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COOPERATIVE SENSING AND ITS APPLICATIONS IN HETEROGENEOUS RADIO ENVIRONMENTS

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ABSTRACT

Interference and collisions are typical problems in wireless networks but the problem is getting more severe with growing number of wireless devices employing various kinds of radio interfaces. Cognitive radio is one of the enabling technologies which is used to minimize interference and collisions in existing as well as in future networks. Internet of Things favours usage of ISM frequency bands due to low cost, power efficiency, free and extended communication radio spectrum. In these frequency bands various standards and radio technologies operate. Spectrum sensing is one of the major mechanisms by which cognitive radio gains awareness of the external radio environment. In order to reduce interference and collisions in these radio environments, spectrum sensing techniques have already been applied in the past but due to radio propagation effects, the performance with individual spectrum sensing is not ideal. Cooperative sensing is one of the diversity techniques where various nearby wireless devices cooperate with each other in order to create a better understanding of the radio environment and guarantee an interference-reduced spectrum usage. The concept of primary and secondary user is used in this thesis which is typical terminology in cognitive radio literature. In this thesis, a cooperative sensing design and development is presented to reduce collisions and interference in heterogeneous radio environments. The proposed design consists of two protocols. The first protocol is associated with selection of cooperative nodes with the secondary user whereas the second protocol deals with collection of spectrum sensing reports from the cooperative nodes and transmission of secondary user data. A new performance evaluation metric (Effectiveness) is proposed to evaluate the performance of the proposed cooperative sensing design in heterogeneous radio environments. Evaluations are performed with IEEE 802.15.4 equipped radio devices in real world hidden node scenarios. Additionally, simulation study is performed to provide recommendations for the use of cooperative sensing in heterogeneous radio environments. Scalability aspects of the proposed cooperative sensing design are briefly discussed. Furthermore, a comparison with standard techniques like RTS/CTS and Busy Tone to reduce interference and collisions in heterogeneous radio environments is performed. In the end, cooperative sensing is applied in the medical field.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION AND PROBLEM STATEMENT

Radio spectrum is a limited resource for wireless communications as stated by Levin "The Radio Spectrum Resource" in 1968 [26] but the demand for high data rate is always on increase. Voice data is one of the earliest kind of application which requires low data rate. With the passage of time video and Internet traffic increased the data rate requirements. The wireless communication systems were redesigned keeping in view the increasing data rate requirements. Recently, besides having high data rate requirement, number of wireless devices is proliferating for example; due to Internet of Things (IoTs) as stated by Ejaz et. al "Internet of Things in 5G Wireless Communications" in 2016 [16]. Gartner predicts in 2017 [83] that there will more than 30 billion "things" on IoT in near future. Additionally, Alwis et. al in "Survey on 6G Frontiers: Trends, Applications, Requirements, Technologies and Future Research" [8] state in 2021 that IoTs is not only research topic for 5G but also for 6G which is expected to operate by 2030. 6G applications include connected Autonomous Vehicles (CAV), Smart Grid 2.0, Industry 5.0, Collaborative Robots and Internet of Everything. An expansion term for IoT towards Internet of Everything (IoE) is being used for 6G research. IoE will connect many ecosystems involving heterogeneous sensors, actuators, user equipment, data types, services, and applications. Therefore, in future, large number of wireless devices using various kinds of radio interfaces are expected to operate even in the same geographical area. The wireless devices will interfere with each other operating in the same geographical area within the same frequency band. Therefore, minimizing the interference imposes new challenges in wireless communications. Although the research work presented in this thesis was performed from 2012 to 2017 but the usage of this work is still applicable for 5G and 6G IoT and IoE fields. As interference minimization is still the problem in wireless communications with IoT and IoE topics due to large number of devices employing various number of technologies within a geographical area.

Figure 1.1 depicts the different candidate frequency bands and the technologies for IoT. In [4], Akpakwu et. al also survey different frequency bands and the applications considered by IoT. The first one is Machine to Machine Communications for IoT (M2M-IoT) which includes smart grid, smart cities and remote monitoring etc. The second type of technology considered by IoT is Long Range Wide Area Network (LoRaWAN). This technology uses unlicensed bands and provides better coverage than Wireless LAN networks. Another group of technologies supporting IoT is 3GPP technologies, e.g. Narrow Band (NB-IoT). It is to be noted that 3GPP technologies and standards use licensed bands for transmission. Although Industrial Scientific and Medical (ISM) unlicensed bands are strong candidates for IoTs due to low cost, power efficiency, free and extended communication radio spectrum as compared with lower and licensed frequency bands as stated by Gonzalo et. al "Evaluating the more suitable ISM Frequency Band for IoT-Based Smart Grids" in 2016 [36]. There are several ISM bands in this regard; for example 900 MHz, 2.4 GHz, 24 GHz and 61 GHz. The last set of technologies considered by IoT are IEEE 802.15.4, IEEE 802.11 and IEEE 802.15.1. All of these standards use 2.4 GHz unlicensed band. The scope of the this thesis is limited to 2.4 GHz whereas consideration of other bands is left for future work.

As described in the last paragraph, there are various standards which operate in 2.4 GHz band; IEEE 802.15.4 (Zigbee), IEEE 802.11 (WLAN) and IEEE 802.15.1 (Bluetooth) besides other proprietary standards. Each standard has its own way of accessing radio spectrum. For example, IEEE 802.15.4 and IEEE 802.11 do carrier sensing for medium access for utilization of radio bandwidth whereas IEEE 802.15.1 adopts the frequency hopping approach. Therefore, there is no single way of accessing radio bandwidth by wireless devices within this ISM band. In this way, different technologies operating in the ISM band make the radio environment heterogeneous. This radio environment is named "heterogeneous radio environment" in this thesis. Concurrent transmission even within same standard leads to interference in this radio environment. Concurrent transmission occurs when at least two wireless transmitters use the same or parts of radio spectrum and a receiver is in reception range. During concurrent transmission, signals interfere with each other on the receiver side which causes errors in the reception. The term collision is also used instead of interference in the later part of this thesis. The collisions occur because of overlapping transmission intervals at the receiver. If the power level of interfering transmission is strong enough to cause errors in detection of actual transmitted signal at the receiver, degradation in performance of wireless network occur. The problem is more severe if large number of wireless devices operate in a particular geographical area (IoTs).

A number of interference mitigation techniques for ISM bands exist in literature. These techniques are divided into two groups; cognitive and non cognitive techniques. The non cognitive techniques include frequency hopping, time and frequency division multiplexing etc. Whereas the cognitive approaches include individual spectrum sensing and cooperative sensing. More details are given in Section 1.3. The focus of this thesis is only on cooperative sensing as interference mitigation technique.

Cognitive techniques are associated with the concept of cognitive radio. Cognitive Radio is the emerging technology which is based upon the idea that the

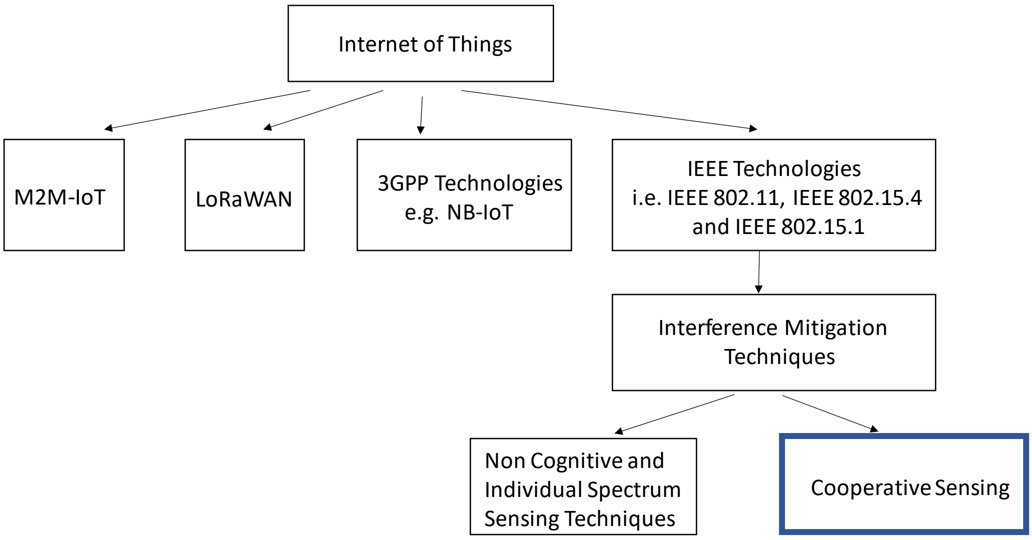

Figure 1.1 – *Cooperative sensing for IEEE 802.11, IEEE 802.15.4 and IEEE 802.15.1*

wireless devices learn about their surrounding environment before transmission. Cognitive radio gains spectrum awareness about its radio environment with spectrum sensing, so that radio spectrum is accessed in a better way to reduce interference. But due to radio propagation effects and inherent noise present with the sensing devices, the cognitive radio does not gain correct information about its radio environment which limits the capability of cognitive radio to reduce collisions. Cooperative sensing is seen as a diversity technique to overcome the imperfect performance with individual sensing devices as stated by Akyldiz et. al "Cooperative Spectrum Sensing in Cognitive Radio Networks: A Survey" in 2011 [5]. In this technique various neighboring nodes also perform spectrum sensing and share their information with the wireless transmitter to improve decisions regarding transmissions and avoid collisions with concurrent transmitters in the same geographical area. Although cooperative sensing improves spectrum awareness of wireless transmitters it also imposes overheads on the system. Therefore, new strategies, approaches and evaluation methods for cooperative sensing are required to minimize interference and collisions in heterogeneous radio environments with respect to the overhead.

1.2 OBJECTIVE AND APPROACH

In this thesis, a new design for cooperative sensing is proposed and evaluated to minimize interference and collisions in heterogeneous radio environments. The terminology of primary and secondary users in this regard abstracts or generalizes the proposed design for various technologies (IEEE 802.15.4, IEEE 802.15.4 and IEEE 802.15.1 besides other proprietary standards) in heterogeneous radio environments.

