frame interval. Any node joining the network may either operate as reduced-function device (leaf node) or full-function device (coordinator node). The coordinator node initially works in passive mode and sends only HELLO messages on the CCC until a new node associates with it and thereby delegates the role of active coordinator to it. Thereupon, it selects a least used channel from the least-interfered channel set and transmits beacon messages on a new channel for maintaining synchronization with its children in the same way that its parent coordinator has had maintained on her channel.

*Pros and Cons:* Being based on a static channel assignment, the protocol may suffer from the communication impedance issue which may not allow a node to directly communicate with a neighbor node on a different channel and may induce additional delay and energy consumption. Using a dedicated control channel is costly because reserving a portion of bandwidth for control purpose not only reduces the bandwidth for data communication, but also disrupts the

#### 3.5. MAC PROTOCOLS FOR MULTICHANNEL MWSNS

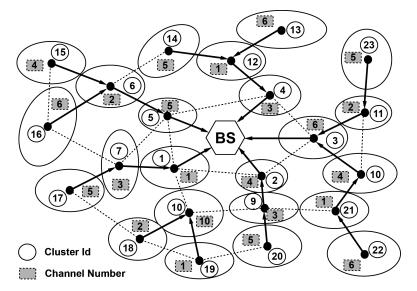


Figure 3.8: Channel Assignment to Clusters in DTFMM Protocol [89]

network communication in case the control channel is jammed or DoS attack is launched against it. Although for energy efficiency, the protocol tries to maintain the clustering arrangement in a way so as to decrease the total number of clusters and to increase the leaf nodes per cluster. Increasing the number of leaf nodes increases the schedule length accordingly which may cause delayed data delivery.

- Distributed Time/Frequency-division Multichannel MAC (DTFMM): In [89], a cluster tree-based multichannel MAC protocol is proposed for WMSNs which assumes a sensor network composed of disjoint clusters (like the one using HEED protocol [100]) as shown in Figure 3.8, redrawn from [89]. The protocol assumes a routing tree of cluster heads (CHs) where CHs lie on non-crossing branches of the routing tree, converging at the base station. Each CH maintains a neighbor table containing both ID and assigned channel of the neighboring clusters. The information in the neighbor table is helpful in assigning distinct channels to adjacent clusters on a public frequency, in a manner that the neighboring cluster(s) with the smallest ID(s) is assigned the channel first and so on. Once a CH is assigned a channel, the associated cluster members are also shifted to that channel. On the basis of the biggest-sized cluster, the BS decides the size of the TDMA frame for intra-cluster communication. Each CH transmits synchronization beacons on the cluster channel for establishing synchronization with the CMs. Afterward, the CMs interested in transmitting data, access the channel using the CSMA approach and send data request messages (along with the node ID and size of data to transmit) to the related CH. Subsequently, the CH decides the schedule for the associated CMs based on their priority and broadcasts to the CMs. Once getting the schedule, the CMs send data on their assigned timeslot to the corresponding CH. The CHs on each disjoint path of the routing tree move to the channel occupied by the immediate CH of the BS on the corresponding path. The CHs use a depth-first-ordering-based TDMA approach for transmitting data to BS. Since all the clusters observe the same TDMA frame

CHAPTER 3. MULTICHANNEL TECHNOLOGY OVERVIEW: AT MAC LAYER

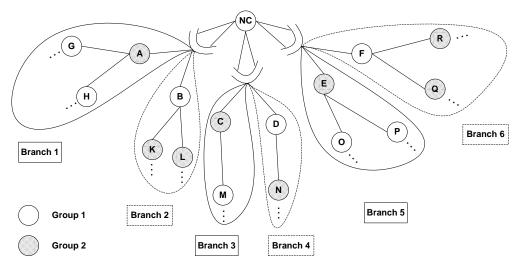


Figure 3.9: Network Segmentation in HMC-MAC Protocol [129]

length, the length of the data collection period across the network is the same.

*Pros and Cons:* Apart from handling a number of issues described in Table 3.3, the protocol may suffer from a variety of challenges. It employs, e.g., tight synchronization for both intra and inter-cluster communication. Such a synchronization is maintained at the intra-cluster level by sending synchronization beacons, however it is not considered during inter-cluster communication. Assigning distinct channels to adjacent clusters on a public frequency may induce dedicated control channel overhead. Consequently, interference/jamming on a public channel may cause communication impedance across the network. The CSMA-based medium access (for sending intra-cluster request messages) may cause collisions and congestion when the cluster size is very large. Due to using TDMA scheduling, the protocol provides poor network performance (worse than MMSN) for smaller numbers of nodes (<100).

- Enhanced Multi-Channel MAC Protocol (Enhanced HMC-MAC Protocol): In [129], a multichannel MAC protocol is proposed which operates in three steps. During the first step, the multi-radio Node Coordinator (NC) broadcasts a TDMA-based beacon propagation schedule for sensor nodes on a semaphore channel. It enables sensor nodes to broadcast beacons on their assigned beaconing timeslot. Providing beacons with one-hop and two-hop bitmaps may enable building a three-hop neighborhood list at a receiver node. Channel allocation is started from NC (sink node) which selects a unique channel for each of its interfaces. Afterward, the highest priority node (having the smallest network address) in the three-hop neighborhood of its group selects a unique channel and so on till all the unassigned nodes select a channel for communication. If a distinct channel is not available in the three-hop neighborhood, then afterward two-hop and one-hop neighborhood of its group is considered for unique channel selection, otherwise random channel allocation is adopted by the corresponding node for selecting a channel among the less used channels in the one-hop neighborhood. After selecting a channel, a node broadcasts it in the beacon. The protocol employs a

hierarchical ZigBee addressing approach for enabling a sensor node to find its tree branch. The tree branch and depth knowledge is required for categorizing sensor nodes into Group 1 or Group 2 for performing data transmission and reception in alternative manner as depicted in Figure 3.9, redrawn from [129]. Subsequently during the second step, sensor nodes belonging to Group 1 and Group 2 may perform data communication on the corresponding receiver channels. If more nodes are interested in sending data to the corresponding receiver, then they may decide among themselves using the CSMA/CA approach. When the network topology is not changed, the same data transmission schedule may be utilized afterward. After data transmission, sensor nodes enter the third step of sleep mode in order to conserve energy.

*Pros and Cons:* The protocol addresses some of the issues outlined in Table 3.3. It has an adaptive data exchange interval which can accommodate traffic of varying size. The protocol avoids beacon collisions by issuing a beacon propagation schedule. The size of beaconing control packets would increase due to sending one-hop and two-hop bitmaps in it. Due to employing static channel assignment, the protocol may suffer from the communication impedance issue. Interference may be caused because the nodes in a neighborhood may be assigned the same channel for communication. The beacon propagation and data delivery phase requires synchronization between sensor nodes, however the protocol neither discusses any such mechanism nor assumes any approach for maintaining synchronization between nodes. Performing the beacon propagation phase on a semaphore channel may be risky because any mishap with the semaphore channel may result in loss of communication in the network. Additionally, the nodes near the sink may suffer from queue overflow and thereby data loss which makes this protocol unreliable for mission-critical high data rate applications.

#### 3.5.2.4 OTHER-NOVEL

It is evident from the classification in Figure 3.1 that this category is composed of the following protocols:

- Control Theory Approach for Throughput Optimization (CTATO) in multichannel collection sensor networks: In CTATO [158], a distributed tree-based multichannel protocol is proposed where sensor nodes perform self-adaptive load balancing and subsequently improve network performance. The protocol employs a multi-sink approach in which sink nodes are associated with each other on the backbone network. Each sink node computes the load on its dedicated channel and shares this information with other sink nodes. A sink node having the load information on corresponding channels broadcasts it on its default channel (through sending a CONTROL message) after a fixed interval, so that the corresponding sensor nodes may get load information regarding all the available channels. Afterward, each sensor node locally computes the switching probability to decide switching to a new channel. If it is more reasonable to stay on the current channel during the current sampling interval T, the sensor node rebroadcasts the CONTROL message to its neighboring nodes. Otherwise for performing load adjustment, it broadcasts a LEAVE ANNOUNCEMENT message and shifts to the new channel using an *on-policy channel selection ap*- *proach.* The child nodes also follow the parent by re-broadcasting the LEAVE ANNOUNCEMENT message and switching to the parent's channel. Such a channel shifting may help to handle congestion and achieving high throughput, low delay and energy efficiency in MWSNs. However, in case a node may not find any parent node on the new channel, it follows an *off-line channel selection approach* and randomly selects a new channel which is not utilized until the last *on-policy channel selection.* After joining a new channel, a node broadcasts a JOIN REQUEST packet. When it gets the JOIN ACCEPT packet from the suitable neighbor node, it connects to that neighbor as child node and forwards the buffered DATA messages right away.

*Pros and Cons:* The protocol may handle a variety of issues described in Table 3.3. At each sampling instant, every sensor node calculates the channel switching probability using a control theoretic approach. It uses the channel load vector from the corresponding sink node which may cause energy and memory overhead. Although the protocol may not suffer from dedicated control channel overhead, it may still suffer from DoS or jamming attacks on each individual channel dedicated to a specific sink node and thereby cause data loss and retransmission overhead. In case of less traffic load, this scheme increases system cost by employing multiple sinks in the network. Additionally, the protocol requires a lot of control overhead by broadcasting either CONTROL or LEAVE ANNOUNCEMENT messages per sampling interval by every node. Too many broadcasts may consume enormous amounts of network bandwidth and induce collisions accordingly.

- Practical Multichannel Media Access Control (PMMAC) protocol for wireless sensor networks: In PMMAC [159], a control theory-based multichannel MAC protocol is proposed for improving bandwidth and enhancing network performance. Each node periodically broadcasts a tuple in its neighborhood which describes the load on its current channel. When, due to congestion/interference, the load on a lower-level channel surpasses a threshold value, an on-channel (sink-like) node on this lower-level channel shifts to the adjacent higher level channel. Afterward the nodes in active coordination with the shifting node also jump to the new channel, so that they may easily coordinate with it. In this way, the cluster size on the next (higher-level) channel is increased which is designated as channel expansion. When a lower-level channel is under-loaded, then nodes on this channel invite the adjoining higher-level nodes to jump back to this lower-level channel. Afterward, an on-channel (sink-like) node on the higherlevel channel jumps to the immediate lower-level channel followed by the associated nodes (which is called *channel shrinking*). Since allowing all the nodes to jump to the higher-level channel simultaneously may cause performance degradation, a balance is maintained by the controller through adjusting the switching probability. In this way, unnecessary channel switchings are handled appropriately and the desired system performance is attained.

*Pros and Cons:* The protocol may handle some issues as described in Table 3.3. It is scalable with both medium and low network densities. The network control is robust because control messages have special reserved places in the nodal queue. As a result, they are not lost in case even with high data loads. Although

the queuing approach for data/control messages provides reliability, it imposes delay, too. The protocol suffers from control overhead caused by (*i*)- periodic broadcasts of channel health messages, (*ii*)- neighborhood broadcasts regarding frequency switching and (*iii*)- home channels discovery of proximate nodes which would be energy consuming. Since lower-level channels are always in use, any periodic DoS and jamming attacks on those channels may result into data loss as well as temporary channel expansion and shrinking. This may cause unnecessary energy overhead and delay.

– Regret Matching-based Channel Assignment (RMCA): In [208], a regret matchingbased distributed multichannel protocol is proposed for improving network performance in MWSNs. Here, on the basis of past knowledge, a sensor node anticipates future changes of network flow and topology in its neighborhood and selects the channel for the next phase accordingly. Initially, a sensor node randomly selects a channel and computes its utility function based on the Valid Received Ratio (VRR) and the Average Transmission Delay (ATD). The VRR is a measure of valid packets received by a node among the total number of sensed packets while ATD specifies the average delay of valid packets received by a node. Afterward, the performance matrix is updated and utilized for computing the average regret for the current stage. Subsequently, this average regret is exploited for calculating the play probability vector for the next stage that may determine the receiving channel for the coming stage. In case the estimated channel is different from the current channel, then it is broadcasted in the neighborhood on the common control channel for handling interference, improving packet delivery ratio and reducing packet delivery delay. Consequently the MWSN behaves sub-optimally due to the indigenous optimal performance of sensor nodes.

*Pros and Cons:* The protocol may handle a variety of issues described in Table 3.3. However, it may also suffer from the idle listening issue due to the always-on receivers. Since no mechanism is devised for refraining a sensor node from waking up on an already busy channel, it may cause the multichannel Hidden Terminal Issue (HTI). The sensor nodes near the sink contend for the medium using the CSMA/CA strategy which, in case of high data rate, may cause the single sink bottleneck issue. The system is memory-based where future channel prediction is based on past knowledge about the environment. Hence, it may be costly in terms of memory and energy consumption.

- Game Theory-based Coalition Formation (GTCF) algorithm: In GTCF [178], a game theory-based multichannel MAC protocol is proposed aiming at optimal channel allocation to sensor nodes for balancing overhearing and achieving energy efficiency in WSNs. Here, all the channels are orthogonal in nature whereby each channel deems to form a coalition of sensor nodes for balancing the coalition structure. The non-leaf nodes are assigned orthogonal channels for receiving data. Initially, all sensor nodes are occupying the base channel. Afterward, for improving its payoff, each node may decide channel switching in the prevailing scenario. The decision is made on the basis of past utility and current knowledge of resident nodes in the corresponding channels. If there is a chance of increasing its payoff, then the node may participate in the game as

Durational	<b>T</b>	NT - (		C	Compa	rison Tool
Protocols	Topology	Network Density	Focal Point	Comparison with	Testbed	Simulator
MMSN [213]	Uniform	Large	Parallel communication, energy efficiency	CSMA		GloMoSim [209]
MCMAC [122]	Cluster	Large	Network lifetime improvement	MMSN [213]		OMNET++ [245]
Multiple-Channel LMAC [238]	Uniform	Medium to large	Performance improvement of LMAC [40]			OMNET++ [245]
CMAC [127]	Chain	Small	Network performance improvement	SMAC [95]		NS-2 [252]
MCPE [139]	Cluster Tree		Network lifetime improvement	Single/Multi channel variations		Glomosim [209]
TFMAC [152]	Random	Large	Throughput & latency improvement	Density & load variations		C++based
HYMAC [179]	Tree	Large	Throughput & latency improvement	RT-Link [177], MMSN [213]		
CTATO [158]	Tree	Medium	Optimization using self-adaptive load balancing	MMSN [213]	MicaZ motes	True-Time [254] Toolbox
PMMAC [159]	Tree	Small to Medium	Throughput & B.W. improvement	Single/Multi channel dense network based variations	MicaZ motes	Tossim [160]
RMCA [208]	Tree	Medium	Flows/topology based channel assignment	MMSN [213], Single Channel CSMA/CA		OMNET++ [245]
IMMAC [102]	Random	Large	Interference aware communication	MMSN [213], MMAC		
MCCT [104]	Cluster Tree	Medium	Delay and PDR enhancement	MeshMAC [172], IEEE 802.15.4 [236]		WSNet [134]
DTFMM [89]	Cluster Tree	Large	High data-rate & low delay communication	MMSN [213]		Glomosim [209]
Enhanced HMC-MAC [129]	Hierarchical Cluster Tree	Medium	High data-rate traffic using limited channels	gh data-rate traffic using limited HMC-MAC without		NS-2 [252]

Table 3.5: Supplementary attributes of medium robust multichannel MAC protocols for WSNs

Large: Nodes > 70, Medium: 20 < Nodes <=70, Small: Nodes <= 20

active player, so that its payoff may increase by switching to another channel. Otherwise the node becomes inactive for the current round and stays in the prevailing channel. The game terminates in case all the nodes are in the inactive state and henceforth, a steady state coalition is achieved.

*Pros and Cons:* The protocol handles some of the issues stated in Table 3.3. However, it does not provide concrete assurance for a unique channel assignment to nodes in the two-hop neighborhood. Additionally, it does not provide any knowledge about important quality assurance parameters such as throughput, delay and reliability. For evaluating the soundness of this approach, a comparison with a widely-accepted technique should have been provided.

- Stochastic Learning Automata (SLA)-based dynamic channel access algorithm: In this paper [103], a game-theory-based distributed protocol is proposed which employs a stochastic learning automata for realizing the Nash Equilibrium (NE) of a channel admission game in energy harvesting MWSNs. Initially each sensor node (or SLA player) randomly selects a channel. Afterward an optimal strategy is employed and data is sent on the channel. Eventually on the basis of the outcome of the data delivery (i.e. successful or failed) on a particular channel, an SLA player calculates a utility value which may revise the corresponding channel selection probabilities and the strategy for the next timeslot. Therefore on the basis of interaction with the environment, the strategy is reviewed in each coming timeslot until an optimal strategy is determined for the available channels. The protocol performs channel assignment in a completely dynamic manner by neither relying on the actions of neighboring nodes and nor on the state-transition probabilities.

*Pros and Cons:* The protocol handles a variety of issues outlined in Table 3.3. It dynamically accesses the environment in each timeslot till the optimal strategy is attained which may cause channel switching overhead. The protocol is iterative with low convergence rate and executes many steps in each iteration (during a timeslot) which may cause additional energy consumption.

#### 3.5.2.5 CONCLUDING REMARKS FOR MEDIUM-ROBUST PROTO-COLS

This section includes six TDMA, three CSMA, four Composite and five Other-Novel protocols. Among these protocols only HYMAC [179] performs channel assignment in a centralized manner. Therefore it is more optimized, however it may experience additional delay, too. The remaining protocols of this category perform distributed channel assignment and are therefore more robust to handle external stimuli, however they would consume more bandwidth and energy for maintaining a network wide synchronization which is required for extensive message passing.

In this category, static channel assignment is performed by three TDMA-based techniques (i.e. MCMAC [122], HYMAC [179], MinMax [71]), one CSMA-based approach (i.e. MCPE [139]) and three Composite-based protocols (i.e. MCCT [104], Enhanced HMC-MAC [129], DTFMM [89]). Being based on static channel assignment, these protocols do not experience any channel switching overhead and

CHAPTER 3. MULTICHANNEL TECHNOLOGY OVERVIEW: AT MAC LAYER

therefore they are suitable to accommodate high data rate applications. However, if the traffic pattern changes or a channel may suffer from interference and jamming, static channel assignment suffers from the communication impedance issue. On the basis of the design challenges oriented analysis of Table 3.3, protocols such as MCMAC [122], DTFMM [89], Enhanced HMC-MAC [129], MinMax [71] are more robust than MCPE [139], MCCT [104], followed by HYMAC [179].

The dynamic channel assignment is exhibited by one TDMA-based protocol, namely LRCH [94]. Although dynamic channel assignment is suitable for handling interference and noise, it may cause frequent channel switching overheads such as switching delays/energy consumption and the associated data losses. In case of high data rate applications, frequent channel switching may increase the amount of queued data which may increase both delay and data loss.

The hybrid channel assignment is exhibited by two TDMA-based approaches (i.e. Multiple-Channel LMAC [238], TFMAC [152]), two CSMA-based protocols (CMAC [127], IMMAC [102]), one Composite-based technique (i.e. MMSN [213]) and five Other-Novel protocols (i.e. CTATO [158], PMMAC [159], RMCA [208], GTCF [178], SLA [103]). On the one hand, hybrid channel assignment helps multichannel protocols in dealing with variations in channel and traffic patterns; on the other hand, it decreases channel switching delays, energy consumption and associated data losses. Therefore, it is more suitable for accommodating high data rate applications which are devised for environments with varying channel conditions and traffic patterns. On the basis of the design-issues oriented anatomization in Table 3.3, it is clear that Multiple-Channel LMAC [238] is more robust than MMSN [213], CMAC [127], TFMAC [152], CTATO [158], IMMAC [102], RMCA [208], GTCF [178], SLA [103], followed by PMMAC [159].

#### 3.5.3 LEAST-ROBUST PROTOCOLS

The least-robust protocols are those which may handle some QoS issues discussed in Section 4.4. In other words, these protocols may address '4 or less' QoS issues as outlined in Table 3.3. All the protocols belonging to this category are CSMA-based. Below we will discuss the functionality of these protocols along with their pros and cons.

#### 3.5.3.1 CSMA-BASED (CONTENTION-BASED MEDIUM ACCESS)

As evident from the classification diagram in Figure 3.1, the multichannel MAC protocols belonging to this category are enlisted below:

- Adaptive Cross-layer MAC (ACMAC) design for improved energy-efficiency in multichannel wireless sensor networks: In ACMAC [72], a cross layered multichannel MAC protocol is devised that achieves energy efficiency by load-adaptive joint optimization of back-off probability (at MAC layer) and modulation order (at Physical layer). Here, the sink node estimates the traffic load on each channel based on the *number of transmissions* that have occurred for *end-to-end* delivery of a data packet to the sink node. Contingent upon this information, the sink determines a suitable modulation order which is transmitted periodically on the

Protocols	Topology	Network	Focal Point	Comparison with	Comparison Tool		
110100015	Topology	Density	rocarronit		Testbed	Simulator	
GTCF [178] Tree		Largo	Improving network life handling	Indigenous variations			
GICF [176]	liee	Large	overhearing	mulgenous variations			
MinMax [71]	Tree	Largo	Interference handling using limited	GBCA [207] & centralized greedy	TelosB motes	Indigenous built	
		Large	channels	algorithm	Telosb motes	margenous built	
SLA [103]		Medium to Enhancing network utility and		Random channel selection			
SLA[105]		large	impartiality in resource assignment	Kandoni channel selection			
LRCH [94]	Flat	Small	Internal/external interference avoidance	PRH Algorithm		NS-2 [252]	

Table 3.5: (Continued...)

Large: Nodes > 70, Medium: 20 < Nodes <= 70, Small: Nodes <= 20

Table 3.6: Supplementary attributes of least robust multichannel MAC protocol	ls for WSNs
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Protocols	Topology	Network	Focal Point	Comparison with	Comparison Tool			
11000015	Topology	Density	rocarronnt	Comparison with	Testbed	Simulator		
ACMAC [72]	Random	Large	Modulation order & back-off probability variations	MMSN [213]		MATLAB [242], CSIM [226]		
SMC MAC [68]		Small	Network performance improvement	CSMA/CA MAC		MATLAB [242]		
MASN [167]	Hierarchical Cluster Tree	Medium	Network bandwidth improvement	Subtree, Random & Mono approaches		NS-2 [252]		

Large: Nodes > 70, Medium: 20 < Nodes <=70, Small: Nodes <= 20

3.5.

control channel, so that the sensor nodes across the network may adopt it. When a node is interested in sending data to a receiver, it initially executes a sequential channel-sensing mechanism where all the channels are scanned one-by-one in a consecutive manner. If a channel is found busy, then a back-off is initiated on it and the next channel is scanned, until either all the busy channels are back-offed (and the node waits for the expiry of the first back-off to re-sense the corresponding channel again) or an idle channel is found. Upon sensing the idle data channel, the sender node checks the availability of the receiver by sending an RTS packet to the corresponding receiver on the control channel. If the receiver responds with a CTS packet, then both sender and receiver move to the corresponding data channel for data transmission. Moreover, each data packet is acknowledged by the receiver by an ACK message. If the sender does not get ACK message from the receiver, it considers that data loss has occurred due to data collision/corruption and leaves the corresponding channel. Subsequently during the next timeslot, the sender rechecks the available channels (both with the expired back-offs and the other for which no back-off has been initiated till now) until it senses an idle channel or waits till a back-off is expired and backedoff channel is sensed again for its availability for the subsequent transmission.

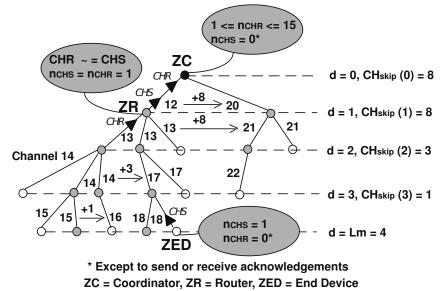
Pros and Cons: The protocol handles some issues described in Table 3.3. In case of heavy traffic load, the sensing process, based on non-persistent CSMA, may contribute to collisions. As a result, the nodes go into the backoff period again and again which causes delay and energy consumption. The non-persistent CSMA may contribute to the single-sink-bottleneck issue because it may increase contention around the sink node in case of high data rate applications. Due to alternative expiry of the backoffs of two sender nodes, they may simultaneously perform channel negotiation with the corresponding nodes on the control channel. Therefore, it may be possible that during the data communication by one node pair, the alternate node pair may start data communication on the same data channel which may cause collisions due to the multichannel hidden-terminal issue in the network. The dedicated control channel decreases the overall bandwidth and may result in network degradation, if it is affected by noise/interference. Employing the IEEE 802.11-based RTS/CTS methodology is costly for IEEE 802.15.4-based WSNs. This is because IEEE 802.15.4-based networks may send small-sized data packets and thereby can not afford sending control packets frequently.

– Sensor Multi-Channel MAC (SMC MAC): In [68], a distributed multichannel MAC protocol is proposed which uses a Dedicated Control Channel (DCC) for performing channel negotiation between sender and receiver nodes. Each node maintains a local 8-bit Channel Status Table (CST). Each bit of the CST corresponds to a separate data channel and may be either 0 (representing an idle channel) or 1 (representing a busy channel). When a node is interested in sending data to a receiver, it sends an RTS packet (along with  $CST_{sen}$ ) to the intended receiver on the control channel. The receiver, if available, responds with a CTS packet (along with  $CST_{rec}$ ). The  $CST_{rec}$  is based on the CSTs of both sender and receiver where the first common available data channel is marked. Afterward both receiver and sender are shifted to the common data channel for performing data communication. Upon completion of data transmission, the receiver sends

an ACK to the sender. Consequently both sender and receiver nodes are shifted to the common control channel and mark the corresponding data channel bit as idle. Since neighboring nodes may also get CTS or ACK messages, they may also know the status (busy or idle) of the corresponding data channel and thus proceed accordingly.

*Pros and Cons:* The protocol handles the node deafness, multichannel hidden terminal, communication impedance and frequent channel switching issues, it may suffer from a variety of issues such as idle listening, dedicated control-channel overhead and so on. The use of a dedicated control channel may cause bandwidth loss and performance degradation due to jamming and interference. Additionally, maintaining a channel status table requires additional energy and memory overhead.

– Multichannel Access for Sensor Networks (MASN): In [167], a hierarchical multichannel clustering protocol is put forth which proposes channel assignment and switching extensions of IEEE 802.15.4/ZigBee. During the network deployment period, the Coordinator Node (CN) runs an association procedure on the common channel 11. The association procedure allocates receiving channels to sensor nodes by employing a hierarchical addressing process as used in Zigbee networks. Here, the coordinator node (sink) centrally computes a frequency offset amid two consecutive child routers by using a *CHskip* function. The children of a parent node share the same sending channel and access it using a CSMA/CA-based procedure for sending information to the parent node. The channel assignment procedure assigns unique sending and receiving channels to a sensor node and builds a hierarchical cluster tree as shown in Figure 3.10, redrawn from [167]. The channel switching between sending and receiving frequencies is executed using the PHY primitive existing in the transceivers.



CHR = Receiving Channel, CHS = Sending Channel

Figure 3.10: Channel Assignment in MASN Protocol [167]

Therefore after data arrival, the default channel receiving mode (*CHR*) is shifted to the channel sending mode (*CHS*) and returns back to the *CHR* mode when the MAC acknowledgment of data delivery is received. Due to the minute adjustment at the MAC layer, the protocol can be incorporated in ZigBee-based sensor nodes.

Pros and Cons: For increasing network throughput, CSMA/CA follows the IEEE 802.15.4 non-beacon enabled mode where the receivers of Zigbee routers are always ON and thereby consume more energy. Therefore, the protocol may experience the idle listening issue. Being based on static channel assignment, the protocol may suffer from the communication impedance issue where a node may send data to a nearby node through either the coordinator or router node. Using distinct sending and receiving channels, the single transceiver of each sensor node may encounter the overhead of frequent channel switching. The CSMA-based cluster channel access mechanism may increase contention around the coordinator node, in case the data rate is high. The protocol may suffer from dedicated control channel overhead which may degrade system performance, in case the dedicated control channel is jammed/interfered. Since sending each data frame may involve CSMA-based channel access overhead (at the sender) and channel switching/MAC acknowledgment overhead (at each receiver), the overhead may increase along with increasing path length between sender and receiver nodes.

#### 3.5.3.2 CONCLUDING REMARKS FOR LEAST-ROBUST PROTOCOLS

This section involves a comprehensive discussion of three CSMA-based multichannel approaches. Among these protocols, only MASN [167] performs centralized channel assignment which makes it more optimized than the remaining protocols employing distributed channel assignment and thereby are more reactive by nature.

In this category, MASN [167] is the only protocol performing static channel assignment. Therefore, the performance of MASN [167] is not impeded by channel switching overheads. Consequently, it may perform well for high data rate applications when the traffic pattern is uniform and the environmental conditions are stable which is rare in real world scenarios.

Hybrid channel assignment is exhibited by the remaining two CSMA-based protocols (i.e. ACMAC [72] and SMC MAC [68]). The hybrid channel assignment allows these protocols to alleviate channel switching overheads and to handle traffic and channel variations (such as interference and jamming). On the basis of the design issues based analysis of Table 3.3, both ACMAC [72] and SMC MAC [68] exhibit more robustness than MASN [167]. Furthermore, this category employs no multichannel MAC protocol which may perform dynamic channel assignment.

# CHAPTER **4**

# MULTICHANNEL TECHNOLOGY OVERVIEW: AT NETWORK LAYER

#### 4.1 INTRODUCTION

The prevailing sensor nodes may contain radio chip such as CC2420 [88] or CC2520 [101] which may provide multichannel capability to WSNs e.g., CC2420 is used in sensor nodes such as MICAz and Telos [82] and therefore they can exhibit multichannel capability in the real world. The multichannel approach is superior to single channel approach because it may afford parallel transmissions by using distinct channels [81] which may result into ensuring high throughput [81], reducing data gathering delay [81] [44] [78] and making sure freshness of data assembly [81]. That is why, multichannel protocols such as MMSN [213], TMMAC [210] and MCMAC [122] show higher performance than single channel protocols [197]. Since multichannel approach extenuates interference, jamming and congestion [81], therefore, it can be a good solution for enhancing system performance. Henceforth a variety of dynamic, hybrid and static multichannel techniques exist today for performing different critical tasks e.g. DEEJAM [195] and EM-MAC [192] may handle jamming, [200] may counter interference, and Typhoon [240] may perform reliable data transmission.

In wireless sensor networks, Quality of Service (QoS) can be measured on the basis of several factors such as mean delay, jitter, bandwidth and reliability. In case of single-channel approach, QoS routing may be more challenging due to inherent health issues of channel such as interference and collision [12]. However, such QoS issues may be dealt with effectively by employing multiple channels for routing. These WSNs based QoS protocols which use multiple channels for routing are coined as multichannel routing protocols in WSNs. These multichannel routing protocols may provide high-performance in WSNs by

enhancing throughput [224], reducing co-channel interference [151], countering jamming [114], providing load-balancing [174] and handling congestion [197]. The general and miscellaneous characteristics of multichannel routing protocols in this survey are outlined in Tables 4.2, 4.3 & 4.4. In case of multi-channel multi-hop QoS routing while performing channel switching becomes a critical issue [58]. One solution to this problem is, to perform careful channel management. In this way, either non-overlapping frequencies can be statically allocated to adjacent links so that packet contention probability may be reduced and high throughput may be ensured [58] or qualitatively best and stabilized channels may be explored dynamically by employing some robust mechanism of channel quality and stability estimation as devised in [4].

Each traffic type has its own demands. These demands can be fulfilled either by exploiting proper routing mechanism that regulates traffic flows on each link and by that impacts channel selection [106] or employing appropriate channel assignment that affects link bandwidth/transmission-interference and thereby influences routing [106]. That is why, channel assignment and routing are dependent on each other [106] and subsequently, multichannel routing may result into performance improvement of wireless networks. For achieving further robustness, the multichannel routing protocols may be further classified into JOINT and DISJOINT categories as considered in Section 4.5 & 4.6. Here JOINT describes that channel assignment & routing are closely associated together whereby routing has role in channel assignment. Whereas DISJOINT describes that channel assignment is performed as a segregated activity from routing and is used in a conventional manner for mainly avoiding interference. Additionally to the best of our understanding, JOINT multichannel routing protocols are more robust and dynamic than DISJOINT multichannel routing protocols.

This chapter focuses on the critical evaluation of the existing multichannel routing protocols in WSNs that claim to provide high performance by relaxing the aggressive environment of competitive routing among sensor nodes. *Furthermore, the literature discussed in this chapter is mainly taken from our multichannel routing based review article [6].* The key contributions and highlights of this survey are outlined below:

- An effort is made to discuss the applications of multichannel routing in different environments.
- An in-depth overview of issues and challenges of multichannel routing is outlined.
- The existing single/multi-path and single/multi-radio multichannel routing schemes are classified into JOINT and DISJOINT categories whereby various schemes are discussed in detail along with their advantages and disadvantages.

The rest of this chapter is structured as follows. In Section 4.2, the significance of survey is put forth while Section 4.3 discusses important applications of multichannel routing protocols in WSNs. In Section 4.4, an in depth discussion of issues and challenges of multichannel routing protocols in WSNs is presented. The Sections 4.5 and 4.6 discuss JOINT and DISJOINT channel assignment &

#### 4.2. SIGNIFICANCE OF SURVEY

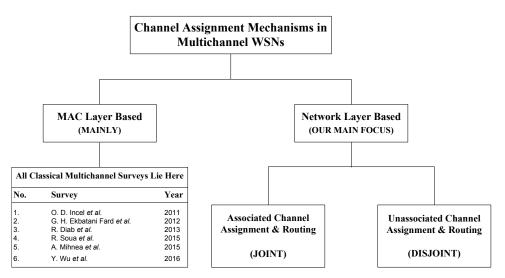


Figure 4.1: Significance of Survey

routing protocols at network layer in a respective manner. These sections discuss the functionality and pros & cons of various multichannel routing protocols along with the *Summaries and Insights* of the relevant sub-sections.

#### 4.2 SIGNIFICANCE OF SURVEY

A handful number of reviews are published so far regarding Multichannel Wireless Sensor Networks (MWSNs) that include [81], [44], [31], [29], [243] and [92] as shown in Table 4.1. These surveys mainly discuss those multichannel protocols that perform channel assignment at MAC layer. Whereas multichannel protocols executing channel assignment at Network layer are least focused in these surveys. To bridge this gap, an initiative is taken in this survey and a detailed and comprehensive analysis of multichannel routing protocols performing channel assignment at Network layer is presented. Moreover, based upon the association of channel assignment & routing at Network layer, an original taxonomy of JOINT and DISJOINT multichannel routing protocols is presented as shown in Figure 4.1. Apart from that, a comparative analysis of already published reviews is outlined in Table 4.1 that may not only unveil the characteristics of already published multichannel surveys for WSNs, but may also differentiate this review from the already published multichannel surveys for WSNs.

The survey in [44] discusses multichannel communication protocols in WSNs and compares them using a taxonomy as outlined in Table 4.1. The survey mainly discusses those multichannel protocols that perform channel assignment at MAC layer. It discusses only two multichannel routing protocols (one JOINT i.e. RBCA [149] and one DISJOINT i.e. TMCP [197]) that perform channel assignment at network layer. The authors in [31] have classified multichannel protocols on the basis of various challenges addressed by those protocols and miscellaneous relevant characteristics as outlined in Table 4.1. Similarly in [29], the

authors have briefly differentiated multichannel protocols in WSNs. Both [31] and [29] focus on those WSNs protocols that mainly perform channel assignment at MAC layer. However, both of them discuss only one network layer based DISJOINT multichannel routing protocol (i.e. TMCP [197]) while no JOINT multichannel routing protocol is outlined in those surveys. The survey in [81] outlines multichannel assignment protocols in WSNs. It majorly categorizes and compares multichannel MAC based protocols in WSNs based on a given taxonomy outlined in Table 4.1. Moreover, the protocol discusses only three network layer based multichannel routing protocols among them two are DISJOINT (i.e. TMCP [197], MCRT [88]) and one is JOINT (i.e. OR+SCP [164]). A. Mihnea *et al.* [243] have discussed important aspects of multichannel algorithms which may help to design new multichannel protocols in WSNs as outlined in Table 4.1. The survey describes two JOINT (i.e. RBCA [149], DRCS [174]) and two DISJOINT (i.e. TMCP [197], MCRT [88]) multichannel routing protocols in WSNs.

Additionally Y. Wu *et al.* [92] have reviewed both traditional and cognitive radio based multichannel WSNs whereby different approaches are classified based on underlined topology outlined in Table 4.1. The survey discusses four JOINT (i.e. DRCS [174], CNOR [186], SEA-OR [187], RMCA-FR [126]) and one DISJOINT (i.e. TMCP [197]) multichannel routing protocols in WSNs. To the best of our knowledge and on the basis of literature reviewed, we can deduce the following conclusions as motivating factors for the rest of this survey.

- Although a few *multichannel surveys* are published so far for WSNs, however, there is need to publish a multichannel survey that mainly focuses on those protocols performing channel assignment at network layer. Since channel assignment at network layer is the property of routing protocols, therefore in other words we can say that no *multichannel routing survey* is published so far for WSNs.
- Our *multichannel routing survey* for WSNs is different from all the above mentioned reviews in Table 4.1 because it is not only the *pioneer survey* considering multichannel routing protocols for WSNs, but also is based on a novel taxonomy considering JOINT and DISJOINT channel assignment & routing protocols in MWSNs as discussed in Section 4.5 & 4.6 respectively. The survey regards *in-depth analysis* of existing multichannel routing protocols for WSNs whereby 24 network layer based multichannel protocols for WSNs are categorized and discussed, among them only 8 protocols are discussed in the already published reviews outlined in Table 4.1.
- The survey not only discusses relevant issues & challenges in this field of research, but is also supported with the relevant classification diagrams and tables which may provide *in-depth categorization and analysis* of multichannel routing protocols in WSNs. Additionally, a brief summary of each discussed multichannel routing protocol is presented along with relevant pros and cons which may critically evaluate functionality of each discussed protocol. At the end of this survey, a handsome number of future research challenges are also presented as guiding research directions for new researchers in this area of research.

Survey	Network	Classification Parameters	Miscellaneous Properties	NL.*	Pub.*	
Survey	Туре	Classification rarameters	Chassification Farameters Miscenaneous Froperties			
O. D. Incel <i>et al.</i> [44]	WSNs	Assignment method, control channel, implementation, synchronization, me- dium access, broadcast support, chan- nel model, interference model and the objectives	Challenges of multichannel commu- nication, future research directions of multichannel WSNs	1	1	2011
G. H. Ekbatani Fard et al. [31]	WSNs	Topology, mobility support, impleme- ntation, channel assignment method, data channel, transceivers, evaluation, medium access and objectives	Challenges addressed by reviewed multichannel WSNs protocols		1	2012
R. Diab et al. [29]	WSNs	Implementation, synchronization, me- dium access, broadcast support, data channel, channel allocation, evaluati- on method and objective	Open issues of multichannel WSNs		1	2013
R. Soua <i>et al.</i> [81]	WSNs	Goals, Properties, Channel Selection and assignment, MAC Type, channel allocation layer, architecture and im- plementation method	Issues of multichannel communicat- ions and future research directions of multichannel WSNs	1	2	2015
A. Mihnea <i>et al.</i> [243]	WSNs	Channel assignment schemes, primary users, network capacity, interference, topology control, and power & traffic awareness	Issues and challenges of multi- channel multiradio WSNs	2	2	2015
Y. Wu et al. [92]	WSNs/ CRWSNs	Frequency band, topology, channel allocation, protocol layer, broadcast support, implementation, objective and evaluation	Challenges and future research directions of CRSNs	4	1	2016

# Table 4.1: Review of Existing Surveys on Multichannel WSNs

NL.\*= Network Layer, Pub.\*= Publication

## 4.3 APPLICATIONS OF MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

Traditional WSNs employ single channel for communication. If channel is busy in two-hop neighborhood due to on-going transmission, then sensor node may suffer from communication impedance. Consequently, data latency (due to temporary storage of data-packets locally) or data loss (due to queue overflow) may occur. Likewise, if channel is available in a locality, but is not of sufficient quality due to on-going attenuation, distortion or jamming, then it may result into interference which causes data loss and may also induce retransmissions. As a result, network throughput and performance is degraded. An illustrative example of anticipated operations of multichannel routing in WSNs is demonstrated in Figure 1.1. Multichannel approach may provide an alternate solution for dealing effectively with prescribed issues of data latency, data loss and retransmissions in single channel WSNs. It may allow sensor nodes to use those channels for communication which are both available in neighborhood and of sufficient quality, for performing data communication. For dealing with runtime degradations in channel quality, multichannel routing protocols may employ mechanisms such as channel hopping [192] (that may allow sensor nodes to dynamically switch to alternate channels of sufficient quality) or channel quality and stability estimation [4] (that may motivate multichannel sensor nodes to switch to those channels that exhibit both good quality and stability). In this way, not only data loss or latency may be avoided, but also, reliability and high throughput is ensured that may result into high performance in WSNs. It is also true that multichannel approach may increase cost and complexity of underlying WSNs, but the advantages it provides such as high performance and secure communication has far more reaching affects than the induced cost and complexity. Below, we will briefly discuss some of the important applications of multichannel routing protocols in WSNs.

#### 4.3.1 DISASTER MANAGEMENT

Natural calamities such as earthquake and volcano eruption are spontaneous and gradual in nature. Their aftereffects are in the form of tsunamis and severeaftershocks which may escalate the overall devastation [55]. Apart from destroying buildings and roads, they may also cause devastation to Information and Communication Technology (ICT) infrastructure which may also increase traffic volume many folds [55]. Such increase in traffic volume may be due to the fact that the leftover ICT infrastructure doesn't have the capacity to accommodate heavy traffic loads and consequently may suffer from congestion and collision. Therefore, ensuring minimum capacity of ICT infrastructure is very important for performing first aid relief operations in the disaster stricken region. It may help to preemptively inform the inhabitants of the disaster stricken region regarding the pending aftereffects and thereby may help in securing their lives. Like the ordinary WSNs, the MWSNs have the characteristics of rapid-deployment, fault-tolerance, self-organization and cooperative-nature, therefore they can be a good candidate for increasing the capacity of leftover ICT infrastructure in the disaster stricken region. The cheap multichannel sensor nodes may be dropped in the disaster affected area immediately after the disaster by using aerial vehicles. Since cognitive WSNs may work on both primary and secondary channels, therefore, they may provide primary infrastructure in those areas where main ICT infrastructure is completely damaged. They may also provide an alternate infrastructure in those areas where primary ICT infrastructure is partially damaged. In this way, MWSNs may help in information dissemination and rescue/rehabilitation activities for the noble cause of saving and serving the humanity.

#### 4.3.2 COMBAT/SURVEILLANCE OPERATIONS

With the advancement in technology, novel communication paradigms are devised such as Opportunistic Routing (OR). Although, OR technique provides high performance to wireless networks [16], but it may readily suffer from security threats [16] and is not reliable. Therefore, it is risky to use it in tactical WSNs for dealing with combat and surveillance operations such as battlefield or border surveillance management. One of the alternate solutions is to enhance the reliability of such approaches by providing them with dynamic multichannel mechanisms such as channel hopping and channel quality/stability estimation. Eventually to some extent, they may refrain an intruder in materializing his aims of either to compromise the identity of a trusted node or to halt communication system by launching jamming or intercepting attacks. Consequently, required high performance and efficiency may be ensured. For example, EM-MAC [192] and LEMR-multichannel [114] are multichannel protocols which may deal with jamming attacks by employing dynamic channel allocation. Likewise Ext-NEAMCBTC [4] may handle jamming attacks and is helpful in stream based communication in MWSNs. Similarly, MMOCR [151] is a multichannel based OR protocol which uses Cumulative Interference Strength (CIS) based metric to find the best among available channel using hybrid channel selection technique and may handle co-channel interference.

#### 4.3.3 INDUSTRIAL EXPLORATION

Industrial exploration is a very important application of WSNs which may allow sensor nodes to sense scalar/vector data and relay final information towards central entity or control room. Since, oil/gas exploration plants and mining sites are located in challenging terrain, therefore they may suffer from both mechanical affects due to industrial equipment and environmental affects from surroundings. It may result into attenuation and distortion of wireless signals which may degrade network performance. The multichannel wireless sensor networks may provide a more flexible solution to this problem and enable sensor nodes to avoid those channels which are of inferior health and quality. Henceforth, propagating wireless signals at good quality channels may result into ensuring cost-effective data transmission towards central entity.

#### 4.3.4 MOVING PHENOMENON TRACKING

For ensuring safety of human lives and public property, it is prime important to track moving phenomena which may cause mass level destruction if turned

uncontrolled and violent. The important examples of pursuing moving phenomena are fire and water currents tracking. The wildfire has affected almost each and every continent of the world. Even the developed countries such as Australia and USA have been its continuous victims and consequently, suffered from both man and material damages. e.g. in Australia, Ash Wednesday Fire of 1983 [217] and Black Saturday Fire of 2009 [219] have killed 75 and 173 people respectively. Likewise in USA, Yarnell Hill Fire of 2013 [259] and Valley Fire of 2015 [256] have killed 19 and 4 people respectively. The MWSN may track moving phenomenon [139] as summarized hereinafter. In this respect, multichannel sensor nodes may be dropped from aerial vehicles in fire region which may automatically tune themselves on specific channel measured in accordance with the outside temperature range. Afterwards, proximate sensor nodes on the same channel may elect cluster head which may aggregate the received data sensed by member sensor nodes through virtual sensing approach. Subsequently cluster head relays aggregated data to sink node on control channel. When temperature of any region increases, then it is a clear indication that fire is moving across a particular geographic region. As a result, corresponding sensor nodes move to analogous channel and increase their sampling rate for correctly tracking the moving phenomenon. If the temperature gets stabilized, then the sampling rate is decreased too [139].

#### 4.3.5 AIR-VEHICLES ON-BOARD COMMUNICATION

One of the main applications of WSNs may be in aerospace communication systems where WSNs may be used to replace airplane communication cables which may not only decrease aircraft weight, but also handle installation, maintenance and troubleshooting costs [109]. Decrease in airplane weight may lower fuel expenditure km/h and the associated costs which may increase flying hours accordingly. The single channel WSNs may not be able to provide secure on-board communication either between mechanical parts of airplane or between cockpit and aircraft cabin. Therefore, multichannel approach may provide a reasonable solution to this problem which may not only handle any natural attenuation from the surroundings, but may also deal with artificial attenuation caused by both on-board/outside miscreants. For ensuring further reliability, dynamic channel allocation such as frequency hopping or hybrid channel selection approach may be employed. Like the ordinary WSNs which may provide structural health monitoring of airplanes [17], the MWSNs may be employed for providing a more robust and reliable solution in this regard.

### 4.4 ISSUES AND CHALLENGES OF MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

Multichannel approach brings about performance improvement in WSNs, however it may also suffer from a variety of inherent issues. When considered appropriately with due responsibility in multichannel routing protocol design, these issues may improve system performance and vice versa. Below, a variety of such issues of MWSNs are briefly discussed.

#### 4.4.1 NETWORK ARCHITECTURE DESIGN

Since network architecture is application dependent, therefore a reasonable design of network architecture may result into proper working and performance of the inherent MWSNs application. The network design model may be flat or hierarchical in nature. The flat network assigns same role to all network entities [64] and therefore, is homogeneous in nature. The hierarchical network assigns varying roles to nodes in a hierarchy [64] and is normally heterogeneous in nature. Sensor nodes in homogeneous network have same energy, memory and processing ability [50] which enable them to perform simplified activities. Whereas sensor nodes in heterogeneous network may perform more diversified tasks and therefore suffer from more practical data routing challenges. Since, MWSNs execute parallel transmissions [81], therefore their throughput would be further enhanced [81] [44] which raise new challenges of proper network design model selection. Therefore, considering the impacts of heterogeneity and channel assignment together would result into devising more robust multichannel routing protocol for WSNs that may ensure high performance. The increase in data rate in MWSNs may also require more robust data reporting model too, so that the information reach successfully to sink node under the desired QoS constraints. It is evident that periodic communication may consume more energy than on-demand transmission, therefore it is cost effective to employ on-demand reporting model (query-based or event based) for MWSNs, unless and until, it is necessary to apply periodic reporting model. The network topology of WSNs may be static or dynamic in nature. In case of static networks such as [197], the neighborhood of a node remains constant which helps sensor nodes to perform neighbor discovery, route initiation and channel assignment with limited control overhead. In case of dynamic networks [139] [110], both network topology and channel status change with time. As a result, sensor nodes have to dynamically exchange a lot of control information with neighbor nodes for getting correct topological and routing information. High volume of control overhead causes additional burden on network in terms of undue bandwidth and energy consumption. Therefore, routing protocols for MWSNs should look for such mechanisms that may help to manage dynamic topology with least possible control overhead.

#### 4.4.2 ENERGY EFFICIENCY

Sensor nodes are the tiny inexpensive devices that are run by small batteries [11] [4]. Normally, they are not provided with energy harvesting capability and become dead after power outage. Therefore, energy efficient monitoring of the terrain may help them to prolong their lifespan and to efficiently execute mission critical applications such as moving phenomenon tracking (e.g. forest fire and water flow detection) [139], intruder identification [34] and so on. Like traditional single channel WSNs, energy efficient communication is the prime goal of multichannel WSNs. The single channel WSNs consume energy mostly for data communication over single channel whereas MWSNs consume additional energy for performing energy-hungry channel coordination and switching operations. Although, parallel transmissions improves capacity and data rate

	Routing	Initiation	Routing Type		No. of Paths		Link Types		No. of Sinks		TT 1		
Routing Protocols	Source	Sink	Pro.*	Rea.*	Single	Multi	Uni.*	Bi.*	Single	Multi	Hole BP.*	Data Agg.*	C/C.* Handle
CCA [193]		$\checkmark$		$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$
RBCA [149]		$\checkmark$		$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$				$\checkmark$
QoS-aware [140]	$\checkmark$			$\checkmark$		$\checkmark$		$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$
TMCP [197]		$\checkmark$		$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$				
ICADAR [96]		$\checkmark$		$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$
LEMR-multi- channel [114]		$\checkmark$		$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$		$\checkmark$
CRDAR [97]		$\checkmark$		$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$
MIMCR [51]	$\checkmark$		$\checkmark$		$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	$\checkmark$
MCC [224]	$\checkmark$			$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$				$\checkmark$
MCRT [88]	$\checkmark$			$\checkmark$		$\checkmark$	$\checkmark$		$\checkmark$				
OR+SCP [164]			$\checkmark$		$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$		
DRM-MAC [147]		$\checkmark$		$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$		$\checkmark$
CDA [109]		$\checkmark$			$\checkmark$			$\checkmark$	$\checkmark$				$\checkmark$
GBCA-G [110]				$\checkmark$									
RPIRM [202]	$\checkmark$			$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$		
QoSECR [53]	$\checkmark$			$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$				

Table 4.2: Comparison of the General Characteristics of Multichannel Routing Protocols for WSNs

Pro.\*= Proactive, Rea.\*= Reactive, Uni.\*= Unidirectional, Bi.\*= Bidirectional, BP.\*= Bypassing, Agg.\*= Aggregation, C/C.\*= Congestion/Collision

Routing Protocols	Routing	Routing Initiation		Routing Type		No. of Paths		Link Types		Sinks	Hole	Data	C/C.*
	Source	Sink	Pro.*	Rea.*	Single	Multi	Uni.*	Bi.*	Single	Multi	BP.*	Agg.*	Handle
MMOCR [151]	$\checkmark$			$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$				$\checkmark$
NODQC [58]				$\checkmark$	$\checkmark$		$\checkmark$		$\checkmark$				$\checkmark$
DRCS [174]	$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$		$\checkmark$		$\checkmark$		
QS-LEERA- MS [19]	$\checkmark$			$\checkmark$		$\checkmark$		$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$
Distributed- CA [117]		$\checkmark$		$\checkmark$		$\checkmark$		$\checkmark$	$\checkmark$		$\checkmark$		
CNOR [186]	$\checkmark$			$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$				$\checkmark$
SEA-OR [187]	$\checkmark$			$\checkmark$		$\checkmark$		$\checkmark$	$\checkmark$		$\checkmark$		
RMCA-FR [126]				$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$			$\checkmark$	

Table 4.2: (Continued...)

Pro.\*= Proactive, Rea.\*= Reactive, Uni.\*= Unidirectional, Bi.\*= Bidirectional, BP.\*= Bypassing, Agg.\*= Aggregation, C/C.\*= Congestion/Collision

ability of MWSNs [81] [44], however it enhances energy consumption rate too because more traffic flows through the network. It increases transmission/processing overhead in battery constrained MWSNs. Therefore, still there is a need to devise such protocols for MWSNs that may provide energy-efficient communication for dealing with different types of applications.

#### 4.4.3 NETWORK SERVICE QUALITY ISSUES

The multichannel routing approach may enhance network capacity, throughput and minimize delay. But, still it may suffer from some challenging issues that may affect data latency, reliability, jitter and bandwidth. In the following, we will discuss some of those issues in brief.

#### 4.4.3.1 END-TO-END DELAY

Unlike single channel approach, multichannel mechanism may afford parallel communication by assigning dissimilar channels to adjoining nodes which increases network throughput [81]. Since distinct channels are available for parallel transmission, therefore data gathering delay is also reduced [44] [78] and eventually freshness of data assembly is ensured. Therefore, multichannel approach may be employed in mission critical applications such as forest fire and water currents tracking [139]. But, there are some issues which may increase data gathering delay in multichannel WSNs. One of such issue is channel switching mechanism which may consume nearly 200 micro seconds to accomplish on CC2420 radios [44]. In case of multi-hop networks, if each node along a path has distinct channel from its neighbors, then channel switching delay would be proportional to the sum of nodes along the path which would enhance End-to-End (ETE) transmission delay [81] and discourage timely delivery of data.

#### 4.4.3.2 RELIABLE PACKET-DELIVERY

Reliable packet-delivery has inverse relation with data loss rate [30] and is the measure of trustworthiness of a system. Normally, reliability can be ensured in a variety of ways e.g. priority based or multipath based communication [30]. However, MWSNs may ensure reliable data-delivery by transmitting mission-critical data on good quality channels that may reduce the chance of data corruption and eventually data retransmission overhead. Reliable packet-delivery should have to be the integral part of mission critical applications e.g. moving phenomenon tracking [139], pipeline monitoring [189] and border intrusion detection [170]. It is because mission critical applications seriously require trusted communication, so that they may figure out and handle the threats appropriately without being compromised and may minimize the risk of grave consequences in future. MWSNs may also suffer from reliability issues due to several factors such as interference, frequent channel switching overhead and clock drift challenges as explained below:

- *Interference Issue*: Interference may affect data delivery and performance of MWSNs. The type of internal interference, caused due to two consecutive links

#### 4.4. issues and challenges of multichannel routing protocols for wsns

on the same channel on a path in MWSNs is called intra-channel interference. It may occur in multichannel routing protocols such as TMCP [197], MCRT [88] and QS-LEERA-MS [19]. The type of internal interference caused between two different but partially overlapping channels in the same MWSNs is called interchannel interference. It may occur in multichannel routing protocols such as QoS-aware [140], NODQC [58] and Distributed-CA [117]. Here, the adjoining frequencies overlap/interfere with each other because radio signals are not restricted in their assigned frequency band which subsequently contradicts the hypothesis of orthogonal frequencies in practice [44]. The external interference is also called co-channel interference which may be caused due to overlap of similar frequencies between different networks (such as ZigBee (802.15.4) and Wi-Fi [233] or 802.15.4 and electrical devices such as microwave ovens and radar signals [81]). Therefore, before designing any multichannel routing protocol, it is very important to figure out different types and sources of interference. Additionally, the designer of routing protocol must not limit their protocols to orthogonal channels only which may cause insufficient usage of available spectrum [44]. For example, instead of using only 3 orthogonal channel, if all the 11 channels of 802.11b are used with acceptable interference constraint, then it may result into enhancing system performance [171].

- Switching Loss Issue: Unlike the Static Channel Assignment (StCA) based multichannel protocols, both Dynamic Channel Assignment (DyCA) and Hybrid (semi-dynamic) Channel Assignment (HyCA) based multichannel protocols can switch their transceivers between different frequencies when required. Since channel switching causes some delay [81] [44], therefore frequent channel switching may result into data loss in case of high data rate applications [174]. Such data loss may decrease system reliability too. Henceforth, multichannel routing protocols may compensate the overhead of channel switching delays by prolonging the data exchange period between on-channel sender-receiver node pair [44]. The designer of multichannel routing protocols should scrutinize the impact of channel switching overhead on system reliability that may help to devise high performance routing protocols for MWSNs.

- Synchronization Issue: A sensor node may waste 90% of power when it is constantly waiting for the arrival of data [70] and may suffer from idle listening issue. This issue can be resolved by employing low-duty-cycle techniques whereby a sensor node awake for short periods and sleep for long periods [81]. But, maintaining accurate duty cycles require tight-synchronization between communicating nodes which may otherwise cause data loss due to incoherence between their wake-up schedules. The synchronization in MWSNs with dynamic channel selection is more challenging and may increase the probability of data loss because it requires sensor nodes to synchronize both their wake-up and channel-hopping schedules together. Therefore, dynamic multichannel routing protocols in WSNs should be designed very carefully, so that they may be able to handle the inherent synchronization challenges.

#### 4.4.3.3 JITTER

Jitter is caused due to inconsistency of delay between received packets and may introduce disruptions in multimedia communication, therefore it is intolerable for real-time monitoring and surveillance applications [30]. Although, multichannel approach provides parallel communication for reducing networks delays [78] and improving network capacity and throughput [81] [44]. However, it may suffer from channel switching and coordination overhead [44] which may cause delay variability in MWSNs. One possible way may be to perform data buffering and stream based data presentation [30]. However, stream-based data buffering is also costly because it causes both energy and memory overhead.

#### 4.4.3.4 BANDWIDTH

WSNs have limited energy and bandwidth [9]. The multichannel approach increases network capacity [81] [44] and is also affected by number of interfaces per node. For example, two radios are enough for using the capacity of six channels [164] in multi-radio multi-channel WSNs. However, employing multi-radio solution brings about additional hardware cost and complexity in MWSNs. Therefore, employing optimal bandwidth throughput at the cost of minimum possible energy is still an open research challenge.

#### 4.4.4 LOAD BALANCING

Multichannel routing protocol should have the ability to accommodate load balancing by fairly utilizing the network links. Using coding techniques, load balancing may be ensured through data fragmentation and transmission over multiple paths [76]. However, if alternate paths suffers from congestion due to interference, then multipath approach may not produce the desired outcomes. The above issue can be addressed by utilizing orthogonal channels that may handle inter-path interference. However, availability of orthogonal channels is dependent on the underlying technology. For example, in 2.4 GHz Industrial, Scientific and Medical band (ISM), IEEE 802.15.4 provides 16 non-overlapping channels [167] whereas IEEE 802.11b provides 3 orthogonal channels [171] [44]. The 12 (out of 16) channels of IEEE 802.15.4 overlap with 3 channels of IEEE 802.11b which do not make them purely orthogonal. A multichannel routing protocol with load balancing may perform frequent channel switchings which may result into additional channel switching delays, energy consumption and can cause data loss in case of high traffic load [174]. Additionally, the design of routing protocol may matter a lot in executing proper load balancing in MWSNs.

#### 4.4.5 DATA FUSION AND AGGREGATION

The data transmission is considered more costly than data processing [69] [250]. For example, a single bit data communication is 500-1000 times expensive than 32-bit data processing [69] [67]. Similarly, 3 joules of energy are required for transmitting 1Kb data over a distance of 100 meters whereas similar quantity of energy is required in executing 3 million instructions on a general-purpose processor accomplishing 100 MIPS/W [65]. Although, multichannel routing

protocols aim to improve network capacity [81], however transmission of unnecessary data, e.g. redundant information in target tracking cloud [67], limits system performance. This unnecessary data can be handled in two ways. First, by using data fusion techniques which allow sensor nodes to process the incoming signals and fuse them using beam-forming methods [79] such as blind-beamforming [93] that are also suitable for noise suppression. Second, by in-network processing, the raw data packets are generated by sensor nodes in a vicinity that are reduced by maxima [50] [111] [150], minima or average [50] [111] [156] and duplicate suppression techniques [50] [11] [144].

#### 4.4.6 NETWORK SCALABILITY ISSUE

Due to densely deployed nature of WSNs [81] [44], network scalability is also an important issue for MWSNs. If nodes in multichannel network are single transceiver based, then each node can communicate with the other nodes in vicinity using only the same channel. But, when the communicating channels of neighboring single transceiver nodes are different, then they would be completely deaf from each other which would cause network partitioning issue that may contradict the notion of network scalability. Therefore, the designer of single transceiver based routing protocol for MWSNs should take such communication impedance issue into consideration. The alternative approach is to consider multi-radio multi-channel solution which may resolve deafness and network partitioning issues, but it is more costly in terms of energy consumption and Hardware (H/W) cost.

#### 4.4.7 BROADCAST ISSUE

Broadcasting is a one-to-all process of communication networks whereby a message originated by one node is reached to all nodes in the network [38]. That is why, broadcasting is very important for network discovery. In case of MWSNs, broadcasting can be carried out either by switching the transceivers of all nodes on the same channel where sender can broadcast a single copy to perform an activity [81] or transmitting a single copy one-by-one on all channels [81], so that all the receivers may get the relevant information. The first approach decreases control traffic [81] and is energy efficient whereas the second approach is more flexible [81], but increases delay proportionate to the number of channels [102] and adds to control overhead too. Therefore, designing a multichannel routing protocol which can make efficient broadcasts is still an open issue to be coped with by research community.

#### 4.4.8 FAULT TOLERANCE

Fault tolerance enhances the resilience of system, so that it may operate in the presence of network issues [107]. Faults in WSNs may be either node-based (that occur due to energy depletion and physical damage of nodes) or environmental-based (that are caused due to interference in the surroundings [11] [50]). The fault tolerance in MWSNs may be discussed under the following headings:

			1			1			1	
Routing Protocols	Channe	el Assign.* Nature	Chann	el Assign.'	Rout	ing Arch	itecture	Protocol Nature		
	Cent.*	Dist.*	Static	Hybrid	Dynamic	Flat	Hier.*	Geog.*	JOINT	DISJOINT
CCA [193]		$\checkmark$		$\checkmark$		$\checkmark$				$\checkmark$
RBCA [149]	$\checkmark$			$\checkmark$		$\checkmark$			$\checkmark$	
QoS-aware [140]	$\checkmark$			$\checkmark$		$\checkmark$			$\checkmark$	
TMCP [197]	$\checkmark$		$\checkmark$			$\checkmark$				$\checkmark$
ICADAR [96]		$\checkmark$		$\checkmark$		$\checkmark$			$\checkmark$	
LEMR-multi- channel [114]	$\checkmark$				$\checkmark$	$\checkmark$				$\checkmark$
CRDAR [97]		$\checkmark$				$\checkmark$			$\checkmark$	
MIMCR [51]				$\checkmark$		$\checkmark$				$\checkmark$
MCC [224]	$\checkmark$			$\checkmark$		$\checkmark$			$\checkmark$	
MCRT [88]	$\checkmark$		$\checkmark$					$\checkmark$		$\checkmark$
OR+SCP [164]	$\checkmark$				$\checkmark$	$\checkmark$			$\checkmark$	
DRM-MAC [147]		$\checkmark$		$\checkmark$		$\checkmark$			$\checkmark$	
CDA [109]		$\checkmark$		$\checkmark$			$\checkmark$			$\checkmark$
GBCA-G [110]		$\checkmark$			$\checkmark$			$\checkmark$	$\checkmark$	
RPIRM [202]				$\checkmark$		$\checkmark$			$\checkmark$	
QoSECR [53]		$\checkmark$		$\checkmark$			$\checkmark$			$\checkmark$

 Table 4.3: Comparison of Channel Access Mechanism of Multichannel Routing Protocols for WSNs

Assign.\*= Assignment, Cent.\*= Centralized, Dist.\*= Distributed, Hier.\*= Hierarchical, Geog.\*= Geographical

Table 4.3: Continue
---------------------

Routing Protocols	Channel Assign.* Nature		Channel Assign.* Methodology			Routing Architecture			Protocol Nature	
Routing Protocols	Cent.*	Dist.*	Static	Hybrid	Dynamic	Flat	Hier.*	Geog.*	JOINT	DISJOINT
MMOCR [151]		$\checkmark$		$\checkmark$		$\checkmark$			<ul> <li>✓</li> </ul>	
NODQC [58]	$\checkmark$		$\checkmark$			$\checkmark$				$\checkmark$
DRCS[174]		$\checkmark$			$\checkmark$	$\checkmark$			$\checkmark$	
QS-LEERA- MS[19]	$\checkmark$		~					$\checkmark$		$\checkmark$
Distributed- CA[117]		$\checkmark$	$\checkmark$				~	$\checkmark$	$\checkmark$	
CNOR [186]		$\checkmark$			$\checkmark$	$\checkmark$			$\checkmark$	
SEA-OR [187]		$\checkmark$			$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	
RMCA-FR [126]		$\checkmark$		$\checkmark$		$\checkmark$			$\checkmark$	

Assign.\*= Assignment, Cent.\*= Centralized, Dist.\*= Distributed, Hier.\*= Hierarchical, Geog.\*= Geographical

#### CHAPTER 4. MULTICHANNEL TECHNOLOGY OVERVIEW: AT NETWORK LAYER

# 4.4.8.1 NODE-ENERGY-BASED FAULT TOLERANCE (DYNAMIC HOLE AVOIDANCE)

Parallel transmissions increase the network throughput and data rate of MWSNs [81] [44]. However, it is equally likely that some sensor nodes on active paths may be exhausted earlier which may result into creation of dynamic holes in the network. Due to network holes, it may be possible that a sensor node does not find any closer neighbors to destination than itself [50]. It may cause routing paths exhaustion which may result into performance impairment in MWSNs. Therefore, MWSNs should employ novel hole-avoidance mechanisms which may enable them to balance energy consumption across network. Additionally, rerouting packets through more energized areas of network [50] or regulating transmission power and data rate [50] may result into avoiding node failures in MWSNs.

## 4.4.8.2 ENVIRONMENT-BASED FAULT TOLERANCE

Due to assignment of separate channels to interfering links, network interference may be reduced whereas network throughput and capacity may be enhanced [44]. If small number of channels are available or node density is high in a neighborhood, then repeating the same frequency in interference range of a node may result into co-channel interference [97]. As a result, network may suffer from energy and delay overhead [97] which may adversely affect system performance.

## 4.4.9 MISCELLANEOUS ISSUES

Multichannel wireless sensor networks require a comprehensive synchronization between sender and receiver nodes, so that they may efficiently coordinate with each other. If sender and receiver nodes are not in harmony with each other, then it may result into some serious coordination challenges as discussed below:

## 4.4.9.1 MULTICHANNEL HIDDEN TERMINAL (MHT) ISSUE

The MHT problem [184] is caused when some nodes switch to a new channel, however being unaware of recent reservation of that channel (for example through Request to Send/Clear to Send (RTS/CTS) mechanism), start transmitting on it which may result into inducing collision [44] and congestion on the new channel.

## 4.4.9.2 NODE DEAFNESS ISSUE

The nod deafness problem [168] is induced when sender and receiver nodes reside on different channels in the same broadcast range and therefore cannot hear (or deaf of) each other [127]. If the sender may not get response from receiver after a reasonable number of attempts, then it is a clear indication that receiver is unapproachable from that sender [44]. As a result, any such communication effort may result into wastage of bandwidth resource, packet loss and undue energy consumption.

#### 4.4.9.3 CONTROL OVERHEAD ISSUE

In a typical 802.15.4 based sensor network, there are 15 data channels and 1 control channel [167]. All the 16 channels are non-overlapping and reside in 2.4 GHz band [167]. Normally, control channel 11 is responsible for sending control traffic while data channels 12-26 are used for data communication [167]. Due to increase in control traffic, the shared control channel may suffer from collisions and congestion which may result into halting the network operations. The designer of multichannel routing protocol should consider the size and frequency of control packets, so that control channel would be able to easily accommodate the control information and may attain high performance in MWSNs.

## 4.4.9.4 NETWORK PARTITIONING ISSUE

The network partitioning issue [44] may result into communication standstillness in a vicinity. This problem may be caused when sender and receiver nodes reside on different channels or there exists a network hole which may halt communication between the nodes. The possible solution for handling channel-mismatch between sender and receiver nodes may be to adopt some alternate path for reaching to such a receiver node that is turned on different communication channel, however it may induce additional delay and energy consumption. The possible solutions for dealing with network hole issue may be, either to employ/devise energy balancing based routing approaches for MWSNs or to exploit energy harvesting mechanisms in the design of MWSNs. The energy harvesting mechanisms may provide multichannel sensor nodes with a continuous recharging resource and thereby enable them to deal effectively with the network partitioning issue. However, employing energy harvesting mechanisms productively in the design of tiny MWSNs is an open research area that requires further brainstorming. Therefore, an optimal solution in this regard still needs further investigation.

# 4.5 JOINT CHANNEL ASSIGNMENT AND ROUTING (JCAR) AT NETWORK LAYER

The conventional multichannel assignment approach discusses those multichannel protocols in WSNs that perform channel assignment at MAC layer. A large number of such multichannel MAC based protocols are published so far that may perform either Static Channel Assignment (StCA) or Hybrid (semidynamic) Channel Assignment (HyCA) or Dynamic Channel Assignment (DyCA) as discussed in [81] [44]. The MAC based static multichannel protocols include MASN [167], MCCT [104], DTFMM [90], MinMax [71] and so on. The hybrid multichannel MAC protocols include MMSN [213], CMAC [127], IM-MAC [102], MC-LMAC [45], MCAS-MAC [56] and so on. Moreover the dynamic multichannel MAC protocols consist of Y-MAC [154], MuChMAC [221], EM-MAC [192], KoN-MAC [201], CogLEACH [131] and so on. Being purely MAC layered based, such multichannel protocols are not specifically considering the role of routing in their channel assignment strategies.

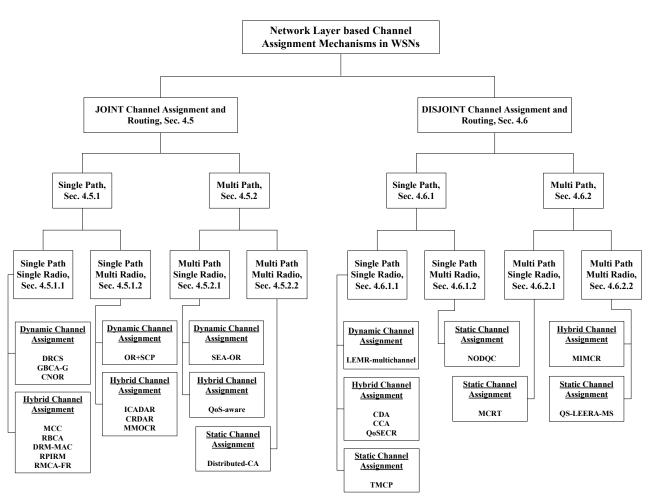


Figure 4.2: Taxonomy of Multichannel Routing Protocols in WSNs

Since all the previous multichannel surveys for WSNs (as outlined in Section 4.2) mainly focus on MAC layer based multichannel protocols, therefore they can be ascribed as conventional natured. Henceforth a step further, an effort is made in this survey to consider such multichannel routing protocols in WSNs that perform StCA, HyCA and DyCA at network layer as already discussed in Sections 4.1 & 4.2. In this respect, the prevailing Section 4.5 and the next Section 4.6 would discuss JOINT (channel assignment and routing) and DISJOINT (channel assignment and routing) based multichannel protocols respectively as shown in the Figure 4.2. Subsequently, each main category is further classified into sub-categories on the basis of network architecture, transceiver H/W and channel assignment mechanism. Moreover, the functionality of protocols belonging to each category are also briefly discussed for the sake of completeness. Furthermore, the general and miscellaneous characteristics of discussed JOINT and DISJOINT multichannel routing protocols are described in Tables 4.2, 4.3 and 4.4.

The JOINT channel assignment and routing protocols (JCAR) perform channel assignment and routing in a cooperative manner where routing has role in channel assignment. Such protocols are therefore more robust to perform load balancing and to achieve high throughput by countering interference. In this way, they may reveal high performance and network efficiency. Moreover, there is normally a great variation among multichannel routing protocols employing JCAR methodology. Some of these protocols are single path while others perform multi path routing. Furthermore on the basis of H/W, both single and multi path based multichannel routing protocols can be further classified into single and multi radio solutions as shown in Figure 4.2. From now onwards, we will discuss JCAR based multichannel routing protocols under the four categories i.e. single path single radio, single path multi radio, multi path single radio and multi path multi radio in the subsections 4.5.1.1, 4.5.1.2, 4.5.2.1, 4.5.2.2 respectively. Towards the end of each subsection, relevant important observations are outlined in the corresponding Summary and Insights subsection, as a manifestation of our concluding remarks about the corresponding subsections.

## 4.5.1 SINGLE PATH MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

# 4.5.1.1 SINGLE PATH SINGLE RADIO MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

The single path single radio multichannel protocols delegate the responsibility of data sensing/transmission to single radio and use only one path for sending data between source and destination nodes in WSN. Unlike single channel approach, multichannel mechanism may afford parallel communication by assigning dissimilar channels to adjoining nodes which improves network capacity and enhances network throughput [81]. Due to parallel communication on multiple channels, the multichannel approach reduces data collection delays [44] [78] while ensuring freshness of data assembly.

On the basis of classification shown in the Figure 4.2, the general operation of

CHAPTER 4. MULTICHANNEL TECHNOLOGY OVERVIEW: AT NETWORK LAYER

single path single radio JCAR based multichannel routing protocols is outlined below.

- Distributed Routing and Channel Selection (DRCS) scheme for multi-channel WSNs: In DRCS [174], a distributed receiver-oriented dynamic multichannel routing protocol is presented which exploits routing and channel assignment dynamically for ensuring load balancing in multichannel WSNs. Each node selects a least recently used channel as its receiving channel in neighborhood and updates neighbors about itself by broadcasting on all available channels in round-robin fashion. When a node is interested in transmitting data, then it selects the best channel in neighborhood using a quality metric composed of battery-health of nodes on a particular channel along with Expected Transmission Count (ETX) on that channel. Afterwards, such a forwarding node is determined on the selected channel whose path exhibits the least ETX-oriented path-vector among all the available paths on that channel. Since, quality assessment of battery health and routing path are periodically performed which helps to dynamically select the channel and the forwarding node and ensures load-balancing across the network. The protocol handles overhearing and interference issues for maximizing network lifetime. But, due to use of single transceiver per node, it may suffer from channel switching overhead which incorporates additional delay and energy consumption, and causes information damage in case of heavy traffic load such as multimedia transmission. Since, each node periodically broadcasts its local information on all available channels, therefore it may trigger additional energy consumption. Increasing node density in neighborhood results into enhancing beacon messages which may induce congestion and collision in network.

- Game-Based Channel Allocation for wsns with Geographic routing (GBCA-G): In GBCA-G [110], a distributed multichannel protocol is proposed which performs game theory based channel assignment to dynamic sensor networks employing geographic routing. Since the protocol is distributed in nature, therefore, the channels are selected by nodes themselves keeping in view the dynamic Topology Information and Routing Information (TIRI). The results show that the protocol achieves high Packet Delivery Ratio (PDR) and decreases per packet delay as compared to the well-known techniques. But geography based channel assignment requires too much broadcasts regarding node position and channel updates in neighborhood which may result into energy consumption and congestion in the neighborhood.

- Cognitive Networking with Opportunistic Routing (CNOR): In CNOR [186], an Opportunistic Routing (OR) protocol with opportunistic spectrum access is proposed for WSNs. When a source node is interested in sending data to receiver then source scans for the available channel and sends RTS packet on it. The receiver residing on that channel and laying closer to sink node with smallest backoff timer responds first with CTS packet. Afterwards DATA packet is sent by source node which is acknowledged with ACK packet by the receiver node. The protocol outperforms the available techniques in terms of throughput, latency and energy consumption. It is secured and employs a cognitive collision avoidance methodology. Moreover it does not need any global scheduler because it can opportunistically and dynamically adjust the paths based on network situation. But it may suffer from additional delay, energy consumption and data loss, when source node does not find any receiver node on the available channel and therefore would not be able to forward data packet in the current timeslot on that channel. Since the protocol may suffer from frequent channel switching delays/energy consumption, therefore it is not suitable to accommodate high data rate applications such as multimedia.

- *Multi-Channel Collection (MCC) protocol:* In MCC [224], a centralized TDMA-FDMA based protocol is devised to improve the sink reception rate in convergecast networks. The protocol requires 100 broadcasts per node for building connectivity graph and interference graph which may result into energy consumption per node. For enhancing the transmission/reception rate of relay nodes, the protocol employs Capacitated Minimum Spanning (CMS) tree topology based on connectivity graph that helps in building balanced routing tree. The protocol adopts centralized time synchronization for achieving time synchronization/scheduling among nodes. Moreover, the channel allocation also follows a centralized mechanism where the nodes in conflict graph are assigned noninterfering channels in a receiver-oriented manner which helps to handle both inter and intra-path interference. The results show that the protocol achieves high throughput, energy efficiency and cost-effective time synchronization. Additionally, the receiver oriented channel switching results in incorporating more delays for small sized data packets and less delays for the packets of large sizes.

- Enhancing the Data-collection Rate of Tree-based Aggregation (RBCA): In RBCA [149], an effort is made to compare the aggregation rate of different tree based techniques. The authors have found that degree constrained multi-channel minimum-hop routing tree strategy based on the *Dijkstra algorithm* minimizes the schedule length. The routing tree building process is initiated at sink node where incoming node can be added to the routing tree if the parent degree remains less than a maximum value and hop-count distance to sink node is minimized. Afterwards, different frequencies are used to handle interference which may result into decreasing the schedule length and increasing the data collection rate at sink node. As a result collision is decreased whereas high throughput and energy-efficiency is ensured. Since the protocol establishes long degree-constrained routing trees which may induce additional delay and energy consumption in WSNs.

- Dynamic Route Multi-channel MAC (DRM-MAC) protocol: In DRM-MAC [147], a multichannel routing protocol is presented where each node is assigned a particular rank/ hierarchy (parent, brother and child) in a neighborhood on the basis of sink broadcast as shown in Figure 4.3. Afterwards, the desired forwarding rank is selected randomly and sensor node of highest energy is chosen from it as the forwarding node. It may not only help to counter energy holes issue, but also handles delay and channel collision problems that may be caused by selecting the same forwarding node again and again. The protocol employs Request to Send-Clear to Send (RTS-CTS) based channel negotiation mechanism between each sender and receiver node which helps to reserve a vacant channel for a specific interval and counters interference because neighbor CHAPTER 4. MULTICHANNEL TECHNOLOGY OVERVIEW: AT NETWORK LAYER

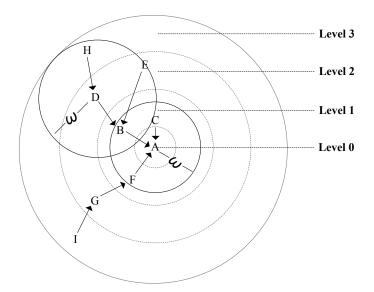


Figure 4.3: Hierarchical Model of Nodes redrawn from DRM-MAC Protocol [147]

nodes would not transmit on that channel during the prescribed interval. The protocol achieves high throughput, low delay and avoids channel collision, however random selection of forwarding rank may result into selecting a rank of inferior quality which may enhance delay and energy consumption. Additionally, the RTS-CTS-ACK based channel negotiation is not suitable when the data packet size is small as in the case of IEEE 802.15.4.

– A Routing Protocol with Integrated Routing Metric (RPIRM) for multi-channel wireless sensor networks: In RPIRM [202], an extension of multi-channel AODV protocol is put forth where the best among available routes is selected on the basis of integrated routing metrics which are composed of aggregated link cost and aggregated delivery cost of the path. The aggregated link cost is the measure of link health and calculates both forward and backward loss rate of all links on the available route. Whereas, the aggregated delivery cost is the measure of remaining energies of all nodes on the available route. Each node along the active path consults its channel information table that may help to select a channel consistent with the receiver node. It may decrease the control information and handshaking overhead while increase network throughput. The protocol achieves energy efficiency, however due to aggregation based path selection technique, it may select those paths where either some link or node of inferior quality may be present. It may result into degradation of communication or creation of early holes in the network. The authors have only demonstrated the impact of aggregated delivery cost while the combined impact of routing metric based on aggregated link and delivery cost is not simulated.

- Routing-based MultiChannel Allocation with Fault Recovery (RMCA-FR) approach: In RMCA-FR [126], a distributed multichannel protocol is proposed which works in two phases. The first phase is preventive and consists of two steps. In the first step, a routing tree is established and afterwards related

information is exchanged between nodes. The nodes at the same hop distance from sink are assigned to the same level. The total number of levels define the schedule length whereby the first slot is reserved for broadcasting control information and remaining slots are used for sending/receiving data at corresponding layers. The data communication is performed in a manner that the nodes at each lower level (parent nodes) are awaked up (in their timeslot) earlier than the corresponding higher level nodes (child nodes). Such a sleep/wakeup strategy may help to conserve energy. In the second step, channel assignment is performed by parent node using the graph coloring approach whereby child node of highest degree is colored first. The nodes not interfering with the already colored nodes are colored with the same color while the adjacent/interfering nodes are colored with a different available color. If no more colors are available then node is assigned that color which is occupied by the least conflicting node. Such a multichannel assignment approach helps to reduce interference. The second phase involves recovery mechanism whereby communication node failure is handled appropriately. The protocol uses heartbeat messages for detecting any failure of neighbor nodes. If failure is occurred then it runs recovery process. Although protocol achieves energy efficiency, collision avoidance and lesser amount of channel switching. However it does not discuss any mechanism of channels coordination between parent and child nodes, therefore it may assign them different channels which may result into network partitioning.

- Summary and Insights: The above discussed single path single radio JCAR protocols may perform only DyCA/HyCA for routing their data in WSNs as shown in Figure 4.2. Here it is important to mention that the DyCA may help to counter jamming and network partitioning issue, however it may suffer from channel switching overhead in terms of delay & energy consumption, deafness, MHT problem and broadcast abandon issue which may affect the performance of a multichannel routing protocol for WSNs. Whereas HyCA may handle network partitioning issue and interference challenges while saving network bandwidth, however it may also suffer from deafness, MHT problem and broadcast abandon issue. The JCAR based DyCA and routing protocols discussed above include two flat and one geographic multichannel routing protocols.

The flat based routing protocols include DRCS [174] and CNOR [186]. Among them, DRCS [174] is very much robust to handle load balancing as it makes dynamic channel selection on the basis of battery and path health metric. That is why, it is very much robust to handle energy holes, interference and retransmissions in network. Due to employing cognitive collision avoidance and OR with spectrum access, CNOR [186] dynamically selects the available channel and opportunistically sends data on it, therefore it does not need any global scheduler and is energy efficient while it ensures security too. But it is costly in terms of channel switching overheads such as channel switching delays/energy consumption and may cause data loss for high data rate stream-based applications. The only geographic routing protocol in this category is GBCA-G [110] that deals with mobile sensors networks and may discover dynamic topology and routing information for channel selection. Henceforth, there is a need to do more research for devising novel mobility based multichannel routing protocols for WSNs. The JCAR based HyCA and routing protocols discussed above

comprise of five flat based multichannel routing protocol which are MCC [224], RBCA [149], DRM-MAC [147], RPIRM [202] and RMCA-FR [126]. Among these protocols, MCC [224], RBCA [149] and RMCA-FR [126] are tree based protocols. The centralized channel assignment in MCC [224] using conflict and connectivity graph would result into handling both inter and intra path interference, however centralized channel assignment makes MCC [224] a less reactive protocol. The rate based channel assignment protocol i.e. RBCA [149] may suffer from additional delay due to increase of hop distance from sink in degree-constrained routing trees. Both RBCA [149] and RMCA-FR [126] employ a TDMA based scheduling mechanism. Although TDMA based scheduling deals with idle listening and overhearing problems, but it may also suffer from clock drift issue too. Additionally, the TDMA based scheduling employed in RMCA-FR [126] makes schedule length equal to the number of levels which may increase data delivery latency if the number of levels are quite large. The protocol in DRM-MAC [147] uses RTS-CTS-ACK based channel handshaking which is not suitable for IEEE 802.15.4 based sensor networks where the packet size is very small ( $\approx 100$  bytes) and may result into bandwidth over-utilization and energy loss. The protocol in RPIRM [202] outlined multichannel version of the most representative and lightweight Ad hoc On-Demand Distance Vector (AODV) routing protocol. But its aggregated path selection criteria may cause communication failure if some node or link of inferior quality is present in the selected path which raises critical questions about its reliability. Both RBCA [149] and MCC [224] perform Centralized Channel Assignment (CnCA) as outlined in Table 4.3 and therefore they are more optimized than reactive. However, the remaining protocols such as DRCS [174], CNOR [186], DRM-MAC [147], RPIRM [202] and RMCA-FR [126] perform Distributed Channel Assignment (DtCA) as discussed in Table 4.3. Henceforth, they are fast reacting and suitable for challenging applications for WSNs. DRCS [174] is the only multichannel routing protocols in this category that employs ETX based quality metric for selecting channels of good quality and is more practical (in this respect) than the counterparts which assume the selected wireless channels are of good quality. Since DRCS [174], GBCA-G [110] and MCC [224] require too much broadcasts, therefore they will consume more energy accordingly. The protocols such as DRCS [174], GBCA-G [110] and CNOR [186] suffer from frequent channel switching overheads which makes them unsuitable for accommodating stream based communication in MWSNs.

# 4.5.1.2 SINGLE PATH MULTI RADIO MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

The multichannel approach increases network capacity, throughput and decreases data collection delay [81] [44] [78]. The performance of multichannel system can be further improved by properly deciding the number of radios. For example two radios can efficiently exploit the capacity of six channels, however if more than six channels are used then their capacity can be fully exploited by increasing the number of radios accordingly [164]. Moreover, increasing the number of radios would also increase system cost and complexity. Therefore, such a design issue should be thoroughly scrutinized during Network Analysis and Design (NAD) for achieving the desired trade-off between network

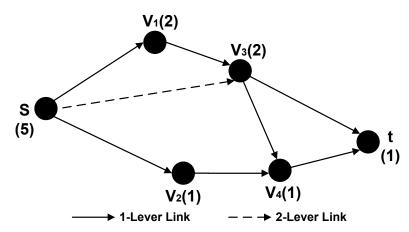


Figure 4.4: Demonstration of Random Walks based Approach depicted from OR+SCP Protocol [164]

cost/complexity and network performance.

On the basis of classification shown in the Figure 4.2, the general operation of single path multi radio JCAR based multichannel routing protocols is outlined below for highlighting their functionality.

- Optimal Routing problem joint with Scheduling, Channel and Power assignment (OR+SCP) in Multi-Power Multi-Radio (MPMR) WSNs: In OR+SCP [164], a cross-layered multi-radio multichannel routing protocol is proposed which uses random walk approach (as shown in Figure 4.4) for finding the best paths between source & destination and employs a dynamic greedy-based-joint channel assignment & scheduling algorithm for decreasing the schedule length. The protocol uses a routing metric based on Weighted Energy and Delay (WED). After random arrival of specific number of packets on different paths, a path with either minimum transmission & reception energy or minimum delay is chosen as the QoS path for data transmission. The concurrent transmission links for the path are identified and assigned to Concurrent Transmission Link Set (CTLS). Subsequently, available channels are assigned one-by-one to concurrent transmitting links in CTLS which is shrinked accordingly. The resulting small sized CTLS would also decrease the schedule length and ETE delay of path. Moreover, delay based path selection may result into network death due to creating energy holes in the network. While, the energy based path may result into selecting those paths which may offer more delay and not suitable for delay tolerant data such as multimedia.

- Iterative Channel Adjustment Data Aggregation Routing algorithm (ICADAR): In ICADAR [96], a data aggregation based iterative protocol is proposed which follows Greedy Incremental Tree (GIT) algorithm and Channel Assignment (CA) algorithm intended for multichannel routing in WSNs. An illustration of ICADAR protocol [96] is delineated in Figure 4.5. The routing tree building process is initiated at the sink node where at each step, the closest neighbor to the current tree node is added as leaf node until the source node is reached. Afterwards, the channel assignment is initiated by source tree node in a manner

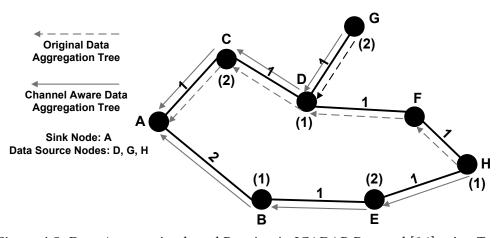


Figure 4.5: Data Aggregation based Routing in ICADAR Protocol [96] using Two Channels

that the two neighbors nodes on the path are assigned different channels until sink node is reached and channel constrained routing path is established. When the channel constraint is infeasible to be met by a node, then, the incoming link to such a challenging node is marked with heavy weight, so that it may be kept aloof from subsequent round of alternate path finding. When the sum of weights of all links on a routing path exceeds a certain threshold level, then that routing path becomes infeasible. The protocol outperforms the compared protocols in terms of transmission cost, however it may result into more energy consumption due to its iterative nature which may induce more delay.

- Channel and Radio Constrained Data Aggregation Routing (CRDAR): In CR-DAR [97], a Lagrangean relaxation based iterative multi-radio multi-channel data aggregation based routing algorithm is proposed whose objective is to minimize the overall transmission cost. The protocol works iteratively in two steps. In the first step, the data aggregation tree is built under energy efficiency constraint by following GIT algorithm. In the second step, collision free channels are assigned to each data source under channel and radio constraint where the source node with small hop-count to sink is entertained first than those with large hop-counts. If channel and radio constraint is not met by any sensor node on routing path of a source node, then the incoming links to that sensor node are assigned heavy weight, so that it may not be considered for future routing path search. Any data source node can have a feasible channel and radio constrained routing path unless its total link weight is less than a threshold value. Data aggregation causes collision and energy loss due to retransmissions which may be handled through multi-channel approach that may help to handle latency. However, multi-radio multi-channel solution is costly and complex to be deployed in WSNs and requires proper planning, to satisfy co-channel interference constraints and to achieve a decrease in total transmission cost.

– *Multi-radio Multi-channel Opportunistic Cooperative Routing (MMOCR) protocol:* In MMOCR [151], a high throughput multichannel protocol is devised which provides reliable transmission and handles co-channel interference. In the

4.5. JOINT CHANNEL ASSIGNMENT AND ROUTING (JCAR) AT NETWORK LAYER

beginning, a forwarding node set is formed with the help of Route Request (RREQ) broadcasts from source to sink node followed by Route Reply (RREP) unicasts from sink to same source. Such a forwarding candidate nodes set is shown in Figure 4.6. Only those RREPs for the same source are entertained which contain minimum hop-count from sink. In this way, duplicate packets are discouraged and reverse path with least hop-count to sink node is ensured. Each node measures the individual CIS of all the available channels based on the received power and Signal to Interference-plus-Noise Ratio (SINR) of all received packets, collected during a particular interval. Afterwards, the channel with least aggregated CIS is selected as the forwarding channel whereas the forwarding node is the node that has most recently acknowledged the data packets. Such acknowledgment broadcast stops the other nodes from forwarding data packets on the same channel. Therefore, it discourages duplicate data transmissions and minimizes data collisions. Sending one broadcast against every data packet may cause energy overhead if the data packet is of small size. Since the employed routing metric does not consider residual energy of sensor nodes, it therefore does not handle the energy hole problem. The protocol handles channel switching delays by using multi-transceiver per node, thereby it increases the hardware cost of sensor nodes.

- Summary and Insights: All the four protocols belonging to this category have flat based routing architecture and perform either DyCA or HyCA for routing their data in WSNs as shown in Figure 4.2. Here OR+SCP [164] performs random walk based routing along with CTLS based DyCA which may help to improve system performance. But it may suffer from either energy holes issue or delay when the path selection criterion is constrained by delay or energy respectively. Both ICADAR [96] and CRDAR [97] execute HyCA and are tree-based protocols whose tree building and channel assignment process are nearly the same. The ICADAR [96] may suffer from interference and throughput loss whenever channel repetition is performed in two hop neighborhood. Since CRDAR [97] is an optimization based protocol due to employing Lagrangean relaxation based iterative multi-radio multi-channel strategy, therefore CRDAR [97] would perform

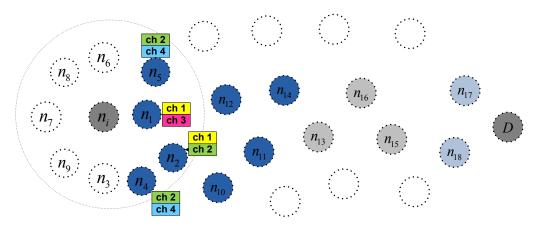


Figure 4.6: Demonstration of Opportunistic Module with 4 Channels and 2 Radio Interfaces sketched from MMOCR Protocol [151]

better than ICADAR [96]. However, the iterative nature of CRDAR [97] may cause it to consume more energy and delay too. The MMOCR protocol [151] is based on HyCA and employs OR mechanism along with CIS based channel assignment which is very robust to select the channel of best quality in premises for sending the information. Therefore, it would be more efficient to handle co-channel interference as compared to both ICADAR [96] and CRDAR [97], however MMOCR [151] may suffer from frequent channel switching overheads. Moreover, the broadcast nature of OR approach would allow all the nodes on forwarding channel to receive data packet until the best node relays it. Since, all the neighbors on forwarding channel participate in data routing of each data packet, therefore it would result into additional energy consumption as compared to the counterparts. Additionally as outlined in Table 4.3, OR+SCP [164] is the only protocol in this category that performs CnCA while the remaining protocols such as ICADAR [96], CRDAR [97] and MMOCR [151] perform DtCA.

## 4.5.2 MULTI PATH MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

# 4.5.2.1 MULTI PATH SINGLE RADIO MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

The single radio multi path multichannel routing protocols have the ability to perform data sensing and transmission using single radio, however use multiple paths for sending data between source and destination in MWSNs. The additional advantage of using multipath approach is that it provides high throughput & PDR, low delay, load balancing, reliability, error resilience, interference avoidance and security. Additionally, selecting the best path for data delivery (on the basis of a specific metric such as path length, energy and interference etc.) may further enhance the performance of MWSNs. The disadvantage of using multi path technique is that it may suffer from extra energy consumption due to utilization of additional resources for multiple paths discovery and maintenance.

On the basis of classification shown in the Figure 4.2, the general operation of single radio multi path JCAR based multichannel routing protocols belonging to this category are outlined below.

- Spectrum and Energy Aware Opportunistic Routing (SEA-OR) protocol: In SEA-OR [187], an opportunistic spectrum access and routing based multipath multichannel routing protocol is proposed for self-powered CRWSNs for identifying gas leakage. The protocol is reactive natured whereby the paths shrink/expand dynamically on the basis of remaining energy of sensor nodes and the accessibility of spectrum. A node interested in sending data scans the available channels and selects the best among them for data transmission. It also selects the best among available links based upon the availability of maximum spectrum. Afterwards, an RTS packet is sent on the selected channel. Eventually, the available receivers on the selected channel compete with each other in their effort to be selected as the forwarding node. The receiver with best composite metric of channel quality, residual energy and distance from sink ultimately wins the competition and responds first with CTS packet. The results show that the protocol achieves energy efficiency and exhibits better PDR. It executes RTS-CTS based handshaking mechanism per data packet which is costly in-terms of energy consumption. Moreover, the transmitting node would suffer from data loss, if it does not find any receiver node on the selected channel. In addition to that, the protocol requires robust and dynamic transceivers for sensor nodes that has the ability to move efficiently across the available channels. Since the protocol may suffer from frequent channel switching delays/energy consumption, therefore it is not suitable to accommodate high data rate applications such as multimedia.

- QoS-aware Routing Protocol: In QoS-aware [140], a centralized multichannel multipath protocol is proposed which uses distributed distance-to-coloring algorithm to assign Mutually Orthogonal Latin Square (MOLS) based distinct timeslot/channel pair to each sender/receiver node pair on the disjoint paths as depicted in Figure 4.7. The MOLS based pre-determined schedule helps to counter interference and run-time channel allocation delay. However, it may result into performance degradation of the whole network, if either the assigned channel is of poor quality or synchronization between the nodes is not maintained. Each node uses a Path length based Proportional Delay Differentiation (PPDD) scheduler. It helps to measure local proportional mean queuing delay among packets of different traffic classes and also helps to counter overall path delay. Based on this knowledge, sink node may perform bandwidth adjustment of real-time delay sensitive data while at the same time not compromising over the minimum bandwidth requirement of non real-time delay tolerant data. The protocol also employs a Waiting Time Priority (WTP) algorithm which helps the scheduler to de-queue one-by-one the header packets (belonging to different data classes with separate queues) for final transmission. Such a dequeuing procedure is based on the priority assigned to each data class and waiting time of the header packet (of a particular class) in the corresponding data queue. The data packets defying QoS criteria are dropped for countering congestion/collision. The protocol achieves high throughput and low delay, however it does not

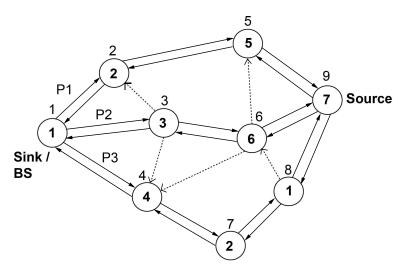


Figure 4.7: Vertex Coloring in QoS-aware Protocol [140] for Assigning Latin Square Symbols to Nodes

put-forth any mechanism for retransmitting the dropped packets for achieving reliability. Since it uses one transceiver per node, therefore it may suffer from channel switching overheads such as switching delays and energy consumption.

- Summary and Insights: This category includes two flat based multichannel routing protocols in WSNs as shown in the Figure 4.2. Among them SEA-OR [187] performs DyCA whereas QoS-aware [140] executes HyCA for routing data in WSNs. Although the opportunistic spectrum access and routing makes SEA-OR [187] secure, energy efficient and with better delivery ratio, however still it suffers from frequent channel switching overheads. Additionally since all the neighbor nodes on idle channel participate in data routing of each packet, therefore OR mechanism may suffer from network wide energy consumption. However, QoS-aware protocol [140] follows MOLS based time slot and channel scheduling by using *distance-to-color algorithm* for avoiding interference in twohop neighborhood and also handles frequent channel switching overheads. Moreover, as described in Table 4.3, OoS-aware algorithm [140] executes CnCA which makes it more optimized while SEA-OR [187] carries out DtCA and is fast reactive. Therefore, SEA-OR [187] would be more robust to be deployed in the challenging environment. Due to small number of routing protocols in this category, there is a need to publish more robust solutions in this field of research.

# 4.5.2.2 MULTI PATH MULTI RADIO MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

These multichannel routing protocols have the ability to perform data sensing and transmission using multi radios and multi paths between source and destination in WSN. They may execute parallel communication using multiple channels on multiple paths and may efficiently exploit the capacity of wireless channels by employing multiple radios. Therefore they have the ability to further improve the performance of multichannel routing protocols for WSNs in terms of throughput, delay, reliability, load balancing, error resilience, interference avoidance and security etc. The improved functionality may result into system complexity, energy drainage, additional processing and H/W costs which are critical factors for consideration while devising such protocols.

On the basis of classification shown in the Figure 4.2, the general operation of the only multi path multi radio JCAR based multichannel routing protocol belonging to this category is outlined below.

- Distributed Channel Assignment (Distributed-CA) protocol: In Distributed-CA [117], a grid topology based distributed channel assignment and routing algorithm is proposed for multi-radio multi-channel CRWSNs which works in two phases. In the first phase, HELLO messages are broadcasted for neighbor discovery by each sensor node, after a random interval for avoiding interference. When sink node receives two-hop knowledge using HELLO message, then it broadcasts HOPS message, so that each sensor node may know about its least hop count from sink node. In the second phase, channel assignment is performed incrementally starting from sink, where the two-hop neighbor nodes are assigned channels in a cyclic manner (equal to the total number of channels) by

#### 4.5. JOINT CHANNEL ASSIGNMENT AND ROUTING (JCAR) AT NETWORK LAYER

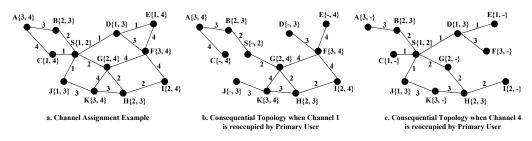


Figure 4.8: Graphical Illustration of channel assignment procedure depicted from Distributed-CA Protocol [117]

using depth-first-search approach. Afterwards two-hop channels are advertised by sink using SinkLNChannelSet message. Each sensor node also broadcasts ChannelSet message with random delay in one-hop neighborhood which helps those sensor nodes to select least used channels in neighborhood that are not assigned channels. It may result into handling interference. Additionally, the protocol exhibits a dynamic topology which changes due to reclamation of channel by primary user as shown by channel assignment procedure depicted graphically in Figure 4.8. The protocol is scalable and has low overhead. Since both inter-cluster and intra-cluster communication may take place on the same channel which may either cause throughput loss (due to increase in schedule length) or interference (due to simultaneous communication on the interfering channels). Therefore, this protocol is not suitable for high data rate applications such multimedia.

- Summary and Insights: This category includes only one hierarchical/geographical based multichannel routing protocol as shown in Figure 4.2. Distributed-CA [117] protocol performs StCA for routing data in MWSNs. Here it is important to mention that since real-time traffic dynamics and interference patterns follow Gaussian distribution and are stochastic in nature, therefore StCA is not suitable to model those natural phenomena. Moreover, StCA does not allow neighboring nodes to communicate with each other until the renewal of channel assignment, therefore it may suffer from network partitioning issue. One advantage of StCA is that, it may not suffer from channel switching delay and corresponding energy consumption. That is why, being based on StCA, Distributed-CA [117] protocol is not suitable to model any natural phenomena and thereby do not suffer from any channel switching overhead. Since the adjacent nodes may communicate on the same channel, therefore Distributed-CA protocol [117] may suffer from throughput degradation or interference issue as explained earlier. Being based on DtCA as delineated in Table 4.3, the Distributed-CA protocol [117] is more reactive than optimized. To conclude, there is a great potential in this area of research and novel protocols are still required for providing high performance to MWSNs. Henceforth, it is an open area of research for new researchers in this field.

# 4.6 DISJOINT CHANNEL ASSIGNMENT AND ROUT-ING (DCAR) AT NETWORK LAYER

This category includes those multichannel routing protocols that carry out channel assignment and routing in a segregated manner. Such multi-channel routing protocols focus on simply assigning orthogonal channels to neighboring nodes or paths, whereby they assume that the interference is mostly handled in this way. On the basis of network architecture, transceiver H/W and channel assignment mechanisms, the DCAR based multichannel routing protocols can be categorized into four subcategories i.e. single path single radio, single path multi radio, multi path single radio and multi path multi radio, as discussed in subsections 4.6.1.1, 4.6.1.2, 4.6.2.1, 4.6.2.2 respectively and depicted in Figure 4.2. Afterwards, the working of protocols belonging to each category is briefly discussed. At the end of each subsection, we have included a discussion subsection entitled as *Summary and Insights* which lay down important observations based on our findings.

## 4.6.1 SINGLE PATH MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

4.6.1.1 SINGLE PATH SINGLE RADIO MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

On the basis of classification shown in the Figure 4.2, the general operation of DCAR based multichannel routing protocols belonging to this category are outlined below.

 Latency Energy MAC and Routing multichannel protocol (LEMR-multichannel): In LEMR-multichannel [114], a cross-layered and dynamic channel polling based multichannel protocol is presented which increases network lifetime and data rate. At the network initialization phase, sink node broadcasts Synchronization (SYNC) packets for maintaining local synchronization among nodes. The SYNC packets are relayed by the forwarding nodes along with their hop-count from sink and remaining energy. It helps source to select a forwarding node laying onehop closer to sink and having the best routing metric (composed of remaining energy and received signal strength on the forwarding link). The protocol employs a dynamic duty cycling procedure which allows a receiver node to poll all the channels subsequent to sender node, in case control or data packets are sensed on the base channel. It improves network throughput, conserves energy and ensures security (due to common hopping approach). Since sensor nodes use single transceiver per node, therefore such a sequential channel switching procedure may cause channel switching overhead in the form of additional delay and energy consumption. The situation may become even more worse in case of heavy traffic which may consequently cause data loss and retransmissions. The protocol employs contention based MAC which may further add to congestion near sink and is not suitable for multimedia transmissions. Since the protocol performs per packet RTS/CTS based mechanism, therefore it is not suitable for accommodating the streaming media applications.

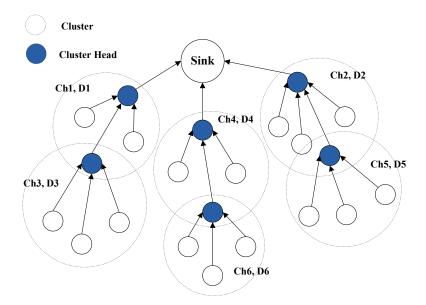


Figure 4.9: Cluster-tree network with channel and delay allocation in CDA protocol [109]

- Channel and Delay Allocation strategy (CDA): In CDA [109], a cluster-tree based distributed multichannel routing protocol is proposed which is based upon a joint channel and delay allocation strategy (CDA) as exhibited graphically in Figure 4.9. The CDA strategy is meant for scheduling beacon frames on different time slots and channels in a manner to minimize the beacon collision to least extremity. The tree building process is started at sink node where a pilot signal is broadcasted on control channel. Each intermediate node would rebroadcast these signals and so on. The re-broadcasted pilot signals also include two indigenously calculated parameters. One of these parameter is the delay which may inform the receiving nodes about their transmission and reception slots, in case the sender becomes cluster head. The other parameter informs about the associated channel selected on the basis of Channel State Information (CSI) which may notify the receiving nodes about the communication channel, if the sender is delegated the role of cluster head. Additionally, a receiving node would prefer and associate to that sender whose cumulative PDR is the highest. When cluster formation is complete, then all the nodes may acquire knowledge of their timeslots and channel in the corresponding cluster and use this information to communicate with the cluster head. When a node observes that it is not receiving beacons properly, then it may be associated to another cluster head that exhibits the second best cumulative PDR and afterwards starts communication with it as per corresponding delay and channel of new cluster. Such cluster tree adjustment process does not require the execution of whole tree reconstruction process and therefore, saves energy and delay accordingly. The protocol improves packet success rate and reduces the probability of beacon collision. Although, the path is selected on the basis of PDR on control channel, however data is sent on the receiver's channel selected on the basis of CSI metric. It may result into performance degradation, if data channel is of inferior quality

CHAPTER 4. MULTICHANNEL TECHNOLOGY OVERVIEW: AT NETWORK LAYER

than the control channel. In addition to that, the protocol does not describes any CSI measurement procedure.

- Tree Construction and Channel Allocation algorithm (CCA): In CCA [193], an aggregation tree based multichannel converge-cast protocol is proposed for WSNs which has the ability to provide energy efficiency and low latency. Starting from sink node, the protocol builds a balanced binary tree in a stepwise process. At each step, a parent node is connected to at most two closest nodes (as child nodes) for growing the tree until leaf nodes are reached. The balanced routing tree reduces latency by accommodating multiple parallel transmissions in a timeslot. For avoiding collisions due to multiple simultaneous transmissions, the protocol employs a CDMA based channel allocation algorithm that assigns available channels to nodes on tree in a manner that the transmission and reception codes of a node are different from each other. Although, the protocol achieves energy efficiency, low delay, reliability and simplicity by employing balanced binary trees methodology, however it may create long data aggregation trees which may enhance transmission cost accordingly.

- QoS-aware Energy-efficient Clustering and Routing (QoSECR): In QoS-aware [53], a game-theory based distributed multichannel routing protocol is proposed for improving the energy efficiency and decreasing the ETE delay in Wireless Multimedia Sensor Networks (WMSNs). This protocol employs clustering on the basis of physical layer information, so that cluster members and cluster heads can communicate directly at lowest power intensity. The next hop (cluster head) is selected on the basis of constraint that it lays on the path which requires least energy for successful delivery, and meets ETE latency criteria. The protocol employs a distributed game based channel assignment strategy whereby such a channel is preferred for the current period that is not selected by any neighboring cluster head in the last period. If no such unique channel is available, the channel with highest average Link Quality Indicator (LQI) is chosen by cluster head for the current period. Since channel information is broadcasted on all channels, therefore neighboring nodes may know about it which helps them in game theoretic channel selection for the next period. The game-based channel assignment for current period for a particular cluster head requires channel selection knowledge of all the neighboring cluster-heads in the previous period. It necessitates all the neighboring cluster heads to broadcast their channel selection information on all the available channels which is an energy consuming process. Moreover, it may result into congestion and information loss in case of dense networks.

- Tree based Multi-Channel Protocol (TMCP): In TMCP [197], a tree based multichannel protocol is proposed which makes routing tree paths and assigns different channels to them for ensuring parallel transmission. The protocol works in three steps. In the first step, the orthogonal channels of good quality are identified. In the second step, these channels are assigned uniquely to the equivalent node-disjoint tree branches as sketched in Figure 4.10. In this way, inter-branch interference is minimized during the third and final step of data communication. For handling the intra-branch interference, a greedy algorithm is also applied which initially makes fat tree using Breadth First Search (BFS).

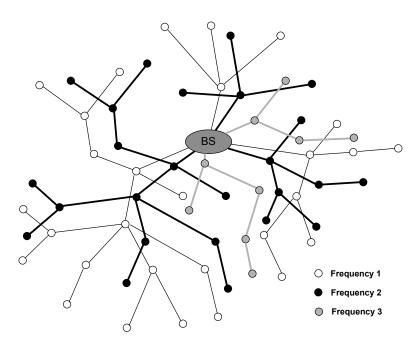


Figure 4.10: Conceptual Design of TMCP Protocol [197]

In this tree, each node lies on tree branches emanating from sink node and is minimum hops away from sink. Afterwards, an iterative procedure is adopted level-by-level, whereby in each iteration, a node is assigned to a specific tree branch on a particular channel. The constraint is that the node must be directly connected with the tree branch and induces least interference in the tree branch in future. Afterwards, the node is connected to the least interfered associated tree branch parent which may help to minimize the intra-channel interference. The protocol may achieve high throughput, low latency and handles packet losses. However, it may result into earlier creation of network holes as the nodes are always on. The StCA is not a good choice towards handling dynamic traffic.