Figure 1.2 shows the approach that is taken to apply cooperative sensing in heterogeneous radio environments. The proposed cooperative sensing design

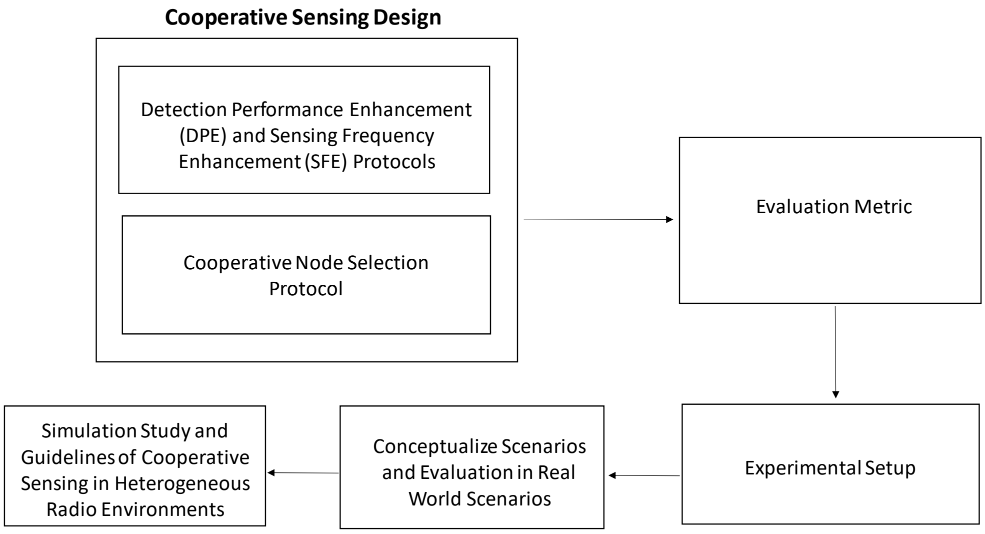

Figure 1.2 – *Approach*

consists of two parts which are shown in the block *Cooperative Sensing Design*. The first part of the design is related with the protocols for getting sensing reports from the cooperative nodes to the secondary user once cooperative node is registered with the secondary user. This is shown in the first sub block *Detection Performance Enhancement (DPE) and Sensing Frequency Enhancement (SFE)*. These protocols collect spectrum sensing reports from cooperative nodes and perform transmissions based upon the spectrum sensing results. The second part is related with a protocol which adds and removes cooperative nodes to the secondary user even in a mobile environment. This is shown in the second sub block *Cooperative Node Selection Protocol*. Previously, the state of the art work of cooperative sensing is focused on discussion of various aspects of cooperative sensing. These aspects are improvement in performance of sensing devices, evaluation of various fusion rules with focus on signal processing and improvement in throughput considering sensing duration. Additionally, the focus of the previous works is on licensed bands but system wide performance evaluation of cooperative sensing in heterogeneous radio environments is not considered yet. Therefore, a new evaluation metric (Effectiveness) related to the block *Evaluation Metric* is proposed which evaluates the cooperative sensing design system wide in heterogeneous radio environments. The proposed evaluation metric considers gain achieved by cooperative sensing (in terms of performance improvement of sensing devices) as well as addresses the overheads associated with cooperative sensing. The proposed design is implemented with the available testbed in the institute. Before evaluation of the proposed cooperative sensing design, a small scale single user scenario is selected to validate the testbed. Validation of the testbed is part of the block *Experimental Setup*. Real world stationary and mobile scenarios are conceptualized and evaluation is done in the testbed scenarios. This is illustrated in the block *Conceptualize Scenarios and Evaluation in Real World Scenarios*.

IEEE 802.15.4 is taken as an example for experimental evaluation in this regard.

Based upon the experimental evaluations, a simulation model is developed so that the parameters of the proposed cooperative sensing design are varied and their impact on Effectiveness is studied. The advantage of performing real world evaluation leads to realistic assumptions while developing the simulation model. The parameters of the simulation study are related with the proposed cooperative sensing design with primary user traffic as well as primary and secondary user technology. The simulation results along with experimental evaluation complete the recommendations for application of cooperative sensing in heterogeneous radio environments. This is shown in the block *Simulation Study and Guidelines of Cooperative Sensing in Heterogeneous Radio Environments*. Although a detailed analysis with scalability is beyond the scope of this thesis, a short discussion is provided in the end. There are other standard techniques like RTS/CTS and Busy Tone to reduce collisions in the wireless networks. Their implementations for heterogeneous radio environments are also presented, evaluated and compared with cooperative sensing. Effectiveness has been chosen to evaluate the performance of cooperative sensing in the heterogeneous radio environments. But regarding application point of view in wireless networks, quality of service requirements also need consideration. Therefore, an exemplary application from the medical field is discussed and a selected scenario is evaluated to demonstrate that quality of service requirements are met with cooperative sensing. In the next section, state of the art work regarding minimization of interference in heterogeneous radio environments is discussed.

1.3 STATE OF THE ART

The scope of this thesis is to apply cooperative sensing for interference minimization in heterogeneous radio environments. Therefore, the related work is divided into three groups; the first one describes state of the art non-cognitive techniques to minimize interference in heterogeneous radio environments whereas the second group describes state of the art techniques of spectrum sensing in heterogeneous radio environments. Finally, state of the art work related to cooperative sensing is discussed. In the following non-cognitive approaches to minimize interference in heterogeneous radio environments are described.

1.3.1 NON COGNITIVE TECHNIQUES

Kleer "ISM Band Coexistence Whitepaper" in 2007 [82] surveys various approaches to improve coexistence among IEEE 802.15.4, IEEE 802.11 and IEEE 802.15.1 technologies. The first approach is Fixed Channel Assignment which proposes to utilize a fixed channel in a static environment for IEEE 802.11 and IEEE 802.15.4 networks. The second approach is Dynamic Frequency Selection which proposes to assign the frequency according to the interference and the approach is applied in IEEE 802.11. The third approach is Time Division Multiple Access (TDMA) which proposes to assign time slots and improve coexistence using this technique. This imposes strict timing requirements among the various collated networks and requires a central coordinator to organize data transmissions. The proposed design in this thesis suggests to use centralized as well as decentralized approach. The fourth approach is frequency hopping mechanism which is applied in Bluetooth technology to minimize interference. All of these techniques are either non-adaptive or selfish for interference minimization and are non-cognitive approaches. Whereas the proposed design in this thesis is cognitive and non-invasive. In this paragraph, general approaches (Fixed, Dynamic, TDMA and Hopping) applied in past for IEEE 802.15.4, IEEE 802.11 and IEEE 802.15.1 networks are presented.

In the following more recent works are presented. The solutions given in these works are non-cognitive and are evaluated for special scenarios and networks. Although, they also lack realistic assumptions (for example radio propagation conditions). Mike et. el "Surviving WiFi Interference in Low Power Zigbee Networks" in 2010 [67] investigate the coexistence of IEEE 802.15.4 networks with IEEE 802.11 network. In this work first interference patterns among IEEE 802.15.4 and IEEE 802.11 are investigated and a BuzzBuzz Medium Access Control (MAC) layer solution is proposed to minimize interference. This solution exploits multi header and forward error correction mechanism to reduce the packet loss due to IEEE 802.11 network. The reception rate of IEEE 802.15.4 is improved by 70% although the number of transmissions of IEEE 802.15.4 are reduced by a factor of 3. The solution is very special and considers only IEEE 802.15.4 and IEEE 802.11 transmissions in the network. Whereas the proposed design in this thesis is more general considering all the technologies in the heterogeneous radio environments. Furthermore, the proposed design in this thesis is cognitive i.e. secondary user performs spectrum sensing to gain spectrum awareness and transmissions are performed based upon primary user traffic pattern.

Woon Chong et. el "An Adaptive WLAN Interference Mitigation Scheme for Zigbee Sensor Networks" in 2015 [12] utilize Markov chain to model interference among IEEE 802.15.4 and IEEE 802.11 transmissions. An algorithm is proposed to mitigate the interference among both networks but the approach presented in this work requires a controller to assess the interference of IEEE 802.11 transmission. On the contrary, the proposed design in this thesis is more general considering any radio technology having one data and a control channel. Furthermore, in the proposed cooperative sensing design in this thesis, recommendations are based upon real world evaluations rather than only with simulations.

Song et. al "WirelessHART: Applying Wireless Technology in Real Time Industrial Process Control" in 2008 [72] discuss an industrial solution WirelessHART. This solution employs IEEE 802.15.4 with TDMA and frequency hopping approach in data link layer. This approach requires a central coordinator to manage the radio resources among various wireless devices. Whereas the proposed design in this thesis supports both centralized and decentralized approach. No real world evaluation of Wireless HART is performed in heterogeneous radio environments in contrast to the real world investigations performed in this thesis. Additionally, no generalization of the solution is presented considering the other technologies (IEEE 802.11 and IEEE 802.15.1) in the heterogeneous radio environments.

In [65], Jung et. al "Interference Mediation for Coexistence of WLAN and Zigbee Networks" in 2008 propose the idea of using TDMA for allocating frequency resources for IEEE 802.11 and IEEE 802.15.4 networks. The proposed approach requires a mediator which coordinates the allocation of bandwidth resources to both networks. Although this work is related with interference mitigation in the heterogeneous radio environments but the solution is special and does not generalize in contrast to the investigations performed in this thesis. Additionally, the proposed approach in that work is evaluated based upon simulations which lack consideration of realistic radio propagation conditions.

There are works which propose improvement of frequency hopping mechanism used in Bluetooth to mitigate interference as IEEE 802.15.1 is related to heterogeneous radio environment which is in the scope of this thesis. Esemann et. al "Limitations of Frequency Hopping in 2.4 GHz ISM-band for Medical Applications due to Interference" in 2011 [63], investigate the usefulness of frequency hopping as applied by Bluetooth for medical applications which is one of the coexistence technique. The authors in that work provide the theoretical limits supported by measurements. In this work, the solution is special and is limited to Bluetooth technology whereas the proposed design in this thesis considers any radio technology supporting multiple channels. Additionally, the proposed design in this thesis is non-invasive in contrast to the selfish approach adopted by frequency hopping in Bluetooth.

Esemann et. el "SAFH-smooth Adaptive Frequency Hopping" in 2011 [55] propose an improved approach of frequency hopping as applied with Bluetooth. The authors propose to exploit active and blacklisting channels based upon the frame error rates due to interference. They propose to use prediction based upon the estimation of frame error rates. Although the proposed approach is the improved version of actual frequency hopping scheme utilized by Bluetooth but it lacks consideration of other technologies in the heterogeneous radio environments. All the techniques discussed so far are related to this thesis as they address interference mitigation techniques with one or more than one technology for the heterogeneous radio environments described in Section 1.1. But none of the work provide a solution which is valid for any radio technology supporting multiple channels either on primary or secondary user side. Their solutions are either based upon measurements or on simulations whereas the proposed design in this thesis exploits the approach of performing real world evaluation before simulation analysis. In this way, optimum parameters of the proposed design are suggested in this thesis. Furthermore, all the proposed solutions in the works described earlier in this section are non-cognitive. On the contrary, the proposed solution in this thesis is based upon the concept of spectrum sensing in which the devices continuously keep on learning the surrounding radio environment while transmitting data.

1.3.2 SPECTRUM SENSING TECHNIQUES

In this subsection, recent works related to spectrum sensing applied in heterogeneous radio environments are discussed. These works are related to this thesis as their goal is to minimize interference and improve coexistence in heterogeneous radio environments.

In 2021, Naseer et. al "Spectrum Sensing for Cognitive Radio: Recent Advances and Future Challenge" [31] present a survey of spectrum sensing techniques for the cognitive radio. The main criteria exploited by secondary user to detect the primary user are presented and discussed. The authors also show the potential of applying spectrum sensing to wireless sensor network and IoT domain. The potential application for 5G networks and future challenges are also explained but no new evaluation results regarding spectrum or cooperative sensing are shown.

In 2019, Arjoune et. al "A Comprehensive Survey on Spectrum Sensing in Cognitive Radio Networks: Recent Advances, New Challenges, and Future Research Directions" [10] elaborate a comprehensive survey of spectrum sensing techniques. The spectrum sensing techniques are classified as narrowband and wideband sensing. In the narrowband sensing, various techniques namely energy detection, cyclostationary detection, matched filter detection etc. are illustrated whereas in the wideband sensing, nyquist based sensing and compressive sensing are discussed. But no new results or new algorithms are shown regarding individual or cooperative sensing.