- Summary and Insights: The multichannel protocols belonging to this category perform channel assignment and routing as a segregated activity and execute either DyCA or HyCA or StCA for routing their data in WSNs as shown in the Figure 4.2. Here, LEMR-multichannel [114] is the only DyCA based multichannel routing protocol which has flat based architecture. The HyCA based routing protocols belonging to this category include flat architecture based CCA [193] and hierarchical architecture based CDA [109] and QoSECR [53]. The only one StCA based multichannel routing protocol belonging to this category is TMCP [197] which has flat based architecture. Among the above protocols, LEMR-multichannel [114] employs common hopping technique for routing data packets and would be more effective in handling jamming attacks. However, it may suffer from channel switching delays that may induce data loss and retransmissions in case of heavy traffic loads. Both CCA [193] and TMCP [197] are tree based protocols. The CCA protocol [193] suffers from creating long data aggregation trees which may increase the transmission cost accordingly. The protocol may also allow the adjacent nodes on two contiguous paths to reside on

the same channel which may result into inducing co-channel interference. Likewise TMCP [197] assigns orthogonal channels of good quality to node-disjoint tree branches for handling inter-branch interference, however it may still suffer from intra-branch interference that may decrease network throughput (although it uses a greedy PMIT algorithm to lower intra-branch interference). The hierarchical multichannel approach counters not only interference, jamming and congestion, but also provides an energy efficient solution. Both QoSECR [53] and CDA [109] exhibit hierarchical based architecture. The QoSECR protocol [53] achieves energy efficiency while decreasing ETE delay. However, underlying game-based channel assignment mechanism necessitates all the neighboring cluster heads to broadcast their past (i.e. previous period) channel selection information on all the available channels which is an energy consuming process and may cause congestion in case of dense networks. The CDA algorithm [109] points out towards a very useful application of wireless sensor networks in aerospace communication where the sensor network may be used to replace the conventional on-board wired system. It may result into lowering the associated cabling cost and also attaining fuel efficiency. Although, CDA [109] drafts a good approach for increasing airplane mileage, but it is prone to many security and reliability threats which may enable miscreants on board or outside to distort or jam the communication network of airplane. As a result, the pilot may not be able to communicate appropriately with the crew and passengers on board which may have very fatal consequences. Therefore, it is very important to consider additional security and reliability aspects too in the design of any such challenging multichannel routing approach for WSNs which may put life of hundreds of people at stake. As outlined in Table 4.3, only TMCP [197] and LEMR-multichannel [114] perform CnCA and are more optimized than reactive. While the remaining protocols i.e. CCA [193], CDA [109] and QoSECR [53] perform DtCA as described in Table 4.3 and are comparatively fast reactive than the centralized channel assignment based protocols. All the protocols in this category except QoSECR [53] assume that the selected channels are of good quality whereby QoSECR [53] employs a mechanism of measuring channel quality based on LQI. Therefore QoSECR [53] is more practical (in this respect) than the counterparts. The LEMR-multichannel protocol [114] suffers from channel switching overheads which makes it unsuitable for accommodating stream based communication in WSNs. Additionally, due to scarcity of protocols in this area of research, there is a need to do more research in this field.

# 4.6.1.2 SINGLE PATH MULTI RADIO MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

On the basis of classification shown in the Figure 4.2, the general operation of DCAR based multichannel routing protocol belonging to this category is outlined below.

- Near-Optimal Distributed QoS Constrained (NODQC) routing algorithm: In NODQC [58], a Lagrangian relaxation based algorithm is proposed for wireless visual sensor networks which maximizes the network throughput and minimizes ETE delay/jitter. The routing metric considers both mean link delay of network along with derivative of queue length of each link. The protocol employs

load balancing through a link state routing strategy where the weight of E2E delay and average network delay is considered for finding out least congested paths between source and destination. The QoS path among the available routes between source and destination is selected where each link is statically assigned a non-overlapping channel. The protocol outperforms the compared protocols in terms of delay and throughput, however it does not elaborate channel selection mechanism in detail. Additionally, using multi-interface per node may result into increasing the hardware cost. Since, protocol does not consider channel health before channel selection, therefore it may result into selecting the channels of inferior quality for data communication.

- Summary and Insights: This category includes only one flat based multichannel routing protocol entitled as NODQC [58] that performs StCA for routing data towards sink in WSNs as shown in the Figure 4.2. NODQC [58] assigns non-overlapping channel to each link in a static manner for handling interference, however it adopts manual channel assignment in a link-by-link fashion that is costly and complex in the context of system implementation. Due to StCA, NODQC [58] may suffer from network partitioning issue because neighbor nodes would not be able to communicate with each other till the renewal of channel assignment for the next session. Additionally NODQC [58] also employs periodic broadcasts which may result into unnecessary bandwidth utilization. The protocol employs CnCA as described in Table 4.3 and would be more optimized than fast reactive. Therefore, it is not suitable for challenging applications for WSNs. Still there is a need to do more research in this field and publish such routing protocols which are fast reactive and have the ability to perform HyCA or DyCA.

## 4.6.2 MULTI PATH MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

# 4.6.2.1 MULTI PATH SINGLE RADIO MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

On the basis of classification shown in the Figure 4.2, the general operation of DCAR based multichannel routing protocol belonging to this category is outlined below.

- *Multi-Channel Real-Time communications (MCRT) protocol:* In MCRT [88], a node-disjoint multipath multichannel protocol is proposed which is designed to provide in-time delivery of data packets and is suitable for real-time communication in MWSNs. In the first step, the protocol iteratively finds out 'K' node-disjoint paths under length and delay bounded constraints where each flow may be assigned single channel and may occupy more than one paths. Although, assigning multi-paths to each flow provides load balancing and reliability, however it may also result into packets reassembly overhead at sink node. Moreover, assigning one channel to each path may result into decreasing throughput to one half because adjacent links are on similar channel and, therefore adjacent nodes cannot transmit and receive simultaneously. In the second step, a power efficient real-time routing algorithm is employed whereby initially a forwarding node is

searched in neighborhood that can provide the required velocity for successful packet delivery to destination. If such a node is not present in the neighborhood, then a power adaptation mechanism is used to search such a forwarding nodes that has provided successful packet delivery in the near past. Otherwise, a RREQ packet is broadcasted with maximum power to find out a new forwarding node. The power adaptation mechanism may ensure in-time packet delivery, however it may also induce energy overhead which is not suitable for energy constrained WSNs. The protocol requires costly sensor nodes that are equipped with power adaptation mechanism along with Global Positioning System (GPS) and localization system.

- Summary and Insights: This category includes only one multichannel routing protocol that performs StCA in WSNs as shown in the Figure 4.2. The protocol has geographic based architecture and assigns non-overlapping channel to each flow for handling inter-path interference whereby each flow may occupy one or more paths. However, it is not providing any mechanism for countering intra-path interference which may seriously bottleneck the overall throughput of protocol. Being StCA based, MCRT [88] may suffer from network partition issue because neighbor nodes would not be able to communicate till the renewal of channel assignment. Moreover, MCRT [88] performs CnCA as described in Table 4.3 and is therefore more optimized than fast reactive. Henceforth, more robust solutions are required in this area of research which may afford high performance based communication in MWSNs such as multimedia stream based communication that necessitates delay sensitive high rate data delivery. Consequently there is a need to publish more protocols in this area of research which may perform HyCA/DyCA in a distributive and fast reactive fashion.

# 4.6.2.2 MULTI PATH MULTI RADIO MULTICHANNEL ROUTING PROTOCOLS FOR WSNS

On the basis of classification shown in the Figure 4.2, the general operation of DCAR based multichannel routing protocols belonging to this category are outlined below.

- Multi-Interface Multi-Channel Routing (MIMCR) protocol for WSNs: In MIMCR [51], a data aggregation based multi-channel routing protocol is presented. For routing, it employs Ad hoc networks based Multi-Interference Multi-channel solution. For data compression or aggregation, the protocol uses Nonlinear Adaptive Differential Pulse Coded Modulation-based Compression scheme. Each node periodically broadcasts HELLO messages, so that neighbor nodes may know about each other's utility factors. This information helps to find multi-point relay nodes (MPRs) that may assist in building two-hop long paths to reach destination. The selected MPRs periodically broadcast topology information and link utilization factor which may help each node in proactively determining routes to desired destinations. Each route is associated with a cost that is the sum of utilization factors of all the MPRs on it, whereby the selected route has the best cost among the available routes. After route establishment, the available channels and interfaces are used for performance improvement of the specific links.

Routing Protocols	Network	Transceiver	Special Focus	Comparison with	Compa	Network Size	
Kouting I lotocols	Design	H/W	Special Focus			Simulator	Small<=20, Medium<=70, Large>70
CCA [193]	2 tier	Single radio	Energy efficiency, low latency	CTCCAA[108], [24]		$\checkmark$	Large
RBCA [149]	2 tier	Single radio	Speedy convergecast	TDMA-scheduling, power-based & frequency -based time scheduling		MATLAB[242]	
QoS-aware [140]	3 tier	Single radio	Delay, energy, throughput	Single-r/ Multi-r techniques[10]		NS-2[252]	Large
TMCP [197]	2 tier	Single radio	Improve throughput, reduce packet losses	MMSN[213] & spanning- tree routing protocol		GloMoSim[209]	Large
ICADAR [96]	2 tier	Multi radio	Transmission cost reduction	SPT, GIT[155], CAGIT		$\checkmark$	Large
LEMR-multi- channel [114]	2 tier	Single radio	Throughput, energy efficiency, low delay, jitter	LEMR[115], SMAC[95], SCP-MAC[204], and TMAC[128]		Qualnet[248]	Small
CRDAR [97]	2 tier	Multi radio	Transmission cost reduction	SPT, GIT[155], CAGIT, ICADAR[96]		$\checkmark$	Large
MIMCR [51]	2 tier	Multi radio	Energy efficiency, high throughput, low delay		Missouri S&T G4 Motes		Small
MCC [224]	2 tier	Single radio	Optimization in Throughput, energy efficiency	CTP[137]	USC Tut- ornet[255]		Small to Medium

Table 4.4: Miscellaneous Characteristics of Multichannel Routing Protocols for WSNs

111

Routing Protocols	Network	Transceiver	Special Focus	Comparison with	Comparison using		Network Size	
Kouting Flotocols	Design	H/W	Special rocus		Testbed	Simulator	Small<=20, Medium<=70, Large>70	
MCRT [88]	2 tier	Single radio	In-time packet delivery	RPAR[124], SIMPLE, node -based multi-channel and MCRT-simple	Tmote motes	NS-2[252]	Large	
OR+SCP [164]	2 tier	Multi radio	Weighted energy or delay	LP technique, MF-Iterative [163]		C++ based[164]	Medium to Large	
DRM-MAC [147]	2 tier	Single radio	Throughput, delay	MMSN[213]		NS-2[252]	Small to Large	
CDA [109]	3 tier	Single radio	PSR improvement	Multi-channel FR, Single- channel CDA, Single- channel FR			Large	
GBCA-G [110]			Delivery ratio, average delay per packet	MMSN[213], GBCA[22]		MATLAB using Prowler WSN simulator[181]	Large	
RPIRM [202]	2 tier	Single radio	Network Lifetime Maximization	Protocol variants		MATLAB[242]	Small	
QoSECR [53]	3 tier	Single radio	Energy efficiency	[214],[157],[142], [33] and [153]		NS-2[252]	Small to Large	
MMOCR [151]	2 tier	Multi radio	High throughput (decreasing CCI), reliability	NBC-OPP[48], AODV-Ramon[222]		NS-2[252]	Small to Medium	
NODQC [58]	2 tier	Multi radio	Low average E2E delay/delay jitter, high throughput	OLSR, AODV, and DSDV		NS-2[252]	Small to Large	

Routing Protocols	Network	Transceiver	Special Focus	Comparison with	Compari	Network Size	
Routing Flotocols	Design	H/W	opecial locus	Comparison with	Testbed	Simulator	Small<=20, Medium<=70, Large>70
DRCS [174]	2 tier	Single radio	Network Lifetime Maximization, good PDR	TMCP[197]	MICAz motes	Castalia simulator[223]	Small and Large
QS-LEERA-MS [19]	2 tier	Multi radio	Energy efficiency, delay	Greedy, LEERA-MS[21]		Java based[19]	
Distributed-CA [117]	2 tier	Multi radio	Robust Topology Control in WSNs	Grid-CA[116]		NS-3[244]	Large
CNOR [186]	2 tier	Single radio	High Performance	Single/ Multiple Chan- nel Traditional Routing, Single Channel Oppor- tunistic Routing		OMNET++[245]	
SEA-OR [187]	2 tier	Single radio	Improves network lifetime & delivery ratio	Geographic Opportu- nistic Routing	Self-Powered Sensor Network (SPSN)	$\checkmark$	Large
RMCA-FR [126]	2 tier	Single radio	Interference Minimization	Simple Channel Allocation[125]		Omnet++[245]	Medium to Large

Table 4.4: (Continued...)

The protocol has the ability to handle link failures through data rerouting while ensures energy efficiency and throughput improvement. Since, protocol employs multi-radio multi-channel methodology along with data aggregation/compression approach, therefore it may result into increasing cost and complexity of the sensor nodes accordingly. The data aggregation may cause additional processing and latency. Although, proactive routing helps to decrease overall delay, however it may consume enormous energy due to periodic broadcasts of HELLO and topology information messages.

- A Multichannel Cross-Layer Architecture for Multimedia Sensor Networks (QS-LEERA-MS): In QS-LEERA-MS [19], a cross-layered disjoint-multipath multichannel protocol is proposed for network lifetime maximization and in-time delivery of multimedia data as depicted in Figure 4.11. The routing metric considers remaining energy of forwarding nodes as the primary QoS criteria and angle of forwarding node from corresponding sink of the sender as the secondary QoS criteria. It not only helps to counter energy holes in the network, but also finds disjoint paths by employing a grid topology. Since, node position can be measured by using either GPS or localization algorithm, therefore it increases H/W cost accordingly. For countering inter-path interference, the protocol assigns non-overlapping channels to adjacent paths, however no-mechanism is discussed to counter intra-path interference, which is caused due to selection of

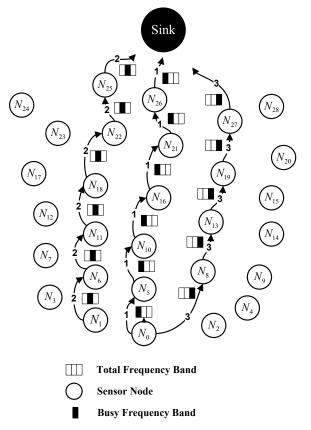


Figure 4.11: Multipath/multichannel data transmission in QS-LEERA-MS Protocol [19]

single channel for the whole path. Since, adjacent links are assigned the same channel, therefore overall network throughput would be decreased. Due to usage of multi-radios per node, the protocol may not suffer from channel switching overheads, however overall H/W cost of nodes may be increased accordingly.

- Summary and Insights: This category involves such routing protocols that perform HyCA and StCA in WSNs as depicted in Figure 4.2. The HyCA is performed by MIMCR [51] which has flat based architecture. While StCA is executed by QS-LEERA-MS [19] that follows geographic based architecture. The protocol in MIMCR [51] is proactive in nature as outlined in Table 4.2 and broadcasts HELLO/topology control messages for maintaining the paths proactively. Although it increases energy consumption required for maintaining the protocol. On the other hand, QS-LEERA-MS [19] is reactive in nature which makes the paths on demand. As a result, it is more energy efficient, however it experiences more delay than MIMCR [51]. The QS-LEERA-MS [19] assigns nonoverlapping channels to the adjacent paths for handling inter-path interference. But, it is not providing any mechanism to handle intra-path interference which may seriously bottleneck the overall system throughput.

The StCA preemptively assumes the knowledge of traffic model or considers that the links are stable which is not practical because network and channel dynamics are probabilistic in nature. Due to StCA, QS-LEERA-MS [19] may suffer from network partitioning issue because neighbor nodes would not be able to communicate till the renewal of channel assignment. Additionally, as delineated in Table 4.3, QS-LEERA-MS [19] executes CnCA and is therefore more optimized than reactive. As a concluding remark, there is a great potential in this field of research and novel hybrid & distributed multichannel routing protocols are required for ensuring more reliable, faster and reactive communication.

# CHAPTER **5**

# CHANNEL QUALITY AND STABILITY ESTIMATION: FOR LONG AND SHORT-TERM STABLE FREQUENCIES

# 5.1 INTRODUCTION

Unlike sensor nodes in conventional networks, nodes in multichannel sensor networks additionally have to deal with a potentially large number of channels for data routing, i.e., they have to decide which channel to use for transmission; the better the choice the better the overall system performance. Therefore, an appropriate channel quality/stability assessment is needed. Since the behavior of wireless channels is probabilistic in nature (which makes channel quality assessment a recurrent task), any instantaneous channel quality assessment cannot, by nature, provide an adequate measure of the channels' health. In [247], the authors have realized that combining current and past channel quality assessments at the receiver may help to predict the Channel Quality Indicator (CQI), which may guide the transmitter to adapt the transmission parameters accordingly and improve the performance of the wireless communication systems.

A large number of multichannel protocols for WSNs uses single radio per node [140, 115, 22, 88, 174]. If transmitting and receiving frequencies of sensor nodes are different, then such sensor networks may suffer from channel switching delays and additional power consumption [174]. When the data rate is very high, frequent channel switching may result in data loss [174], which may adversely affect the system performance. Therefore, for accommodating multimedia traffic, it is more efficient and cost-effective to aim for a stream-based channel assignment rather than to do this on a per-packet base [20, 91]. However, channel behavior is not deterministic in nature; therefore, reserving a channel

CHAPTER 5. CHANNEL QUALITY AND STABILITY ESTIMATION: FOR LONG AND SHORT-TERM STABLE FREQUENCIES

for a whole data stream requires knowledge about average channel response, which may be assessed in advance through channel quality and stability assessment. To the best of our knowledge, there are no multichannel protocols in WSNs that embody any mechanism of channel quality and stability assessment for supporting stream-based channel allocation in multichannel WSNs.

The quality of a channel in a neighborhood can be assessed on the basis of link quality in that vicinity. In [141], a link quality-based channel selection approach is proposed, which ranks channels into different categories and selects good quality channels for improving system performance. Moreover, for measuring link quality, different authors have introduced distinct metrics, such as [188, 112, 215, 138]. The author in [7] has realized that good, intermediate and bad links can be discriminated on CC2420 using the Standard-Deviation of Received Signal Strength Indicator (std(RSSI)) and the Average of Link Quality Indicator (avg(LQI)), as shown in Table 5.1. The advantage of using std(RSSI) and avg(LQI) is that they may measure performance and central tendency, respectively, of link quality in a better manner. On the other hand, the average of RSSI (avg(RSSI)) and the standard deviation of LQI (std(LQI)) are not good estimators of link quality because they may cause overlap of bad with intermediate quality links and intermediate with good quality links, respectively [7]. Since various link quality metrics have their own limitations [194], therefore no consensus has been developed among the research community for the most suitable link quality metric [112]. Consequently, a hybrid metric may ultimately be used for accurately accessing link quality [194].

Link Type	std(RSSI)	avg(LQI)
Good	<4	>104
Intermediate	4-10	70 to ≤104
Bad	>10	<70

Table 5.1: Demarcation link types. LQI, link quality indicator.

Most of the multichannel protocols in WSNs do not consider any scheme of channel quality assessment before channel assignment. For example, tree Construction and Channel Allocation algorithm (CCA) [193], Iterative Channel Adjustment Data Aggregation Routing algorithm (ICADAR) [96], Lagrangean Relaxation algorithm (LGR) [97] and [147] do not employ any mechanism to differentiate between good and bad quality channels. On the other hand, there are some multichannel protocols in WSNs that employ different mechanisms for measuring channel quality, such as Efficient Multichannel MAC protocol (EM-MAC) [192], Decentralized Optimization for Multichannel Random Access (DOMRA) [62], Multi-radio Multi-channel Opportunistic Cooperative Routing algorithm (MMOCR) [151], Distributed Routing and Channel Selection scheme (DRCS) [174], Regret Matching based Channel Assignment algorithm (RMCA) [208] and [53]. However, to the best of our knowledge, there is no multichannel protocol in WSNs that can make channel quality and stability assessment on the basis of both current and past channel quality data.

In this chapter, we focus on accomplishing channel quality and stability assessment for accommodating stream-based communication in WSNs. *It is important to emphasize that this chapter is mainly based on our published article* [4]. In this context, the main contributions of this research can be summarized as below:

- Employing a normal-equation-based supervised machine learning algorithm (NEC algorithm).
- Extending the NEC algorithm by devising the NEWMAC algorithm, which employs a weighted moving average-based criterion for predicting the final channel rank estimation ( $\phi_{t,NEWMAC}^i$ ) of any channel *i* based on both past and current values of channel quality prediction.
- Devising the NEAMCBTC algorithm as an extension of NEC algorithm, which employs an adaptive weighting procedure by considering past and current channel quality predictions for estimating the final channel rank estimation (\$\phi\_{t,NEAMCBTC}\$) of any channel *i* and also promptly tracking channel quality degradations/upgradations. For more robustness, devising an extended version, entitled as Ext-NEAMCBTC algorithm that may perform both channel quality and stability assessment as a composite task.

The rest of this chapter is structured as follows. In Section 5.2, we discuss the related work already mentioned above in a more detailed manner and draw our conclusions for the motivation of our research. Section 5.3 explains the underlying system model. Section 5.4 discusses the channel quality assessment metric. In Section 5.5, we elaborate the proposed supervised machine learning-based algorithms along with their problem statements. Section 5.6 presents and discusses the detailed performance evaluations of those algorithms along with their pros and cons.

# 5.2 RELATED WORK AND MOTIVATION

The objective of this chapter is to propose a robust multichannel algorithm that may perform both channel quality and stability assessment to support stream-based communication in WSNs. For this purpose, we have studied a large number of multichannel techniques in WSNs and found a limited number of protocols that embody some channel quality assessment mechanism for achieving high performance.

Tang et al. [192] have proposed the EM-MAC algorithm where the channel quality assessment criterion is maintained through the Clear Channel Assessment (CCA) technique. When a congested/interfered channel is encountered, it is marked as blacklisted and avoided till the end of the current session. In this way, bad quality channels are differentiated from good ones. Similarly, Jingrong et al. [151] have introduced a new channel quality-based metric called Channel Interference Strength (CIS), which is based on a composite metric of power received  $P_r$  and Signal-to-Interference-plus-Noise Ratio (SINR). It allows sensor nodes to select the channel with the smallest CIS for future communication. CHAPTER 5. CHANNEL QUALITY AND STABILITY ESTIMATION: FOR LONG AND SHORT-TERM STABLE FREQUENCIES

The CIS-based metric does not consider previous channel quality and focus on instantaneous measures.

Khan et al. [53] have proposed a game theory-based multichannel protocol for WMSNs where a channel is selected by a cluster head for the next round when that channel is not selected by its neighboring clusters in the previous round. Otherwise, avg(LQI) is used as a metric for channel selection; however, the approach does not outline how it does that, and it does not consider past channel quality in future channel quality assessment. Similarly, Pal et al. [174] have utilized node energy and an expected number of transmissions (ETX)-based channel quality assessment metric for performing future communication. Although this ETX-based metric is reliable, it may require probing packets and, consequently, is costly to carry out. Moreover, it only considers instantaneous channel quality and does not regard past channel quality and stability assessment for measuring the final channel quality estimation. Likewise, Yu et al. [208] have presented a multichannel protocol where each node maintains a utility function and a past information-based performance matrix that helps to predict future network topology/flows and actions of neighbor nodes. Subsequently, channels are assigned accordingly. The protocol makes future channel assignment on the basis of predictions based on past knowledge only and does not consider current channel quality assessment.

Finally, to the best of our knowledge, we can conclude the related work as outlined in the Table 5.2, where the summarized results clearly show that the multichannel protocols for WSNs are considering either instantaneous channel quality assessment or some past related-knowledge for making channel decisions. Therefore, there is need to develop more robust multichannel protocols for WSNs, considering both current and past channel quality estimation for predicting final channel rank assessment.

In addition to the above discussion, we have noted earlier that std(RSSI) and avg(LQI) of received packets may discriminate links into different categories [7], as shown in detail in Table 5.1. Since each link in the neighborhood of a node may use a specific frequency channel for transmission as shown in Figure 1.1, the quality of these links in the neighborhood of a node may determine the overall quality of a channel in this neighborhood. Consequently we have formulated the Channel Rank Measurement (*CRM*) metric that is used to train a normal equation-based predictor for executing Channel Rank Estimation (*CRE*<sup>*i*</sup><sub>*t*</sub>) of any channel *i* at instant *t* using  $std(RSSI_t^i)$  and  $avg(LQI_t^i)$  of received packets.

Our second observation from the literature review is that there is no multichannel protocol in WSNs that employs channel quality and stability assessment, using present and past channel knowledge to accommodate stream-based applications. Two of the three algorithms we present in this chapter, namely NEWMAC and NEAMCBTC, are closing this gap. We also believe that this is the first work that employs a normal equation-based supervised machine learning algorithm for channel quality approximation in multichannel WSNs.

Protocol Field		Current Knowledge	Past Knowledge
RMCA [208]	Multichannel	-	Regret matching based
EM-MAC [192]	Multichannel	Interference based	-
DRCS [174]	Multichannel	Battery power and	-
	routing	ETX based	
[53]	Multichannel	-	Game-theory based
	routing		
MMOCR [151]	Multichannel	RSSI and SINR based	-
	Routing		

Table 5.2: Summary of related protocols reviewed. ETX, expected number of transmissions.

# 5.3 SYSTEM MODEL

We model a WMSN as a directed graph G(S, E) where the set of vertices V represent N multimedia-enabled sensor nodes, i.e.,  $V = \{n_i | i = 1, 2, 3, ..., N\}$ . The sensor nodes are randomly distributed in the sensing field and may be static or dynamic in nature. There is a bidirectional edge  $e \in E$  between any two neighboring vertices  $n_i$  and  $n_j$ , which may enable them to perform channel negotiation with each other.

The physical layer model allows each sensor node to compute  $std(RSSI_t^i)$  and  $avg(LQI_t^i)$  of received packets on any channel *i* at instant *t*. Afterwards, machine learning-based technology is employed to estimate the quality of the corresponding channel.

The MAC layer model allows each sensor node to sense available channels in the neighborhood and perform channel negotiation with the preferred neighbor node on a path in a manner that the available channel of highest quality is negotiated first, then the one with the second-highest quality, and so on. Once channel handshaking has been performed and the best channel is agreed on, both sender and receiver jump to the desired channel for performing streambased communication and stay there till the data stream ends. All channels are of equal bandwidth and orthogonal in nature. Additionally, it is assumed that all channels are not jammed or degraded simultaneously, and therefore, some channels of good quality are always available for performing stream-based communication.

For simplicity, we assume that the quality of all links on a particular frequency channel in a neighborhood is the same and may reflect channel quality in the corresponding locality. Otherwise, each sensor node may have to record the quality of all available channels for each link in a neighborhood separately, which may increase system complexity accordingly. CHAPTER 5. CHANNEL QUALITY AND STABILITY ESTIMATION: FOR LONG AND SHORT-TERM STABLE FREQUENCIES

## 5.4 CHANNEL RANK MEASUREMENT

We noted earlier that std(RSSI) and avg(LQI) of received packets are useful parameters to describe the link quality [7] and, thus, also the channel quality. In this section, we will discuss a mathematical formulation of our channel rank measurement *CRM* metric, which is used to create the dataset for training our normal-equation-based channel quality predictor.

On the basis of Table 5.1, it is clear that the values of std(RSSI) and avg(LQI) have different ranges and spreads; therefore, for getting the benefits of both worlds, we first have to bring these channel quality metrics into a common scale for calculating the Channel Quality Measurement (CQM) metric. In this way, the final impact of std(RSSI) and avg(LQI) is approximately equalized, and therefore, a clear boundary can be drawn between good, intermediate and bad quality links. The CQM metric is calculated as:

$$CQM = [scale(LQI) + scale(RSSI)]$$
(5.1)

where

$$scale(LQI) = \left[\frac{avg(LQI) - min(LQI)}{\gamma}\right]$$
 (5.2)

$$scale(RSSI) = [\sigma - std(RSSI)]$$
 (5.3)

where, following [7, 49, 216], min(LQI) = 50. We choose the values of the scaling parameters  $\sigma = 15$  and  $\gamma = 4.0$  in order to bring std(RSSI) and avg(LQI) into a common scale.

Our *CRM*, then, is given by:

$$CRM = \left[\frac{CQM \times \tau}{\mu}\right] \tag{5.4}$$

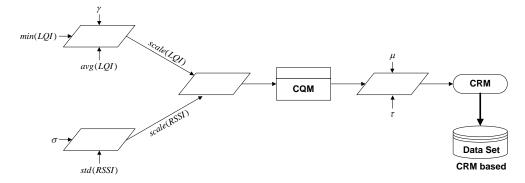


Figure 5.1: Diagrammatic representation of Channel Rank Measurement (CRM) metric-based training dataset generation.

where  $\tau = 3.5$  and  $\mu = 100$  are adjustment parameters that constrain the values of the CRM-based channel quality training dataset in the range [0, 1] as shown in Table 5.3. Thus, Channel Rank Estimation (*CRE*) will fall into the unit interval

Channel Type	std(RSSI)	avg(LQI)	scale(RSSI)	scale(LQI)	CRM
Good	<4	>104	11< to ≤15	13.52 to 15	$0.82 \le \text{to} \le 1.00$
Intermediate	4–10	70≤ to ≤104	5 to 11	5 to 13.50	$0.33 \le \text{to} < 0.82$
Bad	>10	<70	0≤ to <5	0 to 4.97	$0 \le \text{to} < 0.33$

Table 5.3: Channel rank measurement metric.

and, subsequently, channel manipulation of all quality levels is in the range [0, 1]. The detailed representation of *CRM* based metric is shown in Figure 5.1, while channel classification into different categories is explained in Table 5.3. In the next section, we will explain how the *CRM*-based dataset may be used to perform *CRE*.

## 5.5 SUPERVISED MACHINE LEARNING-BASED PRE-DICTION ALGORITHMS

Since each sensor node has limited energy, it is important to employ cost-effective algorithms in WSNs. For this purpose, a dataset is generated on the basis of calculations made in Section 5.4 and is used to train our basic normal-equation-based machine learning algorithm called Normal Equation-based Channel quality prediction (NEC). Afterwards, we propose two more sophisticated extensions of the basic NEC algorithm, namely Normal Equation-based Weighted Moving Average Channel quality prediction algorithm (NEWMAC) and Normal Equation-based Aggregate Maturity Criteria with Beta Tracking-based Channel weight prediction algorithm (NEAMCBTC), which consider both instantaneous and past values of channel quality for making final channel quality prediction. We will discuss the mathematical background of normal equation-based prediction in Section 5.5.1 and the proposed algorithms in Sections 5.5.2–5.5.4, and we also elaborate on their pros and cons.

#### 5.5.1 NORMAL EQUATION-BASED PREDICTION

The normal equation-based prediction is more feasible and cost effective when the number of features is small. Since, in this work, we are considering two features i.e.,  $std(RSSI_t^i)$  and  $avg(LQI_t^i)$ , it is more cost effective to use normal equation-based channel quality prediction rather than employing a gradient descent algorithm for making channel quality assessment.

Consider an over-determined system where m is the number of training examples (corresponding to m linear equations) and n is the number of features (corresponding to n unknown coefficients, i.e.,  $\theta_1, \theta_2, \theta_3, ..., \theta_n$ ) with m > n, then the system can be expressed as [229]:

$$\sum_{j=1}^{n} X_{ij} \theta_j = y_i, \qquad where \ i = 1, 2, 3, ..., m$$
(5.5)

In the matrix form [229], we can write:

$$\mathbf{X}\boldsymbol{\theta} = \mathbf{y} \tag{5.6}$$

where **X** is the feature matrix,  $\theta$  is the learning coefficients vector and **y** is the output vector given by:

$$\mathbf{X} = \begin{bmatrix} x_{11} & x_{12} & x_{13} & \dots & x_{1n} \\ x_{21} & x_{22} & x_{23} & \dots & x_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & x_{m3} & \dots & x_{mn} \end{bmatrix}, \quad \boldsymbol{\theta} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_n \end{bmatrix}, \quad \mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix}$$

Now, by solving the quadratic minimization problem,  $\theta$  is given by [229]:

$$\hat{\theta} = \operatorname{argmin}_{\theta} \emptyset(\theta) \tag{5.7}$$

Here,  $\emptyset$  is the objective function and is given by [229]:

$$\emptyset(\theta) = \sum_{i=1}^{m} |y_i - \sum_{j=1}^{n} X_{ij} \theta_j|^2 = ||\mathbf{y} - \mathbf{X}\theta||^2$$
(5.8)

$$= (\mathbf{y} - \mathbf{X}\boldsymbol{\theta})^{T} (\mathbf{y} - \mathbf{X}\boldsymbol{\theta}) = \mathbf{y}^{T} \mathbf{y} - \boldsymbol{\theta}^{T} \mathbf{X}^{T} \mathbf{y} - \mathbf{y}^{T} \mathbf{X}\boldsymbol{\theta} + \boldsymbol{\theta}^{T} \mathbf{X}^{T} \mathbf{X}\boldsymbol{\theta}$$
(5.9)

$$= \mathbf{y}^T \mathbf{y} - 2\boldsymbol{\theta}^T \mathbf{X}^T \mathbf{y} + \boldsymbol{\theta}^T \mathbf{X}^T \mathbf{X} \boldsymbol{\theta}, \qquad (as \quad \boldsymbol{\theta}^T \mathbf{X}^T \mathbf{y} = \mathbf{y}^T \mathbf{X} \boldsymbol{\theta})$$
(5.10)

Taking the derivative of the above equation with respect to  $\theta$  and equating it to zero, we get the normal equation [229] as shown below:

$$\boldsymbol{\theta} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{y}$$
(5.11)

The above equation clearly indicates that  $\mathbf{X}^T \mathbf{X}$  is an  $[n \times n]$  matrix. Therefore, the cost of inverting this matrix is  $O(n^3)$ . However, it is affordable in our case, because the number of features are only two, i.e., std(RSSI) and avg(LQI). The training of the system with the dataset is carried out only once, at the start of the system execution phase, and the learning coefficients vector  $\boldsymbol{\theta}$  is calculated using Equation (5.11). Since we are dealing with only two features, therefore  $\boldsymbol{\theta}$  and  $\mathbf{y}$  would be  $[(2+1)\times 1]$  and  $[m\times 1]$  vectors, respectively. Moreover  $\mathbf{X}$  and  $\mathbf{X}^T$  would be  $[m \times (2+1)]$  and  $[(2+1) \times m]$  matrices, respectively as given below:

$$\mathbf{X} = \begin{bmatrix} 1 & x_{11} & x_{12} \\ 1 & x_{21} & x_{22} \\ \vdots & \vdots & \vdots \\ 1 & x_{m1} & x_{m2} \end{bmatrix}, \quad \boldsymbol{\theta} = \begin{bmatrix} \theta_0 \\ \theta_1 \\ \theta_2 \end{bmatrix}, \quad \mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix}$$

124

#### 5.5.2 NORMAL EQUATION-BASED CHANNEL QUALITY PRE-DICTION ALGORITHM

The NEC algorithm can perform channel rank estimation  $CRE_t^i$  of any channel i on the basis of current values of  $std(RSSI_t^i)$  and  $avg(LQI_t^i)$  of received packets on the corresponding channel, as shown in Figure 5.2. Since it employs two input features, it is more efficient to use the normal equation-based machine learning algorithm for solving  $\theta$ . Henceforth, the hypothesis function for estimating  $CRE_t^i$  is as follows:

$$h_{\theta}(X) = \theta_o X_o + \theta_1 X_1 + \theta_2 X_2 \tag{5.12}$$

where  $h_{\theta}(X) = CRE_{t,NEC}^{i}$ ,  $X_{o} = 1$ ,  $X_{1} = std(RSSI_{t}^{i})$  and  $X_{2} = avg(LQI_{t}^{i})$ . Moreover, the leaning coefficients  $\theta_{o}, \theta_{1}$  and  $\theta_{2}$  are measured on the basis of available dataset.

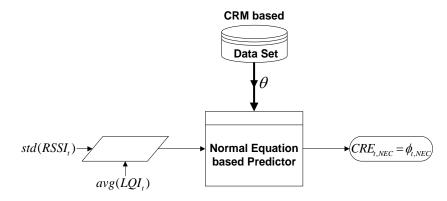


Figure 5.2: Data flow diagram of the NECalgorithm.

#### 5.5.2.1 PROBLEM DEFINITION

Let  $\phi_{t,NEC}^i$  be the measure of channel quality, i.e.,  $(CRE)_{t,NEC}^i$  of any channel *i* at the instant *t*. Let *C* denote a set of all channels in the neighborhood and *Z* denote a set of all channels, except *i*, i.e., C = Z + i. Then, the objective function *F* is to select a channel *i* at instant *t* that exhibits the maximum quality:

Maximize:  $F(\phi_{t,NEC}^{i})$ , i = 1, 2, 3...C (5.13)

Subject to:  $(CRE)_{t,NEC}^{i} \ge (CRE)_{t,NEC}^{Z}$ ,  $C = \{i + Z/i \notin Z\}$  (5.14)

where:

$$0 \le (\phi_{t.NEC}^{i}, (CRE)_{t.NEC}^{i}) \le 1.0$$

The above constraint (Equation (5.14)) elaborates that if any channel i has the highest channel rank estimation  $(CRE)_{t,NEC}^{i}$  at instant *t*, then it would be more suitable to accommodate stream-based data communication. Since the NEC algorithm accesses multichannel quality on the basis of instantaneous channel knowledge only; therefore, it may not be suitable to address stream-based communication that requires average channel knowledge at a particular epoch for accommodating the whole data stream afterwards.

#### 5.5.3 NORMAL EQUATION-BASED WEIGHTED MOVING AVER-AGE CHANNEL QUALITY PREDICTION ALGORITHM

The NEWMAC algorithm employs a simple weight moving average-based criterion where the final channel rank estimation is calculated by assigning equal weights to current and past channel quality predictions. Here, current channel quality is predicted by employing the same mechanism as used in the NEC algorithm, whereas the past channel quality is based on the weighted moving average outcome in the previous iteration, as shown in Figure 5.3. Since the final channel quality assessment is based on past and current channel quality predictions, the NEWMAC algorithm has the ability to accommodate stream-based communication.

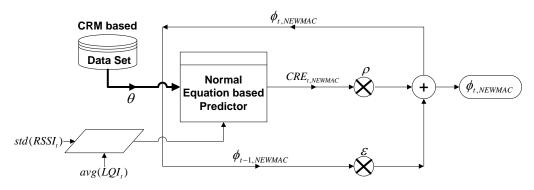


Figure 5.3: Data flow diagram of NEWMAC algorithm.

# 5.5.3.1 WEIGHT MOVING AVERAGE-BASED CHANNEL QUALITY PREDICTION MECHANISM

Let  $\phi_{t-1,NEWMAC}^{i}$  denote the past channel quality prediction and  $(CRE)_{t,NEWMAC}^{i}$  denote the current channel rank estimation. Let  $\epsilon$  and  $\rho$  denote the weights of past and current channel quality predictions, respectively, which have been assigned equal value in this calculation. Then, the moving average-based final channel quality prediction is given by:

$$\phi_{t,NEWMAC}^{i} = \epsilon \times \phi_{t-1,NEWMAC}^{i} + \rho \times (CRE)_{t,NEWMAC}^{i}$$
(5.15)

with

$$\epsilon + \rho = 1 \tag{5.16}$$

#### 5.5.3.2 PROBLEM DEFINITION

Let  $\phi_{t,NEWMAC}^i$  denote the final quality of any channel *i* at time *t*, being measured by taking the moving average of NEWMAC-based past channel quality prediction and normal equation-based current channel rank estimation. Let *C*, *Z* and *i* be defined as above, again with C = Z + i. Then, the objective function *F* is to select a channel *i* at instant *t* that exhibits the maximum quality:

Maximize: 
$$F(\phi_{t,NEWMAC}^{i})$$
,  $i = 1, 2, 3...C$  (5.17)

Subject to: 
$$\phi_{t,NEWMAC}^i \ge \phi_{t,NEWMAC}^Z$$
,  $C = \{i + Z/i \notin Z\}$  (5.18)

where,

$$0 \le (\phi_{t.NEWMAC}^{i}) \le 1.0$$

The above constraint (Equation (5.18)) says that the sensor node would select such a channel *i* for stream-based data communication at a particular epoch that exhibits the maximum quality. While the moving average-based NEWMAC algorithm predicts the average channel behavior by considering the current and past channel quality predictions, it is rather slow in tracking channel quality degradations/upgradations at a particular epoch (as discussed in performance evaluation Section 5.6.1.2), which may adversely affect system performance. Additionally, the NEWMAC algorithm embodies no mechanism for performing channel stability assessment (as discussed in the performance evaluation Section 5.6.1.3).

#### 5.5.4 NORMAL EQUATION-BASED AGGREGATE MATURITY CRITERIA WITH BETA TRACKING BASED CHANNEL WEIGHT PREDICTION ALGORITHM

The NEAMCBTC algorithm has the ability to accommodate stream-based communications, because it estimates the long-term average channel quality on the basis of current and past channel rank estimations, as shown in Figure 5.4. It employs a dynamic channel maturity criterion as a measure of quality-stability of a channel discussed in Section 5.5.4.1. Moreover, it has the ability to immediately track any change in channel quality as explained in Section 5.5.4.2.

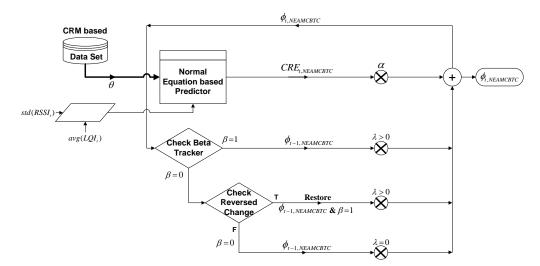


Figure 5.4: Data flow diagram of NEAMCBTC algorithm.

Let  $(CRE)_{t,NEAMCBTC}^{i}$  and  $\phi_{t-1,NEAMCBTC}^{i}$  denote the current and past channel quality predictions of a channel *i*. Let  $\eta_{t}^{i}$  and f(c) represent dynamic weights assigned to current and past channel quality assessment, while  $\beta$ -tracker is the

measure of channel quality tracking. Then, NEAMCBTC-based channel quality assessment is given by:

$$\phi_{t,NEAMCBTC}^{i} = \left(\beta - tracker\right) \times \left(f(c)\right) \times \phi_{t-1,NEAMCBTC}^{i} + \left(\frac{1}{\eta_{t}^{i}}\right) \times (CRE)_{t,NEAMCBTC}^{i}$$
(5.19)

It is clear from Equation (5.19) that NEAMCBTC-based channel quality assessment is performed with the help of four interconnected procedures, i.e., channel maturity criterion  $\eta$ , channel stability criterion  $\psi$ , channel tracking criterion  $\beta$ -tracker and a circular function f(c), as explained below.

#### 5.5.4.1 CHANNEL MATURITY CRITERION $(\eta)$

Unlike the NEWMAC algorithm, the NEAMCBTC algorithm employs a dynamic channel weighting procedure controlled by  $\eta_t^i$ , which adaptively assigns weights to past and current channel quality predictions. If the channel quality level is sustained, then the value of  $\eta_t^i$  is matured (incremented) with time using general-stability criterion  $\psi_t^i$  (Equation (5.20)) and subsequently increases confidence on past channel quality prediction as determined by circular function f(c), unless either the maximum maturity limit (*here*  $\eta_t^i = 10$ ) is obtained or the channel quality procedure is resumed again (*here*  $\eta_t^i = 1$ ). Mathematically, we can write:

$$\eta_t^i = \begin{cases} \psi_t^i, & \text{if } \psi_t^i \le 10\\ 10, & \text{Otherwise} \end{cases}$$
(5.20)

and:

$$\lambda_t^i = f(c) = \begin{cases} \left(\frac{\eta_t^i - 1}{\eta_t^i}\right), & \text{if } \eta_t^i > 1\\ 0, & \text{Otherwise} \end{cases}$$
(5.21)

#### 5.5.4.2 CHANNEL TRACKING CRITERION ( $\beta$ -Tracker)

The  $\beta$ -tracker continuously monitors channel quality levels Q(ch) shown in Table 5.4 and makes the appropriate decision in the case of any degradation/upgradation in channel quality, as outlined in Table 5.5. As a result, it may adjust the channel stability criterion accordingly (Equation (5.25)). Moreover, when a channel enters into new quality level, then both  $\beta$ -tracker and circular function f(c) nullify the past channel rank estimation ( $\phi_{t-1,NEAMCBTC}^i$ ). The NEAMCBTC algorithm also employs a mechanism for handling any abnormal channel quality degradation/improvement, as discussed in section 5.6.1.2.

The  $\beta$ -tracker is dependent on the current and previous values of channel quality level estimations  $Q(ch_{t,t-1}^i)$  and helps to track any change in channel quality level as calculated below:

$$\beta_{t,NEAMCBTC}^{i} = \left\langle \frac{MIN(Q(ch)_{t,NEAMCBTC}^{i}, Q(ch)_{t-1,NEAMCBTC}^{i})}{MAX(Q(ch)_{t,NEAMCBTC}^{i}, Q(ch)_{t-1,NEAMCBTC}^{i})} \right\rangle$$
(5.22)

128

Table 5.4:  $\beta$ -*tracker* based channel quality level Q(ch) assignment with  $q_1 = 0.3$ ,  $q_2 = 0.2$ ,  $q_3 = 0.1$ .

Serial No.	Channel Type	CRE	Q(ch)
1.	Good	$0.82 \le to \le 1.00$	$q_1$
2.	Intermediate	$0.33 \le to < 0.82$	92
3.	Bad	$0 \le to < 0.33$	<i>q</i> <sub>3</sub>

Serial No.	$Q(ch_{t-1}^i)$	$Q(ch_t^i)$	$\beta_t^i$ -Tracker Decision Making	Channel Quality Explanation
1	<i>q</i> <sub>1</sub>	$q_1$	1	Maintaining Good Quality
2	92	92	1	Maintaining Intermediate Qual-
				ity
3	93	93	1	Maintaining Bad Quality
4	$q_1$	92	0	Minor Change (to Intermediate
				Quality)
5	92	$q_1$	0	Minor Change (to Good Quality)
6	92	93	0	Minor Change (to Low Quality)
7	93	92	0	Minor Change (to Intermediate
				Quality)
8	$q_1$	93	0	Major Change (to Bad Quality)
9	93	$q_1$	0	Major Change (to Good Quality)

Table 5.5:  $\beta$ -*tracker*-based channel decision making.

Rewriting Equation (5.19) in simplified form, we get:

$$\phi_{t,NEAMCBTC}^{i} = \beta_{t}^{i} \times \lambda_{t}^{i} \times \phi_{t-1,NEAMCBTC}^{i} + \alpha_{t}^{i} \times (CRE)_{t,NEAMCBTC}^{i}$$
(5.23)

with:

$$\alpha_t^i + \lambda_t^i = 1 \tag{5.24}$$

#### 5.5.4.3 Channel general-stability criterion $(\psi)$

The channel general-stability criterion  $\psi$  is the measure of time since when a channel resides in a specific quality level (i.e., good/intermediate/bad). In this respect, a channel is considered more stable if it maintains a particular quality level for a prolonged interval. When a channel shifts to a new quality level, then the channel stability criterion  $\psi$  is resumed and incremented on each interval as long as the channel remains in that particular quality level as shown in the following equation:

$$\psi_{t}^{i} = \begin{cases} \psi_{(t-1)}^{i} + 1, & \text{if } \beta_{t}^{i} = 1\\ 1, & \text{Otherwise} \end{cases}$$
(5.25)

#### 5.5.4.4 PROBLEM DEFINITION

Since, the behavior of a channel varies with time, the channel quality assessment has to be made repeatedly. For stream-based transmission on a channel, the quality assessment becomes even more critical because it involves sending more volume of data and reserving the channel for a prolonged interval. Therefore, if

the channel quality assessment is done appropriately, it results in selecting an appropriate channel for performing future data transmission and routing. As a consequence, higher throughput and better system reliability may be achieved.

Let  $\phi_{t,NEAMCBTC}^i$  denotes the final quality of any channel *i* at time *t*, which is determined through NEAMCBTC-based past channel quality prediction and normal equation-based current channel rank estimation. Let *C*, *Z* and *i* be defined as above with C = Z + i. Then, the objective function *F* is to select a channel *i* at instant *t* that exhibits maximum quality:

Maximize: 
$$F(\phi_{t,NEAMCBTC}^{i})$$
,  $i = 1, 2, 3...C$  (5.26)

Subject to: 
$$\phi_{t,NEAMCBTC}^{i} \ge \phi_{t,NEAMCBTC}^{Z}$$
,  $C = \{i + Z/i \notin Z\}$ 
(5.27)

where,

$$0 \le (\phi_{t,NEAMCBTC}^{i}) \le 1.0$$

The above constraint (Equation (5.27)) states that the channel *i* with the highest quality will be selected for performing stream-based data communication at instant *t*. Since the NEAMCBTC algorithm also employs the channel maturity criterion ( $\eta$ ) and the channel tracking criterion ( $\beta$ -tracker), therefore it has the capability to perform limited quality stability and to track instantaneously any major/minor channel in channel quality, respectively. That is why the NEAMCBTC algorithm is more suitable to accommodate stream-based data communication than the NEWMAC algorithm.

#### 5.5.4.5 EXTENDED-NEAMCBTC ALGORITHM (WITH GENERAL STA-BILITY ASSESSMENT)

When channel quality is majorly/minorly degraded/upgraded, then the NEAM-CBTC algorithm resumes the channel maturity criterion from scratch. This may result in preferring a channel that has just attained the best quality, although it may have suffered from instability in the recent past (e.g., see the behavior of Channel 7 between interval [36, 39], as discussed in section 5.6.1.1). This issue can be handled if we consider the general stability criterion  $\psi_t^i$  as a metric in the final channel quality estimation  $\phi_{t,NEAMCBTC}^i$  of any channel *i*. The resulting metric ( $\xi_{t,Ext-NEAMCBTC}^i$ ) would be more robust as given below:

$$\xi^{i}_{t,Ext-NEAMCBTC} = \phi^{i}_{t,NEAMCBTC} + \psi^{i}_{t}$$
(5.28)

Rewriting Equation (5.23), we get:

$$\xi_{t,Ext-NEAMCBTC}^{i} = \left(\beta_{t}^{i} \times \lambda_{t}^{i} \times \phi_{t-1,NEAMCBTC}^{i} + \alpha_{t}^{i} \times (CRE)_{t,NEAMCBTC}^{i}\right) + \psi_{t}^{i}$$
(5.29)

The  $\xi_t^i$  metric may enable sensor nodes to predict both quality and stability and make a better choice among available channels for performing streambased communications. The data flow diagram of the Extended-NEAMCBTC (Ext-NEAMCBTC) algorithm is shown in Figure 5.5.

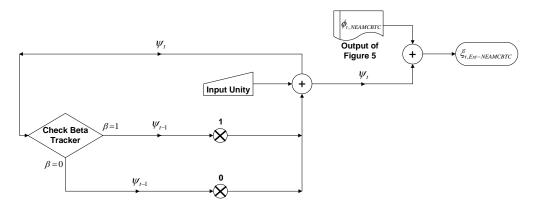


Figure 5.5: Data flow diagram of the Ext-NEAMCBTC algorithm.

#### 5.6 PERFORMANCE EVALUATION

For measuring the performance of the proposed machine learning-based algorithms, we have conducted extensive simulations in MATLAB [242]. In this respect, the experimental section can be divided into two main sub-sections:

- In the first portion of simulations, we discuss channel quality and stability assessment of our machine learning-based algorithms on the basis of randomly-generated samples of *std*(*RSSI*<sup>*i*</sup>) and *avg*(*LQI*<sup>*i*</sup>) in various channel quality ranges, as shown in Table 5.6, and representing the quality of seven channels. For this purpose, we have assumed that sensor nodes have some inherent mechanism for calculating *std*(*RSSI*<sup>*i*</sup>) and *avg*(*LQI*<sup>*i*</sup>) on the basis of received packets. The concluding remarks of this section are outlined in Section 5.6.1.4 and Table 5.7.
- In the second portion of simulations, we perform channel switching energy *Energy<sub>Ch-Switch</sub>* and channel switching delay *Delay<sub>Ch-Switch</sub>* related mea- surements of all discussed algorithms and compare them accordingly. Since, to the best of our knowledge, there is no multichannel scheme for WSNs similar to our work, therefore we have compared the performance of our schemes to the following approaches.
  - i. Random selfish approach: In this technique, the channel is selected randomly among all of the available channels. Afterwards, the sensor node communicates on the selected channel as long as the channel quality is either good  $(Ch_{good})$  or intermediate  $(Ch_{inter})$ .
  - ii. EM-MAC-based approach: It follows the pseudo-random order-based frequency hopping mechanism of EM-MAC [192], whereby channels of acceptable quality are hopped only in a pseudo-random manner,

while bad quality channels  $(Ch_{bad})$ , once identified, are marked as blacklisted for a specific time interval.

#### 5.6.1 CHANNEL QUALITY AND STABILITY ASSESSMENT US-ING THE PROPOSED MACHINE LEARNING-BASED AL-GORITHMS

In this section, we simulate and discuss the functionality of proposed algorithms for accommodating stream-based communication. For this purpose, the proposed algorithms are evaluated using three main factors as given below.

Symbol	Description	Value
N	Number of channels	7
$\theta_o$	Machine learning based weight of parameter $X_0$	0.0824
$ heta_1$	Machine learning based weight of parameter $X_1$	-0.0333
$\theta_2$	Machine learning based weight of parameter $X_2$	0.0083
std(RSSI) <sub>good</sub>	Standard deviation RSSI of good quality channel	<4 [7]
avg(LQI) <sub>good</sub>	Average LQI of good quality channel	>104 [7]
std(RSSI) <sub>inter</sub>	Standard deviation RSSI of intermediate quality channel	4–10 [7]
avg(LQI) <sub>inter</sub>	Average LQI of intermediate quality channel	70 to ≤104 [7]
std(RSSI) <sub>bad</sub>	Standard deviation RSSI of bad quality channel	>10 [7]
avg(LQI) <sub>bad</sub>	Average LQI of bad quality channel	<70 [7]
Chgood	Quality range of good rank channel	$0.82 \le to \le 1.00$
Ch <sub>inter</sub>	Quality range of intermediate rank channel	$0.33 \le to < 0.82$
$Ch_{bad}$	Quality range of bad rank channel	0.0≤ to <0.33
$T_s$	Sampling Time Interval	$1 \times 10^2 \text{ ms}$
Delay <sub>Ch-Switch</sub>	Overall channel switching delay	50 ms (approx) [121]
Delay <sub>Chev</sub>	Delay in calibrating receiver	22.08 ms [121]
Delay <sub>Cbrx</sub>	Delay in calibrating transmitter	23.44 ms [121]
$Delay_{T_{restart}}$	Delay in restarting radio after calibration	4.32 ms [121]
Energy <sub>Ch-Switch</sub>	Total energy consumption in channel switching	1940 nJ (approx) [121]
Energy <sub>Cb<sub>RX</sub></sub>	Energy consumption for calibrating receiver	1005.05952 nJ [121]
$Energy_{Cb_{TX}}$	Energy consumption for calibrating transmitter	838.42536 nJ [121]
Energy <sub>Trestart</sub>	Energy consumption for restarting radio after calibration	96.95376 nJ [121]

Table 5.6: Simulation parameters.