In 2015, Esemann et. al "Receiving more than Data A Signal Model and Theory of a Cognitive IEEE 802.15.4 Receiver" [62] propose to detect interferer with IEEE 802.15.4 during reception as the standard receivers have facility only for data output and no cognitive capability. Theoretical analysis is performed for the proposed cognitive receiver and evaluations are done with simulations and measurements. In this way an approaching mobile interferer is identified in advance by the cognitive receiver and collisions are avoided with this cognitive receiver. Although no evaluations are shown in that work regarding spectrum access as the purpose was only to detect an approaching interferer before it collides with the actual data frames being received at the cognitive receiver.

Esemann et. al "CSOR: Carrier Sensing on Reception" in 2011 [58] evaluate the software defined radio implemented algorithms to distinguish interference from the actual transmitted signal at the receiver. As described earlier standard IEEE 802.15.4 receivers do not have capability to distinguish interferer from its own received actual data packets. This work is related to this thesis as it is focused on interference detection which is one step to reduce interference in heterogeneous radio environments. Although the proposed solution in that work does not consider how collisions are avoided at the receiver or for the interferer which is in the scope of this thesis.

Esemann et. al "Integrated Low Power SDR enabling Cognitive IEEE 802.15.4 Sensor Nodes" [60] in 2014 propose the concept of adding an additional integrated software defined radio module with the IEEE 802.15.4 equipped nodes to detect the interference. The proposed solution in that work enhances the spectrum awareness of IEEE 802.15.4 nodes by distinguishing interference from its own received frames but this also decreases the battery lifetime of the nodes by 27%. Although that work also propose a solution both for interference detection and for transmission based upon the additional information gained by software defined radio but it lacks the evaluations in the real world scenarios.

Esemann et. al "Non-Invasive Cognitive Driven Spectrum Access in Medical Application via Baseband Processing" [61] in 2012 harness the idea presented by them in [59] and perform non-invasive cognitive spectrum access. The proposed approach in that work performs better than carrier sensing but they do not address the problem when receiver is not capable to detect the interference.

Summarizing all the solutions for spectrum sensing in heterogeneous radio environments, they are all related to this thesis as they address minimization of interference in heterogeneous radio environments. Although their focus is on interference detection rather than reduction of collisions in heterogeneous radio environments. The selected works ([58] and [61]) focus on reduction of collisions at a particular transmitter receiver pair. The transmission from other wireless devices is considered as interference but collisions also occur because of the first transmitter receiver pair on the other wireless devices. This aspect is not considered in all of the approaches discussed in the previous paragraph. On the contrary, the solution described in this thesis considers collisions at both pairs of transmitter and receiver which are named as primary and secondary users. After interference mitigation techniques for heterogeneous radio environments are described, in the following, state of the art work related to cooperative sensing is presented which is the topic of study in this thesis.

1.3.3 COOPERATIVE SENSING TECHNIQUES

Akyildiz et. al "Cooperative Spectrum Sensing in Cognitive Radio Networks: A Survey" in 2011 [5] provide a survey of various elements of cooperative sensing; Cooperation Models, Hypothesis Testing, User Selection, Sensing Techniques, Data Fusion and Control Channel and Reporting. These elements are utilized to develop the proposed cooperative sensing design in this thesis. Section 2.5 describes a detailed discussion of these elements. There are works regarding implementation and evaluations of signal processing aspects of cooperative sensing with Field Programmable Gate Arrays (FPGA) and Software Defined Radio (SDR). These works are related to the thesis as they provide implementation aspects and the related platforms on which cooperative sensing has been evaluated.

Bielefeld et. al "Optimization of Cooperative Spectrum Sensing and Implementation on Software Defined Radios" in 2010 [52] evaluate Orthogonal Frequency Division Multiplexing (OFDM) signal with cooperative spectrum sensing algorithms implemented on Software Defined Radio. Yoshimura et. al "A USRP Based Scheme for Cooperative Sensing Networks" in 2014 [43] analyze cooperative sensing algorithms with the Universal Software Radio Peripheral (USRP). Yagi et. al "Experimental Study of Cooperative Spectrum Sensing for Cognitive Radio" in 2010 [77] evaluate cyclostationary energy detection with the experimental setup. Rashid et. al "TDMA Based Cooperative Sensing using SDR Platform for Cognitive Radio" in 2012 [74] evaluate a TDMA protocol with SDR whereas Srinu et. al "FPGA Implementation of Cooperative Spectrum Sensing for Cognitive Radio Networks" in 2010 [73] evaluate cooperative sensing algorithms with FPGA. The implementation works described in this paragraph consider the elements Data Fusion and Hypothesis Testing of cooperative sensing but other elements User Selection, Sensing Techniques and Control Channel and Reporting are ignored. Therefore, for system wide performance evaluation all the elements need to be considered. Or in other words, overhead associated with cooperative sensing needs to be considered while evaluation. In this thesis, real world system wide evaluations are performed considering all the elements of cooperative sensing mentioned in the start of this paragraph. After describing implementation and evaluations of signal processing aspects of cooperative sensing, in the following state of the art works related to cooperative sensing MAC protocols are described. These works are related to this thesis, as the proposed cooperative sensing design is also at MAC layer.

Alshamrani et. al "A Cooperative MAC with Efficient Spectrum Sensing Algorithm for Distributed Opportunistic Spectrum Networks" in 2009 [6] propose a medium access control framework which integrates cooperative sensing at the physical layer. The proposed approach targets licensed bands and minimizes sensing effort for different levels of required probability of detection for limiting interference to the primary user. Furthermore, the proposed design in that work is analytically evaluated and no real world evaluations are performed. Another aspect of the proposed design in this thesis is the detailed impact of primary user traffic which has not been investigated before.

Park et. al "Performance of Joint Spectrum Sensing and MAC Algorithms for Multichannel Opportunistic Spectrum Access Ad Hoc Networks" in 2011 [33] propose an analytical framework to assess MAC layer throughput of multichannel opportunistic spectrum access ad hoc networks. In this work, the target is again licensed bands. Two models are proposed in relation to primary and secondary user traffic; macroscopic model and microscopic model. In macroscopic model, it is assumed that the time limit to detect primary user and vacate its channel is very long compared to the secondary user time slot, frame or packet length duration. On the contrary in microscopic model, the detection time is short in relation to the shortest transmission unit of the secondary user. The microscopic model assumes much higher primary user activity than the macroscopic model which justifies frequent detection cycles in order to avoid interference with the primary user. The authors propose two kinds of control channel schemes (dedicated and hopping). The analysis performed in that work again neglects the real world radio propagation conditions and provides results based upon simulations. Furthermore, the proposed design in that work does not describe any mechanism or protocol to select the cooperative nodes in an efficient manner.

Liu et. al "An Efficient MAC Protocol with Selective Grouping and Cooperative Sensing in Cognitive Radio Networks" in 2013 [27] propose a MAC protocol for cooperative sensing targeting licensed bands. Although the proposed design in that work suggests a cooperative node selection algorithm, it lacks real world radio propagation conditions in the analysis as simulations have assumptions. Lee et. al "Slow Hopping Based Cooperative Sensing MAC Protocol for Cognitive Radio Networks" in 2014 [25] propose a hopping based MAC cooperative sensing protocol to improve throughput as well as minimize interference of secondary users with the primary users. In that work, again simulations are performed which lack consideration of real world radio propagation conditions. In all the designs mentioned in this paragraph the variations in clock speed among various nodes is not considered which is not a realistic assumption in the analysis. In this thesis, this aspect is considered. The MAC protocols described in this paragraph are designed for the licensed bands (regulatory constraints for primary user) or are evaluated with simulations and lacks consideration of real radio propagation conditions. Whereas in this thesis, the design of cooperative sensing is presented for heterogeneous radio environments and evaluations are based upon real experiments rather upon simulations.

In summary, all the works described in this section propose solutions for minimization of interference. The solutions are either non-cognitive based or use spectrum sensing whereas cooperative sensing has been applied to the licensed bands in the previous works. But to the best of the knowledge there is no work which considers using cooperative sensing for interference minimization targeted for heterogeneous radio environments. In the next section, contributions of this thesis are described.

1.4 CONTRIBUTIONS OF THE THESIS

The contributions of the thesis include the complete cooperative sensing design, evaluations from real world as well as from simulation perspective, recommendations for application of cooperative sensing, comparison of cooperative sensing with other standard techniques along with a possible application. In the following, the thesis contributions are described in detail.

A new set of protocols (DPE and SFE) are designed, implemented and evaluated which collect spectrum sensing reports from the cooperative nodes and control transmission of secondary user data based upon the individual and cooperative spectrum sensing results. The idea of the protocols is based upon existing work which propose to either improve the performance of sensing device or reduce the sensing period with the help of cooperative nodes. However the presented design is novel which includes synchronization frames (BEACON) and dedicated control channel. Furthermore, the proposed MAC protocol design is valid for any radio technology supporting multiple channels which is also novel in its kind.

A novel cooperative node selection protocol is proposed so that cooperative nodes are added or removed to the secondary user in a static and mobile environment. The protocol utilizes thresholds to add or remove cooperative nodes to the secondary user. The protocol considers the dynamics of the radio channel conditions as well as the mobility of the primary, secondary and cooperative nodes present in the system. Two novel registration and release procedures are introduced which assist addition or removal of cooperative nodes to the secondary user.

Two novel evaluation metrics are proposed and defined in this thesis. The first evaluation metric namely probability of error illustrates the fundamental difference between licensed and unlicensed bands for individual or cooperative spectrum sensing, although overheads associated with cooperative sensing are not considered. The second evaluation metric (Effectiveness) considers also the overheads associated with cooperative sensing. This evaluation metric is used to evaluate the system wide performance of cooperative sensing in heterogeneous radio environments which has not been discussed in state of the art.

A novel method addressed for evaluation with a testbed is demonstrated to achieve reproducible scenarios. Reproducibility is an important requirement for evaluation of wireless protocols in real world scenarios. In simulations, it is easier to reproduce scenarios to achieve a certain confidence level of the results but in the real world it is challenging to reproduce the same scenario. Mobile robots are automated in a way to achieve reproducible movement. Although selected stationary scenarios do not have sufficient reliability due to unpredictable radio propagation effects, they allow qualitative comparison.

The proposed cooperative sensing design is evaluated in real world scenarios. The scenarios include both static and mobile nodes to show performance of both protocols DPE and SFE as well as cooperative node selection protocol. Real world scenarios provide confidence regarding use of cooperative sensing in real radio propagation environment but they always have limitations due to the fixed parameters of the experimental setup and long duration of experiments.

Recommendations for the parameters of the proposed cooperative sensing design are provided for maximum Effectiveness and optimum sensing period. The testbed has limited range of parameters for the proposed cooperative sensing design, therefore a simulation model has been developed based upon the real world evaluations. The simulation analysis with the developed model provides the guidelines of using cooperative sensing in heterogeneous radio environments. The analysis includes both primary user traffic patterns as well as the related parameters of the proposed DPE protocol. Regarding cooperative sensing, system level recommendations are provided: for example optimum sensing period, maximum effectiveness, control channel usage, performance margin of cooperative sensing as compared with individual spectrum sensing.

Cooperative sensing is compared with other standard techniques. In this regard, RTS/CTS and Busy Tone are techniques for reducing interference and collisions in wireless networks. An exemplary implementation of RTS/CTS and Busy Tone schemes for heterogeneous radio environments are presented and evaluated with the help of MATLAB simulations. A number of scenarios are exploited to compare cooperative sensing to these approaches for hidden node situation.

A medical application along with exemplary evaluation is discussed. The proposed metric Effectiveness is used to evaluate cooperative sensing for reduction of collisions with minimum overhead of cooperative sensing. But application requirements in the wireless networks also need consideration. Therefore, real world evaluation for the medical field is performed where application requirements are also addressed along with reduction of collisions.