#### 5.6.1.1 CHANNEL QUALITY ASSESSMENT

Stream-based communication requires transmitting chunks of information from source to destination rather than performing packet-by-packet delivery of data. When the quality of available channels is overlapping, then those Channel Quality Assessment (CQA) approaches that perform channel quality estimation on the basis of only instantaneous observation(s) of channel quality may suffer from frequent channel switching overheads. This is due to the fact that the sensor node may tend to occupy the best quality channel at each epoch, which may result in inducing frequent channel switchings at the corresponding epochs. Such frequent channel switching may be risky and, therefore, is avoided for high data-rate applications, such as stream-based communication, because it may result in additional energy consumption and data loss [174]. This can be seen, for instance, in Figure 5.6, where an NEC algorithm-based sensor node mostly

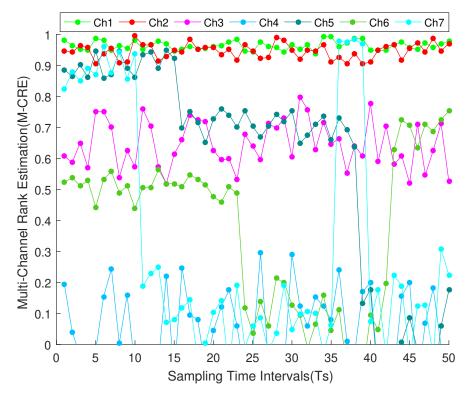


Figure 5.6: Channel quality (and stability) assessment for NEC.

switches between Channels 1 and 2 and sometimes to Channel 7. In addition, at Time Instances 7, 19 and 33, the sensor node rapidly shifts between Channels 1 and 2, which increases the channel switching overhead. Therefore, the NEC algorithm is unsuitable to perform channel quality assessment for stream-based communication.

Figure 5.7 shows the results for NEWMAC algorithm. Here, channel switching happens only between Channels 1 and 2 at Time Instances 12, 20, 30, 46 and 48, which may induce channel switching overhead in stream-based communication. In contrast, the NEAMCBTC algorithm increases the confidence on past channel rank estimation with time. As a result, it gives a better estimate of long-term average channel quality and handles any short-term channel quality degradations and upgradations. From Figure 5.8, it is obvious that the NEAMCBTC algorithm clearly estimates the superiority of Channel 1 over Channel 2; therefore, no switching happens. Additionally, it suffers from only one round-trip channel switching overhead between Channels 1 and 7, and therefore, NEAMCBTC algorithm is more suitable to accommodate stream-based communication in WSNs than NEWMAC algorithm. From Figure 5.9, it is evident that Ext-NEAMCBTC algorithm handles the round-trip channel switching overhead between Channel system is more suitable to accommodate stream-based communication in WSNs than NEWMAC algorithm. From Figure 5.9, it is evident that Ext-NEAMCBTC algorithm handles the round-trip channel switching overhead between Channels 1 and 7 in the Time Interval [36,39], therefore Ext-NEAMCBTC algorithm performs better than the other devised algorithms.

#### 5.6.1.2 CHANNEL QUALITY-TRACKING ASSESSMENT

Channel Quality-Tracking Assessment (CQTA) is the measure of an algorithm's ability to promptly pursue any minor/major degradation/upgradation in channel quality. As shown in Table 5.5, minor degradation or upgradation happens when the quality of a channel changes from a higher to an adjacent lower level, or vice versa, whereas major degradation or upgradation in channel quality takes place when channel quality decreases from good to bad level, or vice versa. The CQTA of our algorithms is discussed below.

- NEC-based channel tracking: The NEC algorithm performs channel rank estimation on the basis of instantaneous channel quality observation(s); therefore, it provides prompt knowledge of a channel quality change, as shown in Figure 5.6.
- NEWMAC-based channel tracking: Due to its moving average-based design, NEWMAC is unable to quickly respond to any change in channel quality. For example, looking at instantaneous knowledge based Figure 5.6 at Time Instant 11, Channel 7 appears to be jammed. However, due to slow tracking ability, the NEWMAC algorithm still considers Channel 7 as of intermediate quality at Instant 11 and therefore prefers Channel 7 over Channel 6, as shown in Figure 5.7. Consequently, this may result in system performance degradation. Similarly, when Channel 7 recovers from jamming at Time Instant 36, then the NEWMAC algorithm again takes some time in tracking the new quality of Channel 7. Hence, due to its poor tracking

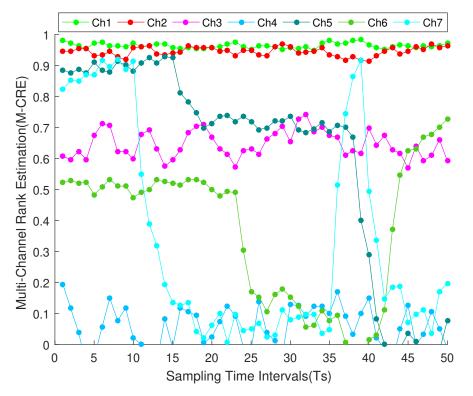


Figure 5.7: Channel quality (and stability) assessment for NEWMAC.

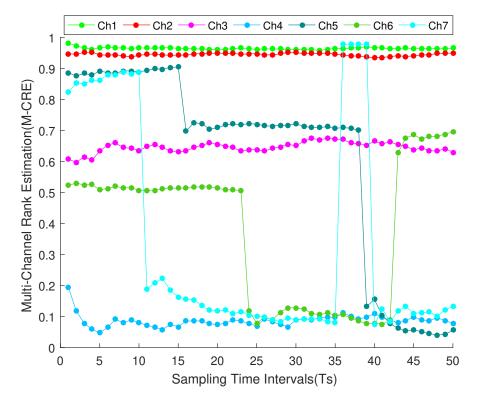


Figure 5.8: Channel quality (and stability) assessment for NEAMCBTC.

ability, the NEWMAC algorithm is not a good candidate for stream-based communication.

- NEAMCBTC-based channel tracking: Whenever any meaningful change in channel quality level is observed, then it is immediately tracked by  $\beta$ tracker, which equalizes its channel quality tracking ability to that of NEC algorithm, as shown in Figure 5.8. For example, as soon as Channel 7 suffers from jamming attack at Time Instant 11, then NEAMCBTC immediately tracks it, as shown in Figure 5.8, and thereby, avoids Channel 7. Unlike NEWMAC, NEAMCBTC is able to promptly track recovery of Channel 7 from jamming, as shown in Figure 5.8, which makes it a good candidate for accommodating stream-based communication. Since Ext-NEAMCBTC is based on NEAMCBTC, therefore it can promptly track any major/minor degradation/upgradation in channel quality at a particular epoch and can accommodate stream-based communication in WSNs.
- Channel abnormal behavior tracking and healing: Sometimes, instantaneous distortions in channel quality estimations crop up due to environmental factors, which may strongly effect the prediction capability of those memory-based systems that consider past knowledge in the future channel quality estimations. Unlike NEWMAC, NEAMCBTC has the ability to effectively handle any such instantaneous quality distortions. This capability of NEAM-CBTC helps its channel maturity criterion to function properly and make better decisions for final channel rank estimations. For example, we have deliberately introduced short-term minor/major abnormalities in Channel 5

and drawn its graph using the NEC, NEWMAC and NEAMCBTC algorithms, as shown in Figure 5.10. Being instantaneous knowledge based, NEC is not affected by any such irregularities from the past. On the other hand, NEWMAC is strongly affected by those oddnesses, while NEAMCBTC employs an inherent mechanism for suppressing these instantaneous abnormal distortions.

5.6.1.3 CHANNEL STABILITY ASSESSMENT

The stability of a channel is the measure of time during which a channel occupies a particular channel quality level. When stability is also considered as a metric for determining the channel rank, then good quality stable channels are assigned more weight and preferred over good quality unstable channels for performing stream-based communication.

More specifically, channel quality assessment aims to select the best quality channel, whereas channel stability assessment focuses on selecting a channel whose quality may remain steady for a prolonged interval. The above discussion has realized the fact that although NEAMCBTC is superior to its counterparts; it embodies only partial quality stability. Therefore, it handles both good quality stable/unstable channels using a similar mechanism, as shown for instance in Figure 5.8, where good quality unstable Channel 7 is preferred over good quality stable Channel 1 in the time interval [36, 39]. To bridge this gap, the extension Ext-NEAMCBTC incorporates a composite metric (Equation (5.29)), which considers both channel quality and stability. It enables sensor nodes to

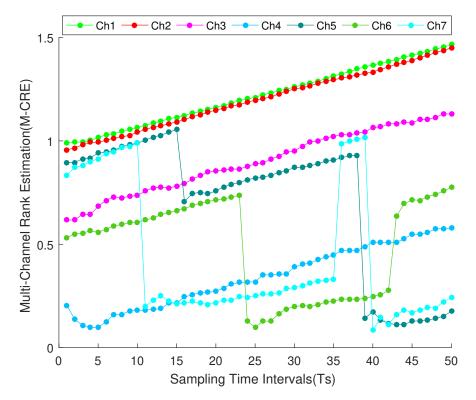


Figure 5.9: Channel quality (and stability) assessment for Ext-NEAMCBTC.

136

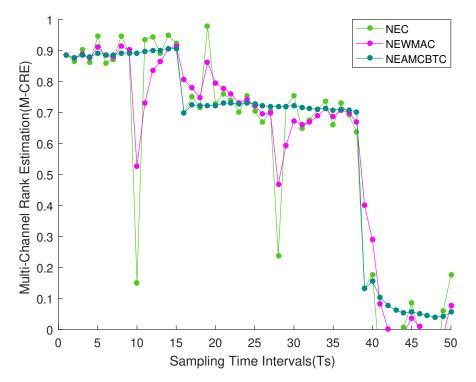


Figure 5.10: Channel abnormal behavior tracking and healing.

prefer Channels 1, 2 and 3 over Channel 7 for time interval [36, 39], as shown in Figure 5.9, and thus, enhances the capability of our system to accommodate stream-based communication.

#### 5.6.1.4 CONCLUDING REMARKS: A BRIEF DISCUSSION

In this section, we will summarize the pros and cons of our algorithms and their appropriateness for performing stream-based data communication in WSNs, as outlined in Table 5.7.

Since NEC makes estimations on the basis of current channel quality observation(s) only, therefore it is computationally the lightest among the discussed algorithms and can figure out the best among the available channels at the current epoch, which enables it to perform channel quality tracking easily. On the other hand, it is unable to give any long-term/average prediction of the channel quality and may suffer from frequent channel switching overheads, which makes it a poor choice for accommodating stream-based communication.

The moving average-based NEWMAC algorithm estimates channel quality on the basis of both past channel knowledge and current channel quality observation(s). Thus, it can predict the average behavior of a channel and may avoid frequent channel switching overheads, which makes it a better candidate for performing stream-based communication. Being based on the moving average approach, it requires more memory and processing power than NEC and exhibits a slow growth rate, which is unsuitable for promptly tracking any ma-

jor/minor changes in channel quality. Hence, in an environment where channels are suffering from rapid quality degradations and/or upgradations, NEWMAC may not provide suitable knowledge of channel quality for accommodating stream-based communication.

NEAMCBTC, finally, estimates channel quality using an adaptive channel maturity criterion that dynamically assigns weight to past channel knowledge and current channel rank observation(s). Thus, it gets long-term average channel behavior required for handling channel switching overheads and accommodating stream-based communication. The approach also embodies a robust channel tracking mechanism, which may accurately track any major/minor change in channel quality. Due to increased functionality, the algorithm may require more memory and processing capability as compared to the already discussed algorithms.

The NEAMCBTC algorithm, however, suffers from preferring those unstable channels that may exhibit better quality than stable channels, even for short intervals of time. This may result in inducing limited channel switching overheads, which may limit the performance of NEAMCBTC for accommodating stream-based communication. The extension, Ext-NEAMCBTC algorithm, solves this outstanding issue and encourages justice between stable channels and good quality unstable channels.

Table 5.7: Feasibility of the proposed schemes for stream-based communication in multichannel WSNs. CQA; CQTA, channel quality-tracking assessment; CSA, channel stability assessment.

Protocol	CQA	CQTA	CSA
NEC	_	$\checkmark$	_
NEWMAC	$\checkmark$	-	-
NEAMCBTC	$\checkmark$	$\checkmark$	Partial
Ext-NEAMCBTC	$\checkmark$	$\checkmark$	$\checkmark$

#### 5.6.2 MEASUREMENT OF CHANNEL SWITCHING OVERHEAD

This section discusses channel switching overheads in terms of switching delay and energy consumption of relevant algorithms, which may help to figure our their efficiency and suitability for accommodating stream-based communication. For more realistic calculations, we have utilized channel switching delay and energy consumption values outlined in [121].

#### 5.6.2.1 CHANNEL SWITCHING ENERGY OVERHEAD

Channel switching energy overhead is the amount of energy consumed by a sensor node when it jumps from one channel to another. The total energy consumed in channel switching is the sum of the energy consumed in calibrating (RX,TX) and restarting the radio afterwards [121]:

$$Energy_{Ch-Switch} = [Energy_{Cb_{RX}}] + [Energy_{Cb_{TX}}] + [Energy_{T_{restart}}]$$
(5.30)

#### 5.6. PERFORMANCE EVALUATION

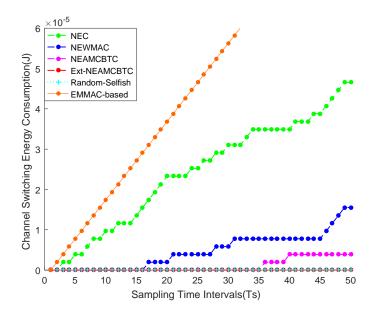


Figure 5.11: Channel switching energy overhead. Case I: the channel switching energy consumption of the compared techniques shows that Ext-NEAMCBTC and random selfish (in the above scenario) are the best due to no switching energy overhead, while the EM-MAC-based approach behaves the worst among all.

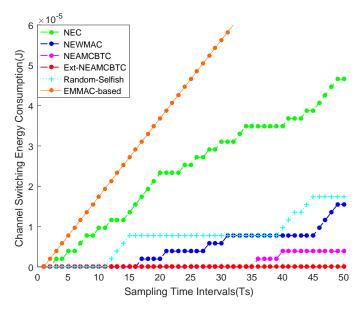


Figure 5.12: Channel switching energy overhead. Case II: the channel switching energy consumption of the compared techniques shows that Ext-NEAMCBTC is superior while random selfish (in the above scenario) performs worse than the NEWMAC approach. Random channel selection gives varying behavior to the random selfish approach.

It is clear from the Figures 5.11 and 5.12 that Ext-NEAMCBTC performs better as compared to other algorithms because it allows sensor nodes to jump to the channel of best quality and stability. Moreover, the sensor node resides on the best available channel as long as the quality of that channel is better than the other available channels. Since Ext-NEAMCBTC helps the sensor node to minimize channel switching overhead as much as possible by taking preemptive channel assessment measures, it encounters the least channel switching energy consumption among the compared techniques. On the other hand, the performance of the EM-MAC-based approach is the lowest among all available approaches because it follows a procedure with frequent frequency hopping, which allows it to switch from one channel to another.

Additionally, the random selfish approach consumes  $0-1.8 \times 10^{-5}$  J energy by making 0–9 channel switchings, respectively, in the current scenario, as is evident from Figures 5.11 and 5.12. This is due to the fact that the random selfish approach hops channels randomly and stays on a channel as long as the channel quality is good. Therefore, if it randomly hops to a channel of good quality and stability, it suffers from the least channel switching overhead, as shown in Figure 5.11. On the other hand, if the random selfish approach selects channels that are either of bad quality or their quality is degraded soon, then it may suffer from frequent channel switchings, resulting in an increase in channel switching energy budget, as shown in Figure 5.12. Consequently, such random behavior may cause performance issues, which may be considered preemptively while employing random-based approaches.

#### 5.6.2.2 CHANNEL SWITCHING DELAY OVERHEAD

The switching delay is the summation of latency experienced by a sensor node while shifting from one channel to other. It is the measure of delay experienced in calibrating (RX,TX) and restarting the radio afterwards [121]. Mathematically, we can write:

$$Delay_{Ch-Switch} = [Delay_{Cb_{RX}}] + [Delay_{Cb_{TX}}] + [Delay_{T_{restart}}]$$
(5.31)

It is clear from Figures 5.13 and 5.14 that Ext-NEAMCBTC suffers from the least channel switching delay among the compared approaches because it has the ability to categorize channels on the basis of its inherent channel quality and stability assessment mechanism. As a result, it avoids channel switching delays as much as possible, which may result in timely delivery of data-stream and ensuring system reliability through avoiding switching-oriented data losses. On the other hand, frequent channel hopping in EM-MAC-based may cause the most persistent channel switching delays and data losses, which makes it a poor candidate for accommodating stream-based communication.

Moreover, the random selfish-based approach shows a mixed trend, as evidenced from Figures 5.13 and 5.14, whereby it may either perform as good as Ext-NEAMCBTC in case it randomly occupies a channel of good quality and stability or it may perform worse than the NEWMAC algorithm in case it is unable to randomly hop to channels of good quality and stability. Thus, the random selfish technique may suffer from a channel switching delay between 0 and 0.45

#### 5.6. PERFORMANCE EVALUATION

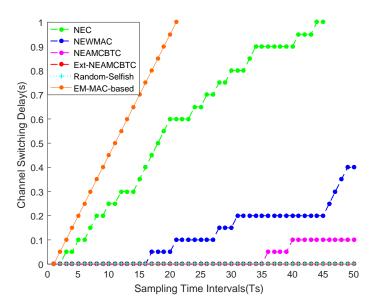


Figure 5.13: Channel switching delay overhead. Case I: the channel switching delay measurement of discussed algorithms where Ext-NEAMCBTC and random selfish (in the above scenario) are behaving the best owing to no switching delay overhead, whereas the EM-MAC-based approach behaves the worst due to frequent channel hopping.

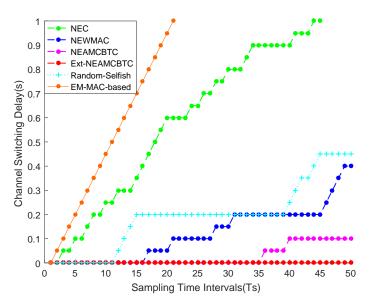


Figure 5.14: Channel switching delay overhead. Case II: the channel switching delay measurement of discussed algorithms where Ext-NEAMCBTC behaves the best while random selfish (in the above scenario) behaves worse than NEWMAC technique. The varying behavior of random selfish approach is due to random channel selection.

chapter 5. channel quality and stability estimation: for long and short-term stable frequencies

sec owing to 0–9 channel switchings, respectively, in the current scenario, as evidenced from Figures 5.13 and 5.14.

# CHAPTER 6

# CHANNEL QUALITY AND STABILITY ESTIMATION: FOR SHORT-TERM STABLE FREQUENCIES

#### 6.1 INTRODUCTION

Channel assignment may be static, semi-dynamic or dynamic natured [6]. The static channel assignment is performed for a specific time interval, therefore it is least-robust to environmental variations. On the other hand, both semi-dynamic and dynamic channel assignment are not time bounded and are robust to environmental changes. In case of dynamic channel assignment, the channel allocation is performed before each data transmission [44], therefore, it is more suitable to unstable environments. Whereas semi-dynamic channel assignment is performed when the environment is stable, at least for some time [81]. Due to frequent channel switchings, dynamic channel assignment suffers from severe channel switching overheads *vis-a-vis* semi-dynamic channel allocation strategy. Such frequent channel switchings may induce data loss when data rate is high [174] [6]. Beside that, semi-dynamic channel assignment [3]. To sum-up, semi-dynamic channel assignment is feasible for high data rate communication in highly-varying environment exhibiting stability, at-least for short intervals.

Critically examining the multichannel MAC literature for WSNs, it is clear that quite a few multichannel MAC protocols perform channel assignment based only on some channel quality assessment criteria. Among them to the best of our knowledge, Ext-NEAMCBTC algorithm [4] is the pioneer multichannel MAC protocol for WSNs that considers both channel quality and stability assessment for assigning wireless channels. However, Ext-NEAMCBTC [4] is designed for

a multichannel environment where some channels exhibit stability in maintaining a particular quality (either good, intermediate or bad) whereas others demonstrate unstable behavior and shift among different quality levels during the communication session. To the best of our knowledge, there does not exist a multichannel MAC protocol that may perform high data rate communication in a more challenging multichannel environment where all the channels exhibit a mixed quality behavior and are stable at-least for short time intervals. To bridge this gap, a novel multichannel MAC protocol, entitled as MAGIC algorithm, is proposed in this chapter. *It is worth mentioning that this chapter is mainly based on our under review article [1]*. The main features of MAGIC algorithm are outlined below:

- *Channel robustness prediction:* Our protocol predicts the robustness-level of available channels at a particular epoch by considering both channel quality and stability analysis (based upon channel behavior in the current and immediate past). The best among available channels is selected for stream based communication.
- *Semi-dynamic nature:* Being semi-dynamic natured, our protocol is suitable for high data rate applications such as stream-based communication that is executed in a highly-varying environment, exhibiting stability at-least for short time intervals.
- Secure communication: Our protocol is secure natured and employs a dynamic channel blacklisting criteria which progressively minimizes the selection probability of an abnormal channel, until the channel is completely boycotted for the ongoing communication session.
- *Adaptive stability adjustment:* Our protocol *dynamically updates* the stability behavior of a channel (based on immediate-past confidence interval at a particular quality level) when the channel is stable beyond current confidence interval limit.
- *Anti-Jamming Mechanism:* Our protocol is capable of handling *accidental jamming* on a channel executing stream-based communication.

The remaining portion of this chapter can be organized as follows. In Section 6.2, the literature review and motivation of this research is discussed. The Section 6.3 describes system model and problem statement while Section 6.4 provides a detailed explanation of the proposed solution. In Section 6.5, the simulation results and discussions are outlined.

#### 6.2 LITERATURE REVIEW AND MOTIVATION

This section discusses the operation of various multichannel MAC protocol for WSNs. For convenience, the relevant properties of the discussed protocols are also highlighted at the end of this section in Table 6.2. Based on the channel assignment methodology, the discussed protocols may be classified into two main categories. i.e.

Symbol	Description	Symbol	Description
ξi	Channel <i>i</i>	$\Omega_{\xi_i}$	Channel state index of channel <i>i</i>
$\varpi_{\xi_i}$	Quality of channel <i>i</i>	$\Phi_{\xi_i}$	Residence probability of channel <i>i</i>
$\Pi_{\xi_i}$	Channel toggling probability of channel $i$	$\Gamma( u)$	Set of available channels at a sensor node $ u$
$\Lambda( u)$	Healthy channels at sensor node $ u$	$\Xi( u)$	Blacklisted channels at sensor node $ u$
ρχ	Past confidence interval of channel $i$ at a quality level	$\zeta_{\chi}$	Current confidence interval of channel $i$ at a quality level
ε	Balancing factor for unfolding the data stream from the current sample	$\Psi_{\xi_i}$	Quality and stability estimation of channel <i>i</i>
β	Blacklisting bound	$\Upsilon_{\xi_i}$	Allowed toggles of a channel <i>i</i>

## Table 6.1: Listing of Symbols with Description

chapter 6. channel quality and stability estimation: for short-term stable frequencies

- *Primus-Inter-Pares based:* It includes those multichannel MAC protocols that perform channel assignment (e.g. random based, 1<sup>st</sup> common channel oriented, node priority based and so on) irrespective of channel quality/stability assessment.
- *Deterministic based:* It encompasses such multichannel MAC protocols that perform channel assignment based on some channel quality/stability assessment mechanism(s) such as interference aware, congestion/load based, Packet Delivery Ratio (PDR) oriented and so on as discussed in Table 6.2.

Below, we will separately discuss a variety of protocols belonging to each of the above mentioned category. For more information regarding the multichannel MAC protocols, the reader may consult [3].

# 6.2.1 PRIMUS-INTER-PARES BASED MULTICHANNEL MAC PROTOCOLS

In [213], the first multichannel MAC protocol is proposed for WSNs that outlines a variety of channel assignment mechanisms (i.e. exclusive, even-selection, eavesdropping and implicit-consensus). Subsequently, the most suitable frequency assignment mechanisms is selected based upon the characteristics of WSNs and application demand. However, none of the channel assignment mechanisms considers the quality/stability measurement of available channels and therefore would not be able to select the best among available channels for data communication in WSNs.

The authors in TFMAC [152] have proposed a multichannel algorithm which executes frequency and time slot assignment in two steps. The channel allocation is random whereby one of the available channels is selected for receiving purpose and subsequently broadcasted in the two-hop neighborhood. Such a random channel assignment may result into selecting a channel of inferior quality and stability, therefore it is not suitable for data communication in Stream-based Multichannel Wireless Sensor Networks (SMWSNs). In HYMAC [179], a tree based centralized multichannel MAC protocol is proposed whereby sink node announces time slot/frequency to sensor nodes in a level-by-level manner. The interfering siblings are assigned different time slots while interfering non-sibling nodes are assigned different frequencies for communication. Being based on centralized approach, the protocol is unable to handle dynamic changes in the network and thereby unable to dynamically perform channel quality and stability estimation.

In Y-MAC [154], a channel hopping algorithm is proposed for dealing with high traffic rate. Here, the receiver jumps from one channel to other followed by the sender interested in data communication with the receiver. Subsequently, the traffic load is distributed among the available channels and fairness may be achieved. Since the protocol is not considering channel quality, therefore both sender and receiver may hop to channels of bad quality which may cause data loss. In MuChMAC [221], a pseudo-random generator calculates the receiving frequency against a time slot based on time slot number and the node ID. However, the protocol does not perform individual quality/stability analysis of

available frequencies and therefore may select channels of inferior quality/stability.

The authors in [45] have proposed a multichannel MAC protocol that uses orthogonal channels for achieving high data rate in WSNs. Upon receiving control messages, each node may get information about the occupied slots in the two-hop neighborhood. The channel assignment is sender oriented whereby a sender node awakes on control channel during the common frequency period of a time slot and requests to the desired receiver for communication. If the receiver is available, then it shifts to the sender channel and communication is started between sender and receiver during the remaining portion of time slot designated as split phase period. To sum up, the protocol does not provide a measure of channel classification in terms of quality/stability that may be helpful in selecting the best among the available channels for performing streambased communication in WSNs.

In [129], beacon frames are broadcasted by sensor nodes for building three-hop neighborhood lists and propagating the information regarding the assigned channels in a neighborhood. The sensor nodes comprise of two groups that may alternate between sending and receiving modes. The sensor node having the least network address in a group selects a distinct channel in the three-hop neighborhood. However if channel selection is not successful, then the node may consider two-hop and afterwards one-hop neighborhood for finding a unique channel. When a node fails to select a distinct channel, then it would randomly select a less used channel in one-hop neighborhood. Since wireless channels are limited, therefore it would be very difficult for a node to select a unique channel in dense WSNs. Subsequently, a sensor node would unsystematically select the less used channel from one-hop neighborhood. Henceforth, the Enhanced HMC-MAC protocol [129] would not be a able to select the best channel under channel quality and stability oriented constraints.

In Enhanced-LRCH [94], a Latin Rectangular (LR) based channel scheduling approach is proposed where each row and column of LR contains unique channels. More specifically, each row of LR corresponds to a specific channel hopping sequence while each column (or time slot) of LR represents a unique frequency. The frequency assignment is performed using an interleaving channel hopping mechanism where consecutive time slots are assigned the non-adjacent frequencies. Subsequently, the protocol may counter both internal and external interference. The Enhanced-LRCH [94] protocol neither consider the quality nor stability analysis of wireless channels.

#### 6.2.2 DETERMINISTIC BASED MULTICHANNEL MAC PROTO-COLS

In [159], the authors have proposed a bandwidth enhancement approach for WSNs whereby each sensor nodes may repeatedly announce traffic load on its channel. When a lower level channel is heavily crowded, then the leader and associated nodes may switch from lower to contiguous higher level channel (channel expansion). However, when load on lower level channel is normalized, then channel shrinking is executed whereby the leader and associated nodes

chapter 6. channel quality and stability estimation: for short-term stable frequencies

may jump from higher to adjacent lower level channel. The protocol is based on control theory based approach and suffers from control overhead. Although a basic traffic load based quality assessment of channels is performed, however no mechanism is outlined for channel stability analysis.

The authors in RMCA [208] have described a regret matching based approach whereby sensor node may predict about network topology and flow by employing the past information and subsequently select the future channel for communication. However the protocol does not consider current quality/stability of available channels during channel selection. In SLA [103], the authors have proposed a game theory based multichannel MAC protocol for WSNs where a sensor node randomly selects a channel for the current slot. On the basis of data delivery on corresponding channel, the channel selection probability is revised and strategy is re-evaluated for the next slot. The process is continued slot-by-slot till optimum strategy for available channels is adopted.

The EM-MAC protocol [192] maintains a quality criteria for avoiding congested and interfered channels that is entitled as channel badness metric. Subsequently, the channels having badness metric greater than a threshold value  $C_{bad}$  are marked as blacklisted by receiver for the blacklist interval  $T_{black}$ . The receiver also informs sender about the blacklisted channels by transmitting blacklist bitmap in beacon messages, so that the sender may also avoid those channels. The sender may predict the wake-up time slot and channel of receiver node based on prediction state information of receiver and thereby sends data to receiver. Although the protocol may avoid congested and interfered channels during  $T_{black}$ , however it may not be able to appropriately quantify the quality/stability of non-congested channels.

In MinMax [71], a distributed link scheduling algorithm is proposed which minimizes interference in WSNs. Here, each node calculates its local conflict on the available channels and avoids those channels where neighbor conflict is higher than local conflict. It is due to the fact that switching to such higher neighbor conflicting channels may enhance the network conflict and causes data loss. Afterwards, the sensor node switches to the channel with least local conflict and broadcast it in the neighborhood. Furthermore, the remaining interference is handled by scheduling links in a conflict free manner. Although the protocol categorizes channels on the basis local conflicts and selects the best among feasible channels (with least local conflict), however it does not outline any mechanism for stability analysis of the feasible channels.

In [25], the authors have discussed a multichannel MAC protocol where sink and sensor nodes calculate the overall-cost of local channels based on RSSI and threshold costs. The best global channel is calculated by sink node based upon the local channels of sink and sensor nodes. The protocol employs reevaluation and recovery procedures that consider Packet Error Rate (PER) and link-connectivity in a respective manner for providing efficient communication. The protocol transmits a lot of control information for measuring the best global channel. Although the protocol employs a less robust metric for channel quality assessment, however it does not discuss any mechanism for channel stability analysis in WSNs.

		Channel Assignment								
Protocols	Network Type	Methodology		Quality Analysis						
		Primus-Inter- Pares	Deterministic	Interference aware	Congestion/ Load based	PDR/PRR/PER based	LQI based	RSSI/SNR based	Prediction based	Stability Analysis
MMSN [213]	WSNs	$\checkmark$								
HYMAC [179]	WSNs	$\checkmark$								
TFMAC [152]	WSNs	$\checkmark$								
PMMAC [159]	WSNs		$\checkmark$		$\checkmark$					
Y-MAC [154]	WSNs	$\checkmark$								
MuChMAC [221]	WSNs	$\checkmark$								
RMCA [208]	WSNs		$\checkmark$						$\checkmark$	
EM-MAC [192]	WSNs		$\checkmark$	$\checkmark$	$\checkmark$					
MC-LMAC [45]	WSNs	$\checkmark$								
Enhanced HMC-MAC [129]	WSNs	$\checkmark$	$\checkmark$		$\checkmark$					
MinMax [71]	WSNs		$\checkmark$	$\checkmark$						
DynMAC [25]	WSNs		$\checkmark$			$\checkmark$		$\checkmark$		

Table 6.2: Review of channel assignment methodology, quality and stability analysis of multichannel MAC protocols for WSNs

149

7	FREQUENCIES	CHAPTER 6. CHANNEL QUALITY AND STABILITY ESTIMATION: FOR SHORT-TERM STABLE
		TY ESTIMATION: FOF
		SHORT-TERM STABLE

**Channel Assignment** Methodology Quality Analysis PDR/PRR/PER based Congestion/ Load based Interference RSSI/SNR based **Prediction** based Stability LQI based Protocols Network Type aware Analysis Primus-Inter-Deterministic Pares CAP [196] WSNs  $\checkmark$  $\checkmark$ Dense MCAS-MAC [56]  $\checkmark$  $\checkmark$ WSNs RC-MAC [43] WSNs  $\checkmark$  $\checkmark$ PWMMAC [180] WSNs  $\checkmark$  $\checkmark$  $\checkmark$ SLA [103] WSNs  $\checkmark$  $\checkmark$  $\checkmark$ Enhanced-LRCH [94] WSNs  $\checkmark$ Ext-NEAMCBTC [4] SMWSNs  $\checkmark$  $\checkmark$  $\checkmark$  $\checkmark$  $\checkmark$ OCP [212] WSNs  $\checkmark$  $\checkmark$  $\checkmark$ 

Table 6.2: (Continued...)

In CAP [196], such channels are located for wireless links that may provide high capacity and improved connectivity in WSNs. The protocol is based upon the induced channel quality metric that considers Packet Reception Rate (PRR) due to multipath affect. Consequently, the operating frequencies of different links may experience different Signal to Noise Ratio (SNR) whereby the most suitable frequency would be allocated to a wireless link for getting high performance in WSNs. Although the protocol devices a mechanism for measuring channel quality, however it does not discuss any criteria for channel stability assessment. Henceforth, it may not be appropriate for finding good quality stable channels that are suitable for stream-based communication in WSNs.

The authors in [56] have outlined an asynchronous scheduled based multichannel MAC protocol whereby a slot-less node may perform channel polling on the available channels. After receiving HELLO messages, a node may get the channel and time slot information of neighboring nodes. It may help the slot-less node to select the least used receiving channel and wake-up slot for data communication in WSNs. However, it may be possible that the least used channel would be of insufficient quality and stability which may cause data loss in WSNs.

The authors in [43] have devised a receiver-oriented multichannel MAC protocol where sensor nodes may employ either duty-cycle or full-active mode for accommodating low or high data rate communication in WSNs. The channel assignment may be executed in a manner that the interference-free frequencies may be allocated to each parent-child set that may improve throughput in WSNs. However, the protocol does not outline any mechanism for assigning the best possible channel to each parent-child set under channel quality and stability oriented constrains.

The authors in [180] outlines a basic channel quality metric for segregating congested and non-congested channels. The non-congested channels having Channel usage ( $C_u$ ) metric below a Channel threshold value ( $C_{th}$ ) are placed in a preferred Channel list ( $C_{list}$ ). However, the protocol does not outline any quality/stability based mechanism for classifying the channels in  $C_{list}$ . In SLA [103], the authors have proposed a game theory based multichannel MAC protocol for WSNs where a sensor node randomly selects a channel for the current slot. On the basis of data delivery on corresponding channel, the channel selection probability is revised and strategy is re-evaluated for the next slot. The process is continued slot-by-slot till optimum strategy for available channels is adopted.

In [4], a robust multichannel MAC algorithm is proposed that calculates the best channel at a particular epoch based on quality and stability assessment of available channels. Here, the instantaneous quality of channels is estimated by normal-equation-based channel quality predictor considering standard deviation of RSSI (std(RSSI)) and average of LQI (avg(LQI)) of received data packets. Afterwards an exponential smoothing approach is employed based on the quality estimation (current and past) and stability assessment of available channels that predicts the best channel at a particular epoch for stream-based communication in Multichannel Wireless Sensor Networks (MWSNs). The Ext-NEAMCBTC algorithm [4] delineates a mixed multichannel environment where some good quality

channels are stable during the communication session whereas the others may suffer from degradation and jamming. It may handle infrequent channel toggling (between good and bad quality levels) that may affect channel prediction capability of memory based protocols [4].

In [212], the authors have proposed Optimal Channel Probing algorithm (OCP) that considers PRR for measuring the quality of available channels in wireless networks. The protocol finds the correlation of available channels based on the measured SNR and predicted PRR. Subsequently, a MAX-separation approach is used whereby uncorrelated channels are selected from the candidate set for each next channel probing and until the ending benchmark of probing channel selection is reached. The MAX-separation approach avoids selecting the correlated channels because they may decrease system performance. Although OCP measures channel quality, however it does not outline any mechanism of measuring channel stability, therefore it may not be suitable for stream-based applications in WSNs.

Based on the literature above, it can be concluded that:

- A larger number of multichannel MAC protocols are published so far for WSNs which may either adopt *Primus-Inter-Pares* or *Deterministic approach* for assigning wireless channels to sensor nodes. The *Primus-Inter-Pares* protocols assume that all the wireless channels are of equal quality and thereby does not employ any channel quality and stability assessment mechanisms. On the other hand, the *Deterministic* protocols may differentiate wireless channels by assuming/employing various channel quality assessment mechanisms as outlined in Table 6.2.
- Among the *Deterministic* protocols, Ext-NEAMCBTC [4] is the only one considering both channel quality and stability for predicting the best among available channels at particular epoch for accommodating stream-based communication in MWSNs. However, it is suitable for a hybrid multichannel environment where some channels exhibit good quality and stability while the others show varying (noisy) behavior. Therefore, there is need to devise a multichannel MAC protocol which may select the best channel in a multichannel environment where all the channels may exhibit varying behavior and are stable only for some time intervals.
- The Ext-NEAMCBTC algorithm [4] takes channel decision per sample for accommodating a data stream (accomplishing in one sample). Therefore, there is a need to devise a more robust multichannel MAC protocol predicting the best channel for accommodating a data stream spanning over many samples. The protocol may also be capable of switching a wireless channel that is degraded during the transmission of data stream.
- The Ext-NEAMCBTC algorithm [4] may handle instantaneous major distortions (called channel toggling in this work), however occurring infrequently and may affect channel prediction capability of memory based protocols [4]. Therefore, there is a need to devise a multichannel MAC protocol that may deal with frequent toggling behavior of wireless channels for accommodating stream-based communication in MWSNs.

### 6.3 PROPOSED SYSTEM MODEL AND PROBLEM STATE-MENT

This section elaborates the system model of the proposed Multichannel Adaptive approach for Grading Immediate Channels (MAGIC). Afterwards, a problem statement is outlined for solving the optimization problem under channel quality and stability oriented constraints.

#### 6.3.1 PROPOSED SYSTEM MODEL

The system architecture is two-tier based, consisting of 'N' multi-channel multimedia sensor nodes and 'S' multi-channel multimedia sinks. The proposed system is based upon the following assumptions:

- All the sensor nodes are assumed to have equal processing capability and may harvest energy for prolonging their operating lifespan. The sinks have high processing capability, unlimited battery resource and are linked to the common back-end data center.
- Due to the fact that information transmission is more expensive than processing [6], the proposed architecture is assumed to render *compressive sensing* based in-network processing. The *compressive sensing* may not only reduce the transmitted information, but may also enhance information security. Following this, when a signal  $x_{nx1}$  is generated due to an event in the surveillance area, then the measurement vector  $y_{mx1}$  (send by a sender to receiver node) would be the inner product of sensing matrix  $\phi_{mxn}$  and the original signal  $x_{nx1}$  [251] given by

$$y_{mx1} = \phi_{mxn} \times x_{nx1} \tag{6.1}$$

Where both  $x_{nx1}$  and  $\phi_{mxn}$  would be sampled at *Nyquist Rate* given by

$$f_s > 2 \times f_h \tag{6.2}$$

Here,  $f_s$  is the sampling rate and  $f_h$  is the highest frequency. On the receiver side, both  $y_{mx1}$  and  $\phi_{mxn}$  would be used to reconstruct the original signal  $x_{nx1}$  by employing some relevant approach (such as pseudo-inverse) [251] given by

$$\hat{x} = \phi^T (\phi \times \phi^T)^{-1} \times y \tag{6.3}$$

• The proposed MAC layer model is multi-channel based allowing each sensor node to measure Channel Selection Index (CSI) of the available channels based on channel quality and stability oriented constraints. The CSI based channel ranking is helpful in assessing the best channel at a particular epoch for transmitting a data stream between the communicating nodes (point-topoint link). Moreover, it is assumed that there may be at least one channel in the active channel pool exhibiting good or intermediate quality.

The channel quality at a particular epoch is the measure of channel condition calculated based on std(RSSI) and avg(LQI) of received data packets [4]. The

chapter 6. channel quality and stability estimation: for short-term stable frequencies

channel stability is determined on the basis of both Channel Residence Probability (CRP) at a particular quality level and Channel Toggling Probability (CTP). The CRP is the measure of staying time of a channel (in terms of samples) at a particular quality level. It is calculated based on data Stream Space (SS), current staying time (entitled as Current Confidence Interval (CCI)) and average-past staying time (entitled as Average-past Confidence Interval (ACI)) of a channel at a specific quality level as depicted in Figure 6.1 and discussed in Section 6.4.1.

On the other hand, Channel Toggling Probability (CTP) is determined on the basis that how often a channel toggles/jumps from good to bad quality levels and vice versa during a communication session as shown in Figure 6.4 and elaborated in Section 6.4.5. The more frequent the toggles are, the more unstable the channel would be. Furthermore, when channel toggling reaches a threshold value, then it is a clear indication that the channel is highly unstable and therefore unsuitable to accommodate stream-based communication. Consequently, such a channel would be *blacklisted* and not considered during the ongoing surveillance session. Additionally, when a channel maintains a particular quality level until the value of CCI surpasses ACI, then the average confidence on such a channel would be further enhanced (doubled in this work), termed as Average-past Confidence Interval Boosting (ACIB) as discussed in Section 6.4.3.

#### 6.3.2 PROBLEM STATEMENT

Let, there is a region  $\Re c$  which is monitored by 'N' surveillance sensors. Let,  $\xi_i$  represents any channel *i* such that  $i = \{1, 2, ..., \Gamma(\nu)\}$  where  $\Gamma(\nu)$  represents the total number of available channels at a sensor node  $\nu$ . Let,  $\Gamma(\nu)$  consists of  $\Lambda(\nu)$  active and  $\Xi(\nu)$  inactive (blacklisted) channels, therefore mathematically we can write that:

$$\Lambda(\nu) \cup \Xi(\nu) = \Gamma(\nu) \tag{6.4}$$

Where

$$\Gamma(\nu) = \{\xi_i \mid i = 1, 2, 3, ...\}$$
$$\Lambda(\nu) = \{\xi_i \mid i = 1, 2, 3, ... \text{ and } \nexists \xi_i \in \Xi(\nu)\}$$
$$\Xi(\nu) = \{\xi_i \mid i = 1, 2, 3, ... \text{ and } \nexists \xi_i \in \Lambda(\nu)\}$$

It is clear from the Equation (7.1) that both  $\Lambda(\nu)$  active and  $\Xi(\nu)$  blacklisted channels are distinct and non-overlapping natured.

Each sensor node  $\nu$  has the ability to measure channel state index  $(\Omega_{\xi_i})$  of the available channels on the basis of channel quality  $(\varpi_{\xi_i})$  and stability estimation criteria  $(\Phi_{\xi_i}, \Pi_{\xi_i})$ . The sensor node may rank the active channels by solving the optimization problem as per the objective function under the channel quality and stability estimation constraints. It can be described mathematically as follows:

 $\Omega_{\xi_i}$ 

#### Maximize:

6.4. PROPOSED MULTICHANNEL ADAPTIVE APPRO-

ACH FOR GRADING IMMEDIATE CHANNELS FOR STREAM-BASED MULTICHANNEL WIRELESS
SENSOR NETWORKS

#### Subject to:

 $C_1$ 

: 
$$\xi_i \in \Lambda(\nu)$$
 (6.6)

$$C_2: \qquad \varpi_{\xi_i} \ge Th_{lim} \tag{6.7}$$

$$C_3: \qquad \Phi_{\xi_i} \ge 0 \tag{6.8}$$

$$C_4: \qquad \Pi_{\xi_i} > 0 \tag{6.9}$$

The objective function in (6.5) aims to rank the available channels  $\xi_i$  under channel quality and stability oriented constraints (outlined in (6.6)-(6.9)) for selecting the most suitable channel for stream-based communication in MWSNs. The first constraint  $C_1$  in (6.6) tells to consider the channels in the active channels pool only. It is because the inactive (blacklisted) channels are highly unreliable for accommodating the stream-based communication in MWSNs. The second constraint  $C_2$  in (6.7) is the measure of channel quality which states to consider those channels for communication whose quality metric is above a threshold limit ( $Th_{lim}$ ). The  $Th_{lim}$  is set to 0.33 and below which bad quality channel(s) exist [4]. In other words, the constraint  $C_2$  narrates to select good and intermediate quality channels for stream-based communication and to avoid bad quality channels.

The third constraint  $C_3$  in (6.8) endorses that CRP (denoted as  $\Phi_{\xi_i}$ ) of a channel (at a particular quality level) shall be non-negative. It is because a channel with non-negative CRP may be more likely to accommodate a data stream at the current epoch as depicted in Figure 6.2. The fourth constraint  $C_4$  in Equation (6.9) is of the view that CTP (represented as  $\Pi_{\xi_i}$ ) of the selected channel must be positive, so that a *blacklisted* channel may not be considered for performing stream-based communication in MWSNs.

## 6.4 PROPOSED MULTICHANNEL ADAPTIVE APPRO-ACH FOR GRADING IMMEDIATE CHANNELS FOR STREAM-BASED MULTICHANNEL WIRE-LESS SENSOR NETWORKS

In this section, we will discuss the implementation of our proposed Multichannel Adaptive approach for Grading Immediate Channels (MAGIC). The proposed MAGIC algorithm is executed in five steps as explained below:

#### 6.4.1 CHANNEL RESIDENCE PROBABILITY ESTIMATION

Channel Residence Probability (CRP) is the measure of likelihood that the channel will occupy a particular quality level. It is estimated on the basis of three factors namely Average-past Confidence Interval (ACI), Current Confidence Interval (CCI) and Stream Space (SS). For the purpose of clarity, a concise definition and explanation of these terms is provided below:

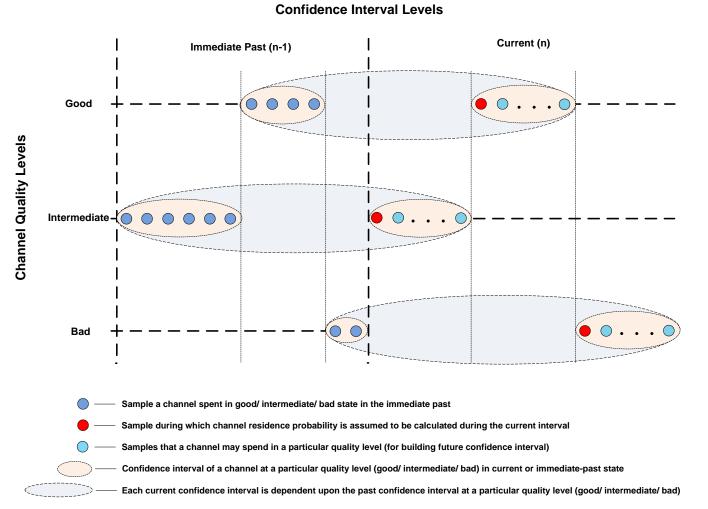


Figure 6.1: Current confidence interval at a particular channel quality level considers only immediate past confidence interval at that channel quality level

6.4. PROPOSED MULTICHANNEL ADAPTIVE APPRO-

ACH FOR GRADING IMMEDIATE CHANNELS FOR STREAM-BASED MULTICHANNEL WIRELESS

**Definition:1** Current Confidence Interval (CCI) is the function of instantaneous maturity index of a channel at a particular epoch. The instantaneous maturity index at a particular instant is determined based on the continuous time interval till the current epoch (i.e. number of samples) during which the channel resides at a particular quality level.

Upon entering into each new quality level, the maturity index of a channel is initialized as unity and incremented sample-by-sample until the channel occupies a particular quality level. Let  $\chi$  represents a particular quality level and  $\mu_{\chi}$  characterizes maturity index of a channel at that quality level in terms of the continuous number of samples  $\eta_{(inst,\chi)}$  traversed so far in the current interval. Then CCI of a channel denoted by  $\zeta_{\chi}$  can be mathematically expressed as:

$$\zeta_{\chi} = f(\mu_{\chi}) \tag{6.10}$$

Where

$$\mu_{\chi} = \eta_{(inst,\chi)} \tag{6.11}$$

and

$$\chi \in \{Good, Intermediate, Bad\}$$

Since the proposed system considers three quality levels (namely good, intermediate and bad), it calculates CCI of a particular quality level upon entry of channel into the concerned level. Furthermore at a particular instant, a channel may occupy only one quality level as evident from the Figure 6.1.

**Definition:2** *Immediate-past Confidence Interval (ICI) is the measure of continuous residence (in terms of number of samples) of a channel at a particular quality level in the recent past.* 

The immediate-past confidence interval delineates the number of samples  $\eta_{(past,\chi)}$  a channel continuously resides at a specific quality level in the immediate past and therefore helps in determining channel response (stability of a channel) at the particular quality level. It is determined at the instant of each change of channel quality level whereby the final value of CCI is used to update ICI. Let, ICI of a channel is denoted by  $(\rho_{\chi})$ , then mathematically we can write that

$$\rho_{\chi} = \eta_{(past,\chi)} \tag{6.12}$$

**Definition:3** Average-past Confidence Interval (ACI) is the measure of average response of a channel at a particular quality level in the past.

The average-past confidence interval determines the average residence time of a channel at a particular quality level in the past, therefore it may be a crucial factor for channel stability estimation in the immediate future. The ACI is always updated at the instance of quality change of a channel and is determined mathematically as: chapter 6. channel quality and stability estimation: for short-term stable frequencies

$$\rho_{\chi (avg,cur)} = \left[\frac{\rho_{\chi (avg,prev)} + \rho_{\chi}}{2}\right]$$
(6.13)

**Definition:4** *Stream Space (SS) is the measure of number of samples required to accommodate a complete data stream.* 

The data stream is assumed to take more than one samples to complete. More specifically, a stream size of three is considered in this work.

Based on the above definitions, we can estimate residence probability  $(\Phi_{\xi_i})$  of a channel  $\xi_i$  at a particular instant as shown in Figure 6.2 and given below

$$\Phi_{\xi_{i}} = \left[\frac{\rho_{\chi \ (avg,cur)} - (\zeta_{\chi} + SS - 1)}{\rho_{\chi \ (avg,cur)}}\right]$$
$$= 1 - \left[\frac{(\zeta_{\chi} + SS)}{\rho_{\chi \ (avg,cur)}} - \frac{1}{\rho_{\chi \ (avg,cur)}}\right]$$
$$= 1 - \left[\frac{(\zeta_{\chi} + SS)}{\rho_{\chi \ (avg,cur)}}\right] + \varepsilon$$
(6.14)

Where  $\varepsilon$  is the balancing factor for unfolding the data stream from the current sample. For the purpose of understanding, a simple scenario is depicted in Figure 6.2. Here, based on the time of arrival of data stream, the SS window of size 3 slides across the ACI window of size 6 for calculating CRP of a channel. For more clarity, the four cases depicted in Figure 6.2 are briefly discussed below.

**Case.I** In this case, CRP prediction is discussed at the inception of channel entry into a particular quality level. Based upon the confidence intervals (ACI & CCI) and stream size, the system may easily accommodate the data stream. Moreover, on the basis of Equation (6.14), the residence probability is estimated as 1/2.

**Case.II** This case discusses the CRP estimation (based on ACI, CCI and SS) when the channel has already entered into a particular quality level in the previous interval (sample). It is clear from the Figure 6.2 that the stream space is well adjusted in the available confidence interval and the system may accommodate the complete data stream. However, the value of CRP in the Case.II is less than the CRP value in the Case.I. Consequently, the system is less confident to accommodate the data stream in the Case.II than the Case.I.

**Case.III** This case discusses the CRP estimation upon the arrival of a data stream at the third interval (sample) given the values of ACI, CCI and SS. In this case, the CRP would be further decreased because the likelihood of accommodating the data stream would be more reduced. However, still CRP is positive and may contribute in channel prediction.

**Case.IV** This is a very special case whereby the channel may accommodate a data stream, however the stream has reached at the brink of channel degradation limit as shown in the Figure 6.2. In this case, the CRP is set to zero and would not be a defining factor in the final channel prediction as outlined in Sections 6.4.4 & 6.4.5.

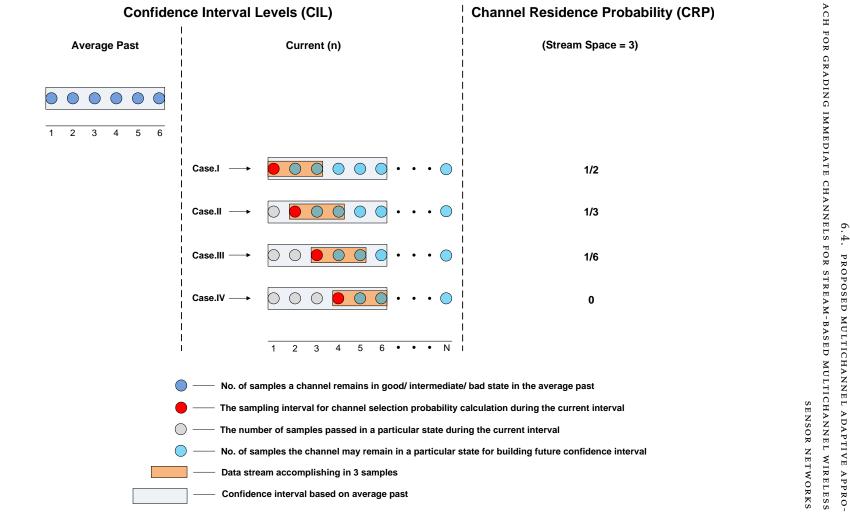


Figure 6.2: Confidence interval based channel selection probability calculation (based on intermediate channel quality level in Fig. 1)

159

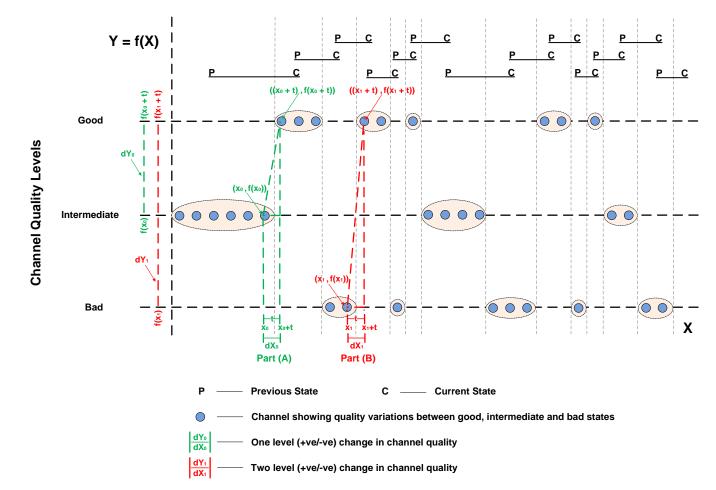


Figure 6.3: Change in channel quality levels Part(A). is showing the change in channel quality from Intermediate to Good level, Part(B). is representing the channel quality change from Bad to Good level

6.4. PROPOSED MULTICHANNEL ADAPTIVE APPRO-ACH FOR GRADING IMMEDIATE CHANNELS FOR STREAM-BASED MULTICHANNEL WIRELESS (4.2. CHANNEL OUTALLIEV TRACKING SENSOR NETWORKS

# 6.4.2 CHANNEL QUALITY TRACKING

Channel Quality Tracking (CQT) determines any change in channel quality when a channel switches from one quality level to the other. At the advent of quality change, the previous quality level of channel becomes the past state (and measure of ACI) whereas the new quality level becomes the current state (and measure of CCI) as shown in Figure 6.3. The change in the quality level may be observed by calculating the slope of tangent line. The equation of line is given by

$$y = mx + c \tag{6.15}$$

Where

$$m = slope = rac{rise}{run} = rac{Change in Y}{Change in X} = rac{dY}{dX}$$

c = y - intercept

Considering the Part(A) of Figure 6.3, the slope of secant line is given by

$$f(x_0) = m_0 = \left| \left( \frac{f(x_0 + t) - f(x_0)}{x_0 + t - x_0} \right) \right|$$
(6.16)

While the slope of tangent line is given by

$$f'(x_0) = \left| \lim_{t \to 0} \left( \frac{f(x_0 + t) - f(x_0)}{t} \right) \right|$$
(6.17)

Likewise for evaluating the Part(B) of Figure 6.3, the slope of tangent line is given by

$$f'(x_1) = \left| \lim_{t \to 0} \left( \frac{f(x_1 + t) - f(x_1)}{t} \right) \right|$$
(6.18)

Since the change in channel quality level may be either positive (when the channel quality is upgraded from low to high quality state as shown in Part(A) & Part(B) of Figure 6.3) or negative (in case the channel quality is degraded from high to low quality state), the absolute symbol is used in Equations (6.16)-(6.18) for determining toggling/switching behavior of a channel.

# 6.4.3 AVERAGE-PAST CONFIDENCE INTERVAL BOOSTING

The channel residence probability is calculated on the basis of sample space and confidence intervals (i.e. average-past and current) as outlined in Equation (6.14). The value of CRP becomes zero when SS reaches the boundary of ACI. However, as a special case a unique condition is considered here for enhancing ACI of a stable channel at a particular quality level entitled as Average-past Confidence Interval Boosting (ACIB). The ACIB is executed when a channel occupying a particular quality level maintains that quality level even after the end of boundary limit of ACI.

Consequently, the confidence that such a stable channel would occupy the prevailing quality level would be further enhanced and ACI of such a stable channel would be doubled. Mathematically, we can write that:

$$\rho_{\chi (avg,cur)} = \begin{cases}
\rho_{\chi (avg,cur)}, & \text{if } \zeta_{\chi} < \rho_{\chi (avg,cur)} \\
\rho_{\chi (avg,cur)} \times 2, & \text{if } \zeta_{\chi} = \rho_{\chi (avg,cur)}
\end{cases} (6.19)$$

#### 6.4.4 CHANNEL QUALITY SMOOTHING

The quality of a channel is the measure of the extent of goodness of a channel at a particular epoch. However, it may be possible for an unstable channel to occupy a highest quality value at a particular epoch. Therefore to handle this issue, this work considers instantaneous value of channel quality (also named current Channel Rank Estimation (CRE) in [4]) and channel stability (entitled as Channel Residence Probability (CRP) in Section 6.4.1) for measuring the extent of goodness of a channel at a particular epoch. Additionally, different ranges of channel quality levels considered in this work are based upon [4] as outlined in Table 6.3 below:

Table 6.3: Channel quality levels

Serial No.	Channel Type	CRE
1.	Good	$0.82 \le to \le 1.00$
2.	Intermediate	$0.33 \le to < 0.82$
3.	Bad	$0 \le to < 0.33$

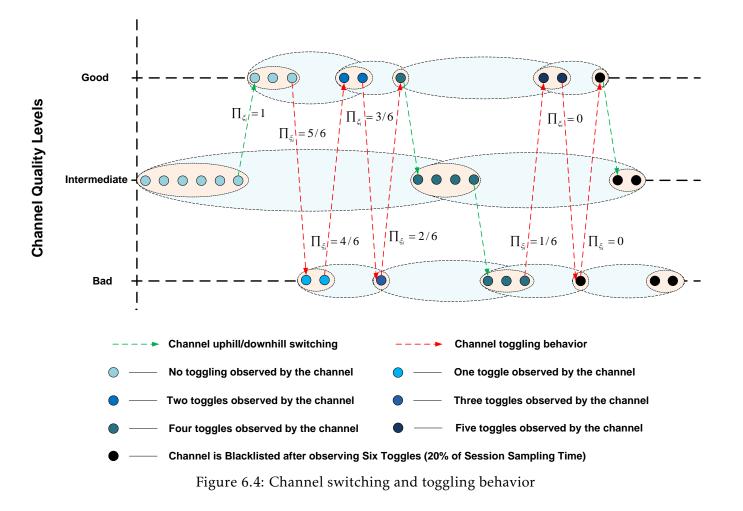
Let,  $\varpi_{\chi}$  is the measure of current quality of a channel at a particular epoch, then channel quality and stability estimation ( $\Psi_{\xi_i}$ ) of channel  $\xi_i$  can be determined by extending Equation (6.14) as given below:

$$\Psi_{\xi_{i}} = \left[\lambda \times \Phi_{\xi_{i}} + (1 - \lambda) \times \varpi_{\chi}\right]$$

$$= \left[\lambda \times \left\{1 - \left(\frac{(\zeta_{\chi} + SS)}{\rho_{\chi \ (avg, cur)}}\right) + \varepsilon\right\} + (1 - \lambda) \times \varpi_{\chi}\right]$$
(6.20)

# 6.4.5 CHANNEL TOGGLING PROBABILITY CALCULATION

Due to environmental impacts, a channel may bounce between good and bad quality levels. Such a quality oscillation is entitled as channel toggling in this work. Besides that the upward/downward jump to a contiguous quality level is termed here as uphill/downhill channel switching. Especially the channel toggling from good to bad quality levels is detrimental for stream-based communication because it may induce data loss (for the remaining portion of data stream). For appropriately handling channel toggling behavior, we have introduced Channel Toggling Probability (CTP) in this work that dynamically calculates the instantaneous toggling behavior of a channel during a communication session.



At the inception of each communication session, the CTP of a channel is maximized (with a value 1). However during each toggle, the CTP of channel is dynamically decremented 10% unless and until the value of CTP reaches zero. Afterwards, the channel would be marked as *blacklisted* and would not be considered for stream-based communication for the ongoing communication session as depicted in Figure 6.4. Let,  $\eta$  be the total number of samples and  $\gamma$  be the blacklisting ratio (set 20% in a communication session), then blacklisting bound  $\beta$  can be calculated as:

$$\beta = \left[\eta \times \gamma\right] \tag{6.21}$$

Let,  $Q_1$ ,  $Q_2$  and  $Q_3$  represents the good, intermediate and bad quality levels and assigned the mark 1, 2 and 3 respectively. Let,  $\alpha_0$  and  $\alpha_1$  are the past and current quality levels of a channel respectively. Let,  $\Upsilon_{\xi_i}$  be the total number of allowed toggles of a channel during a communication session (set equivalent to  $\beta$  at the inception of communication session), then channel toggling probability  $\Pi_{\xi_i}$  of a particular channel can be calculated as:

$$\Pi_{\xi_i} = \left[\frac{\Upsilon_{\xi_i}}{\beta}\right] \tag{6.22}$$

Where

$$\Upsilon_{\xi_i} = \begin{cases}
\Upsilon_{\xi_i} - 1, & \text{if } |\alpha_1 - \alpha_0| = \delta \\
\Upsilon_{\xi_i}, & Otherwise
\end{cases}$$
(6.23)

Where as  $\delta$  is the required value for decrementing  $\Upsilon_{\xi_i}$  (and here  $\delta = 2$ ). On the basis of Equations (6.20) & (6.22), the Channel Selection Index (CSI) represented as  $\Omega_{\xi_i}$  is given by:

$$\Omega_{\xi_{i}} = \Psi_{\xi_{i}} \times \Pi_{\xi_{i}}$$

$$= \left[\lambda \times \Phi_{\xi_{i}} + (1 - \lambda) \times \varpi_{\chi}\right] \times \left[\frac{\Upsilon_{\xi_{i}}}{\beta}\right]$$

$$= \left[\lambda \times \left\{1 - \left(\frac{\zeta_{\chi} + SS}{\rho_{\chi \ (avg, cur)}}\right) + \varepsilon\right\} + \left\{(1 - \lambda) \times \varpi_{\chi}\right\}\right] \times \left[\frac{\Upsilon_{\xi_{i}}}{\eta \times \gamma}\right]$$
(6.24)

By solving the Equation (6.24), we get

$$\Omega_{\xi_{i}} = \left[\lambda - 2\lambda \times \left(\frac{\zeta_{\chi} + SS}{\rho_{\chi \ (avg, prev)} + \rho_{\chi}}\right) + \left(\lambda \times \varepsilon\right) + \left(\varpi_{\chi} - \lambda \times \varpi_{\chi}\right)\right] \times \left[\frac{\Upsilon_{\xi_{i}}}{\eta \times \gamma}\right]$$
(6.25)

Furthermore, the overall flowchart diagram of the system is represented in Figure 6.5.

6.4. PROPOSED MULTICHANNEL ADAPTIVE APPRO-ACH FOR GRADING IMMEDIATE CHANNELS FOR STREAM-BASED MULTICHANNEL WIRELESS SENSOR NETWORKS

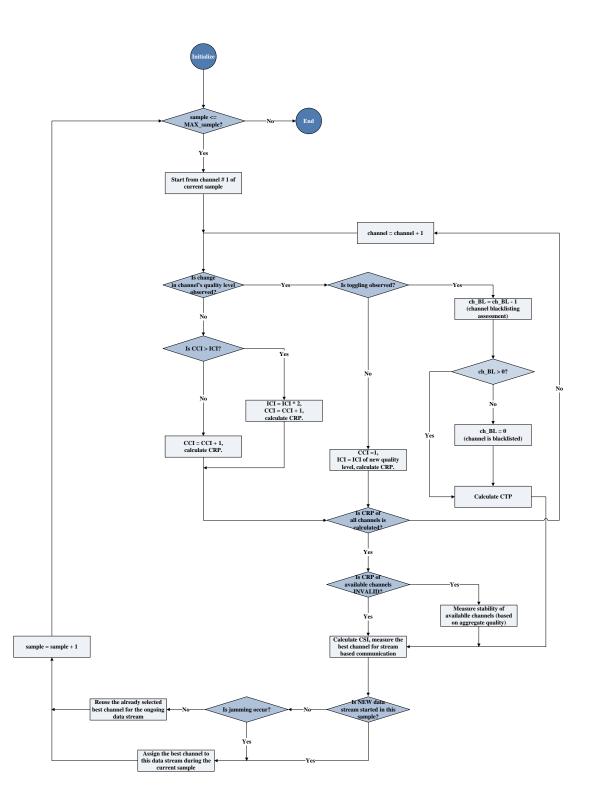


Figure 6.5: Flowchart of the proposed channel prediction architecture

6.4.6 SPECIAL CASES

During the course of channel prediction, two special cases may occur:

- **Special Case.I** When data stream size SS surpasses the boundary limit of ACI, then there may be a likelihood that the channel would degrade before sending the whole data stream.
- **Special Case.II** During the transmission of data stream, there may be a certainty that the channel may suffer from *accidental jamming* due to some environmental issues. If such a channel is not switched, then it may cause complete data loss.

For dealing with the above mentioned special cases, the Equation (6.24) may be modified as:

$$\Omega_{\xi_{i}} = \Psi_{\xi_{i},New} \times \Pi_{\xi_{i}}$$

$$= \left[ \lambda \times \Theta_{\xi_{i}} + (1-\lambda) \times \varpi_{\chi} \right] \times \left[ \frac{\Upsilon_{\xi_{i}}}{\eta \times \gamma} \right]$$
(6.26)

Where

$$\Theta_{\xi_i} = \frac{\sum_{j=1}^{\Delta} \varpi_{\xi_i,j}}{\Delta}$$
(6.27)

Here,  $\Theta_{\xi_i}$  is the measure of channel stability (based on aggregate quality) and is calculated from the start of communication session until the current sample ( $\Delta$ ) is reached. Furthermore, it is evident from the Equation (6.26) that such a channel would be preferred for stream-based communication that exhibits best stability and quality under the CTP constraint  $\Pi_{\xi_i}$  (as discussed in Section 6.4.5).

# 6.5 PERFORMANCE EVALUATION

This section highlights the performance superiority of the proposed MAGIC approach against Enhanced-LRCH [94], Random and Ext-NEAMCBTC [4] protocols. Due to robust channel predictions and avoiding blacklisted channel(s) during stream-based communication, the MAGIC algorithm outperforms its counterparts in terms of channel switching delay, energy consumption and throughput loss. Furthermore, MATLAB [242] is used for performance evaluation and comparison of the proposed MAGIC algorithm with the related approaches.

# 6.5.1 SIMULATION FRAMEWORK

This section summarizes the main features of simulation preliminaries and setup as discussed below:

# 6.5.1.1 SIMULATION PRELIMINARIES

In this work, we have considered three quality levels as outlined in Table 6.3. For achieving more realistic behavior, each channel quality range in Table 6.3 is

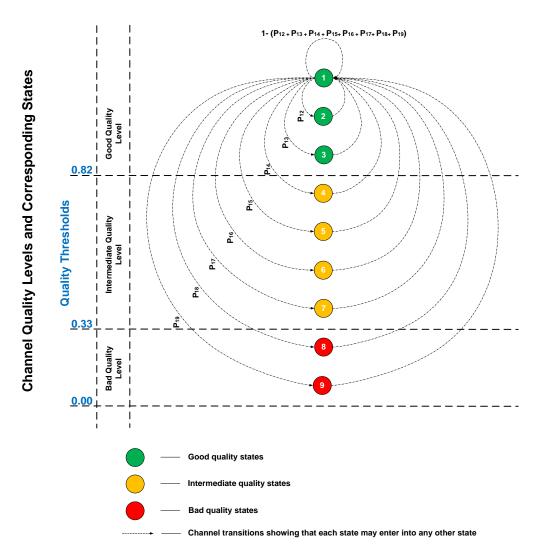
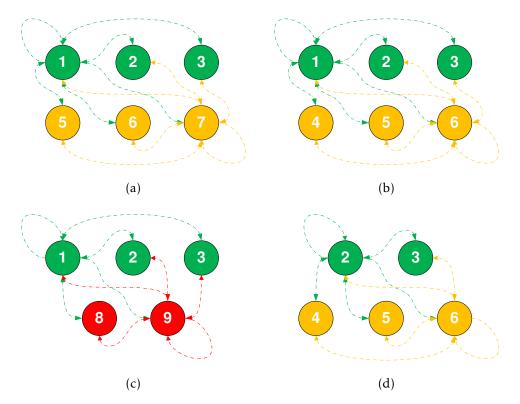


Figure 6.6: Generalized diagram of channel transitions from one state to the other state. For simplicity, only the transitions *from/to* state 1 are depicted here. The quality thresholds are based on Table 6.3.

equally divided into sub-levels called *states*. Doing so, good quality level consists of *states 1, 2 and 3*, intermediate quality level comprised of *states 4, 5, 6 and 7* while bad quality level consists of *states 8, 9* as shown in Figure 6.6. Furthermore in this work, the random behavior of four wireless channels is modeled using discrete time *Markov Chains*. It is evident from the generalized diagram in Figure 6.6 that a channel may move from one to any other state, however for establishing a more diverse scenario, we have restricted the transitions of four channels to distinct states (as shown in Figure 6.7(a-d)) whose behavior is depicted in the Figure 6.8.

# 6.5.1.2 SIMULATION SETUP

In this work, an event based model is assumed where multichannel multimedia sensor node are triggered upon the occurrence of an event in the outside



chapter 6. channel quality and stability estimation: for short-term stable frequencies

Figure 6.7: The quality levels (states) involved in transition of channels 1, 2, 3 and 4 are depicted in Sub-Figures (**a**), (**b**), (**c**) and (**d**) respectively. For simplicity, the transitions *from/to* only two states of each channel are depicted here i.e. (**a**) from states 1 & 7 of channel 1; (**b**) from states 1 & 6 of channel 2; (**c**) from states 1 & 9 of channel 3; (**d**) from states 2 & 6 of channel 4.

environment. Afterwards, the sensed information is sent in the form of data stream to the forwarding node that relays it further and so on till it reaches the sink node. For stream-based communication, it is worthwhile to select such a channel that may accommodate the whole data stream, otherwise sensor node may have to perform channel switching during sending/relaying the data stream. When channel switching is repeatedly performed, then switching delays may occur which may cause extra energy consumption and throughput loss [174]. For handling these issues, MAGIC algorithm is proposed which enables sensor nodes to select such a channel that has the maximum likelihood of accommodating the whole data stream. Furthermore, the performance superiority of MAGIC protocol in terms of channel switching delay, energy consumption and throughput loss is evaluated against the following protocols i.e.

• *Enhanced-LRCH [94]:* This scheme is based on Latin Rectangular based Channel Hopping approach whereby sensor nodes are assigned a schedule for hopping all the channels in a *slot-by-slot* manner. However, neither does a channel repeated before hopping all the non blacklisted channels and nor does two adjoining slots occupy the contiguous frequency. Furthermore following EM-MAC protocol [192], Enhanced-LRCH algorithm [94] also records bad quality channels in the multichannel environment. Moreover, when a channel exhibits bad quality for a definite number of times, then it is marked *blacklisted* for a specific time interval.

- *Random:* This scheme randomly selects a channel from the channel pool at each sample. Being based on random selection, a channel may be repeated for one or more times during the consecutive samples. When a channel of bad quality is encountered, then the sensor node may immediately shift that channel for randomly finding a good quality channel and so on.
- *Ext-NEAMCBTC [4]:* To the best of our knowledge, this is the pioneer work that considers both channel quality and stability for estimating the best channel at each epoch for accommodating stream-based communication in SMWSNs. The protocol has the ability to avoid jammed channels and may improve performance of MWSNs.

The proposed work computes channel switching delay and energy consumption based on the measurements outlined in [121]. For measuring throughput loss, we have assumed the traffic rate of 80kb/sec (as elaborated in the Section 6.5.2.3). Such a data rate is substantially higher than 67kb/sec that is sufficient to accommodate full motion digital video using 100:1 MPEG compression [234].

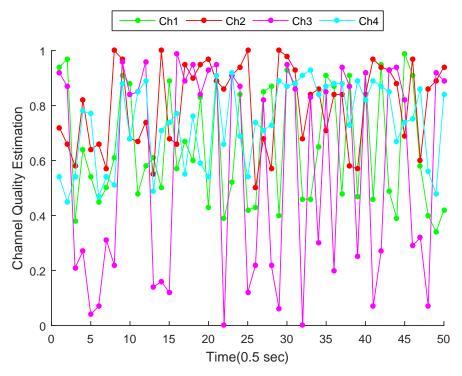


Figure 6.8: Model of four wireless channels.

#### 6.5.2 SIMULATION RESULTS AND DISCUSSION

In this section we have discussed channel switching delay, energy consumption and throughput loss during the transmission of data stream as calculated by MAGIC algorithm and the counterparts. A stream size of three is considered during all these simulations. Since Random algorithm was exhibiting quite a varying results, therefore we have run it 500 times for getting the approximate values of channel switching delay, energy consumption and throughput as explained in Sections 6.5.2.1, 6.5.2.2 and 6.5.2.3 respectively.

# 6.5.2.1 CHANNEL SWITCHING DELAY

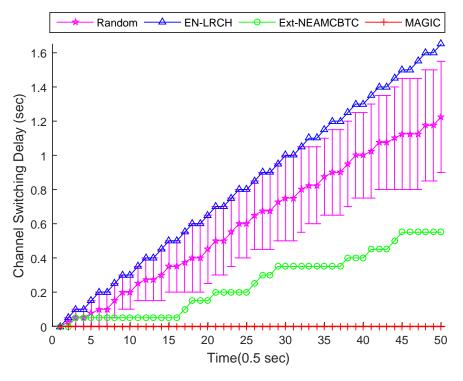
Channel switching delay  $(T_{ChSw})$  is the aggregate of time consumed in calibrating receiver  $(T_{CalRx})$ , transmitter  $(T_{CalTx})$  and subsequently restarting radio  $(T_{RR})$  [121] given by

$$T_{ChSw} = T_{CalRx} + T_{CalTx} + T_{RR}$$
(6.28)

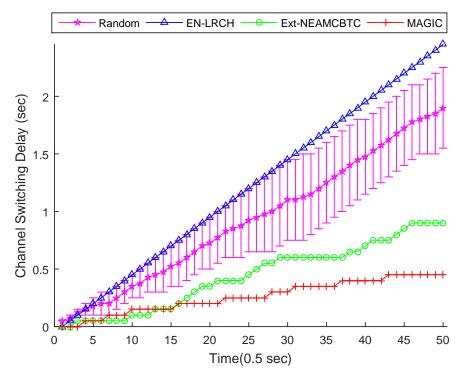
Based upon the calculations in [121], the channel switching delay  $T_{ChSw}$  is approximated as 50 ms in our experiments. Furthermore, a decrease in channel switching delay  $T_{ChSw}$  may reduce the overall end-to-end delay. Below, we will discuss two aspects of  $T_{ChSw}$  in our simulations.

Intra Stream Switching Delay (T<sub>ChSw,Streaming</sub>): Switching wireless channels during the transmission of data streams may increase switching delay in WSNs. Once a data stream is completed, then  $T_{ChSw,Streaming}$  is calculated for the next stream and so on. From Figure 6.9(a), it is clear that MAGIC algorithm does not suffer from any channel switching delay during the transmission of data stream. It is because, it employs a confidence interval based procedure for selecting the best quality stable channel that may accommodate the whole data stream (as discussed in Section 6.4). The Ext-NEAMCBTC algorithm [4] is based on selecting the best channel at particular epoch. However upon encountering a data stream spanning over many samples, the Ext-NEAMCBTC algorithm [4] may induce channel switching when the best channel at current epoch is different from the next sample. Consequently, channel switching delays are induced during the transmission of data stream as observed in Figure 6.9(a). Furthermore, unlike MAGIC algorithm, Ext-NEAMCBTC protocol [4] does not dynamically reduce the selection probability of those channels that may suffer from repetitive toggling during the communication session. Henceforth, when a noisy channel shows good behavior for a short interval of time, then their likelihood of selection at a particular epoch may be increased which however, may induce channel switching if the noisy (instable) channel exhibits poor performance in the immediate future. As a result, channel switching delay is increased.

Both the Enhanced-LRCH [94] and the Random algorithms exhibit higher channel switching delays than the counterparts as depicted in Figure 6.9(a) and 6.9(b). Although the Random algorithm shows a varying behavior of switching delays as evident from the error bar graph in Figure 6.9(a). However, its mean switching delay is less than the switching delay of Enhanced-LRCH protocol [94]. It is because Random algorithm does not suffer from



(a) During data stream transmission



(**b**) During the communication session. Figure 6.9: Channel switching delay assessment.

channel switching when the channel at a particular epoch is both of sufficient quality and same as the previous interval. Whereas the Enhanced-LRCH approach [94] is *Latin Rectangular* based and switches channel in a sample-by-sample manner. Unlike the Random algorithm, the Enhanced-LRCH protocol [94] implements a static blacklisting mechanism akin to EM-MAC protocol [192]. Consequently, it may blacklist a channel exhibiting bad quality for a specific number of times during a communication session.

• Intra Session Switching Delay  $(T_{ChSw,Session})$ : It is the aggregate of channel switching delays (both during and between the transmission of data streams) until the communication session is ended. Based upon Figure 6.9(b),  $T_{ChSw,Session}$  of MAGIC algorithm is the lowest among all the protocols. This delay is only due to channel switchings between the individual data streams because MAGIC algorithm effectively handles channel switching delay during the transmission of data streams. The  $T_{ChSw,Session}$  of MAGIC algorithm is followed by Ext-NEAMCBTC protocol [4] which experiences channel switching delays both inter and intra stream-based communication in WSNs as depicted in Figures 6.9(b) and 6.9(a) respectively. Being based on randomness in channel selection, the Random algorithm is showing varying behavior in terms of  $T_{ChSw,Session}$  as evident from error bar in Figure 6.9(b). Furthermore, switching delay experienced by the Enhanced-LRCH protocol [94] is the highest among all counterparts as shown in the Figure 6.9(b).

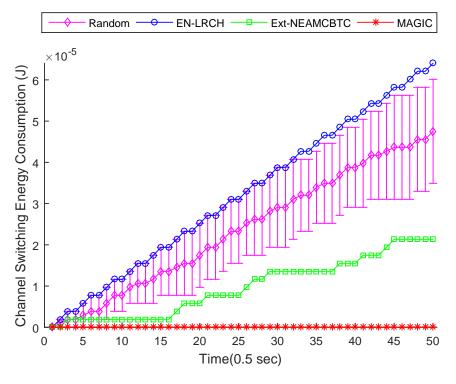
#### 6.5.2.2 CHANNEL SWITCHING ENERGY CONSUMPTION

Due to limited energy resource, energy conservation is one of the important goals of MWSNs. Apart from the conventional causes of energy consumption, the MWSNs may consume extra energy during channel switching. Too frequent channel switchings may decrease the lifetime of sensor nodes, therefore multichannel sensor nodes may switch wireless channels in a controlled manner for energy conservation and network lifetime maximization. Channel switching energy consumption ( $E_{ChSw}$ ) is the aggregate of energy consumed in calibrating receiver ( $E_{CalRx}$ ), transmitter ( $E_{CalTx}$ ) and subsequently restarting radio ( $E_{RR}$ ) [121] given by

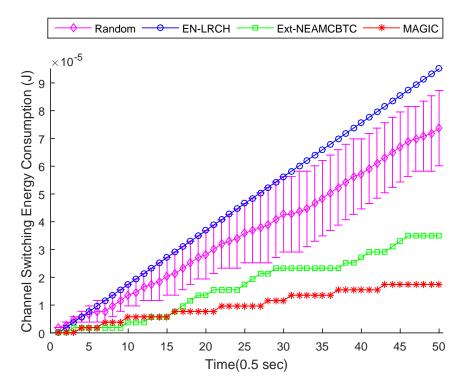
$$E_{ChSw} = E_{CalRx} + E_{CalTx} + E_{RR} \tag{6.29}$$

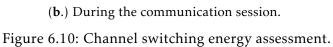
On the basis of measurements in [121], the channel switching energy consumption  $E_{ChSw}$  is approximated as 1940 nJ in our experiments. Here below,  $E_{ChSw}$  is discussed under the two special cases.

• Intra Stream Switching Energy Consumption  $(E_{ChSw,Streaming})$ : Channel switching during the transmission of data streams may enhance energy consumption of sensor nodes. It is evident from the Figure 6.10(a) that  $E_{ChSw,Streaming}$  of MAGIC algorithm is the lowest among the compared protocols. It is because, MAGIC algorithm implements a confidence interval based procedure for selecting the best among the available channels for accommodating a data stream spanning over many samples. In this way, it may avoid channel switchings during the transmission of data stream and thereby conserves energy as shown in the Figure 6.10(a). Being based on dynamic blacklisting



(a.) During data stream transmission





173

procedure, the MAGIC algorithm may avoid less reliable channels that may suffer from channel toggling and thereby conserves energy in SMWSNs. The Ext-NEAMCBTC algorithm [4] consumes more energy for switching wireless channels than the MAGIC algorithm as depicted in Figure 6.10(a). It is due to the fact that rather than calculating the channel for the whole data stream (spanning over many samples), the Ext-NEAMCBTC algorithm [4] determines the best channel at a particular epoch and thereby it may suffer from channel switch and associated overheads during the transmission of data stream. Furthermore, it may even select those channels for stream-based communication that apart from frequent toggling show better behavior at a particular epoch. Consequently, more channel switchings may occur during the transmission of data stream which may enhance switching energy consumption.

The channel switching energy consumption of Random algorithm is comparatively better than the Enhanced-LRCH protocol [94]. It is mainly due to the fact that unlike Enhanced-LRCH protocol [94] that is hopping channels sample by sample (based on Latin Rectangular approach), the Random algorithm does not perform channel hopping if the channel used in the current sample is randomly selected again during the future sample. Besides that, being based on random approach, the switching energy consumption of Random algorithm shows a varying behavior that is evident from the error bar in the Figure 6.10(a). However, it is clear from the Figure 6.10(a) that mean switching energy consumption of the Random algorithm is better than the Enhanced-LRCH protocol [94] that is showing the highest energy consumption than the counterparts.

• Intra Session Switching Energy Consumption ( $E_{ChSw,Session}$ ): It is the sum of channel switching energy consumption during inter and intra stream-based communication in MWSNs. From the Figure 6.10(b), it is clear that channel switching energy consumption during the communication session of MAGIC algorithm outmatches all the counterparts. It is because MAGIC algorithm does not suffer from any intra channel switching energy consumption during the transmission of data stream. However, it may suffer from intra stream switching energy consumption because adjacent streams may be assigned different channels for communication in MAGIC algorithm. Since Ext-NEAMCBTC algorithm [4] may suffer from both intra and inter stream energy consumption, therefore its channel switching energy budget is greater than the MAGIC algorithm. Furthermore, the mean channel switching energy budget of Random algorithm is better than the Enhanced-LRCH protocol [94] as evident from the performance graph in Figure 6.10(b).

# 6.5.2.3 CHANNEL SWITCHING THROUGHPUT-LOSS

Switching a wireless channel takes 50ms(approx) for calibrating transmitter/receiver and subsequently restarting radio [121]. During the channel switching interval, a sensor node cannot transmit a data stream, therefore throughput loss may occur e.g., when data rate is 80 kb/sec, then channel switching delay may cause a throughput loss of 4 kb. For handling channel switching based data loss, a sensor node should minimize channel switchings as much as possible. In the following discussion, we will consider two aspects of throughput loss (due to channel switching) during stream-based communication in MWSNs i.e.

- *Complete throughput-loss:* It occurs when a sensor node switches to a bad quality channel and stays there during the sampling interval. Consequently, data stream is lost during that interval. It is calculated as 40 kb as depicted in the Figure 6.11.
- *Partial throughput-loss:* It takes place during the switching interval when a sensor node jumps from one channel to the other. It is measured as 4 kb as shown in the Figure 6.11.

It is evident from the Figure 6.11, that MAGIC algorithm does not experience any throughput loss because it may not switch channels during the transmission of data stream. However, in the worse case, if accidental jamming may occur (on a channel) during the transmission of a data stream (please refer to Section 6.4.6), then the MAGIC algorithm may switch channel and thereby may suffer from partial throughput loss while avoiding complete throughput loss in MWSNs. The Random algorithm may experience *partial* throughput loss only. It is because whenever it encounters a bad quality channel, then it immediately performs channel switching due to a recovery procedure. Such a channel decision may be taken again and again until a sensor node switches to a good quality channel. Afterwards, the remaining data stream (during the particular interval) is transmitted on the selected channel. Since Random algorithm always switches frequency upon encountering a bad quality channel, therefore it may not suffer from complete throughput loss (until all the channels exhibit bad quality and the protocol is unable to perform stream-based communication during the particular sampling interval).

The Ext-NEAMCBTC algorithm [4] may experience both partial and complete throughput loss for transmitting a data stream during a sampling interval as depicted in the Figure 6.11. The partial throughput-loss is caused due to switching a wireless channel when the best channel during the next epoch is different from the best channel during the current sample. The complete throughput loss is executed when instantaneous abnormal distortion (called channel toggling in this work) is observed (please see sample 22 in Figure 6.8 where channel quality changes from good to bad and then good quality level). Although Ext-NEAMCBTC algorithm [4] devises a mechanism for suppressing such instantaneous abnormal distortions from the environment because they may affect the prediction capability of memory based protocols for WSNs [4]. However due to this suppressing mechanism, it may experience *complete* throughput loss during the suppressed intervals. Furthermore in case of frequent channel toggling, there may be a likelihood of selecting the poor quality channels correspondingly for stream-based communication that may enhance *complete* throughput loss in MWSNs. Unlike the Random algorithm, the Ext-NEAMCBTC protocol [4] does not outline any recovery procedure for dealing with complete throughput loss in MWSNs. However, if Ext-NEAMCBTC protocol [4] does not encounter any channel toggling, then it may not suffer from *complete* throughput loss. Consequently, its throughput behavior would be better than the Random algorithm.

In case of Enhanced-LRCH approach [94], the Latin Rectangular based channel

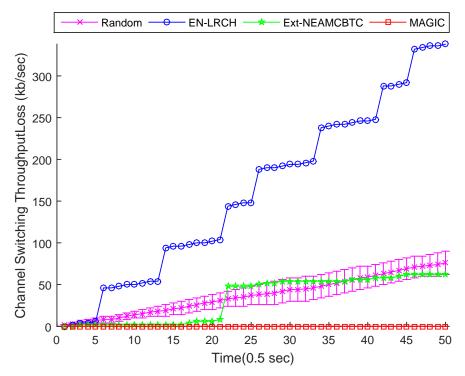


Figure 6.11: Channel switching throughput loss assessment.

hopping procedure allows sensor nodes to switch channels continuously for dealing with both internal and external interference. During the process of channel switchings, any channel exhibiting bad quality again and again is blacklisted and afterwards not considered for a specific interval. Such a *static blacklisting* mechanism does not prevent a sensor node from avoiding a channel exhibiting bad behavior until the channel is marked as blacklisted and therefore may induce throughput loss. It is evident from the Figure 6.11 that Enhanced-LRCH approach [94] may suffer from both *complete* and *partial* throughput loss. Here, complete throughput loss is occurred due to selection of a bad quality channel at a particular epoch for stream-based communication e.g. as evident from the Figure 6.8, channel 3 exhibits bad quality during a variety of intervals. Upon selection of channel 3 during those intervals would induce complete throughput loss. On the other hand, *partial* throughput loss is caused during each streaming interval because Enhanced-LRCH approach [94] performs channel hopping from one sample to other. Furthermore, upon blacklisting a bad channel during the communication session, the *complete* throughput loss is dealt with in the Enhanced-LRCH algorithm [94].

# $_{\text{chapter}}$ 7

# QOS-AWARE CROSS-LAYERED MULTICHANNEL MULTISINK ROUTING

# 7.1 INTRODUCTION

Upon sensing an event in the area of interest, a sensor node forwards it towards data gathering point (aka sink node) in a hop-by-hop manner. When the information is received at sink node, then the network information system may analyze the corresponding event for appropriate decision making. Normally, for transmitting the scalar data, there does not require any strict Quality of Service (*QoS*) requirements than for transmitting the vector data. It is due to the fact that vector data is delay sensitive and requires high bandwidth and reliability for meaningful information delivery. Such stringent *QoS* requirements are very challenging to meet using the conventional strategies such as single-channel and single-sink/path based routing methodologies.

A vast majority of conventional Wireless Sensor Networks (WSNs) use single channel for routing the scalar and vector data across the network (e.g. AntNet [28] and TPGF [77] etc). Since single channel strategy may allocate the same channel to neighboring nodes, therefore it may not afford parallel transmission. Consequently, the nodes in the interference range may wait for their turn to perform communication or contend for the single channel for data transmission, which may enhance network delay. Furthermore, the nodes transmitting simultaneously (on the single channel) in the interference range may contribute to network interference and inevitably network reliability is adversely affected. Besides that, the network operation may even be halted when the single operational frequency suffers from jamming. With the advancements in technology, the researchers have realized that multichannel methodology may provide a reasonable solution to the above mentioned issues and therefore it is better than single channel approach [6]. Moreover, multichannel methodology may effectively enhance the performance of WSNs by ensuring parallel communication, high throughput, less delay and fresh data delivery [6] [81]. The multichannel WSNs may suffer from some quality-related issues such as link stability problem [81], channel switching overhead, interference, broadcast support and so on [6] [81], however such issues may be handled by appropriately designing the multichannel routing protocol.

Traditional WSNs have one data gathering point called sink (aka destination). When either a relevant node in the vicinity of sink or the sink node itself suffers from any critical issue, then network performance may be degraded. One among these issues is congestion that may be caused due to increased data rate in the sink neighborhood. Another issue, may be single point of failure of a related node or even sink, occurring due to energy depletion or channel jamming issues. These issues may adversely affect the performance of WSNs and unfavorably impact QoS oriented data delivery. A reasonable solution to the above mentioned issues is to employ multisink approach that may increase data gathering points. The multisink approach may avoid the congestion problem near sink and circumvent the single point of failure issue in WSNs [132]. Furthermore, multisink approach performs load distribution across sensor network and achieves energy balancing around sink node [32] and therefore network lifetime is extended [35]. Since multisink methodology enhances network throughput [35], henceforth it is suitable for high data rate applications such as stream based communication in WSNs. However, finding the cost effective end-to-end path between source and sink(s) is one of the main issues to be coped with in multisink WSNs [32].

It is clear from the above discussion that both multichannel and multisink methodologies may improve the performance of WSNs. Therefore, to get the benefits of both worlds, this work proposes a reactive *QoS*-aware Multichannel Multisink Routing protocol (*QCM2R*) for WSNs. *It is noteworthy that this chapter is predominantly based on our under review article [5]*. The main properties of QCM2R algorithm are outlined below:

- The proposed protocol establishes *QoS*-aware paths between source and sinks upon the occurrence of an event in the region of interest.
- The proposed protocol selects the best *QoS*-aware path at a particular epoch for end-to-end data delivery. Furthermore, it may dynamically shift the path for ensuring *load balancing* between the available routes during the communication session.
- The proposed protocol executes distributed channel assignment jointly with routing. The channel allocation may be performed in a manner to possibly perform two-hop channel orthogonality.
- The proposed protocol administers a channel refresh mechanism for reassigning wireless channels to the path(s) experiencing a *bad channel event* on one or more links.

The rest of this chapter is organized as follows. The Section 7.2 discusses literature review and motivation. In Section 7.3, proposed network model is

outlined. The Section 7.4 elaborates the proposed solution in a detailed manner. In Section 7.5, the performance evaluation of the proposed protocol is delineated.

# 7.2 LITERATURE REVIEW AND MOTIVATION

Due to multichannel multisink nature of the proposed solution, this section considers a variety of multichannel and multisink routing approaches for WSNs. The multichannel routing approaches may be classified into JOINT Channel Assignment & Routing (JCAR) and DISJOINT Channel Assignment & Routing (DCAR) based categories [6]. However, this work considers only JCAR based multichannel routing strategies. In a nutshell, our literature review consists of three main segments.i.e.

- Firstly, we would briefly discuss various JCAR based routing approaches as examined in our multichannel routing survey [6]. For the sake of completeness, we have also examined some new JCAR approaches that are not discussed in [6].
- Secondly, we would consider various multisink routing techniques for WSNs. To the best of our understanding, the existing JCAR based multichannel routing literature is deficient in multisink based routing approaches.
- Thirdly, based upon the *discussions* and *conclusive remarks* of Sections 7.2.1 and 7.2.2, we would outline a reasonable *motivation* in Section 7.2.3.

# 7.2.1 JOINT CHANNEL ASSIGNMENT & ROUTING BASED AP-PROACHES

As discussed earlier, this section briefly describes those strategies that are already discussed in-detail in our review article [6]. Furthermore, some new multichannel routing techniques are also discussed here namely RM-MAC [166], MCMIMO [120], MCRP [173], LQ-CMST + PCA-MC [98], MOR [211] and ABORt [84]. The classification and summary of JCAR based multichannel routing approaches is given below.

#### 7.2.1.1 SINGLE PATH MULTICHANNEL ROUTING PROTOCOLS

The single path multichannel routing protocols consist of two categories i.e single-radio and multiradio based.

• Single-radio based routing protocols: The single radio based routing approaches may suffer from channel switching overhead in terms of switching energy consumption, delay and throughput loss due to heavy traffic across network. As per [6], they include three dynamic channel assignment based techniques (i.e. DRCS [174], GBCA-G [110], and CNOR [186]) and five hybrid channel allocation oriented approaches (i.e. MCC [224], RBCA [149], DRM-MAC [147], RPIRM [202], and RMCA-FR [126]). In the end of this section, some new approaches are also elaborated that were not discussed in [6]. Among them, two approaches perform dynamic frequency allocation (i.e. RM-MAC [166] and MOR [211]), two techniques execute semi-dynamic channel assignment

(i.e. LQ-CMST + PCA-MC [98] and MCRP [173]) and one protocol performs static frequency allotment (MCMIMO [120]).

The DRCS [174] protocol selects the forwarding channel based on batterypower and Expected Transmission Count (ETX), whereas forwarding node is determined considering the least ETX-oriented path vector. This approach achieves load balancing and deals with interference and overhearing. The protocol may suffer from control overhead due to periodic broadcasts on the available channels. The GBCA-G [110] is a geographic multichannel routing protocol where channel assignment is based on dynamic Topology Information and Routing Information (TIRI). The protocol exhibits high packet delivery ratio and less latency. However, it necessitates enormous broadcasts for advertising node location and channels which may cause energy and control overhead. The authors in CNOR [186] have proposed an opportunistic routing and channel access technique for WSNs. It involves selecting an available channel and performing RTS-CTS-DATA-ACK based four way handshake with node closer to sink node. The protocol achieves high throughput, low delay and energy efficiency. However, the protocol may experience delay and energy overhead, in case of unavailability of a receiver on the selected channel. Moreover, four way handshake is costly to execute in energy constrained WSNs.

In MCC [224], each node broadcasts around hundred packets for constructing the conflict and connectivity graph. Based on this information, a balanced routing tree is established. The protocol considers a centralized time synchronization as well as channel assignment mechanism allocating non-interfering channels to nodes in conflict graph for countering interference. The protocol attains high throughput and energy efficiency, however broadcasting hundred packets per node may cause extra energy consumption and may add to network collision. The authors in RBCA [149] have proposed a tree based algorithm that is based upon building a routing tree centered at sink node and assigning different channels to nodes for countering interference and decreasing the schedule length. The protocol achieves performance improvement by reducing network collisions, however it may suffer from latency and energy consumption due to building long degree constrained routing trees. In DRM-MAC [147], nodes are assigned ranks based on sink broadcasts. The relay node would be the highest energy node from a randomly selected rank for achieving fair energy utilization and load balancing. The Request-to-send (RTS) and Clear-to-Send (CTS) based frequency negotiation and reservation may help in handling interference. The protocol achieves high throughput and less delay, however randomly determining low-quality rank may add to delay and may decrease throughput. Moreover, RTS-CTS-ACK oriented negotiation causes control overhead when data packet is small sized.

The RPIRM [202] protocol involves selecting the best path, determined while considering the overall link and delivery cost of the available routes. The on-path sender node selects the channel concordant with the receiver node. Although, the protocol is energy efficient and achieves high throughput. However being based on aggregation based metric, it may select a route having poor-quality link(s) or low-energy node(s) that may degrade network

performance. The authors in RMCA-FR [126] have proposed a duty-cycle enabled distributed protocol which involves constructing a routing tree and assigning levels to nodes based on hop count distance from sink. The channel assignment considers graph coloring approach whereby non-interfering nodes are assigned the same channel while interfering/adjoining nodes are allocated different (if not available then least interfering) frequency for handling interference. In case of node failure, a recovery procedure is adopted for maintaining communication. The protocol is energy efficient and handles network collisions. However, frequency cooperation between parent and child nodes is not properly elaborated.

In [166], each node employs a pseudorandom channel hopping strategy for selecting a receiving channel during each time slot. Each time slot is further divided into sub-slots whereby receiving sub-slot is based on hop count distance from sink node. Afterwards, the sender having knowledge of receiving channel and sub-slot of corresponding receiver may easily communicate with it. The protocol employs a ripple based broadcast mechanism to forward the broadcast packets to multi-hops and alleviates broadcast storm issue. The channel hopping mechanism may handle control overhead and interference. The protocol my allow the upstream nodes to wake-up chronologically on the sub slots for decreasing the end-to-end delay. However, it may repeatedly experience channel switching overhead in a slot-by-slot manner. In [211], sensor nodes perform fast channel hopping in a slot-by-slot manner. Whereas sink node carries out slow channel hopping whereby a channel is allocated for multiple consecutive time slots. When a node is interested in sending data, then it checks channel as per rendezvous order. If a channel is available, then it anycast data packet on it which is acknowledged (ACK) by the receiver rendezvous on the similar channel. If no ACK is received, then sender attempts again, till a timeout is reached and the packet is sent later on. The protocol may handle interference and achieves reliability, low delay and energy efficiency. It relies on a rendezvous sequence of three channel that are orthogonal to WiFi, however any interference/jamming on these channels may seriously affect the protocol performance in terms of throughput loss, energy consumption and delay.

In [98], a minimum-hop spanning tree is constructed centered at sink node, in a manner that the price of sub-tree construction is limited by the allowed capacity. The maximum interfering parent is assigned a channel, if available. Otherwise, interference is dealt with in the time slot allocation stage. During the process of time slot assignment, the active nodes sharing time slot and channel with conflicting nodes are assigned a time slot one-by-one. The protocol considers traffic prioritization whereby real-time packets are sent first followed by non real-time and best effort packets. The protocol reduces network delay, however it may suffer from scalability issue. The time slots assignment to active (in-conflict) nodes may initiate lengthy schedules when the conflicts are high due to dense environment or heavy traffic load. Building lengthy schedules may increase delay and is not suitable for real-time delay sensitive applications. In [173], initially a tree topology is setup and stabilized by the RPL protocol. Afterwards, Low Power Border Router (LPBR) adopts a 2-hop graph coloring strategy for assigning dissimilar channels to 2-hop neighbor nodes. The channel switching mechanism is responsible for announcing the switching decision of LPBR to a node. The node informs neighbors about the new channel and switches to it for checking its quality using probe messages. If successful then channel is adopted while otherwise old channel is selected again. The decision is announced to LPBR and neighbors. The protocol achieves high throughput. The 2-hop channel coloring approach enables MCRP to avoid interference and to achieve load balancing among wireless channels. However, channel probing may add to control overhead and interference.

In [120], each sensor node locally broadcasts its remaining energy and estimated hop count distance from sink on the default frequency. A sensor node exhibiting the best weight (based on current energy and average hop count distance from 1-hop neighborhood) is selected as Cluster Head (CH). The neighboring CH(s) negotiate on default frequency for selecting the best MIMO link. For avoiding network collision, both the adjoining clusters and MIMO links are assigned dissimilar channels. The protocol achieves energy efficiency and high throughput, however it may suffer from control overhead too. The CSMA/CA based contention mechanism may cause single sink bottleneck issue in case of high data rate applications [3] and may add to congestion and end-to-end delay that is not suitable for real-time data delivery.

• *Multiradio based routing techniques:* The multiradio based approaches may increase the hardware-cost/complexity, however they may also enhance network performance too [6]. As per [6], four such methodologies are discussed including one dynamic channel assignment based (i.e. OR+SCP [164]) and three hybrid frequency allocation oriented (i.e. ICADAR [96], CRDAR [97] and MMOCR [151]).

In OR+SCP [164], the QoS path is chosen based on either lowest delay or smallest transmission/reception energy. The protocol involves identifying such on-path links that are transmitting simultaneously. Afterwards, they are assigned different channels for lowering the schedule breadth which may decrease path latency. Selecting minimum delay based path may induce energy holes issue while minimum transmission/reception energy oriented route may experience more delay. In ICADAR [96], the end-to-end path(s) building is initialized starting from sink node. Afterwards, the channel assignment is performed in the direction from source to sink, so that no two adjacent on-path nodes occupy the same channel. When the aggregate link weight exceeds a limit, then the path is marked unusable. The transmission expenditure of protocol is less than competitors, however being iterative it may experience more delay and energy consumption. The CRDAR [97] initially builds a routing tree and afterwards channels are assigned firstly to source node with less hop count than with more hop count from sink. The protocol diminishes transmission expenditure. The MMOCR [151] protocol involves Route Request (RREQ) broadcasts towards sink followed by Route Reply (RREP) unicasts to source. Among these RREPs, the least hop count RREP from sink establishes the end-to-end route. The sender selects the

forwarding channel (having least interference) and broadcasts data packet on it which is ACKed by the forwarding receiver. Although ACK broadcast prevents data duplication, however it increases control overhead for small sized data packets. Being unaware of residual energy of sensor nodes, the protocol may experience energy holes issue.

# 7.2.1.2 MULTI PATH MULTICHANNEL ROUTING PROTOCOLS

The multi path multichannel routing protocols may be categorized into singleradio and multiradio based approaches.

• *Single-radio based routing approaches:* As per [6], one dynamic frequency allocation based (i.e. SEA-OR [187]) and one hybrid channel assignment based (i.e. QoS-aware [140]) approach is discussed. Besides that, an additional hybrid approach (i.e. ABORt [84]) is also elaborated that was not discussed in [6].

The SEA-OR [187] protocol involves a dynamic mechanism of shrinking and expanding the routes based on residual energy of sensor nodes and frequency availability. Data communication involves selecting the best channel & link and sending RTS packet which is responded with CTS by the best receiver. The protocol achieves good PDR and energy efficiency, however it experiences control overhead due to handshaking mechanism. Additionally, it may experience data loss or delay due to unavailability of receiver on the selected frequency. In QoS-aware [140], disjoint end-to-end paths are built where sensor nodes are allocated different time slot/frequency based on Mutually Orthogonal Latin Square (MOLS) approach. The protocol allows each node to measure queuing delay of various traffic classes which may enable sink to perform bandwidth adjustment of real-time traffic while allocating minimum bandwidth to non real-time traffic. A waiting time priority approach is used that considers packet priority and waiting time in a queue for dequeuing data packets for transmission. The protocol attains high throughput, low delay and avoids congestion by dropping non-QoS data packets. However, it is unreliable being not devising any mechanism for retransmitting the dropped data packets. The MOLS approach may prevent the runtime frequency allocation latency and interference. However, it cannot avoid those channels that are degraded at runtime.

In [84], initially neighbor discovery is performed repeatedly on common channel, so that a node may get knowledge of up-to 3-hop neighbors. Afterwards, the smallest-id node in 3-hop neighborhood selects and announces (possibly) a unique channel, followed by the next-id node and so on till all the nodes are assigned the wireless channels. Each node may calculate its local queuing delay and consequently path delay metric for sending data towards sink. Data packet forwarding involves selecting a receiver randomly from a top-list and shifting to its receiving channel for achieving load balancing. When queue occupancy reaches a threshold level, then the receiver sends an alert message, so that the transmitter may select an alternate node for communication. The protocol achieves high PDR and less end-to-end delay. However, it is not scalable natured. Additionally, it involves repeated ACK transmissions for calculating end-to-end path delay that may enormously increase the control overhead.

• *Multiradio based routing protocols:* As per [6], only one static frequency allocation based protocol is discussed (i.e. Distributed-CA [117]). The Distributed-CA [117] broadcasts HELLO messages in neighborhood for network discovery. Here, sink advertises HOP message, so that sensors may know about hop count distance from sink. Afterwards, frequencies are allocated cyclically in two-hop neighborhood starting from sink node. Moreover, least-used channels are assigned to sensor nodes that are not allocated frequencies so far. The protocol is scalable natured. It may experience throughput loss and interference due to inter/intra-cluster communication on the same channel.

# 7.2.1.3 CONCLUDING REMARKS

To the best of our knowledge, we can deduce the following inferences based on the extensive literature review in Section 7.2.1.

- The existing JCAR literature mainly focuses on single-path based multichannel routing protocols. However, a few multipath based routing approaches are also proposed such as SEA-OR [187], QoS-aware [140], ABORt [84] and Distributed-CA [117]. Among them, only Distributed-CA [117] employs multiradio technology for communication.
- A variety of JCAR protocols employ some channel assignment strategy for countering interference such as RBCA [149], RMCA-FR [126], LQ-CMST + PCA-MC [98], RM-MAC [166], MOR [211], OR+SCP [164], QoS-aware [140], ABORt [84] and Distributed-CA [117]. Likewise, ICADAR [96] prevents adjoining on-path nodes to employ the same channel. Similarly, MCRP [173] uses a 2-hop graph coloring approach for allocating distinct frequencies to 2-hop neighbors. To the best of our knowledge, we have not found any JCAR based mutichannel routing protocol that may distributedly assign the best wireless channels in a link-by-link manner along with maintaining the 2-hop channel orthogonality, for reducing interference and ensuring reliable communication in WSNs.
- Apart from the static and dynamic channel assignment based protocols, the semi-dynamic channel assignment requires channel assignment in a periodic or event-based manner [3]. An event may either be *target detection* & *recognition* in the region of interest (requiring JCAR based end-to-end path establishment) or the occurrence of *bad channel event* on one or more on-path links (requiring an on-demand channel refresh mechanism for the path concerned). However, to the best of our knowledge, no JCAR based multichannel routing protocol is found that employs semi-dynamic channel assignment strategy for on-demand dealing with a variety of events as stated above.

# 7.2.2 MULTISINK ROUTING PROTOCOLS

In this section, a variety of multisink approaches are outlined based on static data gathering points (sinks). A brief description of the operation and characteristics

of these approaches is outlined below:

In P-NLB protocol [132], each node gets knowledge about neighborhood and the hop count distance from sink. Each sink gets information (and afterward disseminates) about the number of nodes connected to it and the other sinks. Subsequently, sensor nodes may take decision about switching their parents, for balancing the network. Initially, a parent may decide the neighbor pool. Afterward, routing metric is applied on the neighbors of least hop count for selecting the best parent node. Furthermore, each node selects such a time slot for communication that is not used in the two hop neighborhood which may counter interference. The protocol is scalable, has less communication overhead and uniformly distributes traffic load among sinks. However, an increase in the number of time slots (allocated to large number of nodes in neighborhood) may enhance latency and decrease the data rate.

GLOBAL protocol [206] involves each sink to periodically flood ADVertisement messages (ADV) at network initialization, for constructing the gradient field. A node receiving the first ADV message considers the corresponding path as the shortest and calculates the gradient based on cumulative Residual Energy Depletion Rate (REDR) and maximum REDR. Afterward, it rebroadcasts the ADV packet. If the hop count of duplicate ADV is under the acceptable range, then new gradient is calculated. It updates the old gradient, if new gradient is less than the old one. Consequently, the link (more broadly path) is updated in the direction of ADV sender. Furthermore during data communication, the gradient field should be refreshed dynamically for accommodating changes in the traffic load distribution. The protocol aims at lifetime maximization of WSNs. Unlike, most gradient based protocols, it may experience less control overhead due to updating the gradient field during data communication.

GRATA protocol [130] involves flooding advertise packets (ADVER) from sink nodes during the network initialization. When ADVER packet is received for the first time or hop count of duplicate ADVER message is less than the stored value (for the corresponding sink), then a receiving node stores the relevant information before rebroadcasting the ADVER packet. When ADVER message of equal hop count is received, then no ADVER rebroadcast is performed. However, the sender node is stored as sibling and traffic cost is kept in the traffic information table. A sender interested in sending a data packet calculates the gradient indexes of neighbor nodes and selects minimum gradient index node as the forwarding node towards the relevant sink and so on. Periodically broadcasting ADVER packet may increase control overhead. Taking the gradient index decision for forwarding each data packet increases delay and processing overhead in WSNs. The protocol does not outline any mechanism for preventing the nodes in two-hop neighborhood from transmitting simultaneously which may induce interference and data loss.