The next section describes the published works which relate to this thesis.

1.5 PUBLICATIONS

The following publications are part of this thesis.

- Tahir Akram, Tim Esemann, Horst Hellbrück, Performance Evaluation Metric for Cooperative Sensing in Heterogeneous Radio Environments , In European Wireless Conference, IEEE, 2013

- Tahir Akram, Tim Esemann, Torsten Teubler, Horst Hellbrück, A Reusable and Extendable Testbed for Implementation and Evaluation of Cooperative Sensing , In The 8th ACM International Workshop on Performance Monitoring, Measurement and Evaluation of Heterogeneous Wireless and Wired Networks PM2HW2N'13, 2013.
- Tahir Akram, Horst Hellbrück, Performance Evaluation of Cooperative Sensing via IEEE 802.15.4 Radio, In Wireless Communications and Networking Conference, IEEE (WCNC 2015), 2015
- Tahir Akram, Tim Esemann, Horst Hellbrück, Cooperative Sensing Protocols and Evalution via IEEE 802.15.4 Devices, In the Special Issue of Self Optimized Radio Technologies (Journal of Physical Communication), 2016

1.6 OUTLINE

The rest of the thesis is organized as follows: In Chapter 2, the related technical background of cognitive radio, formulation of the problem and individual and cooperative spectrum sensing is presented. Chapter 3 describes the proposed cooperative sensing design which includes DPE and SFE protocols and the cooperative node selection protocol. In Chapter 4, mathematical calculations for the metric namely probability of error are shown. Later an improved version of the evaluation metric (Effectiveness) is proposed which considers also overheads associated with cooperative sensing. In Chapter 5, the experimental setup along with testbed validations are shown. Chapter 6 presents the evaluation scenarios and the related results of cooperative sensing with real radio propagation conditions. In Chapter 7, the general recommendations based upon the simulation results, scalability aspects and comparison with other techniques for reduction of collisions are presented. In Chapter 8, a medical application is shown where cooperative sensing is utilized to meet certain quality of service requirements. Finally Chapter 9 concludes the thesis with summary of the findings and the future outlook.

CHAPTER 2

INTRODUCTION TO COGNITIVE RADIO AND COOPERATIVE SENSING

The previous chapter describes the problem that is addressed in this thesis. Before a detailed cooperative sensing design is presented, this chapter shows the background of cognitive radio, spectrum sensing, radio propagation effects, problem formulation and then introduces cooperative sensing. All these topics are important for understanding the proposed cooperative sensing design and the evaluation results in the heterogeneous radio environments. First, basic principle of the cognitive radio is explained with the help of cognitive cycle in Section 2.1. Later three existing techniques of spectrum sensing are presented. These techniques are selected only to illustrate the factors influencing performance of the sensing devices. A sensing device is assumed to be a piece of hardware supported by signal processing algorithms explained in Section 2.2. Radio channel is one source besides noise which deteriorates the performance of the sensing devices. Therefore, the effects of radio channel are described in Section 2.3. After spectrum sensing and the related imperfect performance are described, in the next step the problem addressed in this thesis is formulated with the help of primary and secondary user transmitter and receiver pairs. The collisions are illustrated which occur in the hidden node scenario even with individual spectrum sensing. In order to reduce these collisions, cooperative sensing is described in the last section. The elements of cooperative sensing are presented briefly which are utilized in the proposed cooperative sensing design in the next chapter. The next section illustrates the cognitive radio with the help of cognitive cycle which is exploited by the secondary users in the proposed cooperative sensing design.

2.1 COGNITIVE CYCLE

The cognitive radio term as used by Haykin "Cognitive radio: brain empowered wireless communications" in 2005 [20] and surveyed by Wang et. al "Advances in

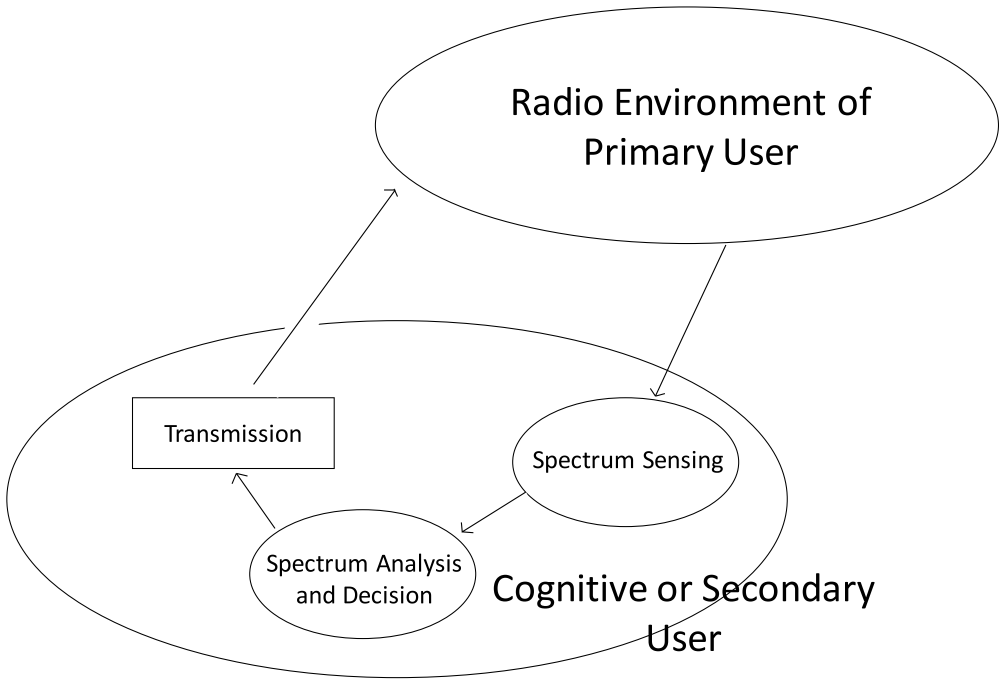

FIGURE 2.1 – *Cognitive cycle of cognitive or secondary user*

Cognitive Radio Networks: A survey." in 2011 [41] is the key technology that allows a wireless device to dynamically access the available radio spectrum. Cognitive radio was defined by Mitola et. al in his seminal work "Cognitive Radio: Making Software Radios more Personal" [30] in 1999 as "a radio or system that senses and is aware of its operational environment, dynamically and autonomously adjusts its radio operating parameters accordingly". This definition was generalized by the Federal Communications Commission "Facilitating Opportunities for Flexible, Efficient and Reliable Spectrum use Employing Cognitive Radio Technologies" [13] in 2003 to be "A radio or system that senses its electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets". From these definitions, a cognitive radio has two features that distinguish it from a traditional radio: the cognition capability and the reconfiguration. The focus of this thesis is on utilizing cognitive capability of the radio device.

Figure 2.1 illustrates how the unique functional blocks of a cognitive radio interact with the radio environment. This illustration is referred to as the cognitive cycle that is continually run by the cognitive radio to find spectrum opportunities and transmit according to the information gained from the radio environment. From hereafter the term secondary user is used instead of cognitive radio whereas primary user corresponds to the user which does not access the spectrum opportunistically. From heterogeneous radio environments point of view, all the interferers are considered as primary user. The analysis and discussion performed with the proposed cooperative sensing design in this thesis is limited to the system where both primary and secondary users are present in the system. The analysis and discussion of the situation is left for future work where all the devices are secondary users or in other words all devices are cognitive devices only and no primary user is present in the system.

In the following, the details of each block of the cognitive cycle are discussed. The first step is *Spectrum Sensing* by which secondary user gains information about the radio environment. The *Radio Environment* in the current case belongs to *Primary User*. There are various techniques regarding spectrum sensing in the literature which are discussed in more detail in Section 2.2. The second step of cognitive cycle is *Spectrum Analysis* which helps to infer the existence of spectrum opportunities in the surrounding radio environment based on the spectrum sensing information. A spectrum opportunity is defined as "a band of frequencies that are not being used by the primary user of that band at a particular time in a particular geographic area" as stated by Kolodzy et. al "Next Generation Communications: Kickoff meeting" in 2001 [66]. The other dimensions besides time, frequency and space are: angle, code, antenna selection. The focus of this thesis is on exploring spectrum opportunities by secondary user in the time and space dimension whereas other dimensions are left for future work. This is due to the reason that the focus of this thesis is on MAC layer protocol design and evaluations rather than physical layer aspects (angle, code and antenna selection) for reduction of collisions in heterogeneous radio environments.

The next step of the cognitive cycle of a cognitive radio is the *Spectrum Decision*, the set of transmission actions to be taken based on the outcome of the spectrum analysis as stated by Masonta et. al "Spectrum Decision in Cognitive Radio Networks: A Survey" in 2013 [29]. More specifically, a cognitive radio utilizes the information gathered regarding the radio spectrum to define the parameters of its radio transceiver for the upcoming transmission(s). The set of transceiver parameters to be decided depends on the underlying transceiver architecture. Examples of the action set include which spectrum is more favorable for an upcoming transmission, the time instant a transmission over a certain band starts, the maximum transmission power, the modulation rate, the spreading codes, the angle of arrival for directional transmissions and the number and identity of the antennas to be utilized in Multiple Input Multiple Output (MIMO) systems, etc. Secondary user transmits in a way that minimizes interference to the primary user.

The three steps described above are part of any design for cognitive radio. These steps are used in the proposed cooperative sensing design described in Chapter 3. After description of each functional blocks of cognitive radio, the next section describes each technique of spectrum sensing which are exploited to gain awareness about the radio environment. The purpose of discussion of each part of spectrum sensing techniques is that the imperfections with individual spectrum sensing devices are illustrated. These imperfections lead to wrong decisions and finally collisions in the networks.

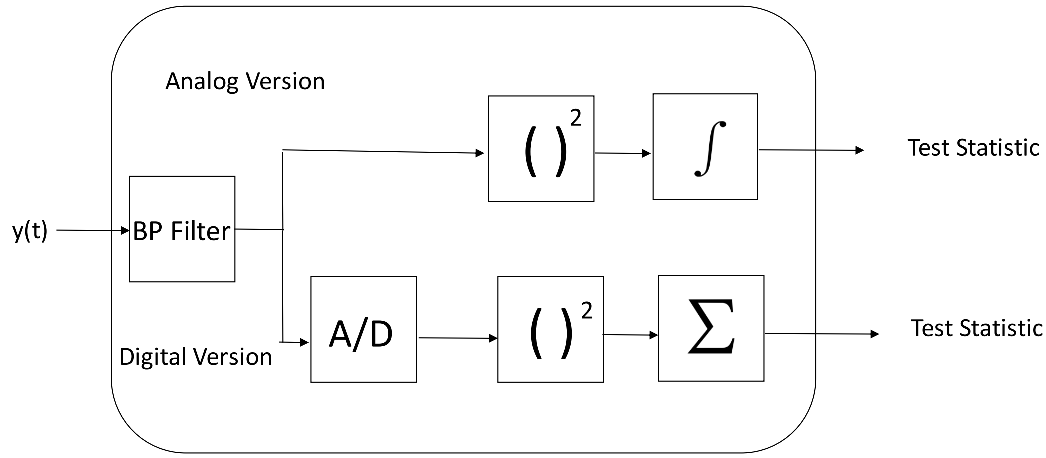

FIGURE 2.2 – *Block diagram of energy detector*

2.2 SPECTRUM SENSING

An extensive survey of spectrum sensing algorithms is given by Yucek et. al "A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications" in 2009 [45]. There are three techniques of spectrum sensing based upon how much information about the primary user signal is available to the secondary users. The most simple and widely used method is energy detection as described by Ramani et. al "Spectrum Sensing in Cognitive Radio using Energy Detection under non Fading Environment" in 2016 [35] and by Atapattu et. al "Energy Detection for Spectrum Sensing in Cognitive Radio" in 2014 [1]. This simple scheme accumulates the energy of the received signal for the sensing duration (T_d) and declares the radio spectrum to be occupied if the energy exceeds a certain threshold. Two kinds of probabilities are defined for a sensing device by Yucek et. al in 2009 ("A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications"); Detection Probability P_d and False Alarm Probability P_f. Detection probability is defined as the probability to detect primary user when primary user is transmitting in the radio environment but due to radio propagation effects the sensing device misses to detect the primary user. False alarm probability is defined as the probability to detect the primary user activity on the radio channel even if there is no primary user transmissions in the radio environment. These two probabilities define the performance of a sensing device and are mentioned throughout in the thesis where desired.