MLBRF protocol [46] uses geographic routing whereby each sensor nodes has the location of its neighbors and sink node. Each sender selects the forwarding node among its neighbors in a manner that the forwarder lies at least distance from sink and has the minimum buffer occupancy. Afterwards, data (i.e. video frame) moves in the direction of corresponding sink and congestion is avoided. Normally, the destination for a particular frame is determined at source node. However, when the routing class of a sensor node changes before forwarding a multimedia frame, then the destination of multimedia frame is updated accordingly. The MLBRF protocol may achieve load balancing, energy efficiency and reliability in video sensor networks. Since, the dynamic sink selection in MLBRF does not consider the load towards sink node, therefore the protocol may send frame towards the heavily loaded sink which may add to congestion. Being geographic based, MLBRF protocol requires Global Positioning System (GPS) and/or localization system which may increase the H/W cost. Subsequently, network energy consumption may be enhanced.

EORA protocol [47] avoids low energy nodes and performs load balancing among sinks for handling energy imbalance in WSNs. It builds a hybrid virtual potential field based on hop count and residual energy of sensor nodes. It is because the hop count based virtual potential field selects the shortest endto-end forwarding path and may cause an imbalance in energy consumption. Whereas residual energy based virtual potential field may select the next hop of high energy that may either cause unreliability in data delivery to sink node or induce the selection of routing loops. Therefore, hybrid virtual potential field would achieve reliable and energy efficient data delivery in WSNs. When the average energy of sink neighbors is reduced, then data is sent to alternate sinks for achieving load balancing in WSNs.

DTAR protocol [85], each sink broadcasts ADVertising packet (ADV) during network deployment which informs a receiver about hop count distance from sink and buffer occupancy of 1-hop and 2-hop neighbors. The receiver rebroadcasts the ADV packet after marking sender as parent, incrementing the hop count and updating the buffer occupancy of 1-hop and 2-hop neighbor nodes. When ADV packet of less hop count is received, then sender is marked as parent. Subsequently, hop count and buffer occupancies are updated. After receiving a duplicate ADV packet of equal or high hop count, the sender is marked as sibling or child node. When a node is interested in sending/forwarding a data packet, then it calculates the gradient of neighbor nodes. Afterwards, minimum gradient node is selected as the receiver. The protocol claims to avoid congested nodes and improves delivery ratio, network life-time while reducing delay. It may suffer from control overhead because each node may broadcast ADV packet either regularly (during light traffic load) or on-demand (during heavy traffic load). The protocol does not prevent 2-hop neighbors to transmit simultaneously which may add to congestion and interference in 2-hop neighborhood.

ERAM protocol [18] operates in the three steps. The first step involves backbone formation whereby sensor nodes in a neighborhood work together to form clusters. In the second phase, routing tree is built based on local knowledge in a manner to perform load balancing. The sink node is at level 0. The levels are incremented in the ascending manner towards the leaf nodes. A node may communicate with such a precursor that provides least distance to nearest sink and has less children. The third phase involves data transmission to cluster head which may communicate with other clusters through intermediate nodes and so on till the data is delivered to the sink node. The protocol follows a

recovery strategy for dealing with any lost connections. The proposed scheme reduces energy consumption and delay. It may suffer from interference when the nodes in the two-hop neighborhood may send data simultaneously on the same channel. Allowing three times retransmission may add to congestion in a bottlenecked network.

In REBTAM [35], a multisink routing protocol is proposed for object tracking in WSNs. The protocol initially involves sink broadcasts for informing network nodes about their hop count distance from sink. A sensor node receiving a broadcast packet of less/equal hop count considers the corresponding sender as a possible relay node for data forwarding. Upon the occurrence of an event, source node broadcasts a control packet towards each sink. After getting sink reply, the source may identify the least energy on-path node and minimum hop count towards the corresponding sink. Subsequently, the source may determine the best sink. Once sink is identified, then source node (and eventually all the forwarders) employ a broadcast-acknowledgment mechanism (for locally determining the forwarding node with the best cost) before sending each data packet towards the preferred sink node. The protocol achieves energy efficiency, reliability, high throughput and low congestion. However, it may suffer from enormous control overhead during data transmission. Such a control overhead may add to energy consumption, congestion, collision and throughput loss in case of high data rates. Additionally, determining the forwarding node before each data packet transmission may enhance end-to-end delay too.

#### 7.2.2.1 CONCLUDING REMARKS

On the basis of discussion in Section 7.2.2, we can outline that:

- To the best of our knowledge, the existing multisink routing approaches employ single channel for communication. Being based on single channel approach, the multisink protocols (such as [130] [85] [18]) may readily suffer from interference, when the nodes in two-hop neighborhood may transmit simultaneously.
- Assigning a unique slot to two-hop neighbor nodes [132] may assist in countering interference. However, due to increase in network density in two-hop neighborhood, the number of time slots may also increase accordingly. Consequently, network latency may be increased and throughput may be decreased. Therefore, there is a need to employ technologically advanced solutions for multisink WSNs that may enable the two-hop neighbor nodes to communicate in parallel manner without compromising on their performance.
- Majority of the multisink approaches [132] [206] perform static sink assignment while some perform dynamic sink selection [46]. Therefore, there is need to devise more robust multisink strategies for WSNs that may dynamically perform QoS-aware sink assignment for ensuring *load balancing* between the available sink nodes.

CHAPTER 7. QOS-AWARE CROSS-LAYERED MULTICHANNEL MULTISINK ROUTING

# 7.2.3 MOTIVATION

To the best of our knowledge and based on the *discussions* and *concluding remarks* in Section 7.2.1 and 7.2.2, we are motivated to outline and brainstorm the following issues:

- The conventional JCAR based multichannel routing protocols has single data gathering point (i.e. based on single sink methodology). Consequently, they may more readily drain the energy of sensor nodes in the vicinity of sink in comparison to multisink approaches. Due to single point of failure and congestion, the single sink approaches are not very suitable for the mission critical applications. Furthermore, the communication towards a single data gathering point may be interrupted with less effort, requiring technologically robust solutions for securing wireless communication. For the purpose of high performance communication, there is a need to devise JCAR protocol(s) employing multisink technology in WSNs.
- The traditional multisink approaches for WSNs employ a single channel for communication. Using single channel is not ideal for mission critical environment that requires high data rate and more secure communication for WSNs. The performance of multisink protocols may be further improved by employing multichannel methodology, allowing neighbor nodes to communicate in a parallel manner for improving throughput, delay, and delivery ratio while ensuring energy efficiency (by handling overhearing) in WSNs.

As a concrete solution of the above mentioned main issues and those outlined in Section 7.2.1.3 and 7.2.2.1, a multichannel multisink routing protocol is devised entitled as *QoS*-aware Multichannel Multisink Routing protocol (*QCM2R*) and aiming at high performance communication in stream based multichannel WSNs. The network model and operation of the proposed *QCM2R* protocol are discussed in Sections 7.3 and 7.4 respectively.

# 7.3 PROPOSED NETWORK MODEL

This section discusses system model of the proposed *QoS*-aware Cross-layered Multichannel Multisink Routing protocol (*QCM2R*) as explained below:

The proposed network may be modeled as a digraph G(V, E) consisting of a set of vertices  $V = \{n_i/i = 1, 2, 3, ..., N\}$  and edges  $E = \{e_k/k = 1, 2, 3, ..., M\}$ . Each edge  $e_k$  is bidirectional and bridging two vertices (aka sensor nodes)  $n_p$  and  $n_q$  where  $(n_p, n_q) \in V$ . All the sensor nodes are multichannel multimedia sensor enabled. The network has multiple data gathering points called destinations (or equivalently sink nodes) represented as  $SK = \{D_j/j = 1, 2\}$ . All the sensor nodes have equal communication range and use omni-directional multi radios for communication. Let, *IF* is a set of radios, then  $IF = \{R_r/r = 1, 2\}$ . The sink nodes have unlimited resources and are connected to a common backbone. Therefore, the information arrived at any sink would be available to the back-end system. Besides that, the proposed system may be deployed for surveillance of sea shores or border areas. The QCM2R protocol is based upon the following assumptions:

- The sensor nodes are assumed to harvest energy and recharge their batteries in parallel. It may counter the *energy holes issue* occurred due to complete energy depletion of sensor nodes in WSNs. Furthermore, when the energy of a sensor node decreases than a threshold level (i.e. 10% of initial energy or 30 *Joule* in this work), then it may harvest energy continuously till reverting to normal state.
- Each sensor node is assumed to employ two radios for communication. The radio R<sub>1</sub> would be *half-duplex* and dedicated for sending/receiving control information. Whereas the radios R<sub>2</sub> would be *full-duplex* and employed for sending and receiving surveillance data simultaneously. However, each sink node employs unlimited *full-duplex* radios for communication.
- Being based on IEEE 802.15.4 technology in 2.4 GHz band, the proposed system may use 16 non-overlapping channels [167] for communication namely channels 11 to 26. However among these channels, only four channels (i.e. 15, 20, 25 and 26) are non-overlapping with the operational frequencies of channels 1, 6 and 11 of IEEE 802.11 [241]. Therefore, the proposed system is assumed to select the best among these four channels for control traffic communication. Such a control channel decision may be taken before each communication session using either Ext-NEAMCBTC [4] or MAGIC [1] algorithm.
- The proposed system may use fifteen channels for data communication. However in this work, we assume that each node may periodically update six locally preferable channels (assumed to be three good and three intermediate quality) employing either Ext-NEAMCBTC [4] or MAGIC [1] algorithm. Furthermore, each adjoining on-path node pair is assigned the best common channel selected among their locally preferable channels. Moreover, the best common channel is assigned in a manner that it may possibly ensure 2-hop orthogonality or otherwise 1-hop orthogonality or at-least non-orthogonality for least possible streaming the surveillance information, as discussed in Algorithm 5 and Section 7.4.2.1. Additionally, a channel refresh mechanism is also employed for dealing with bad channel events on the on-path wireless link(s) as elaborated in Section 7.4.2.3.
- The proposed system is assumed to be reactive like Ad hoc On-Demand Distance Vector (AODV) Routing strategy and gets a reasonable impression from AODV path setup approach. Like AODV protocol, QCM2R also establishes an *end-to-end* path dynamically between source and destinations whenever an event is occurred in the surveillance region. However, contrary to AODV protocol, the proposed QCM2R protocol may follow a *divide-&-conquer* strategy for selecting the preferred neighbor during the *Qos-aware* path establishment. Besides that, the routing paths are both node & link-disjoint.
- The proposed system achieves *load balancing* both b/w the communication paths and among the wireless channels, during the communication session. The *load balancing* b/w the communication paths is accomplished by dynamically selecting the preferred route for delivering the surveillance information. Whereas fair *load balancing* among the wireless channels is attained by possibly avoiding the *channel reuse* in the 2-hop neighborhood that may counter interference too.

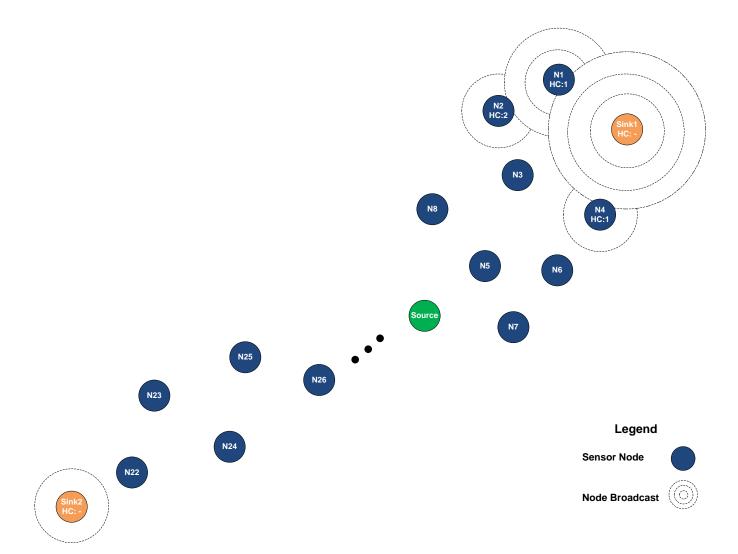


Figure 7.1: SAP Message Broadcast from Sink 1 (aka Destination 1)

# 7.4 PROPOSED QOS-AWARE CROSS-LAYERED MUL-TICHANNEL MULTISINK ROUTING PROTOCOL FOR STREAM-BASED WSNS

This section discusses in detail the proposed QoS-aware cross-layered multichannel multisink routing protocol for stream based WSNs. Here, firstly a brief operational overview of the proposed QCM2R protocol is delineated (in Section 7.4.1) and afterwards various modules are briefly discussed (in Section 7.4.2). Besides that, the relevant diagrams are depicted in Figures 7.1–7.7 and the algorithms are shown in Figures 7.8–7.11.

# 7.4.1 QCM2R: A BRIEF OPERATIONAL OVERVIEW

The proposed QCM2R protocol is a reactive multichannel routing protocol where, upon the occurrence of an event, node-link-disjoint paths are established between source and the available destinations. Afterwards, those paths are maintained during the communication session. Each source dynamically shifts between the available routes for balancing the network load and avoiding congestion in the network. Furthermore, QCM2R dynamically updates channels on a path, whenever a bad channel event is occurred on an on-path link.

At the network initialization or communication session expiration time, a Sink Advertisement Packet (*SAP*) is broadcasted by each destination  $D_{j/j=1,2}$  and forwarded by the intermediate nodes after incrementing hop count, so that all the sensor nodes may get hop count ( $hc_{(D_j)}$ ) distance from the corresponding destinations  $D_{j/j=1,2}$ . When an event is occurred, then a Route Request packet (*RREQ*) is broadcasted from the corresponding Source *S* to each destination  $D_{j/j=1,2}$ . Each forwarding node of *RREQ* would be decided among the neighbors that are not reserved for any path. The selection of forwarding node is based on the combined metric of hop count (from the corresponding destination) and residual energy (of the forwarding neighbor). Each sender transmits its preferred local channels along with *RREQ* message, so that the receiver may get knowledge about them. Additionally, preferred local channels are determined based on Ext-NEAMCBTC [4] or MAGIC [1] algorithm.

When a *RREQ* packet is arrived at the corresponding destination, then Route Reply packet (*RREP*) is initiated and unicasted on the reverse route. Each sender of *RREP* calculates the best common channel with the corresponding receiver of *RREP* by either possibly maintaining the channel orthogonality criteria (i.e. preferably 2-*hop* or otherwise 1-*hop* orthogonality) or just nonorthogonality criterion for affording the possible wireless communication. When a *RREP* packet is arrived at the corresponding source, then end-to-end path is established between the related source and destination. Similarly, end-toend path is established between the source and all the available destinations. During the course of sending *RREP*, each destination also initiates path statistics information on the reverse route towards the source. This information is helpful in deciding the best among the available routes for data delivery, once all the paths are setup initially. Afterwards, the Path Statistics packets (*PS*) are also sent periodically by each destination for the purpose of load balancing (among

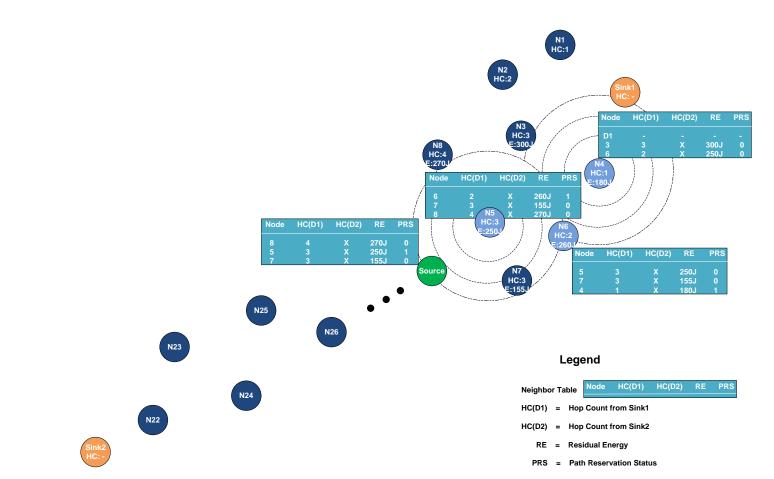


Figure 7.2: Hello Messages Broadcasts for Updating hop count, Residual Energy and Path Reservation Status of Sensor Nodes

Pkt (Id)	Pkt Architecture	Pkt Description
RREQ (0x02)	Packet Size: 37bytes. Packet Fields: Type/8bits, Hop count/8bits,	The RREQ packet is broadcasted from Source <i>S</i> to each destination $D_{j/j=1,2}$ .
	Broadcast ID/32bits, Nexthop/8bits, Reserved/48bits, Destination	When a preferred intermediate node receives a RREQ packet, then it
	IP/32bits, Destination seqno/32bits, Source IP/32bits, Source	establishes a reverse route with the sender and rebroadcasts the packet
	seqno/32bits, Time stamp/64bits	& so on till RREQ packet is arrived at the corresponding destination.
RREP (0x04)	Packet Size: 61bytes. Packet Fields: Type/8bits, Hop count/8bits,	The RREP packet is unicasted from the destination $D_{j/j=1,2}$ to Source
	Reserved/24bits, Destination IP/32bits, Destination seqno/32bits,	S in response to the received RREQ packet. Upon receiving a RREP
	Source IP/32bits, Lifetime/64bits, Time stamp/64bits, Residual	packet, each receiver establishes a forwarding route with the corres-
	energy/64bits, Hop count to sink/16bits, Sink load/8bits, Path	ponding sender till RREP packet is arrived at Source $S$ and end-to-end
	total energy/64bits, Path min energy/64bits, Node reservation/8bits	path is established.
SAP (0x14)	Packet Size: 7bytes. Packet Fields: Type/8bits, Hop count/8bits, Broadcast ID/32bits, Sink Id/8bits	Each destination broadcasts a SAP message which is forwarded by
		intermediate nodes. SAP provides hop count distance from the
		available sink nodes or destinations.
PS (0x16)	Packet Size: 20bytes. Packet Fields: Type/8bits, Hop count/8bits, Sink load/8bits, Path total energy/64bits, Path min energy/64bits, Bad channel event/8bits	The PS packets is sent periodically on the reverse path from each
		destination to the source node. It helps source node to switch to
		the best among the available routes for end-to-end data delivery
		and maintaining load-balancing across the network.
RPCREQ	Packet Size, Thytee Packet Fields, Type/Ohite Deserved /49hite	The RPCREQ packet is sent on demand from Source $S$ to destination
(0x22)	Packet Size: 7bytes. Packet Fields: Type/8bits, Reserved/48bits	$D_{j/j=1,2}$ , when bad channel event occurs on one or more on-path links.
RPCREP	Packet Size, Abytes, Packet Fields, Type/Obits, Deserved/24bits	The RPCREP packet is sent in response to RPCREQ packet from the
(0x24)	Packet Size: 4bytes. Packet Fields: Type/8bits, Reserved/24bits	corresponding destination $D_{j/j=1,2}$ towards the Source S.
CTSIG (0x26)	Packet Size: 1byte. Packet Fields: Type/8bits	The CTSIG packet is sent in response to RPCREP packet from Source S to
		the corresponding destination $D_{j/j=1,2}$ . It tunes wireless radios of the
		corresponding on-path nodes with the fresh channels.

# Table 7.1: Overview of QCM2R Control Packets

the available routes) during the communication session.

During data communication, a Bad Channel Event (BCE) may occur due to poor performance of a wireless link. When a source gets knowledge about the occurrence of a  $BCE_{(D_i)}$  on a path towards  $D_{j/j=1,2}$ , then it sends Refresh Path Channel Request packet (RPCREQ) to the corresponding destination on the forwarding route. Each *RPCREQ* packet encapsulates the fresh local preferred channels of the related sender node. When RPCREQ packet is arrived at the corresponding destination  $D_{j/j=1,2}$ , then each on-path node may get information about the local preferred channels of its previous node. Afterwards, the Refresh Path Channel Reply packet (*RPCREP*) is initiated and sent on the reverse path towards the corresponding source. Before sending the RPCREP packet, each sender of *RPCREP* calculates the best common channel with the corresponding receiver by either possibly maintaining channel orthogonality criteria (i.e. preferably 2-hop or otherwise 1-hop orthogonality) or just non-orthogonality criterion for affording the possible wireless communication. When RPCREP packet is arrived at the corresponding source node, then a Channel Tune Signal (CTSIG) is sent on the forwarding route towards the corresponding destination. The *CTSIG* packet tunes the wireless radios of each node with the refreshed frequencies.

It is clear from the above discussion that the proposed QCM2R protocol employs seven control messages, namely *SAP*, *RREQ*, *RREP*, *PS*, *RPCREQ*, *RPCREP* and *CTSIG*, for its operation. A brief description of these packets is outlined in the Table 7.1. In the next section, a concise discussion of various modules of the proposed QCM2R protocol is delineated.

# 7.4.2 QCM2R: A COMPENDIOUS MODULAR OVERVIEW

QCM2R protocol has four main modules namely Path Setup Module (*PSM*), Preferred Path Selection Module (*PPSM*), Channel Tuning Module (*CTM*) and Data Communication Module (*DCM*). Normally, each main module is composed of a variety of sub modules as elaborated below.

# 7.4.2.1 PATH SETUP MODULE

*PSM* is the main module of the proposed QCM2R protocol. It includes six submodules namely Sink Advertisement Packet (*SAP*), Hello message, Next Hop Selection approach (*NHS*), Route Request packet (*RREQ*), Route Reply packet (*RREP*) and Best Common Channel Selection strategy (*BCCS*). The *pseudocode* of these submodules is depicted in the Figures 7.8 and 7.9. Here below, a brief overview of each sub-module is delineated.

*i).* Sink Advertisement Packet: It is broadcasted by each destination  $D_{j/j=1,2}$  (or sink node) either at the network initiation or communication-session-termination time as shown in Figure 7.1. Upon receiving a valid *SAP* message, each intermediate node updates its hop count  $hc_{(D_j)}$  distance from the corresponding sink node. Afterwards, it increments the hop count value before rebroadcasting SAP and so on till all the nodes in the network receive *SAP* message. Consequently, each node may get knowledge about its hop count distance from the related sink

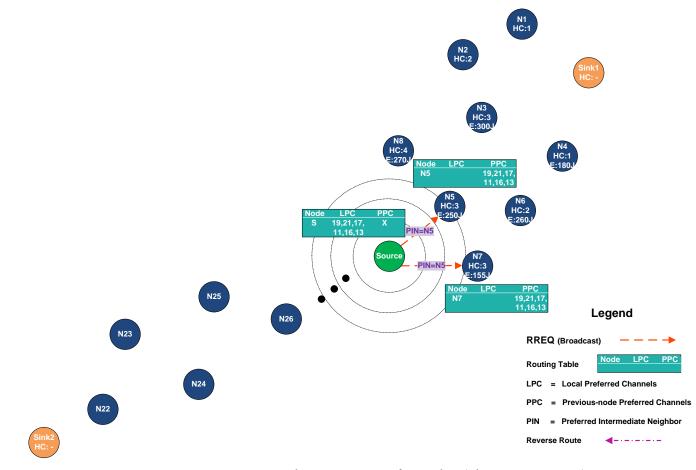


Figure 7.3: RREQ Broadcasts at Source for Sink 1 (aka Destination 1)

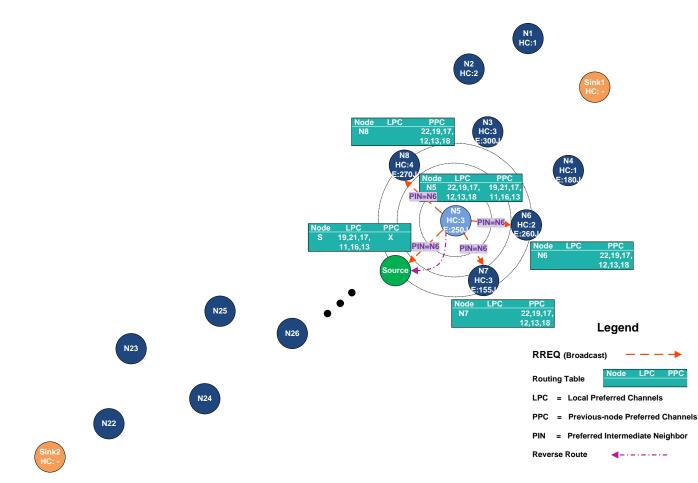


Figure 7.4: Preferred intermediate neighbor rebroadcasts RREQ for Sink 1 (aka Destination 1)

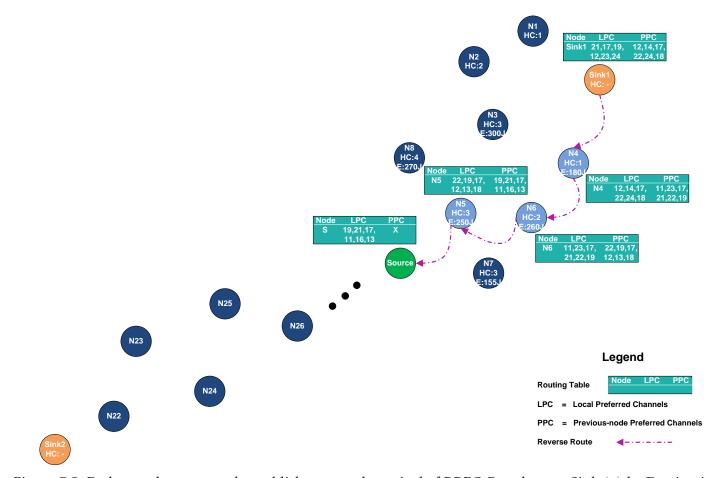


Figure 7.5: End-to-end reverse path establishment at the arrival of RREQ Broadcast at Sink 1 (aka Destination 1)

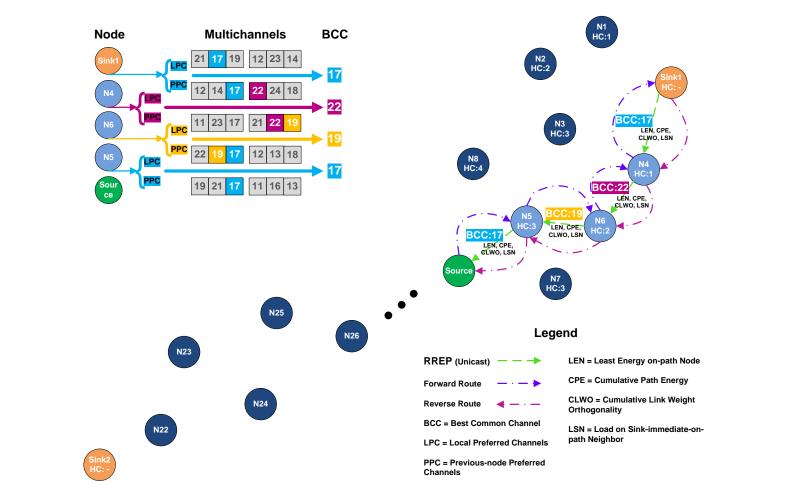


Figure 7.6: RREP Unicasts from Sink 1 (aka Destination 1) to Source and simultaneous execution of BCCS Mechanism at each on-path node

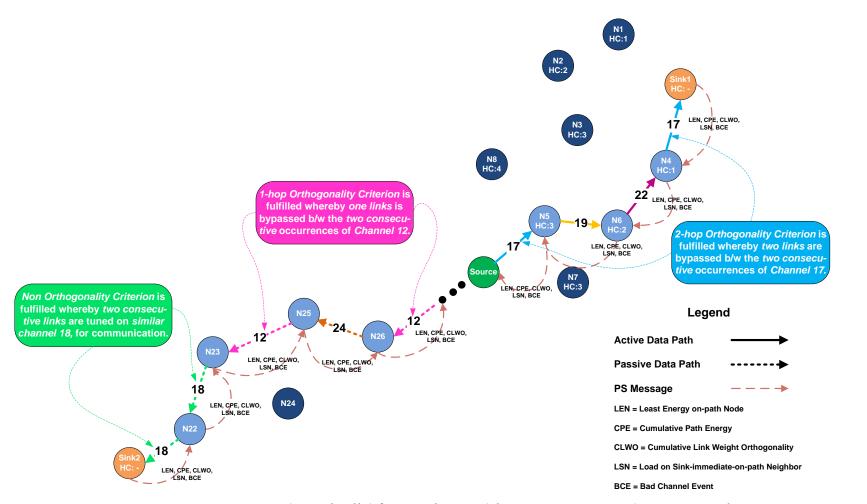


Figure 7.7: PS transmission (periodically) from Sink 1 & 2 (aka Destinations 1 & 2) to Source node

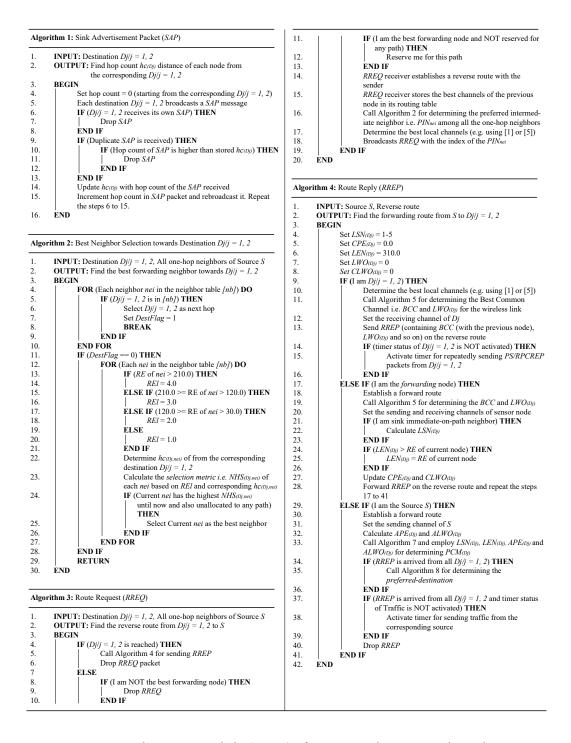


Figure 7.8: Path Setup Module (*PSM*) of QCM2R: depicting Algorithms regarding Sink Advertisement Packet (*SAP*), Next Hop Selection (*NHS*), Route Request message (*RREQ*) and Route Reply message (*RREP*).

nodes. Since each node prefers least hop count distance from the corresponding destinations, therefore, only the incoming *SAP* with less hop count updates the stored hop count value (from the corresponding sink node) and would be marked as a valid *SAP* packet.

*ii*). *Hello message:* It is broadcasted periodically by each neighbor in its vicinity. The Hello message informs receiver about the Residual Energy ( $RE_{(nei)}$ ), hop count ( $hc_{(D_j,nei)}$ ) distance (from the available destinations  $D_{j/j=1,2}$ ) and Path Reservation Status ( $PRS_{(nei)}$ ) of the corresponding neighbor as depicted in Figure 7.2. These values (i.e.  $RE_{(nei)}$ ,  $hc_{(D_j,nei)}$  and  $PRS_{(nei)}$ ) are used in the next hop selection.

Residual Energy-level (REl)	<b>Residual Energy</b> ( <i>RE</i> )
4	<i>RE</i> > 210.0
3	210.0 >= RE > 120.0
2	120.0 >= RE > 30.0
1	30.0 >= RE

Table 7.2: Energy Levels during NHS

*iii). Next Hop Selection:* Starting from a source, each RREQ sender determines the Preferred Intermediate Neighbor  $(PIN_{(nei)})$ , prior to broadcasting RREQmessage towards the corresponding destination. For this purpose, the sender node initially considers those neighbors which are not reserved for any path, as a prerequisite for establishing node-link-disjoint paths. Afterwards, the neighbor exhibiting the highest  $NHS_{(D_j,nei)}$  (for the corresponding destination  $D_{j/j=1,2}$ ) is selected as the  $PIN_{(nei)}$ . Let, *R* and *A* represent the set of reserved and available nodes respectively for a path. Mathematically, we can write that

$$V = R \cup A \tag{7.1}$$

Where

and

 $R = \{x \mid x \notin V \cap A\}$  $A = \{y \mid y \notin V \cap R\}$ 

Let, [nb] denotes the set of unreserved neighbors of a node. Moreover, it is assumed that there would always be some neighbors that are not assigned to any path, for creating node-link-disjoint paths. Mathematically, it can be written as

$$[nb] = \{z \mid z \in A \text{ or } z \notin R\} \text{ s.t. } [nb] \neq \emptyset$$

$$(7.2)$$

On the basis of hop count distance of sender and neighbor nodes from corresponding destination  $D_{j/j=1,2}$  (i.e.  $hc_{(D_j,sen)}$  and  $hc_{(D_j,nei)}$ ) and Residual Energy-level of the neighbor node  $(REl_{(nei)})$ , the NHS metric of each neighbor  $(NHS_{(D_j,nei)})$  may be calculated as:

$$NHS_{(D_{j},nei)} = \left[\frac{hc_{(D_{j},sen)} - hc_{(D_{j},nei)} + 1}{hc_{(D_{j},nei)}}\right] \times 2^{\{REl_{(nei)}\}-1}$$

$$= \left[\left\{\frac{hc_{(D_{j},sen)} + 1}{hc_{(D_{j},nei)}}\right\} - 1\right] \times 2^{\{REl_{(nei)}\}-1}$$
(7.3)

Where

$$j = 1, 2$$

The, preferred intermediate neighbor may be determined mathematically as

$$PIN_{(nei)} \stackrel{\wedge}{=} \max_{nei \in [nb]} \{ NHS_{(D_j, nei)} \}$$
(7.4)

The NHS metric has three main properties i.e. firstly, it may enable sender to prefer such a forwarding neighbor that lies either less or same distance from the corresponding destination. In this way, it may avoid the occurrence of *routing loops* in the network. Secondly, it may allow sender to prefer next hop neighbors of high *RE* and would avoid the creation of early *network holes* in the sensor network. Thirdly, it may allow sender to consider those neighbors which are not reserved for any path and would make possible the establishment of node-link-disjoint end-to-end paths for communication.

*iv).* Route Request packet: When network is activated due to the occurrence of an event in the vicinity, then source node initiates end-to-end path setup with the available destinations. For this purpose, a *RREQ* packet is sent by the corresponding source in the similar fashion as does by the Ad hoc On-demand Distance Vector routing protocol (AODV). However unlike AODV where all the receivers broadcast *RREQ* packet, the *RREQ* packet of the proposed QCM2R protocol is re-broadcasted only by the preferred intermediate node (as shown in Figures 7.3 and 7.4). Following this, *RREQ* packet is finally reached at the desired sink node and end-to-end reverse path is established between the corresponding sink and source node as depicted in Figure 7.5.

Before broadcasting *RREQ*, each sender performs two operations i.e. (i)– It consults its neighbor table for calculating the preferred intermediate neighbor based on *NHS metric* as discussed above. (ii)– It calculates its Local Preferred Channels (*LPC*) based on some algorithms such as [4] or [1]. Afterwards, the sender broadcasts *RREQ* along with *LPC* and *PIN<sub>nei</sub>* (as shown in Figure 7.3). Upon receiving *RREQ* message, the preferred intermediate neighbor initially performs two operations i.e. (i)– It establishes a reverse route with the sender. (ii)– It locally stores wireless channels of the sender as Previous-node Preferred Channels (PPC). Afterwards, the preferred intermediate neighbor also calculates *LPC* and *PIN<sub>nei</sub>* for re-broadcasting *RREQ* and so on (as depicted in Figure 7.4). In this way, *RREQ* travels *hop*–*by*–*hop* till it reaches the corresponding destination and an *end*–*to*–*end* reverse path is established as illustrated in Figure 7.5.

### 7.4. proposed Qos-Aware cross-layered multichannel multisink routing protocol for stream-based wsns

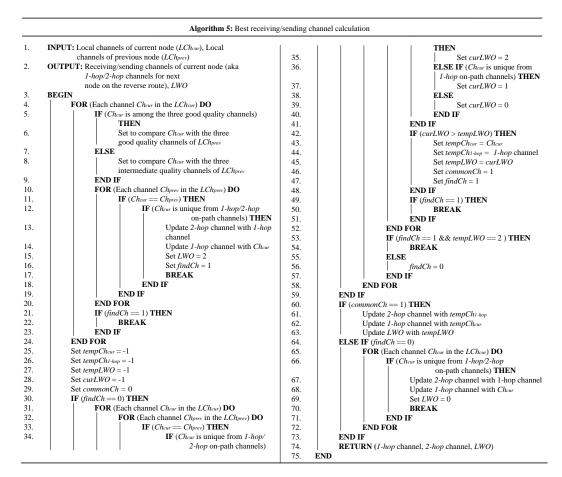


Figure 7.9: Path Setup Module (*PSM*) of QCM2R: depicting Algorithms regarding Best Common Channel Selection (*BCCS*).

It can be clearly comprehended from the Figure 7.5 that *RREQ* message is broadcasted by the source node and hops through  $N5 \rightarrow N6 \rightarrow N4$  till it reaches  $D_1$ . Furthermore, there would be no *routing loops* on end-to-end routing path  $S \rightarrow D_1$  and it would also be resilient to *network holes* because forwarding nodes of high energy are selected for the route  $S \rightarrow D_1$ . Additionally, the routing paths would be node-link-disjoint based.

*v*). *Route Reply packet:* Upon the arrival of *RREQ* packet, the corresponding destination responds with a *RREP* message on the reverse route. When a node receives *RREP* packet, then it unicasts it on the reverse path and so on till *RREP* message arrives at the corresponding source as shown in Figure 7.6.

Before unicasting a *RREP* packet, the corresponding destination determines the Best Common Channel (*BCC*) with the immediate-previous on-path node on the reverse path as discussed in Algorithm 5 (elucidated in Figure 7.9). Afterwards, it updates the *receiving* data-channel radio with *BCC* and unicasts *RREP* message on the reverse path. The receiver of *RREP* packet establishes the forwarding route with the corresponding destination and updates its *sending* data-channel radio with the received *BCC*. Afterwards, this node (i.e. immediate-previous

	<b>INPUT:</b> Source S, Reverse route	31. IF $(LEN(Dj) > RE$ of current node) THEN 32. $LEN(Dj) = RE$ of current node	
	<b>OUTPUT:</b> Find path statistics for $Dj/j = 1, 2$	33. END IF	
3.	<b>BEGIN</b>	34. IF (Bad channel event is occurred) THEN	
,. 1.	Set $LSN(Di) = 1-5$	35. Set $BCE_{(Dj)} = 1$	
+. 5.	Set $LSIN(D) = 1-5$ Set $CPE(D) = 0.0$	36. END IF	
5.	Set $CP[E[b]) = 0.0$ Set $LEN(D) = 310.0$	<ol> <li>Forward PS on the reverse route following steps 13</li> </ol>	
7.	Set $LWO(D) = 0$	to 39	
7. 3.	Set $LWO(D) = 0$ Set $CLWO(D) = 0$	38. END IF	
9.	Set $BCE(D) = 0$	39. END	
10.	<b>IF</b> (Bad Channel Event is occurred at $Dj/j = 1, 2$ ) <b>THEN</b>		
11.	Set $BCE_{(Dj)} = 1$		
12.	END IF	Algorithm 7: Path metric calculation	
13.	IF (Sis reached) THEN		
14.	Calculate APE(Dj) and ALWO(Dj)	1. INPUT: LSN(Dj), LEN(Dj), APE(Dj), AWLO(Dj)	
15.	Call Algorithm 7 and employ LSN(Dj), LEN(Dj), APE(Dj)	2. <b>OUTPUT:</b> Find <i>PCM</i> ( <i>Dj</i> ) 3. <b>BEGIN</b>	
	and ALWO(Dj) for determining PCM(Dj)	<ul> <li>3. BEGIN</li> <li>4. Set equal weight wi/i = 1-4 to given four inputs</li> </ul>	
16.	IF (PCM(Dj) is updated) THEN	4. Set equal weight $Wl/l = 1-4$ to given four inputs 5. Calculate $PCM_{(Dj)}$ for the path based on $LSN_{(Dj)}$ , $LEN_{(Dj)}$ ,	
17.	Update LSN(Dj), LEN(Dj), APE(Dj) and ALWO(Dj)	5. Calculate $PCM(Dj)$ for the path based on $LSIV(Dj)$ , $LEIV(Dj)$ , APE(Dj) and $AWLO(Dj)$	
18.	<b>IF</b> ( <i>RREP</i> is received from all $Dj/j = 1, 2$ )	6. <b>RETURN</b> $PCM_{(Dj)}$	
	THEN	7. END	
19.	IF (Path decision is not taken till now)	7. END	
	THEN		
20.	Call Algorithm 8 for determining	Algorithm 8: Preferred sink calculation	
	the preferred-destination		
21.	ELSE IF ( <i>PCM</i> ( <i>Dj</i> ) is decreased by 5%)	1. <b>INPUT:</b> $PCM_{(Dj)}$ of Destinations $Dj/j = 1, 2$	
~~	THEN	2. <b>OUTPUT:</b> The preferred-destination $Dj/j = 1, 2$	
22.	Call Algorithm 8 for determining	3. BEGIN	
	the preferred-destination	4. Set $tempMetric = PCM(D_1)$	
23.	END IF	5. Set preferred-destination = $D_1$	
24. 25.	END IF END IF	6. <b>FOR</b> ( <i>PCM</i> <sub>(Dj)</sub> of the corresponding $Dj/j = 2$ ) <b>DO</b>	
25. 26.	END IF ELSE	7. <b>IF</b> $(tempMetric < PCM_{(Dj)})$ <b>THEN</b>	
26. 27.		8. $tempMetric = PCM_{(Dj)}$ 9. $preferred-destination = Dj/j = 2$	
27. 28.	IF (I am sink immediate-on-path neighbor) THEN Calculate LSN(Dj)	9. $prejerred-destination = Dj/j = 2$ 10. END IF	
28. 29.	END IF	10. END IF 11. END FOR	
29. 30.	Update $CPE_{(D)}$	11. END FOR 12. RETURN preferred-destination	
50.	Opuale CF E(D)	13. END	

Figure 7.10: Preferred Path Selection Module (*PPSM*) of QCM2R: depicting Algorithms for Path Statistics (*PS*) calculation, Path Calculation Metric (*PCM*) and Preferred Sink Calculation (*PSC*).

node of sink) measures *BCC* with its immediate previous on-path node and unicasts *RREP* packet on the reverse path and so on till the *RREP* packet is arrived at the source node. As shown in the Figure 7.6, the *RREP* message is unicasted by  $D_1 \rightarrow S$  on the reverse route by following the hops  $D_1 \rightarrow N4 \rightarrow N6 \rightarrow N5 \rightarrow S$ . Additionally, *BCC* is also selected for each link as depicted in the Figure 7.6.

The *RREP* packet also informs the corresponding source about the initial statistics of a path in terms of Load on Sink-immediate-on-path Neighbor  $(LSN_{(D_j)})$ , Cumulative Link Weight Orthogonality  $(CLWO_{(D_j)})$ , Cumulative Path Energy  $(CPE_{(D_j)})$  and Least Energy on-path Node  $(LEN_{(D_j)})$ . These parameters are used in selecting the preferred *Qos-aware* path as explained in the next Section 7.4.2.2. Among these values,  $LSN_{(D_j)}$  is always updated by the immediate neighbor of sink node on the reverse path, however,  $CLWO_{(D_j)}$ ,  $CPE_{(D_j)}$  and  $LEN_{(D_j)}$  are updated in a hop - by - hop manner on the reverse path till the corresponding source is arrived. It is at the source node that  $ALWO_{(D_j)}$  and  $APE_{(D_j)}$  are calculated. Afterwards, path calculation metric  $PCM_{(D_j)}$  for the corresponding route is determined.

*vi). Best Common Channel Selection:* QCM2R performs receiver oriented channel assignment whereby channel decision is executed at each receiver node. In this respect, the best common channel selection is initiated at sink node before

7.4. proposed Qos-Aware cross-layered multichannel multisink routing protocol for stream-based wsns

unicasting *RREP* packet. Afterwards, *BCCS* is executed hop - by - hop on each intermediate node on the reverse path (before unicasting *RREP* message) until the corresponding source is arrived and each on-path link is assigned the *BCC* as depicted in Figure 7.6.

The best common channel is selected on the basis of Local Preferred Channels (LPC) and Previous-node Preferred Channels (PPC), keeping in view the channel orthogonality strategy as outlined in Figure 7.9. Initially, BCC is selected among the good (first three channels) of both LPC and PPC under 2-hop channel orthogonality constraint. When BCC search is unsuccessful, then an attempt is made to select BCC among the intermediate (last three channels) of both LPC and PPC under 2-hop channel orthogonality criterion. If BCC is still not found, then initially all the six channel of LPC and PPC are considered together for selecting BCC under 2-hop channel orthogonality approach. When 2-hop orthogonal channel is not found, then 1-hop channel orthogonality principle is assumed. Otherwise, non-orthogonality criterion is adopted. It is a fact that non-orthogonal channels may more readily suffer from interference and data loss, however they are selected for ensuring possible communication between the corresponding nodes. Furthermore, when no common channel exists between LPC and PPC, then the corresponding receiver sends its first channel to the sender for maintaining the least possible communication between the corresponding nodes.

Employing channel orthogonality criterion is beneficial for handling interference and thereby minimizing packets drop across the sensor network. Because of the significance of this metric, we have employed Average Link Weight Orthogonality (*ALWO*) as a path selection metric which is the average of Link Weight Orthogonality (*LWO*) of all the links on the corresponding end-to-end path. For this purpose, the links meeting 2-*hop*, 1-*hop* or non-orthogonality criterion are assigned *LWO* as 2, 1 and 0 respectively. Moreover for the purpose of understanding, various channel orthogonality criteria are concisely depicted in Figure 7.7.

#### 7.4.2.2 PREFERRED PATH SELECTION MODULE

The Preferred Path Selection Module (*PPSM*) involves three submodules i.e. Route Reply (*RREP*), Path Statistics messages (*PS*) and Path Calculation Metric (*PCM*). The role of *RREP* in the initial determination of path calculation metric is already discussed above in Section 7.4.2.1. Below we would explain the operation of *PS* messages and *PCM*. The *pseudocode* of the stated submodules is shown in the Figure 7.10.

*i).* Path Statistics message: Like the RREP message, the PS message is also sent on the reverse path. Unlike RREP message which provides only the initial statistics of  $LSN_{(D_j)}$ ,  $CLWO_{(D_j)}$ ,  $CPE_{(D_j)}$  and  $LEN_{(D_j)}$  to corresponding source (once after the path establishment), the PS message is sent periodically from each destination  $D_{j/j=1,2}$  to the related source, so that the source may get upto-date knowledge about  $LSN_{(D_j)}$ ,  $CLWO_{(D_j)}$ ,  $CPE_{(D_j)}$  and  $LEN_{(D_j)}$ . On the basis of these parameters, the source node calculates  $PCM_{(D_j)}$  of the paths towards the corresponding destinations. Upon comparing the  $PCM_{(D_i)}$  of the

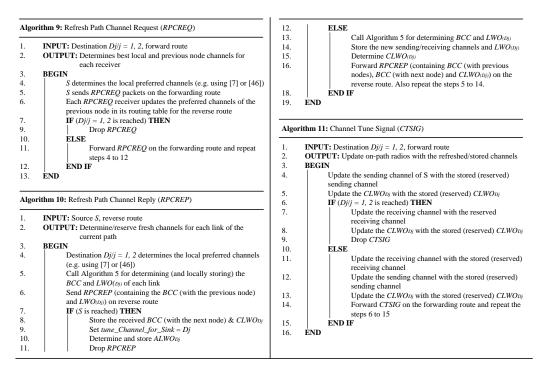


Figure 7.11: Channel Tuning Module (*PSM*) of QCM2R: depicting Algorithms regarding Refresh Path Channel Request (*RPCREQ*), Refresh Path Channel Reply (*RPCREP*) and Channel Tune Signal (*CTSIG*).

available paths at an epoch, the source may determine the QoS-aware best route for performing stream based communication in WSNs. Besides that, the *PS* message also informs source about the occurrence of a  $BCE_{(D_j)}$  on an on-path link. Consequently Channel Tuning Module (*CTM*) may be activated for the corresponding path as discussed in Section 7.4.2.3.

*ii).* Path Calculation Metric: PCM is determined either upon the arrival of *RREP* packet (upon path setup) or *PS* messages (during the communication session). It measures the quality of corresponding path in the range between 0to1. The best among the available paths may be determined on the arrival of *RREP/PS* packets from the available destinations  $D_{j/j=1,2}$  (two in our case) and afterwards, the preferred path is selected for data communication. However, once the preferred path is selected, then it is not changed until  $PCM_{(D_j)}$  of the already selected path is decreased 5%. Such a mechanism is adopted for dealing with the *Ping* – *Pong* – *Effect* related to path selection.

Since  $PCM_{(D_j)}$  is measured on the basis of  $LSN_{(D_j)}$ ,  $ALWO_{(D_j)}$ ,  $APE_{(D_j)}$  and  $LEN_{(D_j)}$ , therefore firstly it is very important to provide a brief description of these metrics here below:

• Load on Sink-immediate-on-path Neighbor: The proposed QCM2R protocol may assign different channels to the neighboring links and thereby enables neighboring nodes to transmit in parallel manner. However, if the wireless communication of a sink-immediate-on-path neighbor experiences inter-

7.4. proposed Qos-Aware cross-layered multichannel multisink routing protocol for stream-based wsns

ference (in the same network or external network) due to overlapping or partially overlapping channels, then link-level congestion may be induced. Subsequently, load may be increased on the sink-immediate-on-path neighbor. Henceforth, packet loss ratio and packet latency may be increased and network throughput may be decreased. Therefore, upon increasing the load on sink immediate-on-path neighbor, the *LSN* metric of the proposed QCM2R protocol may be determined as

$$LSN_{(D_j)} = \frac{lsn_{(maxLd)} - lsn_{(D_j,curLd)}}{lsn_{(maxLd)}}$$
$$= 1 - \left\{ \frac{lsn_{(D_j,curLd)}}{lsn_{(maxLd)}} \right\}$$
(7.5)

Where  $lsn_{(D_j,curLd)}$  is the current load on sink immediate-on-path neighbor which is assumed between 1 to 5. Whereas,  $lsn_{(maxLd)}$  is the maximum affordable load on sink immediate on-path neighbor and is assumed as 5 in this work. The value of LSN may be calculated on the basis of a variety of metrics such as the number of interfering nodes, packet loss ratio, packet latency or network throughput loss, however it is beyond the scope of this work.

• Average Link Weight Orthogonality: As discussed earlier in Section 7.4.2.1 that each BCC may be either 2-hop orthogonal, 1-hop orthogonal or nonorthogonal, exhibiting respectively the interference forbearance capability of wireless links in the descending manner. Following this, each on-path wireless link is assigned a link weight orthogonality based on the orthogonality criterion followed by the wireless link during the process of channel assignment. Starting from the corresponding destination  $D_{j/j=1,2}$  (when RREP or PS packets are sent on the reverse path towards Source S), the LWO<sub>(D<sub>j</sub>)</sub> of each link would be summed up on the reverse path and so on till the corresponding source is arrived and  $CLWO_{(D_j)}$  is determined. Afterwards, the source node determines  $ALWO_{(D_j)}$  given by

$$ALWO_{(D_j)} = \frac{CLWO_{(D_j)}}{hc_{(D_j,src)} \times LWO_{(max)}}$$

$$= \frac{\sum_{i=1}^{hc_{((D_j),src)}} \{LWO_{(D_j,lnk_i)}\}}{hc_{(D_j,src)} \times LWO_{(max)}}$$
(7.6)

Here,  $hc_{(D_j,src)}$  is the hop count distance of source from the corresponding destination  $D_{j/j=1,2}$  on the reverse path. Moreover,  $LWO_{(max)}$  is the maximum value of channel orthogonality on a link (2 in this work) and is used for normalization only. Additionally,  $LWO_{(D_j,lnk_i)}$  represents the link weight orthogonality of each link on the corresponding path.

 Average Path Energy: Although, sensor nodes of varying energy are present on a routing path, however, APE<sub>(Di</sub>) (corresponding to average end-to-end

#### CHAPTER 7. QOS-AWARE CROSS-LAYERED MULTICHANNEL MULTISINK ROUTING

energy occupied by the on-path nodes) is the measure of energy soundness of a route for performing wireless communication. During sending *RREP* or *PS* messages, the residual energy of sensor nodes on the reverse path is summed up in a hop - by - hop manner and  $CPE_{(D_j)}$  of the path is determined at the source node. Mathematically,  $APE_{(D_j)}$  can be calculated as:

$$APE_{(D_j)} = \frac{CPE_{(D_j)}}{hc_{(D_j,src)} \times E_{(max)}}$$

$$= \frac{\sum_{i=1}^{hc_{(D_j,src)}} \{RE_{(n_i)}\}}{hc_{(D_j,src)} \times E_{(max)}}$$
(7.7)

Where  $RE_{(n_i)}$  is the residual energy of an on-path node and  $E_{(max)}$  is the maximum/initial energy occupied by a sensor node which is set as 300 *Joule* in this work. The reason for using  $E_{(max)}$  is to normalize the  $APE_{(D_i)}$  metric.

• *Least Energy on-path Node:* The *LEN* metric tells about the least energy occupied by a sensor node on the reverse path. While sending *RREP* or *PS* packet, this metric is updated regularly whenever a sensor node of less energy is found on the reverse path. Mathematically, *LEN*<sub>(D<sub>i</sub>)</sub> can be calculated as:

$$LEN_{(D_j)} = \min_{len \in [pth_{(D_j)}]} \{RE_{(len)}\}$$
(7.8)

Where

$$[pth_{(D_j)}] = \{n_{(i,D_j)}/i = 1, 2, ..., hc_{(D_j,src)} and (n_{(i,D_j)} \in V)\}$$

Here,  $RE_{(len)}$  is the residual energy of each on-path node, for determining the least energy on-path node. Moreover,  $[pth_{(D_j)}]$  denotes the set of nodes  $n_{(i,D_j)}$  traversed on the desired route from destination  $D_{j/j=1,2}$  to source *S*.

Combining the Equations 7.5, 7.6, 7.7 and 7.8, we can write the mathematical expression of  $PCM_{(D_i)}$  for the corresponding destination  $D_{j/j=1,2}$  as follows:

$$PCM_{(D_{j})} = w_{1} \times LSN_{(D_{j})} + w_{2} \times APE_{(D_{j})} + w_{3} \times LEN_{(D_{j})} + w_{4} \times ALWO_{(D_{j})}$$
(7.9)

208

7.4. proposed Qos-aware cross-layered multichannel multisink routing protocol for stream-based wsns

$$PCM_{(D_{j})} = w_{1} \times \left[ 1 - \left\{ \frac{lsn_{(D_{j},curLd)}}{lsn_{(maxLd)}} \right\} \right] + w_{2} \times \left[ \frac{\sum_{i=1}^{hc_{(D_{j},src)}} \{RE_{(n_{i})}\}}{hc_{(D_{j},src)} \times E_{(max)}} \right] + w_{3} \times \left[ \min_{len \in [pth_{(D_{j})}]} \{RE_{(len)}\} \right] + w_{4} \times \left[ \frac{\sum_{i=1}^{hc_{(D_{j},src)}} \{LWO_{(D_{j},lnk_{i})}\}}{hc_{(D_{j},src)} \times LWO_{(max)}} \right]$$

$$(7.10)$$

Where  $w_1$ ,  $w_2$ ,  $w_3$  and  $w_4$  are the weights assigned to the above metrics. In the above Equation 7.9, all the weights have the same value.