Figure 2.2 shows the block diagram of the energy detector. Both *Analog* and *Digital* versions are shown. A *BP filter* (bandpass) lies in the first stage to reject noise and pass the relevant radio frequency signals to be measured. In analog version, the squaring device measures the energy of the signal and later an integrator averages the signal. The output of the integrator is passed through *Test Statistics*. The test statistic decides for presence or absence of the primary user signal received y(t)at the sensing device which is given as follows:

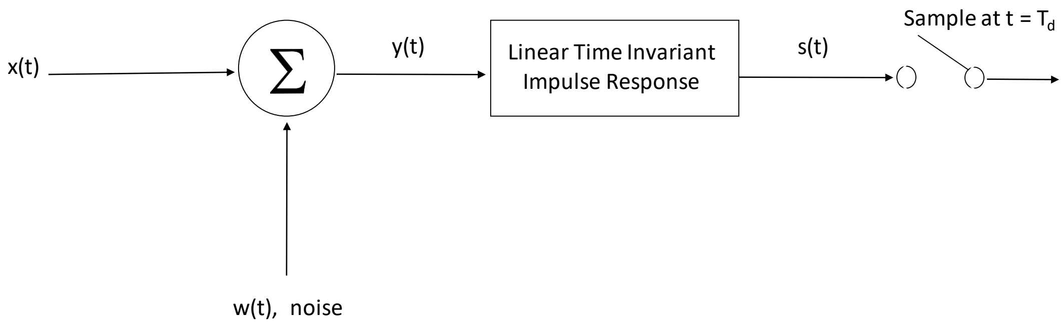

FIGURE 2.3 – *Block diagram of matched filter*

$$\Lambda = 1/T_d \int_{t-T_d}^{t} y(t)^2 \mathrm{d}t \tag{2.1}$$

Where T_d is the sensing duration of the energy detector. Λ greater than a threshold indicates presence of primary user signal while less than that threshold means absence of primary user signal. In digital version, the signal is first sampled via analog to digital convertor (A/D), then passed through squaring device $()^2$ and finally through summing device $\sum$. Finally test statistic decides for presence or absence of signal. The test statistic in digital version is given as follows:

$$\Lambda = \frac{1}{P} \sum_{n=0}^{P-1} y(n)^2 \tag{2.2}$$

Where P is the number of samples which are considered for deciding primary user presence or absence. Similar to analog version, Λ greater a threshold indicates presence of primary user signal while less than that threshold indicates absence of primary user signal. The test statistic does not distinguish noise from the actual signal rather it sums up received signal energy. Furthermore, radio propagation effects (explained in the next section) are also not distinguishable from the actual primary user signal. Therefore, energy detection is liable to noise and radio propagation effects which leads to imperfect performance of the sensing devices. Energy detection, unlike other schemes does not require any information about the primary signal (periodicity or information regarding input symbols) as its principle is based upon accumulation of the received signal energy. Although the information regarding frame durations are useful for the sensing device in this regard. The received signal includes both transmitted primary user signal with noise and radio propagation effects. Compared to other methods (discussed later in this section) it has simpler implementation and hence is less expensive. Therefore, in literature energy detection is often the choice for spectrum sensing.

Another technique of spectrum sensing is matched filter as described by Zhang et. al "Matched Filter based Spectrum Sensing and Power Level Detection for Cognitive Radio Network" in 2014 [78]. Matched filter is a coherent detection technique that employs a correlator matched to the signal of interest or certain parts of it such as pilots, preambles, spreading codes and training sequences. It is used for applications where transmitted signal is known a priori as shown by Mathews et. al in 2005 ("An FPGA Implementation of a Matched Filter Detector for Spread Spectrum Communications Systems"). The concept of this kind of spectrum sensing technique is shown in Figure 2.3. White noise w(t) is considered which is added to the unknown signal x(t). After the noise is added, the received signal y(t) is passed through a filter (*Linear Time Invariant Impulse Response*) whose impulse response is the complex conjugate of the pulse it is matched to. The signal x(t) is assumed to consist of a series of these pulses. After the received signal is filtered, the signal s(t) is sampled at time instant t = T_d which is the observation interval or sensing duration for the received signal. The design of the filter is optimized so as to minimize the effects of noise at the filter output in some statistical sense and maximize the signal to noise ratio (SNR) of the received signal, thereby enhancing the detection of the signal x(t). For the optimal performance of the matched filter, perfect knowledge of the structure and waveforms of the primary user signal (including modulation type, frame format and pulse shape) and accurate synchronization at the sensing device is required. The output Λ of the matched filter is obtained with the following equation,

$$\Lambda = \frac{1}{T_d} \int_0^{T_d} y(t) x^*(t) \mathrm{dt} \tag{2.3}$$

Where the received signal y(t) is multiplied with $x^*(t)$, the impulse response of the matched filter that is matched to the reference signal x(t) for maximizing SNR at the output of matched filter. The derivations for determining whether matched filter results in maximal SNR at the output of matched filter is described by Proakis "Digital Communications" in 1995 [34]. Finally, a threshold Λ infers presence or absence of primary user signal. In case Λ is greater than the threshold, primary user is declared to be present otherwise it is declared to be absent. As an example for matched filter, Mathews et. al in 2005 "An FPGA Implementation of a Matched Filter Detector for Spread Spectrum Communications Systems" [68] describe the use of matched filter for detection of direct sequence spread spectrum communications (spreading codes). Energy detection is not suitable for this kind of signals as the goal of spread spectrum technique is to spread the energy of a signal to a wider spectrum which makes it difficult to detect the actual signal and interference with other signals. Therefore, the impulse response of the matched filter is matched to the known code sequence of the transmitted signal in order to maximize the SNR at the output of matched filter. The implementations show that the bit serial circuit operates at an input rate of 3.4 MHz whereas 15 filter coefficients are there in the matched filter. This filter even performs better than the conventional sliding correlator synchronizer.

Another detection method that is applied for spectrum sensing is cyclostationary feature detector as described by Enserink "A Cyclostationary Feature Detector" in 1994 [57] and by Aparna et. al "Cyclostationary Feature Detection in Cognitive Radio for Ultra-wideband Communication using Cooperative Spectrum Sensing" in 2013 [9]. This detector distinguishes between modulated signals and noise as shown by Yucek et. al "A Survey of Spectrum Sensing Algorithms for Cognitive

Radio Applications" in 2009 [46] and by Cabric et. al "Spectrum Sensing Measurements of pilot, energy and Collaborative Detection" in 2006 [54]. This detector exploits the fact that the primary user signals are cyclostationary with spectral correlation due to the built-in redundancy of signal periodicity (e.g., sine wave carriers, pulse trains and cyclic prefixes) while the noise is a wide-sense stationary signal with no correlation as described by Kay "Wide Sense Stationary Random Processes" in 2006 [81]. Cyclostationary features in primary user signals are analyzed with the help of spectral correlation function. Cyclic auto correlation function $R_y^\alpha(\tau)$ of the received signal y(t) at the sensing device is given below:

$$R_y^\alpha(\tau) = \int_{-\infty}^{\infty} y(t-\frac{\tau}{2})y^*(t+\frac{\tau}{2})e^{-i2\pi\alpha t}\mathrm{d}t \tag{2.4}$$

Where α is the cyclic frequency and τ is the lag parameter as defined by April in 1991 "The Advantage of Cyclic Spectral Analysis" [79]. Using Wiener–Khinchin theorem by Leon in 1998 "The Generalization of the Wiener-Khinchin Theorem" [56], spectral correlation density $S_y^\alpha(f)$ is then described as follows:

$$S_y^\alpha(f) = \int_{-\infty}^{\infty} R_y^\alpha(\tau)e^{-i2\pi f\tau}\mathrm{d}\tau \tag{2.5}$$

Spectral correlation density is highly useful for characterization of various classes of signals. Cyclostationary feature detectors are robust to the uncertainty in noise power which is due to excessive computational complexity and long observation times for calculation of the spectral correlation function. For example, Turunen et. al in 2009 ("Implementation of Cyclostationary Feature Detector for Cognitive Radios") describe 0.82ms detection time for calculation of FFT block for WLAN signals. This detection time is comparatively long as compared to the energy detection time (2.4μs) as calculated by Liu in 2003 ("Design and Evaluation of Energy Detection Algorithms for IEEE 802.11a Systems") for WLAN signals. Furthermore, the cyclostationary feature detectors work with knowledge of the signal characteristics (periodicity, waveform shape etc.) of primary users, which may not be available to the sensing devices. As the cognitive radio is assumed to work in an environment where various technologies operate as that described for heterogeneous radio environments. Whereas these detectors have comparatively long sensing durations and they have superior performance than the energy detectors in presence of noise or radio propagation effects specially in low SNR (-30 dB) as shown by Verma et. al in 2012 "Performance Analysis of Energy Detection, Matched Filter Detection and Cyclostationary Feature Detection Spectrum Sensing Techniques" [39].

Summarizing all three kinds of detectors, the performance of spectrum sensing is not perfect due to inherent noise present in the sensing devices, limited sensing duration time and radio propagation effects. As seen from the principles of spectrum sensing, none of the spectrum sensing techniques is perfect (P_d = 100%, P_f = 0%) due to inherent noise present in the received signal and the radio propagation effects. Therefore in reality the range of detection and false alarm probabilities are $P_d \leq 100\%$ and $P_f \geq 0\%$ respectively (imperfect sensing performance). The purpose of describing spectrum sensing techniques is that the imperfect performance is illustrated. In the rest of the thesis, the signal processing aspects of spectrum sensing devices are not discussed rather only detection probability and false alarm probability are considered. As the scope of this thesis is on investigation of MAC layer design of cooperative sensing in heterogeneous radio environment rather than physical layer aspects. As described in this section that radio propagation effects are one source (besides noise and limited sensing duration) of imperfect sensing performance. The next section describes radio propagation effects.

2.3 RADIO PROPAGATION

Radio propagation is the way radio signals are transmitted from one point to another inside the earth's atmosphere or free space while traveling, the radio waves reflect from objects and multiple waves are created in this way. The reflected waves then combine at the receiving end and cause constructive or destructive interference. Radio propagation consists of various phenomena; free space path loss, multipath fading and shadowing besides others (reflection, diffraction, scattering etc.) as stated by Sarkar et. al "A Survey of Various Propagation Models for Mobile Communications" in 2003 [37]. Free Space Path Loss (FSPL) attributes to loss in radio signal strength of primary user which is mathematically described as follows.

$$FSPL = (\frac{4\pi Rf}{c})^2 \tag{2.6}$$

Where f is the radio frequency in Hertz, R is the distance from the primary user in meters to the sensing device and c is the speed of light in vacuum, 2.99792458 x 10^8 meters per second. With larger distance between sensing device and the primary user, the sensing device is not able to detect the primary user transmission due to FSPL. As the received signal strength for primary user at the sensing device becomes low and the sensing device is not able to distinguish the actual primary user signal from the noise. Based upon a threshold, the sensing device considers a low signal strength signal as noise (please see Figure 2.3 and its explanation in the previous section).

Radio environment discussed earlier contains different kinds of *Objects* in the surroundings as shown in Figure 2.4. The radio signal of the primary user reflects from these objects, therefore various copies of the same signal arrives at the sensing device. 1 represents direct whereas 2 and 3 represent reflected versions of the radio signal of Primary User (PU) arriving at the sensing device. These signals (the direct ray and the reflected versions) combine constructively or destructively at the sensing device. The attenuation or variation in signal strength of primary user due to constructive or destructive interference is known as multipath fading. The direct signal and its reflected versions are illustrated mathematically in the following. The cumulative signal y(t) arriving at the sensing device is mathematically written as

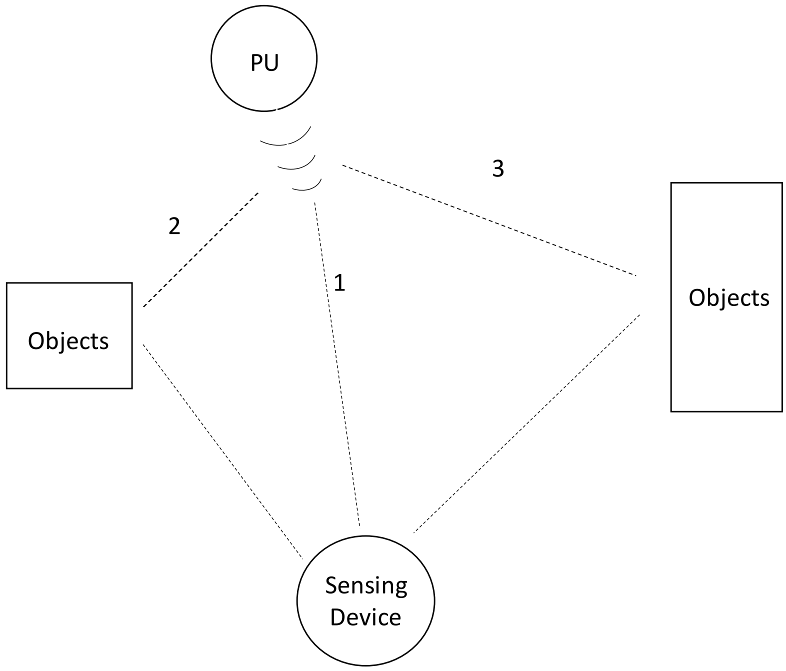

Figure 2.4 – *Various versions of PU signal superimpose at the sensing device*

$$y(t) = \sum_{n=0}^{Q-1} k_n e^{j\phi_n} x(t - \tau_n) \tag{2.7}$$

where x(t) is the transmitted signal of the primary user. Q is the number of versions of primary user signal arriving at the sensing device via different paths. $k_n e^{j\phi_n}$ denotes the complex amplitude of the individual copy of the radio signal. τ_n denotes the time delay of n_{th} version of primary user signal.

Another phenomenon is shadowing which is due to obstacles like walls or other parts of building specially in indoor environment. These obstacles reduce the strength of the primary user signal leading to situations where the sensing device is not able to detect the primary user. Multipath fading leads to small scale variations in signal strength whereas shadowing leads to large scale variations in the radio signal of primary user. Further details of these effects are given by Puccinelli et. al "Multipath Fading in Wireless Sensor Networks: Measurements and Interpretation" in 2006 [71], by Sarkar et. al "A Survey of Various Propagation Models for Mobile Communication" in 2003 [37] and by Hashemi "The Indoor Radio Propagation Channel" in 1993 [19]. Although the details are not discussed in the later part of the thesis but they are important to account for unpredictable indoor radio propagation effects in the results of Section 6.2.3. Furthermore, due to these radio propagation effects and noise in the signals, sensing device is not always able to detect primary user. In the next section, the problem described in Section 1.1 is formulated with the help of primary and secondary transmitter and receiver pairs.

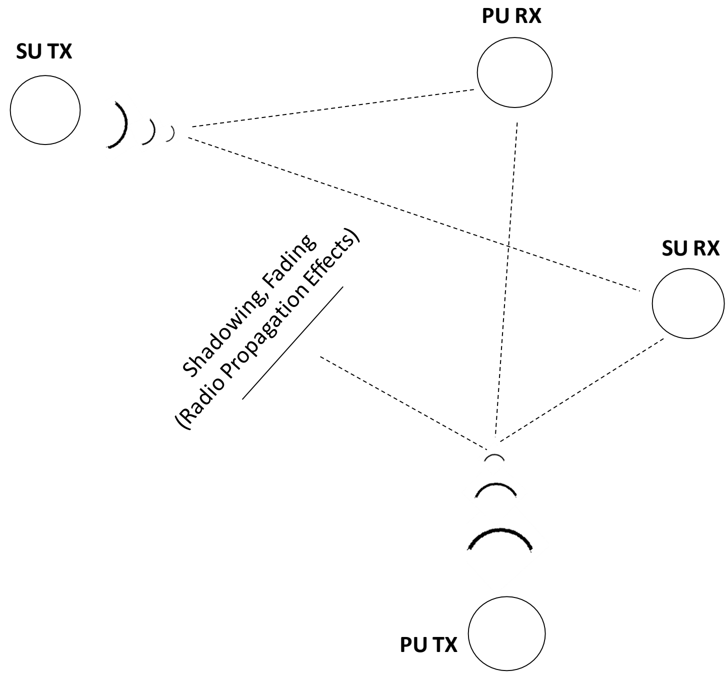

Figure 2.5 – *Primary user transmission is hidden to secondary user transmitter (SU TX)*

2.4 PROBLEM FORMULATION

The scope of this thesis is limited to heterogeneous radio environments as described in Section 1.1. The technologies (IEEE 802.15.4, IEEE 802.11 and IEEE 802.15.1 besides other proprietary standards) operate in these radio environments. All these technologies are abstracted with the introduction of cognitive radio concept as primary and secondary users. Secondary user performs spectrum sensing as described in the cognitive cycle of Figure 2.1. The performance of individual spectrum sensing devices is not ideal as described in the previous section. Therefore, the transmissions performed by the secondary user with imperfect spectrum sensing (in cognitive cycle) leads to collisions with the primary user signal.

Figure 2.5 shows the situation where secondary user transmitter is not able to detect primary user transmission. Primary User Transmitter (*PU TX*) communicates with its receiver (*PU RX*) for certain duration. Secondary User Transmitter (*SU TX*) performs spectrum sensing and transmits data based upon its spectrum sensing result to its receiver (*SU RX*) if it finds an opportunity to transmit. Due to radio propagation effects or noise, SU TX is not able to detect primary user transmission. The outcome is that the signals collide at the respective receivers of primary and secondary user. This hidden node scenario is the one where cooperative sensing is evaluated throughout in this thesis. All the nodes namely PU TX, PU RX, SU TX and SU RX are considered mobile in the scenario. In the next paragraph, the collisions are illustrated.

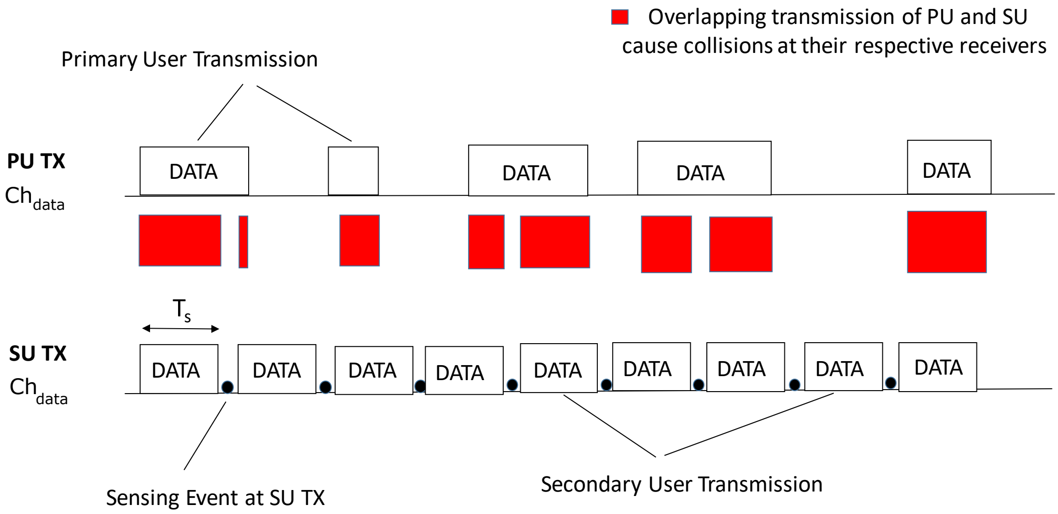

FIGURE 2.6 – *Collisions due to overlapping transmissions from PU and SU*

Figure 2.6 shows occurrence of collisions due to overlapping of primary and secondary user transmissions for the hidden node scenario shown in Figure 2.5. SU TX performs spectrum sensing (sensing event) with sensing period T_s but due to radio propagation effects, secondary user is not able to detect primary user transmissions and transmits *DATA* at the time primary user is also transmitting. The red rectangles show the times where the transmission frames from primary (PU TX) and secondary (SU TX) users collide with each other. The purpose of cooperative sensing is to reduce these collisions (red rectangles). Before the proposed cooperative sensing design is presented, the next section presents the elements of cooperative sensing which have been investigated in the past. These elements are highlighted in the next chapter to illustrate the complete design.

2.5 COOPERATIVE SENSING

Cooperative sensing is a technique where various nearby nodes cooperate and share their sensing results to improve the spectrum awareness of the wireless transmitter. As discussed in the previous section the imperfections (radio propagation effects and noise) associated with individual sensing devices leads to collisions. With the help of cooperative sensing nearby nodes cooperate with the wireless transmitter and help the transmitting device in a way that collisions are reduced in the system. Figure 2.7 shows various elements (taken from the work of Akyildiz et. al in 2011 "Cooperative Spectrum Sensing in Cognitive Radio Networks: A Survey") of cooperative sensing which are used to develop a complete cooperative sensing design in the next chapter. In the following, each element is discussed briefly.