#### 7.4.2.3 CHANNEL TUNING MODULE

*CTM* is comprised of three submodules entitled as Refresh Path Channel Request (*RPCREQ*), Refresh Path Channel Reply (*RPCREP*) and Channel Tune Signal (*CTSIG*). The *pseudocode* of these submodules is depicted in the Figure 7.11. A brief description of each sub module is given below:

*i).* Refresh Path Channel Request: When PS message informs Source S about the occurrence of a bad channel event on the routing path, then an RPCREQ packet is sent by Source S towards the corresponding destination  $D_{j/j=1,2}$  on the forwarding path. Each sender updates RPCREQ packet with its local preferred channels which upon reception are saved in the routing table of the corresponding receiver node. Furthermore, LPC are calculated on the basis of some algorithms such as [4] or [1].

*ii*). Refresh Path Channel Reply: Upon the reception of RPCREQ packet, the corresponding destination  $D_{j/j=1,2}$  sends RPCREP packet towards Source S on the reverse route. The RPCREP packet contains the sending/receiving channels and  $CLWO_{(D_j)}$  of the routing path which are stored/reserved in the routing table of each receiver node for future usage.

*iii). Channel Tune Signal:* Once *RPCREP* packet is received at Source *S*, then *CTSIG* packet is sent on the forwarding path. The *CTSIG* packet updates the sending/receiving channels and  $CLWO_{(D_j)}$  of the corresponding on-path nodes with the newly stored/reserved values. The refreshed channels remain intact till the occurrence of a fresh  $BCE_{(D_j)}$  on the routing path.

#### 7.4.2.4 DATA COMMUNICATION MODULE

Upon the occurrence of an event in the region of interest, the routing paths are setup from source to available destinations  $D_{j/j=1,2}$ . Subsequently, Data

Typecast	Parameter	Description
Network-Layers Synopsis		
PHY	Propagation Model	Two-ray Ground
	Antenna Model	Omni Antenna
	Wireless Range	100m
MAC	МАС Туре	Mac/Macng
	Interface Queue Type	Queue/DropTail/PriQueue
	Queue Length	50
	No. of Channels	16
	Radios per Node	2
Network	Routing Protocol	QCM2R (proposed)
		REBTAM [35] multi-
		channel version aka
		multi-REBTAM
Transport	Protocol	User datagram protocol based
Application	Traffic	Constant Rate based
	Data Rates	1, 4, 8, 16, 32, 64, 100 packet(s)/sec
	Data Sources	1 to 3
	Data Sinks	2
	Packet Size	100 bytes
Miscellaneous Synopsis		
Simulator Type	Event based	Network Simulator - ns-2, version 2.31
Simulation	Duration	300 sec
Network Type	Mobility Model	Static based
	Wireless Topology	Grid based
Energy Model	Initial Energy	300 Joule
	idlePower	0.060[8]
	rxPower	0.063 [8]
	txPower	0.057[8]
	Energy Threshold	30 Joule (10% of 300 Joule)

Table 7.3: Overview of Simulation Parameters

Communication Module (DCM) is activated and streaming data is sent on the preferred route. In this work, streaming traffic is locally generated and the data packet size is set to be 100 *Bytes* which is feasible for WSNs.

#### 7.5 PERFORMANCE EVALUATION

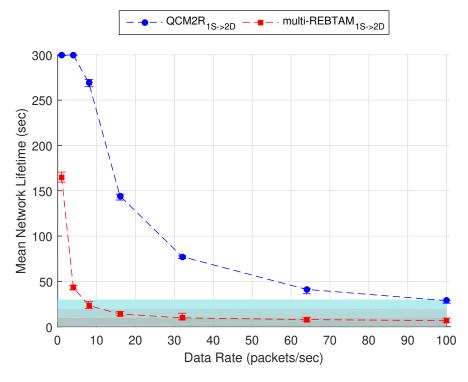
For evaluating the performance of the proposed QCM2R protocol, we have implemented it in a multichannel environment based on ns-2.31 [253]. In this context, the normal ns-2.31 [253] is patched with CRCN Multichannel Patch [225]. For the purpose of comparison, an enhanced multichannel version of the competitor REBTAM protocol [35] is also implemented in multichannel oriented ns-2.31 and is coined as multi-REBTAM. Furthermore, the simulation results of both QCM2R and multi-REBTAM are evaluated in MATLAB [242] based on four main performance criteria namely (i)- Network Lifetime, (ii)- Reliability (aka Packet Delivery Ratio), (iii)- End-to-End Delay, and (iv)- Throughput. Besides that, a brief overview of the simulation parameters is given in Table 7.3. In the next section, we will discuss the performance comparison of the proposed QCM2R and multi-REBTAM based on the above mentioned performance criteria.

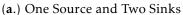
#### 7.5.1 NETWORK LIFETIME

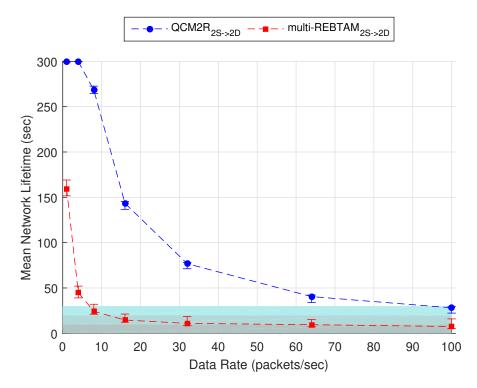
The network lifetime is the measure of the operational lifetime of the wireless network. The operational lifetime is defined as the time till energy of a node in sensor network is drained to the energy threshold level. As given in Table 7.3, the operational lifetime (aka energy threshold) is set as 30 *Joule* in this work. When energy threshold is reached then sensor nodes are assumed to enter into sleep-mode for harvesting energy to make possible future network operations. Consequently, the network may avoid the creation of permanent energy holes.

The Figures 7.12(a), 7.12(b), and 7.13 depict the network lifetime against the data rates of 1, 4, 8, 16, 32, 64 and 100 packet(s)/sec. It is evident from the Figure 7.12(a) and 7.12(b) that the network lifetime of QCM2R is better than the multi-REBTAM. The main reason for this is the network control overhead that is very high in multi-REBTAM and low in the proposed QCM2R protocol. In case of QCM2R, some control packets (i.e. *SAP*, *RREQ* and *RREP*) are used for path setup. Whereas others (i.e. *PS*, *RPCREQ*, *RPCREP* and *CTSIG*) are utilized for protocol operation. Among them, only *PS* is unicasted (for getting the path statistics) after a delay of 2 seconds. Whereas the others (i.e. *RPCREQ*, *RPCREP* and *CTSIG*) are unicasted on-demand only, for refreshing wireless channels whenever any bad channel event is occurred.

On the other hand, multi-REBTAM employs some control packets (i.e. *SAP*, *RREQ* and *RREP*) for best sink selection, however others (i.e. *BR* broadcasts and *ACK* unicasts) before sending each data packet. Consequently, the network control overhead increases enormously. Furthermore, by increasing the packet rate, the network control overhead increases tremendously. As a result, the network lifetime is decreased accordingly as evident from the Figures 7.12(a) and 7.12(b). Besides that, the network lifetime of multi-REBTAM reaches around







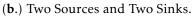


Figure 7.12: Network Lifetime of QCM2R and multi-REBTAM.

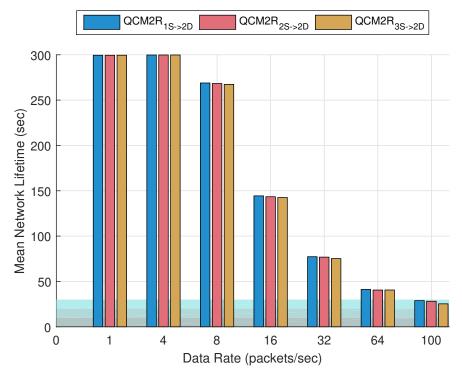


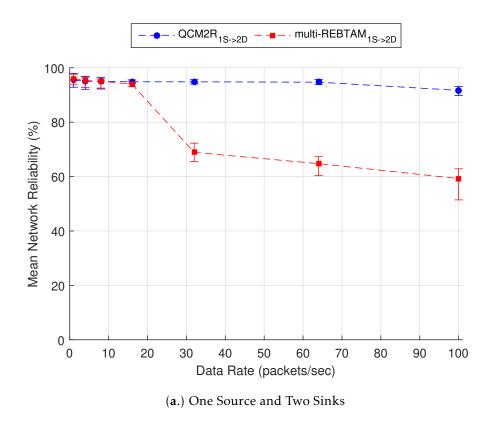
Figure 7.13: Network Lifetime of QCM2R for One, Two and Three Source and Two Sinks (Destinations).

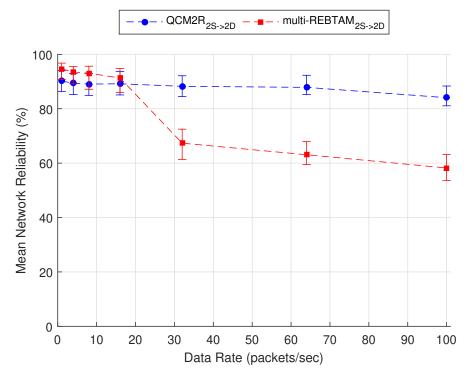
30 sec for sending 8 packets/sec while QCM2R attains the same level by sending 100 packets/sec. For further investigation regarding the network lifetime performance of the proposed QCM2R protocol, we have increased the source nodes. When three sources are used, then the performance of QCM2R protocol is very little affected even for the high data rates of 100 packets/sec as shown in Figure 7.13. on the basis of above examination, it can be deduced that QCM2R outperforms multi-REBTAM in terms of network lifetime.

#### 7.5.2 NETWORK RELIABILITY

The network reliability can be defined as number of packets successfully received at the destination node. It is also called Packet Delivery Ratio (PDR) or Packet Delivery Function (PDF). A reliable network has high PDR because it would enable the successful end-to-end delivery of data packets. On the contrary, a network with high Packet Loss Ratio (PLR) would not be able to successfully transmit the sensed information towards the destination and would be inconsistent in quality and performance.

In this work, the network reliability is examined vis-a-vis the data rates of 1, 4, 8, 16, 32, 64 and 100 packet(s)/sec as shown in Figures 7.14(a), 7.14(b), and 7.15. It is noticeable from the Figures 7.14(a) and 7.14(b) that, in case of less data rate (1, 4, 8, 16 packet(s)/sec) the reliability of multi-REBTAM is either approximately equal (please see Figure 7.14(a)) or better (please see Figure 7.14(b)) than the





(**b**.) Two Sources and Two Sinks.

Figure 7.14: Network Reliability of QCM2R and multi-REBTAM.

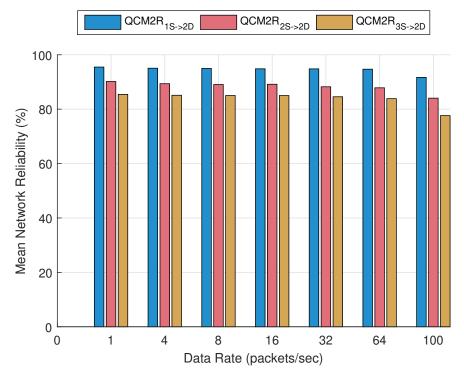


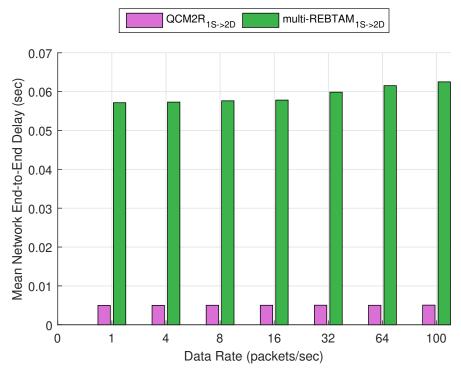
Figure 7.15: Network Reliability of QCM2R for One, Two and Three Source and Two Sinks (Destinations).

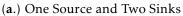
proposed QCM2R protocol. However, when the data rate is increased then the PDR of multi-REBTAM is sharply decreased and this trend is continued afterwards. It is because the control traffic is increased which may hinder the successful delivery of data towards the destination. On the other hand, QCM2R protocol maintains the overall better PDR as depicted in Figures 7.14(a) and 7.14(b) respectively. More specifically, the QCM2R protocol maintains higher than 92% (approx) PDR and 85% (approx) PDR even for high data rates of 100 packet(s)/sec as shown in Figures 7.14(a) and 7.14(b) respectively.

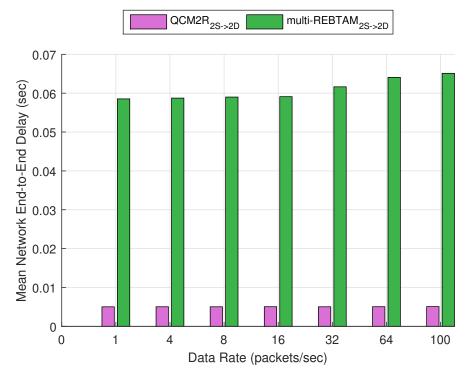
For the purpose of further analysis, the reliability of QCM2R protocol is evaluated by increasing the number of sources. It is evident from the Figure 7.15 that QCM2R protocol exhibits 85% (approx) PDR for data rates of 64 packet(s)/sec and 78% (approx) PDR for data rates of 100 packet(s)/sec. The above discussion is sufficient to concluded that QCM2R protocol surpasses multi-REBTAM in terms of overall network reliability.

#### 7.5.3 NETWORK END-TO-END DELAY

The network end-to-end delay is the measure of time that the network consumes for delivering the sensed information from source to destination. It is the measure of system responsiveness to the events occurring in the terrain of interest. A highly responsive sensor network quickly reacts to the events in the region of interest and delivers the sensed information with less delay to







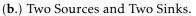


Figure 7.16: Network End-to-End Delay of QCM2R and multi-REBTAM.

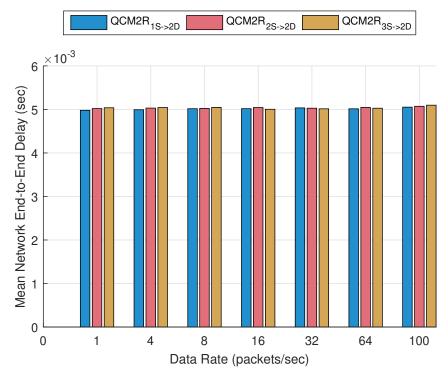
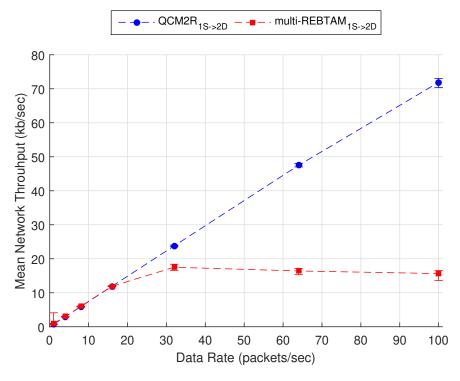


Figure 7.17: Network End-to-End Delay of QCM2R for One, Two and Three Source and Two Sinks (Destinations).

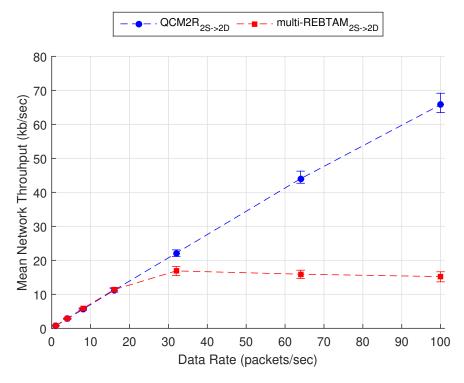
the intended destination and vice versa. Furthermore, a real-time/interactive system is of good quality if its end-to-end does not exceed 150 msec [231].

In this work, we have measured the network average end-to-end delay under the data rates of 1, 4, 8, 16, 32, 64 and 100 packet(s)/sec as shown in Figures 7.16(a), 7.16(b), and 7.17. It is obvious from the Figures 7.16(a) and 7.16(b) that the average end-to-end delay of multi-REBTAM is 12 times (approx) higher than the proposed QCM2R protocol. It is mainly due to the fact that before sending each data packet, multi-REBTAM requires each sender node to broadcast BR and wait for ACK unicasts from the corresponding neighbor nodes. Subsequently, the sender may get the statistics of neighbor nodes and may decide the best among neighbors for data communication. On the contrary, the proposed QCM2R protocol does not experience any delay regarding next hop selection (before data transmission) because it simply sends the information directly to the next on-path node.

For further investigation, the number of sources are increased for evaluating the network average end-to-end delay performance of QCM2R protocol. From the Figure 7.17, it is clear that QCM2R protocol does not suffer from high delays even when three sources are transmitting at high data rate of 100 packet(s)/sec. The above result clearly demonstrate that QCM2R protocol is better in performance than the multi-REBTAM protocol. Furthermore, it is also evident from the Figures 7.16(a), 7.16(b) and 7.17 that the average end-to-end delay of both



(a.) One Source and Two Sinks



(**b**.) Two Sources and Two Sinks.

Figure 7.18: Network Throughput of QCM2R and multi-REBTAM.

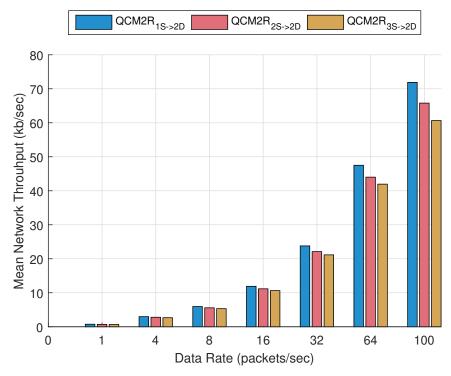


Figure 7.19: Network Throughput of QCM2R for One, Two and Three Source and Two Sinks (Destinations).

QCM2R and multi-REBTAM is below 150 msec. Therefore, both QCM2R and multi-REBTAM are suitable for performing real-time/interactive communication.

#### 7.5.4 NETWORK THROUGHPUT

The network throughput corresponds to the traffic rate (in terms of kilo bits per second (kb/sec)) at which the data is received at the destination node. The higher the network throughput, the more data may be transmitted through the network and consequently gathered at the destination for executing surveil-lance/reconnaissance of the region of interest.

The Figures 7.18(a), 7.18(b), and 7.19 depict the network throughput in relation to the data rates of 1, 4, 8, 16, 32, 64 and 100 packet(s)/sec. It can be deduced from the Figure 7.18(a) that the throughput of QCM2R and multi-REBTAM is approximately equivalent for the data rates of 1, 4, 8 and 16 packet(s). Likewise from the Figure 7.18(b), the throughput of multi-REBTAM is slightly better than the QCM2R for the data rates of 1, 4, 8 and 16 packet(s). However afterwards, the throughput of multi-REBTAM sharply decreases because the packet loss ratio increases due to control overhead. On the other hand, the proposed QCM2R protocol does not experience any such acute packet losses for high data rates and therefore demonstrates a linear relationship. From the Figures 7.18(a) and 7.18(b), it is clear that QCM2R protocol achieves even a data rate of 72

CHAPTER 7. QOS-AWARE CROSS-LAYERED MULTICHANNEL MULTISINK ROUTING

kb/sec (approx) and 65 kb/sec (approx) respectively whereas the throughput of multi-REBTAM is below 18 kb/sec (approx).

To explore further the throughput performance of the QCM2R protocol, the number of sources are further increased as depicted in Figure 7.19. It is apparent from the Figure 7.19 that QCM2R protocol provides substantial throughput performance for high data rates of 32, 64 and 100 packet(s)/sec when the number of sources are increased. Based on the above discussion, it can be deduced that the overall throughput performance of the proposed QCM2R protocol is superior than the multi-REBTAM protocol.

# CHAPTER 8

## CONCLUSION AND FUTURE RESEARCH

This thesis discusses multichannel technology at MAC/Routing layer and corresponding technical solutions for high performance communication in stream based multichannel WSNs. The technical solutions include two MAC layer based approaches (i.e. Ext-NEAMCBTC and MAGIC) and one cross layer (MAC+Network) based technique entitled as QCM2R protocol. The MAC layer based contributions are proposed for selecting the best quality stable channel at a particular epoch for performing stream based communication in multichannel WSNs. The cross layer based contribution is devised for dispensing surveillance information (of the region of interest) on the best quality stable channels to multiple data gathering points in a multi-hop fashion. In the following sections, we will initially provide a synopsis of our contributions as the concluding remarks for this thesis. Afterwards, numerous guidelines are also provided for further brainstorming in multichannel WSNs.

#### 8.1 CONCLUSION: A SYNOPSIS OF CONTRIBUTIONS

In this thesis, three review contributions are delineated. Among them, *general survey design framework* was discussed in a very brief manner. In fact, GSDF enabled us to systematically organize and evaluate multichannel literature at MAC and Routing layers. Due to advantages of multichannel technology, we discussed/proposed the usage of multichannel technology in various applications. At the same time, we also mentioned issues and challenges of multichannel technology at MAC and Network layers. Especially, we determined the robustness of a variety of multichannel MAC protocols on the basis of various design issues and challenges. Furthermore, we classified a handsome number of MAC and Routing approaches and discussed the operation of each protocol along with pros and cons. Particularly, the classification employed for taxonomizing

CHAPTER 8. CONCLUSION AND FUTURE RESEARCH

the Routing based techniques is completely novel and original in this area of research.

Stream-based communication requires high data rate transmission. However, when the data rate is high and frequent channel switching is performed, then it may cause additional energy consumption and data loss [174]. To avoid frequent channel switching, we proposed Ext-NEAMCBTC algorithm [4] which is a pioneer mutichannel MAC protocol that considers both channel quality and stability assessment for assigning wireless channels. Furthermore, Ext-NEAMCBTC algorithm [4] determines channel quality (i.e. good, intermediate and bad) based on standard deviation of RSSI and the average of LQI of the received data packets. On the other hand, stability is determined based on the amount of time that a channel resides in a particular quality level. It outperforms the compared techniques in terms of channel switching delays and energy consumption. Furthermore, it may avoid those channels that may exhibit poor quality due to interference and jamming etc. The Ext-NEAMCBTC [4] is designed for a multichannel environment where some channels exhibit stability in maintaining a particular quality (either good, intermediate or bad) whereas others demonstrate unstable behavior and shift among different quality levels during the communication session.

To the best of our knowledge, there does not exist a multichannel MAC protocol that may perform high data rate communication in a more challenging multichannel environment where all the channels exhibit a mixed quality behavior and are stable at-least for short time intervals. To bridge this gap, a novel multichannel MAC protocol, entitled as MAGIC algorithm, is proposed. Like Ext-NEAMCBTC algorithm [4], MAGIC algorithm employs exponential smoothing approach. The proposed MAGIC algorithm selects the best channel at a particular epoch for accommodating data streams spanning over many samples and effectively handles channel switching overheads in terms of switching delay, energy consumption and associated throughput-loss. The MAGIC protocol has the ability to avoid bad quality channels using a *dynamic blacklisting* mechanism which steadily diminishes the selection probability of a bad channel during the continuing session. Moreover, it dynamically updates the channel stability in case the channel is stable beyond the current confidence interval limit. Furthermore, it may also handle accidental jamming during data stream transmission.

The final contribution of this thesis is the QCM2R protocol which is a crosslayered on-demand multichannel multisink routing protocol for high performance communication in stream based WSNs. The proposed QCM2R protocol establishes *QoS*-aware routes between source and destination nodes, when an event has occurred in the surveillance region. Afterward, data is sent to the best sink that is decided on the basis of a *QoS*-based metric. The QCM2R protocol allows each source to dynamically switch communication between the available sinks and subsequently maintains load balancing during the communication session. Besides that, QCM2R protocol distributedly allocates the best channels to the corresponding on-path nodes for possible load balancing among the available frequencies. Furthermore, it has the ability to refresh on-demand the wireless channels of on-path links for making possible reliable communication. The simulation results exhibit that the proposed QCM2R protocol outperforms counterpart in terms of network lifetime, reliability, end-to-end delay and throughput. Additionally, it is suitable for real-time communication in stream based WSNs. In future, we are interested in implementing this protocol on a testbed.

## 8.2 OPEN RESEARCH DIRECTIONS: AN OVERVIEW OF RECOMMENDATIONS

To conclude our dissertation, we would outline a large number of research directions in Section 8.2.1 and 8.2.2, which may serve as guiding points for further research and development in this area of research. Furthermore, it is worth mentioning here that the guidelines in Section 8.2.1 are outlined from our MAC based survey [3] while the recommendations in Section 8.2.2 are described from our Routing based survey [6].

#### 8.2.1 BASED ON MAC BASED REVIEW [3]

For more than a decade, MWSNs technology is constantly evolving and making headway towards becoming a mature technology. However, it is facing numerous challenges which require proper attention. In this respect, a variety of open issue and challenges of MWSNs are discussed below.

#### 8.2.1.1 TWO-HOP CHANNEL COLORING ISSUE

The interference range of a sensor node is greater than its communication range. For handling interference effectively, orthogonal channels should be properly assigned in the two-hop neighborhood. However, orthogonal channels are limited in number, therefore their proper assignment becomes a real challenge, especially in dense MWSNs. Furthermore, assigning channels in a manner so that they are not repeated in the two-hop neighborhood may minimize interference and termed as the two-hop channel coloring issue, however it is an NP-complete problem [31] and novel solutions are required in this regard.

#### 8.2.1.2 BROADCAST PACKETS ISSUE

Proper network discovery is subject to effective broadcasting in a neighborhood. However, effective broadcasting is a real challenge in single-radio MWSNs, because single-radio interface may tune to only one channel at a time. The solution is to employ a schedule-based broadcast mechanism whereby sensor nodes may follow a schedule for switching to each available channel or to the common control channel for making broadcasts. However, both of the above solutions may suffer from separate issues: e.g., in the first case, energy consumption and delay due to broadcasting are proportional to the number of available channels, whereas in the second case, tight synchronization is required among the sensor nodes, so that all the nodes may simultaneously jump to the control channel for sending/receiving broadcast packets. In case of multiradio MWSNs, effective broadcasting is easier to perform in a neighborhood, because multichannel sensor nodes may permanently reserve one interface for broadcasting on the control channel while the other radio interface(s) may be turned on the available channel(s) for data communication in a neighborhood. However, employing multi-radio technology in MWSNs is costly and complex, too. Therefore, an optimal solution requires further investigation.

#### 8.2.1.3 IN-BAND SYNCHRONIZATION CHALLENGE

A variety of multichannel protocols for WSNs execute software-oriented *in-band synchronization* where sensor nodes broadcast synchronization messages. Such messages are assumed to adjust clocks rates of sensor nodes and normalize the clock drift issue. In case of indoor static WSNs, more than one-third of wireless links has an error rate of above 50% [179], therefore broadcasting synchronization messages may not provide the desired performance. The solution may be to employ some *out-of-band H/W synchronization mechanism* which may effectively handle the links with high error rate. Therefore, there is a need to do more research in this area for devising more robust and smart solutions which may ensure high performance in MWSNs.

#### 8.2.1.4 COMMUNICATION IMPEDANCE ISSUE

As discussed in Section 3.4, the static channel assignment may result in communication impedance in MWSNs. However, there are a variety of other issues causing network partitioning and communication impedance e.g., node failures due to corrosion, physical damage and battery-power outage. Additionally, presence of obstructions in the communication range may also hinder communication. Henceforth, there is a need to employ novel energy harvesting mechanisms for handling battery-power outage issues in MWSNs. Likewise, for dealing with corrosion, physical damage and communication impedance related challenges, more brainstorming is required.

#### 8.2.1.5 DATA AGGREGATION CHALLENGE

Since data aggregation may cause additional *data processing overheads* at the node level, employing lightweight and smart data aggregation techniques may handle data processing overheads (in the form of energy consumption and delay) in MWSNs. However, there is a need to do more research for devising new lightweight aggregation and compression solutions for MWSNs.

#### 8.2.1.6 NETWORK SCALING ISSUE

In case of dense MWSNs, proper network monitoring and management is a very challenging task. It not only requires sensor nodes to properly join the network/sub-network, but also to discover a suitable channel for communication. Employing an interfering channel for network scaling/connectivity may disrupt communication in a neighborhood and thereby decrease network performance. Henceforth, devising an efficient mechanism for network scaling/connectivity is an important issue to be coped with in MWSNs.

#### 8.2.1.7 CHANNEL QUALITY AND STABILITY ESTIMATION

When data rate is high, frequent channel switchings may cause extra energy consumption and data loss [174]. To minimize the switching overheads, a multichannel sensor node should select a stable channel for communication so that it may maintain its quality for the longer intervals of time and may provide high throughput, reliability, and energy efficiency in MWSNs. To the best of our knowledge, the Ext-NEAMCBTC [4] is the only multichannel MAC protocol that considers both channel quality and stability for estimating the best channel at a particular epoch for providing high data rate stream based communication in MWSNs. Therefore, more novel solutions are required in this regard.

#### 8.2.1.8 MULTI-SINK CHALLENGE

The alternative solution for dealing with the single sink bottleneck problem is to increase the number of sink nodes. Eventually, the number of data aggregation points also increases accordingly. As a result, the traffic aggregation load experienced by the single-sink MWSNs is distributed among multiple-sinks which may reduce interference and collision at each data delivery point. If multiple sink nodes are properly placed in different regions of the network, data packets may reach the nearby sink node in shorter time which may decrease the *end-to-end* data delivery delay. Additionally, it may cause even consumption of energy across various regions of the MWSNs and may counter the creation of early holes in the network. Furthermore, the multi-sink approach also requires coordination among the sink nodes, so that they may share the relevant information with each other in an effective manner. Since multichannel multi-sink WSNs are less explored, therefore this field me be an interesting direction for future research.

#### 8.2.1.9 ZIGBEE-WIFI COEXISTENCE CHALLENGE

The IEEE 802.15.4 specification-based ZigBee[237] network may suffer from co-channel interference from other networks in the 2.4 GHz Industrial, Scientific and Medical (ISM) radio bands such as Wi-Fi and Bluetooth [162] (e.g. four channels of IEEE 802.15.4 collide with one channel of IEEE 802.11 [218]). Since frequency hop spread spectrum (FHSS)-based Bluetooth networks affect ZigBee networks less seriously than the direct sequence spread spectrum (DSSS)-based Wi-Fi networks, for ensuring acceptable co-channel interference, ZigBee and Bluetooth should be outside of 0.75 meter scope [218] whereas ZigBee and Wi-Fi access-point should be 8 meters apart [218]. The coexistence of ZigBee and Wi-Fi is also discussed in [148] [199]. However, there is a need to do more research in this field for devising novel robust coexistence-based solutions among the available wireless technologies for achieving high performance in MWSNs.

#### 8.2.2 BASED ON ROUTING BASED SURVEY [6]

Although, research in multichannel routing protocols for WSNs is started some years back and a reasonable number of protocols are published in this regard, however still, there lies a great potential in this field of research. Outlined below are open research challenges which may be considered for future investigations regarding multichannel routing in WSNs.

#### 8.2.2.1 LINK/CHANNEL QUALITY DETERMINATION

Although different protocols have outlined various metrics for measuring link quality in multichannel WSN, however each of these metrics have their own pros and cons. The Received Signal Strength Indicator (RSSI) based metrics are unable to measure interference and ETX based metrics require additional control overhead. Therefore, there is a need to explore new link quality metrics which may handle both control overhead and interference effectively for increasing network capacity.

Normally, channel/link quality metrics such as RSSI or ETX are calculated using current channel quality observations which, due to stochastic nature of wireless channels, are a poor estimate of their actual behavior. There is another solution entitled as Regret Matching based Channel Assignment (RMCA) protocol [208] which makes future channel predictions on the basis of historic data and may anticipate both environmental changes and sensor nodes activities. A more recent solution is proposed by Rehan *et al.* [4] which considers both past and present channel quality and stability observations for estimating future channel quality and stability observations for estimating future channel quality and stability observations for estimating future channel quality predictions. Although, Yu *et al.* [208] and Rehan *et al.* [4] are the two solutions for MWSNs which consider past channel knowledge for future channel quality predictions. However, there is a great potential in this field of research and new solutions are required for link/channel quality determination in MWSNs.

#### 8.2.2.2 MULTI-RADIO DESIGN CHALLENGE

Single radio based static MWSNs are unable to attain optimum throughput [202]. Single radio based dynamic MWSNs may suffer from channel switching overheads such as switching delays and energy consumption [174] [88]. One possible outcome may be to employ multi-radio multichannel solution for increasing performance of MWSNs, however it may also suffer from various challenges. On the one hand, increase in the number of channels is bounded by the number of radios e.g. in OR+SCP [164], the authors have described that the capacity of six channels can be exhausted by using two-radios. Therefore, a further increase in the number of channels beyond this limit (while keeping the radio fixed) may result into no performance improvement. On the other hand, increasing the number of radios per node also increases the H/W, processing and transmission costs of sensor nodes accordingly. Therefore, an optimum model and solution in this regard is still an open challenge which requires serious attention of research community.

#### 8.2.2.3 IN-NETWORK PROCESSING CHALLENGE

Normally sensor nodes spend more energy in data transmission than processing [67] [65] which may quickly deplete their energy and adversely affects network performance. One possible solution for network longevity is in-network processing of the sensed data. The in-network processing techniques suppress the redundant information and consequently, decrease data transmission burden on sensor nodes. In this way, energy efficiency is ensured at the cost of compromising over reliability, fault-tolerance and data processing delay due to additional in-network computations [61]. That is why, there is a need to explore such multichannel application-oriented metrics in WSNs which may enable the designers of multichannel routing protocols in WSNs to decide between additional-computation-cost (by employing in-network processing) or original-data-communication cost (by not-employing in-network processing). Due to complexity and high processing cost, traditional in-network processing techniques are not suitable for MWSNs, therefore there is a need to devise new simple and light weight solutions in this regard.

#### 8.2.2.4 INTERFERENCE MITIGATION MECHANISM

The studied multichannel routing protocol for WSNs provide different mechanism for handling inter and intra path interference. The interference can also be handled by employing directional antennas for data communication. However, it requires knowledge of the three dimensional coordinates of both sensor nodes and their corresponding directional antennas which is really a challenging issue. Therefore, there is a need to employ new multichannel routing protocol in WSNs that may utilize directional antennas oriented approach for achieving high performance in MWSNs. Furthermore, interference mitigation is still a hot topic of research in multichannel routing protocols for WSNs and awaiting novel robust solutions.

#### 8.2.2.5 POWER ADAPTATION CHALLENGE

In case of single channel protocols, an increase in transmission power may result into increasing interference (due to overlap of transmissions regions of nodes), power-loss, packet loss rate and delay [88]. Multichannel based power adaptation mechanism may reduce interference, enhance PDR and decrease the retransmission overheads [88]. But, it is still an open research question that what power level would be optimum under the constraints of residual energy of sensor nodes and available bandwidth [221].

#### 8.2.2.6 TRAFFIC PATTERNS CHALLENGE

The real-time traffic pattern is not fixed and changes with the passage of time according to the external environment. However, the dynamicity of data patterns is not considered so far in the design of multichannel routing protocols for WSNs. Therefore, there is a need to put forth light-weight machine learning based multichannel routing solutions for WSNs that can anticipate and handle the dynamic data patterns on the basis of current and past knowledge of data. It would also result into devising more robust and resilient MWSNs that may handle traffic abnormalities effectively and give birth to a new brain storming direction for future research.

#### 8.2.2.7 BANDWIDTH MANAGEMENT

Unlike the wired medium exhibiting link stability, wireless medium is not stable because it is easily affected by many environmental activities such as noise and distortion. Therefore, it is important to consider the available link bandwidth as a random variable following Gaussian Distribution which may reflect instantaneous link capacity and may handle congestion in MWSNs. For example, in QoS-aware multichannel routing protocol [140], a PPDD procedure is devised for bandwidth management that may provide QoS delivery of real-time data. But, to the best of our knowledge, the rest of multichannel routing protocols for WSNs don't consider the bandwidth management in their link quality based operations. Therefore, for more realistic solutions, the link bandwidth management may be further explored as a new area of future research for MWSNs.

#### 8.2.2.8 SINK NODE DESIGN CHALLENGE

The design of sink node is very important for increasing the network throughput. The throughput of single transceiver sink node is limited because it can only receive data on single path at one time. For increasing the sink data-reception rate, one solution is to increase the number of sink nodes [224], however it may cause data collection and aggregation challenges at final destination. The other solution is to increase the number of transceivers at sink node, however determining whether the number of transceivers is the function of path(s) or channels is still an open research challenge in MWSNs.

#### 8.2.2.9 MOBILE SENSOR NETWORKS

Although, majority of multichannel routing protocols for WSNs are focused on stationary networks where both sensor nodes and sink are static in nature. But, most of the real-time monitoring applications such as battlefield and earthquake require sensor networks to be dynamic in nature. To the best of our knowledge, a handful number of geographic based routing protocols (such as GBCA-G [110] etc.) are published so far for MWSNs that deal with mobile sensors. Thus, there is a need to do more research for devising mobility based multichannel routing protocols for WSNs.

#### 8.2.2.10 SECURE ROUTING

WSNs are employed in a challenging area where sensor nodes can be harmed physically and their communication may be distorted through malicious activities. Discussing various physical security & resilience mechanisms in WSNs is out of the scope of this paper, however secure communication may be provided by employing multichannel approach in WSNs. Furthermore, using multichannel approach with proper modeling in the design of multichannel routing protocols for WSNs can be a source of opportunity for not only increasing throughput, but also providing protection against various security threats e.g. common hopping technique employed in LEMR-multichannel routing protocol [114] has the ability to handle *jamming attacks* to a certain extent. Likewise, channel quality & stability estimation approach exploited in Ext-NEAMCBTC protocol [4] may be used for tackling jamming attacks to a certain degree and thereby assist stream-based multichannel routing protocols for getting high performance in MWSNs. Still, secure routing in MWSNs is an open area of research and requires further investigation regarding possible security threats and appropriate countermeasures for providing more robustness in MWSNs.

#### 8.2.2.11 CROSS-LAYERED OPTIMIZATION APPROACH

Contrary to layering restrictions of Open System Interconnection (OSI) model where data strictly resides in a given layer, cross-layered approach allows different layers to interact with each other and access each other data which may result into enormous performance improvements [36] [66] [75] as recognized by Internet Engineering Task Force (IETF) [239]. But, cross-layered approach may also cause design-complexities [59] and suffers from some issues [52] too, therefore it would be utilized by considering design intricacies, so that the desired optimization may be achieved. Henceforth, getting further optimization in terms of throughput, delay, energy efficiency and reliability in multichannel routing protocols in WSNs using cross-layer design is still an open research area.

# LIST OF PUBLICATIONS

## ARTICLES FROM TRADE JOURNALS

- Waqas Rehan and Stefan Fischer: "A Novel Dynamic Confidence Interval based Secure Channel Prediction Approach for Stream-based Multichannel Wireless Sensor Networks" 
   *in Elsevier Ad Hoc Networks (Under Review)* (2018), (IF = 3.490)
- [2] Waqas Rehan, Stefan Fischer, and Maaz Rehan: "A Critical Review of Surveys Emphasizing on Routing in Wireless Sensor Networks—An Anatomization under General Survey Design Framework" · *in MDPI Sensors* vol. 17, no. 8 (July 2017), 1713 (IF = 3.031)
- [3] Waqas Rehan, Stefan Fischer, and Maaz Rehan: "Anatomizing the robustness of multichannel MAC protocols for WSNs: An evaluation under MAC oriented design issues impacting QoS" · in Elsevier Journal of Network and Computer Applications vol. 121 (2018), pp. 89–118 · ISSN: 1084-8045 (IF = 5.273)
- [4] Waqas Rehan, Stefan Fischer, and Maaz Rehan: "Machine-Learning Based Channel Quality and Stability Estimation for Stream-Based Multichannel Wireless Sensor Networks" · *in MDPI Sensors* vol. 16, no. 9 (Sept. 2016), p. 1476 · ISSN: 1424-8220 (IF = 3.031)
- [5] Waqas Rehan, Stefan Fischer, Maaz Rehan, Yasser Mawad, and Shahzad Saleem: "QCM2R: A QoS-aware Cross-layered Multichannel Multisink Routing Protocol for Stream based Wireless Sensor Networks" · *in Elsevier Journal of Network and Computer Applications (Under Review)* (2019), (IF = 5.273)
- [6] Waqas Rehan, Stefan Fischer, Maaz Rehan, and Mubashir Husain Rehmani: "A Comprehensive Survey on Multichannel Routing in Wireless Sensor Networks" · in Elsevier Journal of Network and Computer Applications vol. 95, no. Supplement C (Oct. 2017), 1–25 (IF = 5.273)

# BIBLIOGRAPHY

#### DISSERTATIONS AND SPECIALIST BOOKS

[7] Ana Bildea: "Link Quality in Wireless Sensor Networks" · PhD thesis · Grenoble, France: Universite de Grenoble, 2013

## ARTICLES FROM TRADE JOURNALS

- [8] Hadi Aghdasi, Maghsoud Abbaspour, Mohsen Moghadam, and Yasaman Samei: "An energy-efficient and high-quality video transmission architecture in wireless video-based sensor networks" · Sensors vol. 8, no. 8 (2008), pp. 4529–4559
- [9] Kemal Akkaya and Mohamed Younis: "A Survey on Routing Protocols for Wireless Sensor Networks" · *in Ad Hoc Networks* vol. 3, no. 3 (Nov. 2005), pp. 325–349 · ISSN: 1570-8705
- [10] Kemal Akkaya and Mohamed Younis: "Energy and QoS Aware Routing in Wireless Sensor Networks" · English · *in Cluster Computing* vol. 8, no. 2 (July 2005), pp. 179–188 · ISSN: 1386-7857
- [11] I.F. Akyildiz, Weilian Su, Y. Sankarasubramaniam, and E. Cayirci: "A Survey on Sensor Networks" · in IEEE Communications Magazine vol. 40, no. 8 (Aug. 2002), pp. 102–114 · ISSN: 0163-6804
- [12] Ian F. Akyildiz, Tommaso Melodia, and Kaushik R. Chowdhury: "A Survey on Wireless Multimedia Sensor Networks" · *in Computer Networks* vol. 51, no. 4 (Mar. 2007), pp. 921–960 · ISSN: 1389-1286
- [13] C. M. García Algora, V. Alfonso Reguera, N. Deligiannis, and K. Steenhaut: "Review and Classification of Multichannel MAC Protocols for Low-Power and Lossy Networks" · *in IEEE Access* vol. 5 (Sept. 2017), pp. 19536–19561
- [14] M Aminian and HR Naji: "A Hospital Healthcare Monitoring System using Wireless Sensor Networks" · in Journal of Health and Medical Informatics vol. 4, no. 2 (2013), p. 121
- [15] Muhammad Ayaz, Imran Baig, Azween Abdullah, and Ibrahima Faye: "A Survey on Routing Techniques in Underwater Wireless Sensor Networks" *in Journal of Network and Computer Applications* vol. 34, no. 6 (Nov. 2011)
   Control and Optimization over Wireless Networks, pp. 1908–1927 · ISSN: 1084-8045

- [16] Azzedine Boukerche and Amir Darehshoorzadeh: "Opportunistic Routing in Wireless Networks: Models, Algorithms, and Classifications" · *in* ACM Computing Surveys (CSUR) vol. 47, no. 2 (Nov. 2014), 22:1–22:36 · ISSN: 0360-0300
- [17] K. Bur, P. Omiyi, and Yang Yang: "Wireless Sensor and Actuator Networks: Enabling the Nervous System of the Active Aircraft" · *in IEEE Communications Magazine* vol. 48, no. 7 (July 2010), pp. 118–125 · ISSN: 0163-6804
- [18] Miriam Carlos-Mancilla, Ernesto Lopez-Mellado, Mario Siller, and Abraham Fapojuwo: "An efficient reconfigurable ad-hoc algorithm for multisink wireless sensor networks" · In International Journal of Distributed Sensor Networks vol. 13, no. 9 (Aug. 2017)
- [19] Taner Cevik and Abdul Halim Zaim: "A Multichannel Cross-layer Architecture for Multimedia Sensor Networks" · in International Journal of Distributed Sensor Networks vol. 2013, no. 457045 (Mar. 2013), p. 11
- [20] Taner Cevik and Abdül Halim Zaim: "EETBR: Energy efficient token based routing for wireless sensor networks" · in Turkish Journal of Electrical Engineering & Computer Sciences vol. 21, no. 2 (2013), pp. 513– 526
- [21] Taner Cevik, Abdul Halim Zaim, and Derya Yiltas: "Localized Power Aware Routing with an Energy Efficient Pipelined Wakeup Schedule for Wireless Sensor Networks" · in Turkish Journal of Electrical Engineering & Computer Sciences vol. 20, no. 6 (2012), pp. 964–978
- [22] Jiming Chen, Qing Yu, Peng Cheng, Youxian Sun, Yanfei Fan, and Xuemin Shen: "Game Theoretical Approach for Channel Allocation in Wireless Sensor and Actuator Networks" · in IEEE Transactions on Automatic Control vol. 56, no. 10 (Oct. 2011), pp. 2332–2344 · ISSN: 0018-9286
- [23] K. Chintalapudi, T. Fu, J. Paek, N. Kothari, S. Rangwala, J. Caffrey, R. Govindan, E. Johnson, and S. Masri: "Monitoring civil structures with a wireless sensor network" · *in IEEE Internet Computing* vol. 10, no. 2 (Mar. 2006), pp. 26–34 · ISSN: 1089-7801
- [24] I. Chlamtac and S. Kutten: "Tree-Based Broadcasting in Multihop Radio Networks" · *in IEEE Transactions on Computers* vol. C-36, no. 10 (Oct. 1987), pp. 1209–1223 · ISSN: 0018-9340
- [25] Luiz H.A. Correia, Thanh-Dien Tran, Vasco N.S.S. Pereira, João C. Giacomin, and Jorge M. Sá Silva: "DynMAC: A resistant MAC protocol to coexistence in wireless sensor networks" · *in Computer Networks* vol. 76 (Jan. 2015), pp. 1–16 · ISSN: 1389-1286
- [26] Daniel-Ioan Curiac, Constantin Volosencu, Dan Pescaru, Lucian Jurca, and Alexa Doboli: "Redundancy and Its Applications in Wireless Sensor Networks: A Survey" · in WSEAS Transactions on Computers vol. 8, no. 4 (2009), pp. 705–714
- [27] I. Demirkol, C. Ersoy, and F. Alagoz: "MAC protocols for wireless sensor networks: a survey" · in IEEE Communications Magazine vol. 44, no. 4 (Apr. 2006), pp. 115–121 · ISSN: 0163-6804

- [28] Gianni Di Caro and Marco Dorigo: "AntNet: Distributed Stigmergetic Control for Communications Networks" · in Journal of Artificial Intelligence Research vol. 9, no. 1 (Dec. 1998), pp. 317–365 · ISSN: 1076-9757
- [29] Rana Diab, Gerard Chalhoub, and Michel Misson: "Overview on Multichannel Communications in Wireless Sensor Networks" · in Network Protocols and Algorithms vol. 5, no. 3 (Oct. 2013), pp. 112–135
- [30] S. Ehsan and B. Hamdaoui: "A Survey on Energy-Efficient Routing Techniques with QoS Assurances for Wireless Multimedia Sensor Networks"
   *in IEEE Communications Surveys & Tutorials* vol. 14, no. 2 (Feb. 2012), pp. 265–278 · ISSN: 1553-877X
- [31] Gholam Hossein Ekbatani Fard and Reza Monsefi: "A Detailed Review of Multi-Channel Medium Access Control Protocols for Wireless Sensor Networks" · International Journal of Wireless Information Networks vol. 19, no. 1 (Mar. 2012), pp. 1–21 · ISSN: 1572-8129
- [32] Mohammadreza Eslaminejad and Shukor Abd Razak: "Fundamental lifetime mechanisms in routing protocols for wireless sensor networks: A survey and open issues" · in Sensors vol. 12, no. 10 (Oct. 2012), pp. 13508– 13544
- [33] E. Felemban, Chang-Gun Lee, and E. Ekici: "MMSPEED: Multipath Multi-SPEED Protocol for QoS Guarantee of Reliability and Timeliness in Wireless Sensor Networks" · in IEEE Transactions on Mobile Computing vol. 5, no. 6 (June 2006), pp. 738–754 · ISSN: 1536-1233
- [34] Emad Felemban: "Advanced Border Intrusion Detection and Surveillance using Wireless Sensor Network Technology" · in International Journal of Communications, Network and System Sciences vol. 6, no. 5 (May 2013), pp. 251–259
- [35] Fatma Hanafy El-Fouly, Rabie Abd Ramadan, Mohamed I. Mahmoud, and Moawad I. Dessouky: "REBTAM: reliable energy balance traffic aware data reporting algorithm for object tracking in multi-sink wireless sensor networks" · *in Wireless Networks* vol. 24, no. 3 (Apr. 2018), pp. 735– 753 · ISSN: 1572-8196
- [36] A.J. Goldsmith and S.B. Wicker: "Design Challenges for Energy-constrained Ad Hoc Wireless Networks" · *in IEEE Wireless Communications* vol. 9, no. 4 (Aug. 2002), pp. 8–27 · ISSN: 1536-1284
- [37] Eren Gurses and Ozgur B. Akan: "Multimedia Communication in Wireless Sensor Networks" 
   *in Annals of Telecommunications* vol. 60, no. 7 (Aug. 2005), pp. 872–900
- [38] Sandra M. Hedetniemi, Stephen T. Hedetniemi, and Arthur L. Liestman:
   "A Survey of Gossiping and Broadcasting in Communication Networks"
   *in Networks* vol. 18, no. 4 (Dec. 1988), pp. 319–349 · ISSN: 1097-0037
- [39] J. L. Hill and D. E. Culler: "Mica: a wireless platform for deeply embedded networks" · in IEEE Micro vol. 22, no. 6 (Nov. 2002), pp. 12–24 · ISSN: 0272-1732

- [40] L. van Hoesel, T. Nieberg, Jian Wu, and P. J. M. Havinga: "Prolonging the lifetime of wireless sensor networks by cross-layer interaction" · *in IEEE Wireless Communications* vol. 11, no. 6 (Dec. 2004), pp. 78–86 · ISSN: 1536-1284
- [41] R. Holman, J. Stanley, and T. Ozkan-Haller: "Applying Video Sensor Networks to Nearshore Environment Monitoring" · in IEEE Pervasive Computing vol. 2, no. 4 (Oct. 2003), pp. 14–21 · ISSN: 1536-1268
- [42] Fei Hu, Yu Wang, and H. Wu: "Mobile Telemedicine Sensor Networks with Low-Energy Data Query and Network Lifetime Considerations" · in IEEE Transactions on Mobile Computing vol. 5, no. 4 (Apr. 2006), pp. 404– 417 · ISSN: 1536-1233
- [43] P. Huang, C. Wang, and L. Xiao: "RC-MAC: A Receiver-Centric MAC Protocol for Event-Driven Wireless Sensor Networks" · in IEEE Transactions on Computers vol. 64, no. 4 (Apr. 2015), pp. 1149–1161 · ISSN: 0018-9340
- [44] Ozlem Durmaz Incel: "A Survey on Multi-channel Communication in Wireless Sensor Networks" · *in Computer Networks* vol. 55, no. 13 (Sept. 2011), pp. 3081–3099 · ISSN: 1389-1286
- [45] Ozlem Durmaz Incel, Lodewijk van Hoesel, Pierre Jansen, and Paul Havinga: "MC-LMAC: A Multi-channel MAC Protocol for Wireless Sensor Networks" · *in Ad Hoc Networks* vol. 9, no. 1 (Jan. 2011), pp. 73–94 · ISSN: 1570-8705
- [46] Sinan Isik, Mehmet Yunus Donmez, and Cem Ersoy: "Multi-sink load balanced forwarding with a multi-criteria fuzzy sink selection for video sensor networks" · *in Computer Networks* vol. 56, no. 2 (Feb. 2012), pp. 615– 627 · ISSN: 1389-1286
- [47] Haifeng Jiang and Renke Sun: "Energy optimized routing algorithm in multi-sink wireless sensor networks" · in Applied Mathematics & Information Sciences vol. 8, no. 1L (Apr. 2014), pp. 349–354
- [48] S. Jingfang, W. Muqing, Z. Yan, and Z. Qinjuan: "Robust On-demand Routing Mechanism for Wireless Multi-hop Networks" · English · *in IET Communications* vol. 5, no. 5 (5 Mar. 2011), pp. 620–628 · ISSN: 1751-8628
- [49] Sharly Joana Halder and Wooju Kim: "A fusion approach of RSSI and LQI for indoor localization system using adaptive smoothers" · *in Journal of Computer Networks and Communications* vol. 2012, no. 790374 (Aug. 2012)
- [50] J.N. Al-Karaki and A.E. Kamal: "Routing Techniques in Wireless Sensor Networks: A Survey" · in IEEE Wireless Communications vol. 11, no. 6 (Dec. 2004), pp. 6–28 · ISSN: 1536-1284
- [51] Priya Kasirajan, Hao Xu, Maciej J Zawodniok, and S Jagannathan: "Demonstration of a multi-interface multi-channel routing protocol (MMCR) for WSNs using Missouri S&T Motes" · in LCN demo (2010)
- [52] V. Kawadia and P. R. Kumar: "A Cautionary Perspective on Cross-Layer Design" · in IEEE Wireless Communications vol. 12, no. 1 (Feb. 2005), pp. 3–11 · ISSN: 1536-1284

- [53] Zeeshan Ali Khan and Michel Auguin: "A Multichannel Design for QoS Aware Energy Efficient Clustering and Routing in WMSN" · *in International Journal of Sensor Networks* vol. 13, no. 3 (June 2013), pp. 145– 161
- [54] Eui-Jik Kim, Meejoung Kim, Sung-Kwan Youm, Seokhoon Choi, and Chul-Hee Kang: "Priority-based service differentiation scheme for IEEE 802.15.4 sensor networks" · AEU - International Journal of Electronics and Communications vol. 61, no. 2 (2007), pp. 69–81 · ISSN: 1434-8411
- [55] M. Kobayashi: "Experience of Infrastructure Damage Caused by the Great East Japan Earthquake and Countermeasures against Future Disasters" · in IEEE Communications Magazine vol. 52, no. 3 (Mar. 2014), pp. 23–29 · ISSN: 0163-6804
- [56] Jun Bum Lim, Beakcheol Jang, and Mihail L. Sichitiu: "MCAS-MAC: A Multichannel Asynchronous Scheduled {MAC} Protocol for Wireless Sensor Networks" · in Computer Communications vol. 56 (Feb. 2015), pp. 98–107 · ISSN: 0140-3664
- [57] Jun Bum Lim, Beakcheol Jang, Suyoung Yoon, Mihail L. Sichitiu, and Alexander G. Dean: "RaPTEX: Rapid Prototyping Tool for Embedded Communication Systems" · in ACM Transactions on Sensor Networks (TOSN) vol. 7, no. 1 (Aug. 2010), 7:1–7:40
- [58] Frank Yeong-Sung Lin, Chiu-Han Hsiao, Hong-Hsu Yen, and Yu-Jen Hsieh: "A Near-Optimal Distributed QoS Constrained Routing Algorithm for Multichannel Wireless Sensor Networks" · *in Sensors* vol. 13, no. 12 (Dec. 2013), pp. 16424–16450 · ISSN: 1424-8220
- [59] Xiaojun Lin, N.B. Shroff, and R. Srikant: "A Tutorial on Cross-layer Optimization in Wireless Networks" · in IEEE Journal on Selected Areas in Communications vol. 24, no. 8 (Aug. 2006), pp. 1452–1463 · ISSN: 0733-8716
- [60] K. Lorincz, D. J. Malan, T. R. F. Fulford-Jones, A. Nawoj, A. Clavel, V. Shnayder, G. Mainland, M. Welsh, and S. Moulton: "Sensor Networks for Emergency Response: Challenges and Opportunities" · in IEEE Pervasive Computing vol. 3, no. 4 (Oct. 2004), pp. 16–23 · ISSN: 1536-1268 · DOI: 10.1109/MPRV.2004.18
- [61] Hong Luo, Yonghe Liu, and S.K. Das: "Routing Correlated Data in Wireless Sensor Networks: A Survey" · in IEEE Network vol. 21, no. 6 (Nov. 2007), pp. 40–47 · ISSN: 0890-8044
- [62] G. Miao, G. Y. Li, and A. Swami: "Decentralized optimization for multichannel random access" · in IEEE Transactions on Communications vol. 57, no. 10 (Oct. 2009), pp. 3012–3023 · ISSN: 0090-6778
- [63] S. Misra, M. Reisslein, and Guoliang Xue: "A Survey of Multimedia Streaming in Wireless Sensor Networks" · in IEEE Communications Surveys and Tutorials vol. 10, no. 4 (2008), pp. 18–39 · ISSN: 1553-877X

- [64] N.A. Pantazis, S.A. Nikolidakis, and D.D. Vergados: "Energy-Efficient Routing Protocols in Wireless Sensor Networks: A Survey" · in IEEE Communications Surveys & Tutorials vol. 15, no. 2 (Feb. 2013), pp. 551– 591 · ISSN: 1553-877X
- [65] G. J. Pottie and W. J. Kaiser: "Wireless Integrated Network Sensors" · in Communications of the ACM vol. 43, no. 5 (May 2000), pp. 51–58 · ISSN: 0001-0782
- [66] Qi Qu, Yong Pei, James W. Modestino, Xusheng Tian, and Bin Wang: "Cross-Layer QoS Control for Video Communications over Wireless Ad Hoc Networks" · in EURASIP Journal on Wireless Communications Networking vol. 2005, no. 5 (Oct. 2005), pp. 743–756 · ISSN: 1687-1472
- [67] V. Raghunathan, C. Schurgers, Sung Park, and M.B. Srivastava: "Energyaware Wireless Microsensor Networks" · in IEEE Signal Processing Magazine vol. 19, no. 2 (Mar. 2002), pp. 40–50 · ISSN: 1053-5888
- [68] M Ramakrishnan and P Vanaja Ranjan: "Multi Channel MAC for Wireless Sensor Networks" · in International Journal of Computer Networks & Communications (IJCNC) vol. 1, no. 2 (July 2009), pp. 47–54
- [69] Mohammad Abdur Razzaque and Simon Dobson: "Energy-efficient Sensing in Wireless Sensor Networks using Compressed Sensing" · in Sensors vol. 14, no. 2 (Feb. 2014), pp. 2822–2859
- [70] Jonathan M. Reason and Jan M. Rabaey: "A Study of Energy Consumption and Reliability in a Multi-hop Sensor Network" · *in ACM SIGMOBILE Mobile Computing and Communications Review* vol. 8, no. 1 (Jan. 2004), pp. 84–97 · ISSN: 1559-1662
- [71] A. Saifullah, Y. Xu, C. Lu, and Y. Chen: "Distributed Channel Allocation Protocols for Wireless Sensor Networks" · in IEEE Transactions on Parallel and Distributed Systems vol. 25, no. 9 (Sept. 2014), pp. 2264–2274 · ISSN: 1045-9219
- [72] Haythem Bany Salameh, Tao Shu, and Marwan Krunz: "Adaptive crosslayer MAC design for improved energy-efficiency in multi-channel wireless sensor networks" · *in Ad Hoc Networks* vol. 5, no. 6 (2007), pp. 844– 854 · ISSN: 1570-8705
- [73] Muhammad Saleem, Gianni A. Di Caro, and Muddassar Farooq: "Swarm Intelligence Based Routing Protocol for Wireless Sensor Networks: Survey and Future Directions" · *in Information Sciences* vol. 181, no. 20 (Oct. 2011), pp. 4597–4624 · ISSN: 0020-0255
- [74] Navrati Saxena, Abhishek Roy, and Jitae Shin: "Dynamic duty cycle and adaptive contention window based QoS-MAC protocol for wireless multimedia sensor networks" · *in Computer Networks* vol. 52, no. 13 (Sept. 2008), pp. 2532–2542 · ISSN: 1389-1286
- [75] E. Setton, Taesang Yoo, Xiaoqing Zhu, A. Goldsmith, and B. Girod: "Crosslayer Design of Ad Hoc Networks for Real-time Video Streaming" · *in IEEE Wireless Communications* vol. 12, no. 4 (Aug. 2005), pp. 59–65 · ISSN: 1536-1284

- [76] Kewei Sha, Jegnesh Gehlot, and Robert Greve: "Multipath Routing Techniques in Wireless Sensor Networks: A Survey" · English · in Wireless Personal Communications vol. 70, no. 2 (May 2013), pp. 807–829 · ISSN: 0929-6212
- [77] Lei Shu, Yan Zhang, Laurence T. Yang, Yu Wang, Manfred Hauswirth, and Naixue Xiong: "TPGF: geographic routing in wireless multimedia sensor networks" · *In Telecommunication Systems* vol. 44, no. 1 (June 2010), pp. 79–95 · ISSN: 1572-9451
- [78] Sivaramakrishnan Sivakumar and Adnan Al-Anbuky: "Dense Clustered Multi-channel Wireless Sensor Cloud" · in Journal of Sensor and Actuator Networks vol. 4, no. 3 (Aug. 2015), pp. 208–225
- [79] K. Sohrabi, J. Gao, V. Ailawadhi, and G. J. Pottie: "Protocols for Selforganization of a Wireless Sensor Network" · in IEEE Personal Communications vol. 7, no. 5 (Oct. 2000), pp. 16–27 · ISSN: 1070-9916
- [80] Katayoun Sohrabi, Jay Gao, Vishal Ailawadhi, and Gregory J Pottie: "Protocols for Self-Organization of a Wireless Sensor Network" · In IEEE personal communications vol. 7, no. 5 (Oct. 2000), pp. 16–27
- [81] Ridha Soua and Pascale Minet: "Multichannel Assignment Protocols in Wireless Sensor Networks: A Comprehensive Survey" · in Pervasive and Mobile Computing vol. 16, Part A (Jan. 2015), pp. 2–21 · ISSN: 1574-1192
- [82] Kannan Srinivasan, Prabal Dutta, Arsalan Tavakoli, and Philip Levis: "An Empirical Study of Low-power Wireless" · in ACM Transactions on Sensor Networks (TOSN) vol. 6, no. 2 (Feb. 2010), 16:1–16:49 · ISSN: 1550-4859
- [83] Robert Szewczyk, Eric Osterweil, Joseph Polastre, Michael Hamilton, Alan Mainwaring, and Deborah Estrin: "Habitat Monitoring with Sensor Networks" · *in Communications of the ACM* vol. 47, no. 6 (June 2004), pp. 34–40 · ISSN: 0001-0782
- [84] Hamadoun Tall and Gerard Chalhoub: "ABORt: Acknowledgement-Based Opportunistic Routing Protocol for High Data Rate Multichannel WSNs" · *in Journal of Sensor and Actuator Networks (JSAN)* vol. 6, no. 4 (Oct. 2017), p. 23
- [85] Do Duy Tan and Dong-Seong Kim: "Dynamic traffic-aware routing algorithm for multi-sink wireless sensor networks" · *in Wireless Networks* vol. 20, no. 6 (Aug. 2014), pp. 1239–1250 · ISSN: 1572-8196
- [86] S Umamaheswari and RM Priya: "An Efficient Healthcare Monitoring System in Vehicular Ad Hoc Networks" · in International Journal of Computer Applications vol. 78, no. 7 (2013)
- [87] R. Annie Uthra and S. V. Kasmir Raja: "QoS Routing in Wireless Sensor Networks - A Survey" · in ACM Computing Surveys (CSUR) vol. 45, no. 1 (Dec. 2012), 9:1–9:12 · ISSN: 0360-0300
- [88] Xiaorui Wang, Xiaodong Wang, Xing Fu, and Guoliang Xing: "MCRT: Multichannel Real-Time Communications in Wireless Sensor Networks" • in ACM Transactions on Sensor Networks (TOSN) vol. 8, no. 1 (Aug. 2011), 2:1–2:30 • ISSN: 1550-4859

- [89] Lu Wei and Zhang Longmei: "A Novel Multi-Channel MAC Protocol for Cluster Based Wireless Multimedia Sensor Networks" · in Physics Procedia vol. 25 (2012), pp. 2203–2210 · ISSN: 1875-3892
- [90] Lu Wei and Zhang Longmei: "A Novel Multi-Channel MAC Protocol for Cluster Based Wireless Multimedia Sensor Networks" · in Physics Procedia vol. 25 (2012), pp. 2203–2210 · ISSN: 1875-3892
- [91] Peng Jung Wu and Chung Nan Lee: "Connection-oriented multi-channel MAC protocol for ad-hoc networks" · in Computer Communications vol. 32, no. 1 (Jan. 2009), pp. 169–178 · ISSN: 0140-3664
- [92] Yueshi Wu and Mihaela Cardei: "Multi-channel and Cognitive Radio Approaches for Wireless Sensor Networks" · in Computer Communications vol. 94 (Nov. 2016), pp. 30–45 · ISSN: 0140-3664
- [93] Kung Yao, R. E. Hudson, C. W. Reed, Daching Chen, and F. Lorenzelli:
   "Blind Beamforming on a Randomly Distributed Sensor Array System" · in IEEE Journal on Selected Areas in Communications vol. 16, no. 8 (Oct. 1998), pp. 1555–1567 · ISSN: 0733-8716
- [94] L. Ye, J. Fulong, L. Hao, W. Jianhui, H. Chen, and Z. Meng: "Interference Robust Channel Hopping Strategies for Wireless Sensor Networks" · *China Communications* vol. 13, no. 3 (Mar. 2016), pp. 96–104 · ISSN: 1673-5447
- [95] Wei Ye, John Heidemann, and Deborah Estrin: "Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks" · In IEEE/ACM Transactions on Networking (TON) vol. 12, no. 3 (June 2004), pp. 493–506 · ISSN: 1063-6692
- [96] H.-H. Yen and C.-L. Lin: "Integrated Channel Assignment and Data Aggregation Routing Problem in Wireless Sensor Networks" · English · *in IET Communications* vol. 3, no. 5 (5 May 2009), pp. 784–793 · ISSN: 1751-8628
- [97] Hong-Hsu Yen: "Optimization-based Channel Constrained Data Aggregation Routing Algorithms in Multi-radio Wireless Sensor Networks" · in Sensors vol. 9, no. 6 (June 2009), pp. 4766–4788
- [98] Melike Yigit, V. Cagri Gungor, Etimad Fadel, Laila Nassef, Nadine Akkari, and Ian F. Akyildiz: "Channel-aware routing and priority-aware multichannel scheduling for WSN-based smart grid applications" · in Journal of Network and Computer Applications (JNCA) vol. 71 (Aug. 2016), pp. 50– 58 · ISSN: 1084-8045
- [99] M. Aykut Yigitel, Ozlem Durmaz Incel, and Cem Ersoy: "QoS-aware MAC protocols for wireless sensor networks: A survey" · in Computer Networks vol. 55, no. 8 (Feb. 2011), pp. 1982–2004 · ISSN: 1389-1286
- [100] O. Younis and S. Fahmy: "HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks" · *IEEE Transactions on Mobile Computing* vol. 3, no. 4 (Oct. 2004), pp. 366–379 · ISSN: 1536-1233

- [101] Yan Yu, Jie Wang, Xingquan Mao, Hongbo Liu, and Lei Zhou: "Design of a Wireless Multi-radio-frequency Channels Inspection System for Bridges" · In International Journal of Distributed Sensor Networks vol. 8, no. 12 (Dec. 2012)
- [102] Zeng Yuanyuan, Naixue Xiong, Jong Hyuk Park, and Laurence T. Yang:
   "An Interference-aware Multichannel Media Access Control Protocol for Wireless Sensor Networks" · *in The Journal of Supercomputing* vol. 60, no. 3 (June 2012), pp. 437–460 · ISSN: 1573-0484
- [103] J. Zheng, H. Zhang, Y. Cai, R. Li, and A. Anpalagan: "Game-Theoretic Multi-Channel Multi-Access in Energy Harvesting Wireless Sensor Networks" · in IEEE Sensors Journal vol. 16, no. 11 (June 2016), pp. 4587– 4594 · ISSN: 1530-437X

### **CONFERENCE ARTICLES**

- [104] N. Abdeddaim, F. Theoleyre, F. Rousseau, and A. Duda: "Multi-Channel Cluster Tree for 802.15.4 Wireless Sensor Networks" · IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications · PIMRC '12 · Sept. 2012, pp. 590–595
- [105] Gahng-Seop Ahn, Se Gi Hong, Emiliano Miluzzo, Andrew T. Campbell, and Francesca Cuomo: "Funneling-MAC: A Localized, Sink-oriented MAC for Boosting Fidelity in Sensor Networks" · Proceedings of the 4th International Conference on Embedded Networked Sensor Systems · SenSys '06 · Boulder, Colorado, USA, 2006, pp. 293–306 · ISBN: 1-59593-343-3 · DOI: 10.1145/1182807.1182837 · URL: http://doi.acm.org/10.1145/ 1182807.1182837
- [106] Mansoor Alicherry, Randeep Bhatia, and Li (Erran) Li: "Joint Channel Assignment and Routing for Throughput Optimization in Multi-radio Wireless Mesh Networks" · Proceedings of the 11th Annual International Conference on Mobile Computing and Networking · MobiCom '05 · Cologne, Germany, Aug. 2005, pp. 58–72 · ISBN: 1-59593-020-5
- [107] H. Alwan and A. Agarwal: "A Survey on Fault Tolerant Routing Techniques in Wireless Sensor Networks" · 3rd International Conference on Sensor Technologies and Applications · SENSORCOMM '09 · June 2009, pp. 366–371
- [108] V. Annamalai, S.K.S. Gupta, and L. Schwiebert: "On Tree-based Convergecasting in Wireless Sensor Networks" · *IEEE Wireless Communications and Networking* · vol. 3 · WCNC '03 · Mar. 2003, pp. 1942–1947
- [109] M. Barcelo, J.L. Vicario, G. Seco-Granados, J.M. Puig, and J.M. Laborda:
   "Multi-Channel Routing Algorithm for Cluster-Tree Wireless Sensor Networks in Aerospace Applications" · 4th Annual Caneus Fly by Wireless Workshop, 2011 · FBW '11 · June 2011, pp. 1–4

- [110] C.H. Barriquello, G.W. Denardin, A. Campos, and R.N. do Prado: "Game Theoretic Channel Assignment for Wireless Sensor Networks with Geographic Routing" · 38th Annual Conference on IEEE Industrial Electronics Society · IECON '12 · Oct. 2012, pp. 6007–6012
- [111] B. D. Beheshti and H. E. Michel: "Middleware/API and Data Fusion in Wireless Sensor Networks" · IEEE Long Island Systems, Applications and Technology Conference · LISAT '11 · May 2011, pp. 1–4
- [112] C. A. Boano, M. A. Zuniga, T. Voigt, A. Willig, and K. Romer: "The Triangle Metric: Fast Link Quality Estimation for Mobile Wireless Sensor Networks" · Proceedings of 19th International Conference on Computer Communications and Networks (ICCCN) · Aug. 2010, pp. 1–7 · DOI: 10. 1109/ICCCN.2010.5560118
- [113] Michael Buettner, Gary V. Yee, Eric Anderson, and Richard Han: "X-MAC: A Short Preamble MAC Protocol for Duty-cycled Wireless Sensor Networks" · Proceedings of the 4th International Conference on Embedded Networked Sensor Systems, SenSys '06 · Boulder, Colorado, USA, 2006, pp. 307–320 · ISBN: 1-59593-343-3
- [114] A. C. Cabezas, N. M. Pena T., and M. A. Labrador: "An Adaptive Multichannel Approach for Real-time Multimedia Wireless Sensor Networks" *· IEEE Latin-American Conference on Communications (LATINCOM)* · Sept. 2009, pp. 1–6
- [115] A.C. Cabezas, R.G. Medina, N.M. Pea T, and M.A. Labrador: "Low Energy and Low Latency in Wireless Sensor Networks" · *IEEE International Conference on Communications (ICC)* · June 2009, pp. 1–5
- [116] M. Cardei and A. Mihnea: "Channel Assignment in Cognitive Wireless Sensor Networks" · International Conference on Computing, Networking and Communications · ICNC '14 · Feb. 2014, pp. 588–593 · DOI: 10.1109/ ICCNC.2014.6785402
- [117] M. Cardei and A. Mihnea: "Distributed Protocol for Channel Assignment in Cognitive Wireless Sensor Networks" · IEEE 32nd International Performance Computing and Communications Conference · IPCCC '13 · Dec. 2013, pp. 1–9
- [118] M. Castillo-Effer, D. H. Quintela, W. Moreno, R. Jordan, and W. Westhoff: "Wireless sensor networks for flash-flood alerting" · Proceedings of the Fifth IEEE International Caracas Conference on Devices, Circuits and Systems · vol. 1 · Nov. 2004, pp. 142–146
- [119] H. Cha, S. Choi, I. Jung, H. Kim, H. Shin, J. Yoo, and C. Yoon: "RETOS: Resilient, Expandable, and Threaded Operating System for Wireless Sensor Networks" · 6th International Symposium on Information Processing in Sensor Networks · IPSN '07 · Apr. 2007, pp. 148–157 · DOI: 10.1109/ IPSN.2007.4379674
- [120] A. Chaibrassou and A. Mouhsen: "A multi-channel cooperative MIMO routing protocol for clustered WSNs" · International Conference on Electrical and Information Technologies (ICEIT) · May 2016, pp. 231–236

- [121] Haiming Chen, Li Cui, and Shilong Lu: "An experimental study of the multiple channels and channel switching in wireless sensor networks" · Proceedings of the 4th International Symposium on Innovations and Real-Time Applications of Distributed Sensor Networks (IRADSN) · May 2009, pp. 54–61
- [122] Xun Chen, Peng Han, QiuSheng He, ShiLiang Tu, and Zhang-Long Chen:
   "A Multi-Channel MAC Protocol for Wireless Sensor Networks" · The Sixth IEEE International Conference on Computer and Information Technology · CIT '06 · Sept. 2006, pp. 224–224
- [123] C. H. Cheng, Y. L. Shiue, Y. Yan, C. C. Lin, and H. C. Chen: "Design Monitoring Systems for Multi-channel Technology in Wireless Sensor Networks" · 18th International Conference on Network-Based Information Systems · NBiS '15 · Sept. 2015, pp. 586–590
- [124] O. Chipara, Z. He, Guoliang Xing, Qin Chen, Xiaorui Wang, Chenyang Lu, J. Stankovic, and T. Abdelzaher: "Real-time Power-Aware Routing in Sensor Networks" · 14th IEEE International Workshop on Quality of Service · IWQoS '06 · June 2006, pp. 83–92
- S. Chouikhi, I. E. Korbi, Y. Ghamri-Doudane, and L. A. Saidane: "Fault Tolerant Multi-channel Allocation Scheme for Wireless Sensor Networks"
   *IEEE Wireless Communications and Networking Conference* · WCNC '14 · Apr. 2014, pp. 2438–2443 · DOI: 10.1109/WCNC.2014.6952731
- [126] Samira Chouikhi, Ines El Korbi, Yacine Ghamri-Doudane, and Leila Azouz Saidane: "Routing-based Multi-Channel Allocation with Fault Recovery for Wireless Sensor Networks" · IEEE International Conference on Communications- Ad-hoc and Sensor Networking Symposium · ICC' 15 · June 2015, pp. 6424–6430
- K.R. Chowdhury, N. Nandiraju, D. Cavalcanti, and D.P. Agrawal: "CMAC
   A Multi-channel Energy Efficient MAC for Wireless Sensor Networks" · *IEEE Wireless Communications and Networking Conference* · vol. 2 · WCNC
   '06 · Apr. 2006, pp. 1172–1177
- [128] Tijs van Dam and Koen Langendoen: "An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks" · Proceedings of the 1st International Conference on Embedded Networked Sensor Systems · SenSys '03 · Los Angeles, California, USA, Nov. 2003, pp. 171–180 · ISBN: 1-58113-707-9
- [129] R. Diab, G. Chalhoub, and M. Misson: "Enhanced Multi-channel MAC Protocol for Multi-hop Wireless Sensor Networks" · *IFIP Wireless Days* · WD '14 · Nov. 2014, pp. 1–6
- [130] N. Q. Dinh, T. D. Hoa, and D. Kim: "Distributed traffic aware routing with multiple sinks in wireless sensor networks" · 9th IEEE International Conference on Industrial Informatics · July 2011, pp. 404–409
- [131] R. M. Eletreby, H. M. Elsayed, and M. M. Khairy: "CogLEACH: A spectrum aware clustering protocol for cognitive radio sensor networks" · 9th International Conference on Cognitive Radio Oriented Wireless Networks and Communications · CROWNCOM '14 · June 2014, pp. 179–184

- [132] A. T. Erman, T. Mutter, L. van Hoesel, and P. Havinga: "A cross-layered communication protocol for load balancing in large scale multi-sink wireless sensor networks" · *International Symposium on Autonomous Decentralized Systems* · Mar. 2009, pp. 1–8
- [133] G. H. E. Fard, M. H. Yaghmaee, and R. Monsefi: "An adaptive Cross-Layer multichannel QoS-MAC protocol for cluster based wireless multimedia sensor networks" · *International Conference on Ultra Modern Telecommunications Workshops* · ICUMT '09 · Oct. 2009, pp. 1–6
- [134] A. Fraboulet, G. Chelius, and E. Fleury: "Worldsens: Development and Prototyping Tools for Application Specific Wireless Sensors Networks" · 6th International Symposium on Information Processing in Sensor Networks
   · IPSN '07 · Apr. 2007, pp. 176–185 · DOI: 10.1109/IPSN.2007.4379677
- [135] Saurabh Ganeriwal, Deepak Ganesan, Hohyun Shim, Vlasios Tsiatsis, and Mani B. Srivastava: "Estimating Clock Uncertainty for Efficient Duty-cycling in Sensor Networks" · Proceedings of the 3rd International Conference on Embedded Networked Sensor Systems · SenSys '05 · San Diego, California, USA, Nov. 2005, pp. 130–141 · ISBN: 1-59593-054-X
- [136] Tia Gao, D. Greenspan, M. Welsh, R. R. Juang, and A. Alm: "Vital Signs Monitoring and Patient Tracking Over a Wireless Network" · *IEEE 27th Annual Conference on Engineering in Medicine and Biology* · IEEE-EMBS '05 · Jan. 2005, pp. 102–105
- [137] Omprakash Gnawali, Rodrigo Fonseca, Kyle Jamieson, David Moss, and Philip Levis: "Collection Tree Protocol" · Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems · SenSys '09 · Berkeley, California, Nov. 2009, pp. 1–14 · ISBN: 978-1-60558-519-2
- [138] R. D. Gomes, G. B. Rocha, A. C. L. Filho, I. E. Fonseca, and M. S. Alencar: "Distributed approach for channel quality estimation using dedicated nodes in industrial WSN" · *IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC)* · Sept. 2014, pp. 1943–1948 · DOI: 10.1109/PIMRC.2014.7136489
- [139] A. Gupta, Chao Gui, and P. Mohapatra: "Exploiting Multi-Channel Clustering for Power Efficiency in Sensor Networks" · First International Conference on Communication System Software and Middleware, 2006 · Comsware '06 · 2006, pp. 1–10
- [140] M.A. Hamid, Muhammad Mahbub Alam, and Choong Seon Hong: "Design of a QoS-aware Routing Mechanism for Wireless Multimedia Sensor Networks" · IEEE Global Telecommunications Conference, 2008 · GLOBE-COM '08 · Nov. 2008, pp. 1–6
- [141] Markku Hanninen, Jukka Suhonen, Timo D Hamalainen, and Marko Hannikainen: "Link quality-based channel selection for resource constrained WSNs" · Advances in Grid and Pervasive Computing · ed. by Jukka Riekki, Mika Ylianttila, and Minyi Guo · Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 254–263

- [142] Tian He, J.A. Stankovic, Chenyang Lu, and T. Abdelzaher: "SPEED: A Stateless Protocol for Real-time Communication in Sensor Networks"
   23rd International Conference on Distributed Computing Systems • May 2003, pp. 46–55
- [143] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan: "Energy-Efficient Communication Protocol for Wireless Microsensor Networks" · Proceedings of the 33rd Annual Hawaii International Conference on System Sciences · vol. 2- · Jan. 2000, pp. 1–10 · DOI: 10.1109/HICSS.2000.926982
- [144] Wendi Rabiner Heinzelman, Joanna Kulik, and Hari Balakrishnan: "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks" · Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking · MobiCom '99 · Seattle, Washington, USA, Aug. 1999, pp. 174–185 · ISBN: 1-58113-142-9
- [145] Shagufta Henna: "SA-RI-MAC: Sender-Assisted Receiver-Initiated Asynchronous Duty Cycle MAC Protocol for Dynamic Traffic Loads in Wireless Sensor Networks" · Third International ICST Conference on Mobile Lightweight Wireless Systems · MOBILIGHT '11 · May 2011
- [146] Amre El-Hoiydi and Jean-Dominique Decotignie: "WiseMAC: An ultra low power MAC protocol for multi-hop wireless sensor networks" · Proceedings of the First International Workshop on Algorithmic Aspects of Wireless Sensor Networks, ALGOSENSORS '04 · vol. 4 · July 2004, pp. 18– 31
- [147] Chao Huang, Yunqing Fu, Mingyang Zhong, and Chengguo Yin: "Multi-Channel Wireless Sensor Network MAC Protocol based on Dynamic Route" · International Conference on Multimedia Technology · ICMT '11 · July 2011, pp. 420–424
- [148] J. Huang, G. Xing, G. Zhou, and R. Zhou: "Beyond co-existence: Exploiting WiFi white space for Zigbee performance assurance" · *The 18th IEEE International Conference on Network Protocols* · ICNP '10 · Oct. 2010, pp. 305–314
- [149] O.D. Incel and B. Krishnamachari: "Enhancing the Data Collection Rate of Tree-Based Aggregation in Wireless Sensor Networks" · 5th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks · SECON '08 · June 2008, pp. 569–577
- [150] Chalermek Intanagonwiwat, Ramesh Govindan, and Deborah Estrin: "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks" · Proceedings of the 6th Annual International Conference on Mobile Computing and Networking · MobiCom '00 · Boston, Massachusetts, USA, Aug. 2000, pp. 56–67 · ISBN: 1-58113-197-6
- [151] Wen Jingrong, Wu Muqing, L.V. Bo, and Wang Dongyang: "Opportunistic Cooperative Routing in Multi-radio Multi-channel Wireless Sensor Networks" · IEEE International Conference on Communications Workshops · ICC '13 · June 2013, pp. 276–280

- [152] M. D. Jovanovic and G. L. Djordjevic: "TFMAC: Multi-channel MAC Protocol for Wireless Sensor Networks" · 8th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services · Sept. 2007, pp. 23–26
- [153] Zeeshan Ali Khan, Cecile Belleudy, and Michel Auguin: "Energy Efficient Multi Channel Design for Clustered Wireless Sensor Networks" · 24th International Conference on Architecture of Computing Systems · ARCS '11
   · Feb. 2011
- [154] Youngmin Kim, Hyojeong Shin, and Hojung Cha: "Y-MAC: An Energy-Efficient Multi-channel MAC Protocol for Dense Wireless Sensor Networks" · International Conference on Information Processing in Sensor Networks, 2008 · IPSN '08 · Apr. 2008, pp. 53–63
- [155] Bhaskar Krishnamachari, Deborah Estrin, and Stephen Wicker: "Modelling Data-Centric Routing in Wireless Sensor Networks" · *IEEE Infocom* · vol. 2 · Infocom '02 · 2002, pp. 39–44
- [156] L. Krishnamachari, D. Estrin, and S. Wicker: "The Impact of Data Aggregation in Wireless Sensor Networks" · Proceedings of the 22nd International Conference on Distributed Computing Systems Workshops · ICDCSW '02 · July 2002, pp. 575–578
- [157] Kisuk Kweon, Hojin Ghim, Jaeyoung Hong, and Hyunsoo Yoon: "Grid-Based Energy-Efficient Routing from Multiple Sources to Multiple Mobile Sinks in Wireless Sensor Networks" · 4th International Symposium on Wireless Pervasive Computing · ISWPC '09 · Feb. 2009, pp. 1–5
- [158] Hieu Khac Le, Dan Henriksson, and Tarek Abdelzaher: "A Control Theory Approach to Throughput Optimization in Multi-channel Collection Sensor Networks" · Proceedings of the 6th International Conference on Information Processing in Sensor Networks · IPSN '07 · Cambridge, Massachusetts, USA, 2007, pp. 31–40 · ISBN: 978-1-59593-638-7
- [159] Hieu Khac Le, Dan Henriksson, and Tarek Abdelzaher: "A Practical Multi-channel Media Access Control Protocol for Wireless Sensor Networks" · Proceedings of the 7th International Conference on Information Processing in Sensor Networks · IPSN '08 · 2008, pp. 70–81 · ISBN: 978-0-7695-3157-1
- Philip Levis, Nelson Lee, Matt Welsh, and David Culler: "TOSSIM: Accurate and Scalable Simulation of Entire TinyOS Applications" · Proceedings of the 1st International Conference on Embedded Networked Sensor Systems
  SenSys '03 · Los Angeles, California, USA, Nov. 2003, pp. 126–137
  · ISBN: 1-58113-707-9 · DOI: 10 . 1145/958491 . 958506 · URL: http://doi.acm.org/10.1145/958491.958506
- C. Li, P. Wang, H. H. Chen, and M. Guizani: "A Cluster Based On-demand Multi-Channel MAC Protocol for Wireless Multimedia Sensor Networks"
   *IEEE International Conference on Communications* • May 2008, pp. 2371– 2376

- [162] Feng Li, Jun Luo, Gaotao Shi, and Ying He: "FAVOR: Frequency Allocation for Versatile Occupancy of Spectrum in Wireless Sensor Networks" · Proceedings of the Fourteenth ACM International Symposium on Mobile Ad Hoc Networking and Computing · MobiHoc '13 · Bangalore, India, 2013, pp. 39–48 · ISBN: 978-1-4503-2193-8
- [163] Hongkun Li, Yu Cheng, Chi Zhou, and P. Wan: "Multi-dimensional Conflict Graph Based Computing for Optimal Capacity in MR-MC Wireless Networks" · IEEE 30th International Conference on Distributed Computing Systems · ICDCS '10 · June 2010, pp. 774–783
- [164] Jinbao Li, Xiaohang Guo, and Longjiang Guo: "Joint Routing, Scheduling and Channel Assignment in Multi-power Multi-radio Wireless Sensor Networks" · IEEE 30th International Performance Computing and Communications Conference · IPCCC '11 · Nov. 2011, pp. 1–8
- [165] Shan Lin, Jingbin Zhang, Gang Zhou, Lin Gu, John A. Stankovic, and Tian He: "ATPC: Adaptive Transmission Power Control for Wireless Sensor Networks" · Proceedings of the 4th International Conference on Embedded Networked Sensor Systems · SenSys '06 · Boulder, Colorado, USA, 2006, pp. 223–236 · ISBN: 1-59593-343-3
- [166] Y. Liu, H. Liu, Q. Yang, and S. Wu: "RM-MAC: A routing-enhanced multi-channel MAC protocol in duty-cycle sensor networks" · *IEEE International Conference on Communications (ICC)* · June 2015, pp. 3534– 3539
- S. Lohier, A. Rachedi, I. Salhi, and E. Livolant: "Multichannel Access for Bandwidth Improvement in IEEE 802.15.4 Wireless Sensor Networks" · *IFIP Wireless Days* · WD' 11 · Oct. 2011, pp. 1–6
- [168] R. Maheshwari, H. Gupta, and S. R. Das: "Multichannel MAC Protocols for Wireless Networks" · 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks · vol. 2 · SECON '06 · Sept. 2006, pp. 393–401
- [169] Miklos Maroti, Branislav Kusy, Gyula Simon, and Akos Ledeczi: "The Flooding Time Synchronization Protocol" · Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems · SenSys '04 · Baltimore, MD, USA, Nov. 2004, pp. 39–49 · ISBN: 1-58113-879-2
- [170] A. Mishra, K. Sudan, and H. Soliman: "Detecting Border Intrusion using Wireless Sensor Network and Artificial Neural Network" · 6th IEEE International Conference on Distributed Computing in Sensor Systems Workshops
   · DCOSSW '10 · June 2010, pp. 1–6
- [171] Arunesh Mishra, Eric Rozner, Suman Banerjee, and William Arbaugh: "Exploiting Partially Overlapping Channels in Wireless Networks: Turning a Peril into an Advantage" · Proceedings of the 5th ACM SIGCOMM Conference on Internet Measurement · IMC '05 · Berkeley, CA, Oct. 2005, pp. 311–316

- [172] Panneer Muthukumaran, Rodolfo de Paz, Rostislav Spinar, and Dirk Pesch: "Meshmac: Enabling mesh networking over ieee 802.15. 4 through distributed beacon scheduling" · *First International Conference on Ad Hoc Networks, ADHOCNETS '09* · Sept. 2009, pp. 561–575
- [173] N. Nordin, R. G. Clegg, and M. Rio: "Multichannel cross-layer routing for sensor networks" · 23rd International Conference on Telecommunications (ICT) · May 2016, pp. 1–6
- [174] A. Pal and A. Nasipuri: "DRCS: A Distributed Routing and Channel Selection Scheme for Multi-Channel Wireless Sensor Networks" · IEEE International Conference on Pervasive Computing and Communications Workshops · PERCOM Workshops '13 · Mar. 2013, pp. 602–608
- [175] G. Patti, G. Muscato, N. Abbate, and L. Lo Bello: "Demo Abstract: A Real-Time Low Datarate Protocol for Cooperative Mobile Robot Teams" · *IEEE Real-Time and Embedded Technology and Applications Symposium* · RTAS '16 · Apr. 2016, pp. 1–1
- [176] I. Rhee, A. Warrier, M. Aia, and J. Min: "Z-MAC: A hybrid MAC for wireless sensor networks" · Proceedings of the 3rd international conference on Embedded networked sensor systems, SenSys '05 · Nov. 2005, pp. 90–101
- [177] A. Rowe, R. Mangharam, and R. Rajkumar: "RT-Link: A Time-Synchronized Link Protocol for Energy- Constrained Multi-hop Wireless Networks"
   • 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks • vol. 2 • SECON '06 • Sept. 2006, pp. 402– 411
- [178] S. Roy, N. Darak, and A. Nasipuri: "A Game Theoretic Approach for Channel Selection in Multi-channel Wireless Sensor Networks" · 11th Annual High Capacity Optical Networks and Emerging/Enabling Technologies (Photonics for Energy) · HONET '14 · Dec. 2014, pp. 145–149
- [179] M. Salajegheh, H. Soroush, and A. Kalis: "HYMAC: Hybrid TDMA/FDMA Medium Access Control Protocol for Wireless Sensor Networks" · IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications · Sept. 2007, pp. 1–5
- [180] M. B. Saleemi and S. Henna: "PW-MMAC: Predictive-Wakeup Multichannel MAC Protocol for Wireless Sensor Networks" · 18th International Conference on Computer Modelling and Simulation · UKSim-AMSS '16 · Apr. 2016, pp. 299–304 · DOI: 10.1109/UKSim.2016.40
- [181] G. Simon, P. Volgyesi, M. Maroti, and A. Ledeczi: "Simulation-based Optimization of Communication Protocols for Large-scale Wireless Sensor Networks" · IEEE Aerospace Conference · vol. 3 · Mar. 2003, pp. 1339–1346
- [182] Gyula Simon, Miklos Maroti, Akos Ledeczi, Gyorgy Balogh, Branislav Kusy, Andras Nadas, Gabor Pap, Janos Sallai, and Ken Frampton: "Sensor Network-based Countersniper System" · Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems · SenSys '04 · Baltimore, MD, USA, 2004, pp. 1–12 · ISBN: 1-58113-879-2

- [183] H. S. W. So, J. Walrand, and J. Mo: "McMAC: A Parallel Rendezvous Multi-Channel MAC Protocol" · *IEEE Wireless Communications and Networking Conference* · WCNC '07 · Mar. 2007, pp. 334–339 · DOI: 10.1109/WCNC. 2007.67
- [184] Jungmin So and Nitin H. Vaidya: "Multi-channel Mac for Ad Hoc Networks: Handling Multi-channel Hidden Terminals Using a Single Transceiver"
   Proceedings of the 5th ACM International Symposium on Mobile Ad Hoc Networking and Computing · MobiHoc '04 · Roppongi Hills, Tokyo, Japan, May 2004, pp. 222–233 · ISBN: 1-58113-849-0
- [185] Philipp Sommer and Roger Wattenhofer: "Gradient Clock Synchronization in Wireless Sensor Networks" · Proceedings of the 2009 International Conference on Information Processing in Sensor Networks · IPSN '09 · 2009, pp. 37–48 · ISBN: 978-1-4244-5108-1
- [186] P. Spachos, P. Chatzimisios, and D. Hatzinakos: "Cognitive Networking with Opportunistic Routing in Wireless Sensor Networks" · IEEE International Conference on Communications · ICC' 13 · June 2013, pp. 2433– 2437
- [187] Petros Spachos and Dimitrios Hatzinakos: "Poster SEA-OR: Spectrum and Energy Aware Opportunistic Routing for Self-powered Wireless Sensor Networks" · Proceedings of the 20th Annual International Conference on Mobile Computing and Networking · MobiCom '14 · Maui, Hawaii, USA, Sept. 2014, pp. 429–432 · ISBN: 978-1-4503-2783-1
- [188] Kannan Srinivasan and Philip Levis: "RSSI Is Under-Appreciated" · Proceedings of the Third Workshop on Embedded Networked Sensors (EmNets) · May 2006
- [189] I. Stoianov, L. Nachman, S. Madden, T. Tokmouline, and M. Csail: "PIPENET: A Wireless Sensor Network for Pipeline Monitoring" · 6th International Symposium on Information Processing in Sensor Networks · IPSN '07 · Apr. 2007, pp. 264–273
- [190] Yanjun Sun, Omer Gurewitz, and David B. Johnson: "RI-MAC: A Receiverinitiated Asynchronous Duty Cycle MAC Protocol for Dynamic Traffic Loads in Wireless Sensor Networks" · Proceedings of the 6th ACM Conference on Embedded Network Sensor Systems · SenSys '08 · Raleigh, NC, USA, Nov. 2008, pp. 1–14 · ISBN: 978-1-59593-990-6 · DOI: 10.1145/1460412. 1460414 · URL: http://doi.acm.org/10.1145/1460412.1460414
- [191] L. Tang, Y. Sun, O. Gurewitz, and D. B. Johnson: "PW-MAC: An energyefficient predictive-wakeup MAC protocol for wireless sensor networks"
   *Proceedings of the IEEE International Conference on Computer Communications* · INFOCOM '11 · Apr. 2011, pp. 1305–1313
- [192] Lei Tang, Yanjun Sun, Omer Gurewitz, and David B. Johnson: "EM-MAC: A Dynamic Multichannel Energy-efficient MAC Protocol for Wireless Sensor Networks" · Proceedings of the 12th ACM International Symposium on Mobile Ad Hoc Networking and Computing · MobiHoc '11 · Paris, France, May 2011, 23:1–23:11 · ISBN: 978-1-4503-0722-2

- [193] S. Upadhyayula, V. Annamalai, and S. K. S. Gupta: "A Low-latency and Energy-efficient Algorithm for Convergecast in Wireless Sensor Networks" · *IEEE Global Telecommunications Conference* · vol. 6 · GLOBECOM '03 · Dec. 2003, pp. 3525–3530
- [194] A. Vlavianos, L. K. Law, I. Broustis, S. V. Krishnamurthy, and M. Faloutsos: "Assessing link quality in IEEE 802.11 Wireless Networks: Which is the right metric?" · IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) · Sept. 2008, pp. 1–6 · DOI: 10.1109/PIMRC.2008.4699837
- [195] A. Wood, J.A. Stankovic, and Gang Zhou: "DEEJAM: Defeating Energy-Efficient Jamming in IEEE 802.15.4-based Wireless Networks" · 4th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks · SECON '07 · June 2007, pp. 60–69
- [196] Y. Wu, Y. Zhao, and Y. Liu: "Channel Adjustment for Performance Enhancement in Wireless Networks" · International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery (CyberC) · Sept. 2015, pp. 463–472
- [197] Yafeng Wu, J.A. Stankovic, Tian He, and Shan Lin: "Realistic and Efficient Multi-Channel Communications in Wireless Sensor Networks" · *The 27th Conference on Computer Communications* · IEEE INFOCOM 2008. · Apr. 2008
- [198] Ning Xu, Sumit Rangwala, Krishna Kant Chintalapudi, Deepak Ganesan, Alan Broad, Ramesh Govindan, and Deborah Estrin: "A Wireless Sensor Network For Structural Monitoring" · Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems · SenSys '04 · Baltimore, MD, USA, Nov. 2004, pp. 13–24 · ISBN: 1-58113-879-2
- [199] R. Xu, G. Shi, J. Luo, Z. Zhao, and Y. Shu: "MuZi: Multi-channel ZigBee Networks for Avoiding WiFi Interference" · International Conference on Internet of Things and 4th International Conference on Cyber, Physical and Social Computing · iThings/CPSCom '11 · Oct. 2011, pp. 323–329 · DOI: 10.1109/iThings/CPSCom.2011.43
- [200] Wenyuan Xu, Wade Trappe, and Yanyong Zhang: "Channel Surfing: Defending Wireless Sensor Networks from Interference" · Proceedings of the 6th International Conference on Information Processing in Sensor Networks · IPSN '07 · Cambridge, Massachusetts, USA: ACM, 2007, pp. 499–508 · ISBN: 978-1-59593-638-7
- [201] Yanchao Xu, Chengyu Wu, Chen He, and Lingge Jiang: "A Cluster-based Energy Efficient MAC Protocol for Multi-hop Cognitive Radio Sensor Networks" · IEEE Global Communications Conference · GLOBECOM '12 · Dec. 2012, pp. 537–542
- [202] Yang Yang, Xutao Yu, and Min Tan: "A Routing Protocol with Integrated Routing Metric for Multi-Channel Wireless Sensor Networks" · 7th International Conference on Communications and Networking in China · CHI-NACOM '12 · Aug. 2012, pp. 467–469 · ISBN: 978-1-4673-2698-8

- [203] Wei Ye, J. Heidemann, and D. Estrin: "An Energy-Efficient MAC Protocol for Wireless Sensor Networks" · Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies · vol. 3 · INFOCOM '02 · June 2002, pp. 1567–1576
- [204] Wei Ye, Fabio Silva, and John Heidemann: "Ultra-low Duty Cycle MAC with Scheduled Channel Polling" · Proceedings of the 4th International Conference on Embedded Networked Sensor Systems · SenSys '06 · Boulder, Colorado, USA, Oct. 2006, pp. 321–334 · ISBN: 1-59593-343-3
- [205] J. Yick, B. Mukherjee, and D. Ghosal: "Analysis of a Prediction-based Mobility Adaptive Tracking Algorithm" · 2nd International Conference on Broadband Networks · vol. 1 · Oct. 2005, pp. 753–760
- [206] Hongseok Yoo, Moonjoo Shim, D. Kim, and Kyu Hyung Kim: "GLOBAL: A Gradient-based routing protocol for load-balancing in large-scale wireless sensor networks with multiple sinks" · *The IEEE symposium on Computers and Communications* · June 2010, pp. 556–562
- [207] Q. Yu, J. Chen, Y. Fan, X. Shen, and Y. Sun: "Multi-Channel Assignment in Wireless Sensor Networks: A Game Theoretic Approach" · Proceedings of the IEEE International Conference on Computer Communications, INFOCOM '10 · Mar. 2010, pp. 1–9
- [208] Qing Yu, Jiming Chen, Youxian Sun, Yanfei Fan, and Xuemin Shen: "Regret Matching Based Channel Assignment for Wireless Sensor Networks"
   *IEEE International Conference on Communications* · ICC '10 · May 2010, pp. 1–5
- [209] X. Zeng, R. Bagrodia, and M. Gerla: "GloMoSim: A Library for Parallel Simulation of Large-scale Wireless Networks" · 12th Workshop on Parallel and Distributed Simulation · PADS '98 · May 1998, pp. 154–161
- [210] Jingbin Zhang, Gang Zhou, Chengdu Huang, S. H. Son, and J. A. Stankovic: "TMMAC: An Energy Efficient Multi-Channel MAC Protocol for Ad Hoc Networks" · *IEEE International Conference on Communications* · ICC '07 · June 2007, pp. 3554–3561
- [211] Peilin Zhang, Olaf Landsiedel, and Oliver Theel: "MOR: Multichannel Opportunistic Routing for Wireless Sensor Networks" · Proceedings of the 2017 International Conference on Embedded Wireless Systems and Networks
  · EWSN '17 · Uppsala, Sweden, Feb. 2017, pp. 36–47 · ISBN: 978-0-9949886-1-4
- [212] Y. Zhao and T. Yu: "Channel Quality Correlation Based Channel Probing in Multiple Channels" · 26th International Conference on Computer Communication and Networks (ICCCN) · July 2017, pp. 1–9
- [213] Gang Zhou, Chengdu Huang, Ting Yan, Tian He, John A Stankovic, Tarek F Abdelzaher, et al.: "MMSN: Multi-Frequency Media Access Control for Wireless Sensor Networks." · 25th IEEE International Conference on Computer Communications · vol. 6 · INFOCOM 2006 · 2006, pp. 1–13

- [214] Zehua Zhou, Xiaojing Xiang, and Xin Wang: "An Energy-Efficient Data-Dissemination Protocol in Wireless Sensor Networks" · International Symposium on a World of Wireless, Mobile and Multimedia Networks · WoWMoM '06 · June 2006, pp. 13–22 · ISBN: 0-7695-2593-8
- [215] M. Zuniga, I. Irzynska, J. Hauer, T. Voigt, C. A. Boano, and K. Roemer: "Link quality ranking: Getting the best out of unreliable links" · International Conference on Distributed Computing in Sensor Systems and Workshops (DCOSS) · June 2011, pp. 1–8 · DOI: 10.1109/DCOSS.2011.5982169

# OTHERS

- [216] 2.4 GHz IEEE 802.15.4/ZigBee-Ready RF Transceiver · (n.d.). In Texas Instruments · Retrieved March 2016 · URL: http://www.ti.com/lit/ ds/symlink/cc2420.pdf
- [217] Ash Wednesday bushfires · (n.d.). In Wikipedia · Retrieved February 2016 · URL: https://en.wikipedia.org/wiki/Ash\_Wednesday\_bushfires
- [218] Atmel AT02845: Coexistence between ZigBee and Other 2.4GHz Products · tech. rep. 42190A · Atmel Corporation, Sept. 2013
- [219] Black Saturday bushfires · (n.d.). In Wikipedia · Retrieved February 2016 · URL: https://en.wikipedia.org/wiki/Black\_Saturday\_bushfires
- [220] Bluetooth · (n.d.). In Wikipedia · Retrieved September 2018 · URL: https: //en.wikipedia.org/wiki/Bluetooth
- [221] Joris Borms, Kris Steenhaut, and Bart Lemmens: "Low-Overhead Dynamic Multi-channel MAC for Wireless Sensor Networks" · Wireless Sensor Networks · ed. by Jorge Sa Silva, Bhaskar Krishnamachari, and Fernando Boavida · LNCS, vol. 5970 · Springer Berlin Heidelberg, Feb. 2010, pp. 81–96 · ISBN: 978-3-642-11917-0
- [222] Ramon Aguero Calvo and Jesus Perez Campo: Adding Multiple Interface Support in NS-2 · by University of Cantabria · Jan. 2007
- [223] Castalia · Accessed April 2017 · URL: https://research.csiro.au/ data61/castalia/
- Ying Chen and Bhaskar Krishnamachari: MCC: A High-throughput Multichannel Data Collection Protocol for Wireless Sensor Networks · tech. rep.
   · by Viterbi School of Engineering, University of Southern California, 2011
- [225] CRCN Multichannel Patch · Apr. 2019 · URL: https://sites.google. com/site/ejazahmedprofile/faq-ns-2-linux/tk-8.4-lastevent. patch?attredirects=0&d=1
- [226] CSIM 20 Development Toolkit for Simulation & Modeling · Mesquite Software, Inc. · Retrieved November 2017 · URL: http://www.mesquite. com/
- [227] Denial-of-Service Attack (DoS) · (n.d.). In Wikipedia · Retrieved January 2017 · URL: https://en.wikipedia.org/wiki/Denial-of-service\_ attack

- [228] Denial-of-Service Attack (DoS) · (n.d.). In US-CERT · Retrieved January 2017 · URL: https://www.us-cert.gov/ncas/tips/ST04-015
- [229] Derivation of the Normal Equations · (n.d.). In Wikipedia · Retrieved December 2015 · URL: https://en.wikipedia.org/wiki/Linear\_ least\_squares\_(mathematics)
- [230] Dubai tests drone taxi service · (n.d.). In BBC NEWS · Retrieved October 2017 · URL: http://www.bbc.com/news/technology-41399406
- [231] End-to-End Delay · (n.d.). In ScienceDirect · Retrieved April 2019 · URL: https://www.sciencedirect.com/topics/computer-science/endto-end-delay
- [232] G. P. Halkes and K. G. Langendoen: "Crankshaft: An Energy-Efficient MAC-Protocol for Dense Wireless Sensor Networks" · Wireless Sensor Networks · ed. by Koen Langendoen and Thiemo Voigt · LNCS, vol. 4373 · Springer Berlin Heidelberg, 2007, pp. 228–244 · ISBN: 978-3-540-69830-2
- [233] Jan-Hinrich Hauer, Vlado Handziski, and Adam Wolisz: "Experimental Study of the Impact of WLAN Interference on IEEE 802.15.4 Body Area Networks" · Wireless Sensor Networks · ed. by Utz Roedig and Cormac J. Sreenan · LNCS, vol. 5432 · Springer Berlin Heidelberg, Feb. 2009, pp. 17–32 · ISBN: 978-3-642-00224-3
- [234] How Big Is a Single Frame of Video? · Apr. 2018 · URL: https://www.cl. cam.ac.uk/~jac22/books/mm/book/node111.html
- [235] IEEE 802.11 · (n.d.). In Wikipedia · Retrieved September 2018 · URL: https://en.wikipedia.org/wiki/IEEE\_802.11
- [236] IEEE 802.15 WPAN Task Group 4 (TG4) · (n.d.). In IEEE802 · Retrieved November 2017 · URL: http://www.ieee802.org/15/pub/TG4.html
- [237] IEEE Standard 802.15.4 · IEEE Standard Association, Sept. 2011
- [238] Ozlem Durmaz Incel, Stefan Dulman, and Pierre Jansen: "Multi-channel Support for Dense Wireless Sensor Networking" · Smart Sensing and Context · ed. by Paul Havinga, Maria Lijding, Nirvana Meratnia, and Maarten Wegdam · LNCS, vol. 4272 · Springer Berlin Heidelberg, 2006, pp. 1–14 · ISBN: 978-3-540-47845-4
- [239] JH Lee, S Singh, and YS Roh: Interlayer Interactions and Performance in Wireless Ad Hoc Network · Internet-Draft · by IRTF ANS Working Group, Internet Engineering Task Force (IETF), Sept. 2003
- [240] Chieh-Jan Mike Liang, Razvan Musaloiu-E, and Andreas Terzis: "Typhoon: A Reliable Data Dissemination Protocol for Wireless Sensor Networks" · Wireless Sensor Networks · ed. by Roberto Verdone · LNCS, vol. 4913 · Springer Berlin Heidelberg, 2008 · chap. 17, pp. 268–285
- [241] List of 2.4 GHz radio use · (n.d.). In Wikipedia · Retrieved September 2018 · URL: https://en.wikipedia.org/wiki/List\_of\_2.4\_GHz\_radio\_use
- [242] MATLAB · URL: http://www.mathworks.com/products/matlab/

- [243] Amalya Mihnea and Mihaela Cardei: "Multi-channel Wireless Sensor Networks" · Recent Development in Wireless Sensor and Ad-hoc Networks · ed. by Srikanta Patnaik, Xiaolong Li, and Yeon-Mo Yang · Springer India, 2015, pp. 1–24 · ISBN: 978-81-322-2129-6
- [244] NS-3 · URL: https://www.nsnam.org/
- [245] Objective Modular Network Testbed in C++ OMNET++ · OpenSim Ltd. · Retrieved November 2017 · URL: https://omnetpp.org/
- [246] Personal area network · (n.d.). In Wikipedia · Retrieved September 2018 · URL: https://en.wikipedia.org/wiki/Personal\_area\_network
- [247] Philip J Pietraski: "Method for channel quality prediction for wireless communication systems" · U.S. Patent 7,912,490 B2 · 22 March 2011
- [248] *QualNet* · SCALABLE Network Technologies, Inc. · Accessed October 2015 · URL: http://web.scalable-networks.com/content/qualnet
- [249] Radio Versions · (n.d.). In Wikipedia · Retrieved September 2018 · URL: ht tps://www.bluetooth.com/bluetooth-technology/radio-versions
- [250] Jaydip Sen: "Security in Wireless Sensor Networks" · Wireless Sensor Networks: Current Status and Future Trends · ed. by Shafiullah Khan, Al-Sakib Khan Pathan, and Nabil Ali Alrajeh · CRC Press: Taylor and Francis Group, 2013, pp. 407–460
- [251] The Fundamentals of Compressive Sensing, Part I: Introduction · (n.d.). In IEEE.tv Specials · Retrieved January 2018 · URL: https://ieeetv.ieee. org/ieeetv-specials/fundamentals-of-compressive-sensing-pt1
- [252] The Network Simulator 2 ns-2 · URL: http://www.isi.edu/nsnam/ns/ index.html
- [253] The Network Simulator 2 ns-2, version 2.31 · URL: http://sourceforge. net/projects/nsnam/files/allinone/ns-allinone-2.31/
- [254] *TrueTime: Simulation of Networked and Embedded Control Systems* · Retrieved November 2017 · URL: http://www.control.lth.se/truetime/
- [255] *Tutornet* · University of Southern California (USC) · Accessed October 2015 · URL: http://anrg.usc.edu/www/tutornet/
- [256] Valley Fire · (n.d.). In Wikipedia · Retrieved February 2016 · URL: https: //en.wikipedia.org/wiki/Valley\_Fire
- [257] Wi-Fi · (n.d.). In Wikipedia · Retrieved September 2018 · URL: https: //en.wikipedia.org/wiki/Wi-Fi
- [258] Wireless ad hoc network · (n.d.). In Wikipedia · Retrieved September 2018 · URL: https://en.wikipedia.org/wiki/Wireless\_ad\_hoc\_network
- [259] Yarnell Hill Fire · (n.d.). In Wikipedia · Retrieved February 2016 · URL: https://en.wikipedia.org/wiki/Yarnell\_Hill\_Fire
- [260] Zigbee · (n.d.). In Wikipedia · Retrieved September 2018 · URL: https: //en.wikipedia.org/wiki/Zigbee