The first element of cooperative sensing is the *Cooperation Model*. There are two kinds of cooperation models; decentralized and centralized. With decentralized model, the cooperative nodes form coalitions accordingly by appropriate grouping. Jiang et. al in 2017 "Coalition Formation and Spectrum Sharing of Cooperative

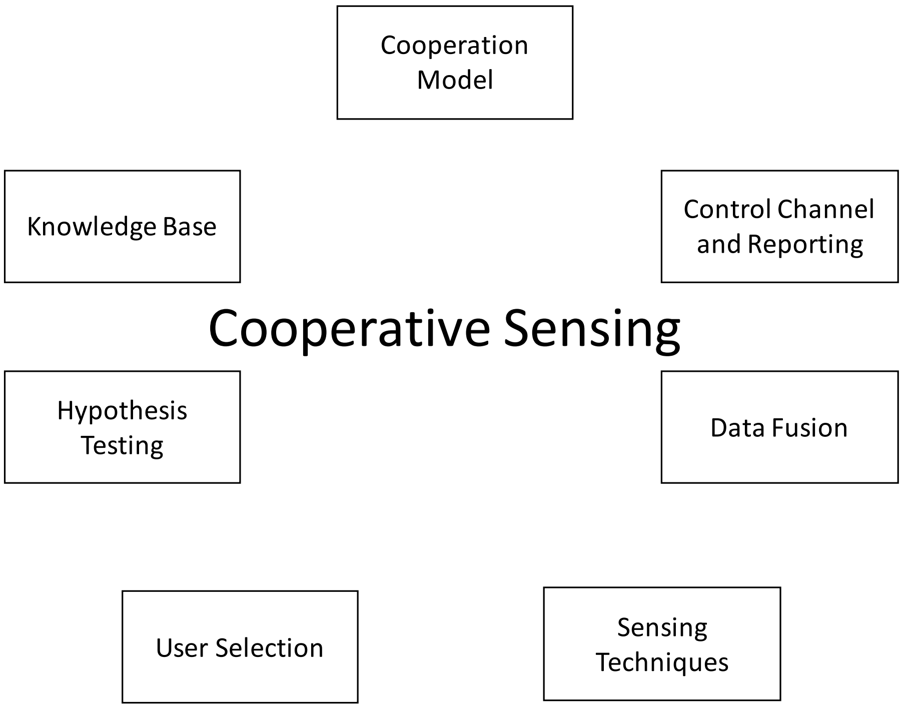

FIGURE 2.7 – *Elements of cooperative sensing*

Spectrum Sensing Particpants" [22] compare traditional techniques of coalition formation as well as spectrum sharing and present a novel technique of coalition formation and spectrum sharing. Spectrum sharing in this regard refers to the sharing of radio bandwidth for transmission among secondary users. This aspect is similar to the *Transmission* block of cognitive cycle shown in Figure 2.1. The goal of forming coalitions is to improve detection probability and efficient usage of radio spectrum (spectrum sharing). There are three coalitions shown in Figure 2.8. Each coalition has a head which finalizes the cumulative decision for cooperative sensing. Therefore in this approach cooperation is performed independently by the coalitions. The advantage of coalitions is similar to decentralized approach in general; no single point of failure and more efficient spectrum usage although forming appropriate coalitions in unpredictable radio environment is by itself challenge. The other form of cooperation model is centralized which is applied in the proposed cooperative sensing design presented in the next chapter. Figure 2.9 shows the centralized model where N cooperative nodes perform spectrum sensing and report their results to the fusion center which merges the results. Primary user transmission from PU TX is hidden to C_1 due to radio propagation effects whereas the nodes C_2 .. C_N are able to detect primary user transmission. At the fusion center cooperative spectrum sensing results are merged according to a fusion rule described later in this section. The next element of cooperative sensing is *Knowledge Base*.

The performance of cooperative sensing is improved with Knowledge Base as

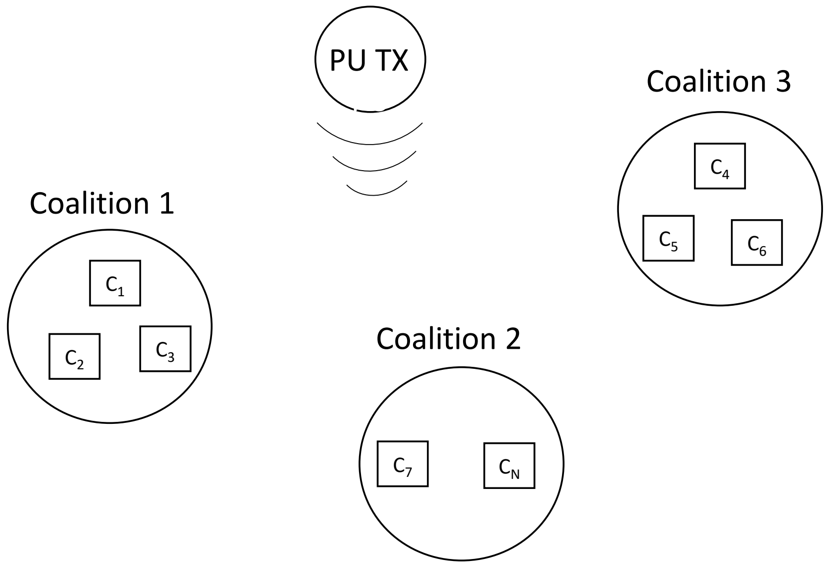

FIGURE 2.8 – *Coalition model of cooperative sensing*

additional information is provided to the cognitive or secondary users by a priori information or that gained with experience. This information assists the wireless devices in making better decisions and thereby reducing collisions in the system. This element is not addressed in the proposed cooperative sensing design and is left for future work.

Hypothesis testing is another element of cooperative sensing. There are two main approaches; threshold detector and sequential testing. In threshold detection (Neymann Pearson (NP) test), the objective is to maximize P_d given the constraint $P_f < d$ where d is maximum false alarm probability. In sequential testing, sensing time is reduced as variable number of samples are exploited subject to the detection performance constraint. On the contrary in NP based method, the number of samples are fixed. In the proposed cooperative sensing design only a threshold is utilized as experimental evaluations are based upon standard radio technology IEEE 802.15.4 supporting received signal measurements. The discussion for more complex detectors is outside the scope of this thesis.

User Selection is important element of cooperative sensing. An increase in number of cooperative nodes increases overhead. Therefore selecting an optimal number of cooperative nodes is necessary so that a balance between the gain (reduction in collisions) and the overheads are maintained. In the proposed cooperative sensing design, a cooperative node selection protocol handles the issue of user selection which is explained in Section 3.3. *Sensing Techniques* or *Scheduling* is also another element of cooperative sensing which addresses how often and in which order the cooperative nodes perform spectrum sensing. In the proposed design, two protocols (Detection Performance Enhancement and Sensing Frequency Enhancement) are described which address sensing scheduling (along with cooperative sensing report collection) of cooperative sensing.

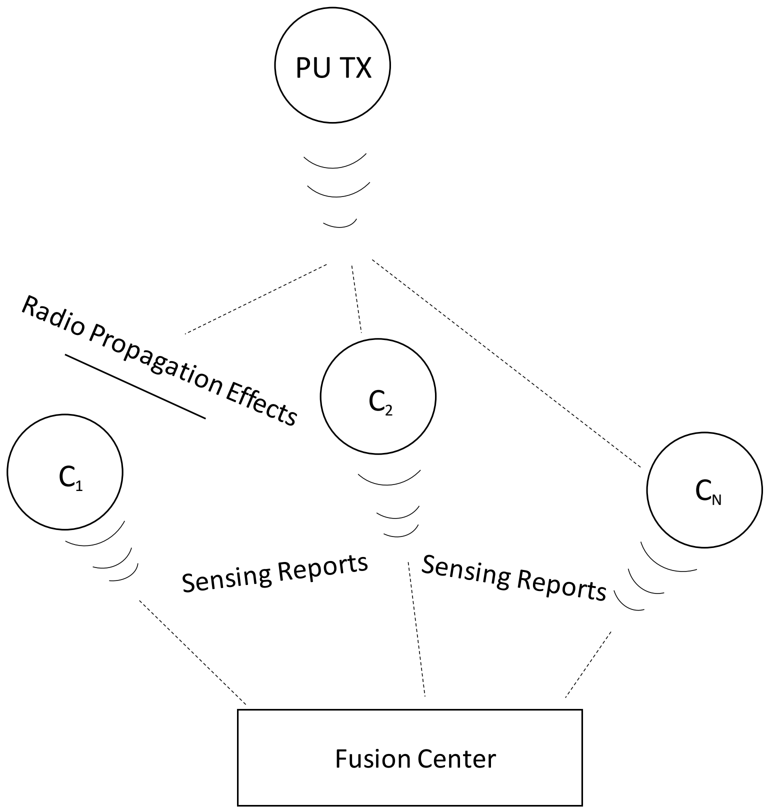

Figure 2.9 – *Centralized cooperative sensing model*

Data Fusion is the element of cooperative sensing which describes how sensing information is merged after it is collected from the cooperative nodes. There are two types of fusion rules; hard decision and soft decision as stated by Teguig et. al "Data Fusion Schemes for Cooperative Spectrum Sensing in Cognitive Radio Networks" in 2012 [75]. Hard decision relates to yes or no decision regarding the observed channel status of primary user and consists of OR, AND and Majority rule. Let v_i (i ∈ 1...N) be the individual decision of spectrum sensing performed by the cooperative node and v be the cumulative decision made by the fusion center where (v_i, v) ∈ (0,1). '0' and '1' indicates primary user absence and presence respectively. OR rule refers to the fusion rule; v = 1 if $v_i = 1$ for any i. AND rule refers to the fusion rule; v = 1 if $v_i = 1$ ∀. Majority rule refers to the fusion rule where v = 1 if at least half of the cooperative nodes report primary user channel activity as '1'.

Soft decision approaches involve sensing information rather than just yes or no decision in order to reach consensus among the cooperative nodes. The main methods for soft combining techniques are; Equal Gain Combining (EGC), Weighted Linear Combing (WLC) and Optimal Combining (OC) as stated by Alvi et. al "A weighted Linear Combining Scheme for Cooperative Spectrum Sensing" in 2014 [48]. EGC method considers spectrum sensing results from each cooperative node to be equal. Although this approach does not perform in all the conditions; for example if secondary user experiences different channel condition. Therefore, WLC solves this problem. In this approach, spectrum sensing report which receives higher signal strength is given high weight thus improving reliability of the cumulative results. The optimal combining approach is based upon likelihood ratio test and for a given hypothesis H, sensing data of a secondary user is assumed to be independent of other secondary users. The performance of WLC and OC are superior to EGC but at the cost of higher processing overheads. The scope of this thesis is limited to hard decision fusion rules whereas soft decision approach is left for future work.

The last element shown in Figure 2.7 is *Control Channel and Reporting*. In order to report spectrum sensing results by the cooperative nodes to the fusion center, both in band and out of band techniques for the control channel are discussed by Brandon "A survey of Common Control Channel Design in Cognitive Radio Networks" in 2011 [28]. Although in this article an extensive study and approaches are described, in the proposed cooperative sensing design only dedicated control channel approach is addressed. As the performance of cooperative sensing is dependent upon reliability of the transmission of cooperative sensing reports to SU TX, a dedicated control channel ensures successful transfer of cooperative sensing reports to SU TX. This leads to ease in analysis of the proposed design.

2.6 SUMMARY

Before the complete cooperative sensing design is introduced. A related background literature of cognitive radio, spectrum sensing and cooperative sensing was presented. The problem introduced in the previous chapter is formulated with the help of primary and secondary user model in a hidden node scenario. In the last step, the elements of cooperative sensing are illustrated as individual components of the complete cooperative sensing design in the next chapter. The proposed design considers all the elements described in this section except Knowledge Base which is left for future work. The goal of the proposed cooperative sensing design is to reduce collisions between SU TX and PU TX (primary and secondary users) illustrated in the problem formulation. The cooperative nodes (C_1 - C_N) perform spectrum sensing and report their sensing results to SU TX. Based upon reception of individual and cooperative spectrum sensing results, SU TX decides for transmission at appropriate times as described in the cognitive cycle as shown in Figure 2.1.

CHAPTER 3

COOPERATIVE SENSING DESIGN

In the previous chapter, an introduction is provided related to cognitive radio, spectrum sensing and its imperfections and the formulation of the problem. In the last step elements of cooperative sensing are shown. In this chapter, the complete cooperative sensing design is presented. A number of cooperative sensing MAC protocols or frameworks are discussed in Section 1.3 on Page 10. The designs proposed in these works target licensed bands. Furthermore, the goal of the previous designs is either to minimize sensing duration or to maximize secondary user throughput keeping the constraint imposed by the primary user. On the contrary the concept behind the proposed design in this thesis is to reduce collisions in heterogeneous radio environments shown in Section 1.1 and Section 2.4. The proposed cooperative sensing design is more general considering primary and secondary users and is valid for any radio technology supporting multiple channels. The proposed cooperative sensing design is implemented at the physical and MAC layer as both radio transmission and efficient radio channel utilization by primary and secondary users are part of the design. The proposed design is considered and evaluated in later chapters with special focus on heterogeneous radio environments. In this chapter, the related protocols of the proposed design are followed by an overall view of cooperative sensing design.

3.1 DESIGN OVERVIEW

The proposed cooperative sensing design uses a dedicated control channel for collecting sensing reports from the cooperative nodes. The proposed design specifies each state which SU TX and the cooperative nodes pass in Figure 3.1. The proposed design considers mobility of the nodes therefore the proposed design introduces a mechanism to add or remove cooperative nodes to SU TX (*User Selection*) based upon the radio environment. Therefore, SU TX and all the cooperative nodes C_j support three states. Initially, both SU TX and the cooperative nodes are in NO-COOP state. In this state, the cooperative

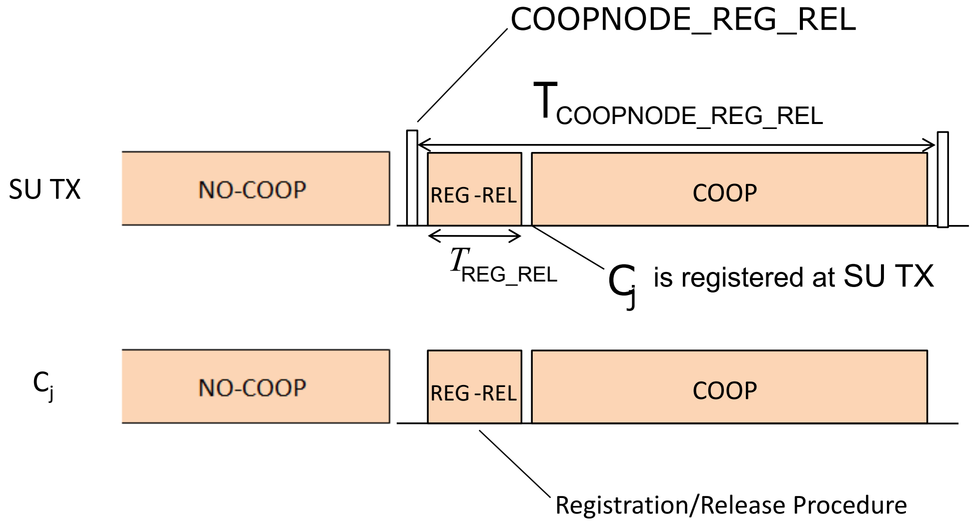

Figure 3.1 – *The states and COOPNODE_REG_REL frame of the cooperative sensing design*

nodes perform spectrum sensing but do not cooperate with SU TX. SU TX performs spectrum sensing with sensing period of T_s and transmits data based upon its own spectrum sensing results. If the result of spectrum sensing indicates that the data channel is free for transmission, SU TX transmits data until the next sensing event, otherwise secondary user transmission is postponed until the next sensing event. SU TX transmits COOPNODE_REG_REL frame periodically with $T_{COOPNODE\_REG\_REL}$ time. The purpose of this frame is to inform the presence of SU TX to the surrounding cooperative nodes. When COOPNODE_REG_REL frame is received by a cooperative node, SU TX and the related cooperative node switches to REG-REL state during which registration or release procedures are performed. Registration or release procedures add or remove the cooperative nodes at SU TX respectively. REG-REL state last for T_{REG_REL} time. If a cooperative node is registered during REG-REL state, both SU TX and the cooperative node switch to COOP state where DPE or SFE is started which are described in the next section.

Figure 3.2 shows the state diagram of the proposed cooperative sensing design at SU TX. As described earlier, SU TX transmits COOPNODE_REG_REL frame periodically requesting the surrounding nodes about its presence. Initially SU TX is in NO-COOP state. After the timeout for COOPNODE_REG_REL frame and its transmission, SU TX switches to REG-REL state and communicates with the cooperative nodes for registration or release procedures. If no cooperative node is registered or all the cooperative nodes are released during REG-REL state, SU TX switches again to NO-COOP state and performs only individual spectrum sensing. If at least one cooperative node is registered at SU TX, the state of SU TX is changed to COOP state where protocols (described in next section) for sensing scheduling and cooperative sensing report collection are started as desired. Upon timeout for COOPNODE_REG_REL frame transmission, SU

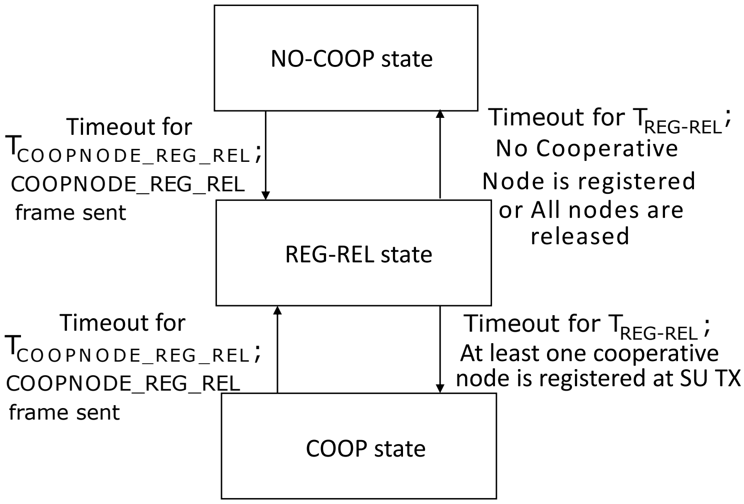

FIGURE 3.2 – *The states of the design of SU TX*

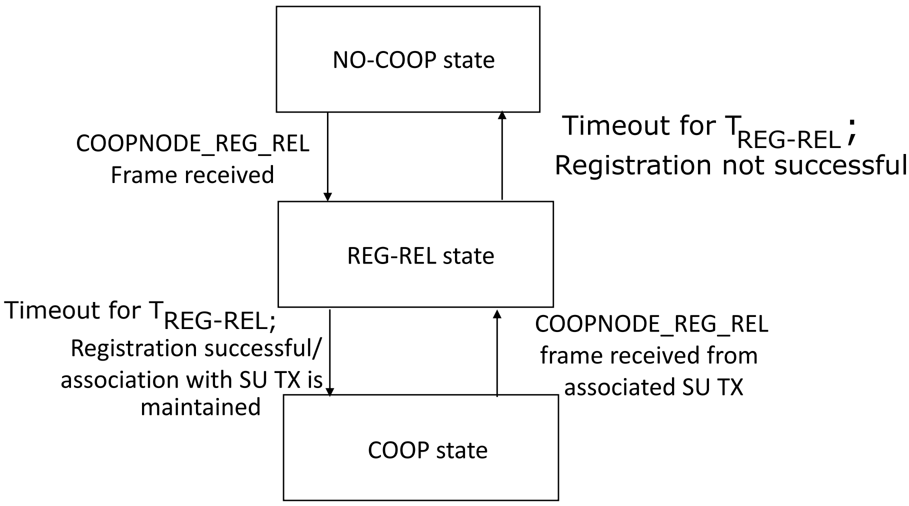

FIGURE 3.3 – *The states of the design at C_j*

TX changes its state to REG-REL state and the process is repeated as described earlier.

Figure 3.3 shows the state diagram of the cooperative sensing design at the cooperative nodes. As described earlier, initially cooperative nodes are in NO-COOP state and perform individual spectrum sensing. In NO-COOP state, the cooperative nodes continuously monitor the control channel for COOPNODE_REG_REL frame from any SU TX. If COOPNODE_REG_REL frame is received by the cooperative node, it switches to REG-REL state. In this state, it exchanges messages with the SU TX and registers itself to that SU TX. After the registration is successful, the cooperative node switches to COOP state during

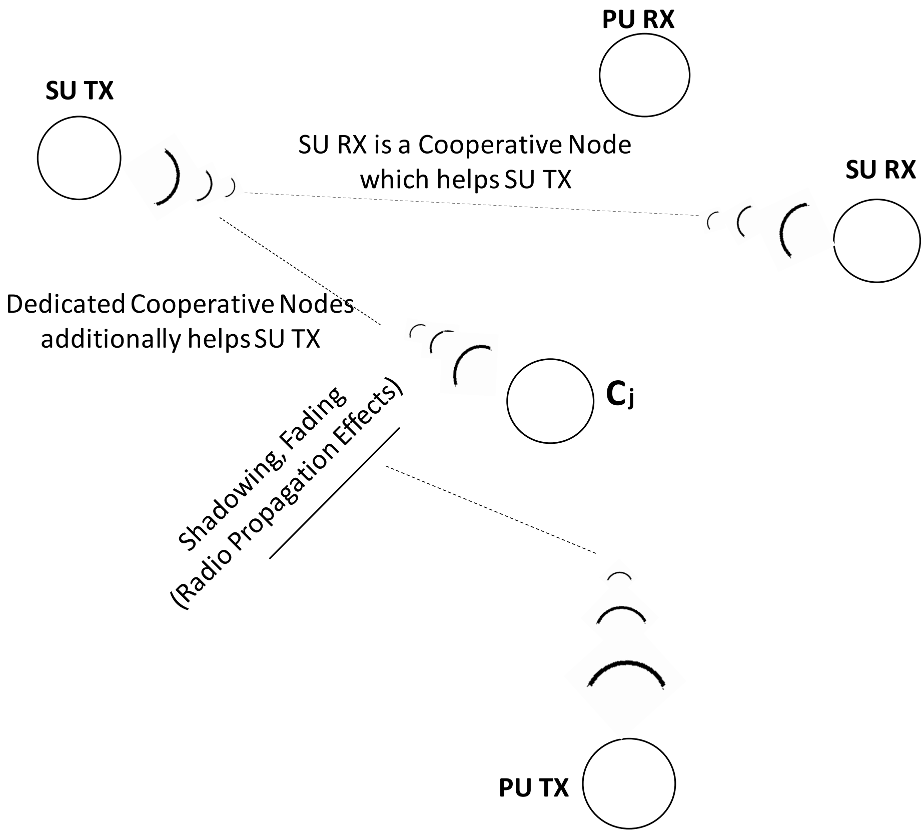

Figure 3.4 – *Candidate nodes cooperating with SU TX*

which protocols for sensing scheduling and cooperative sensing report collection are started based upon the request from the related SU TX. Later if new COOPNODE_REG_REL frame is received by the cooperative node from its associated SU TX, the cooperative node switches to REG-REL state. During this state, the cooperative nodes are released from its associated SU TX based upon the statistics of cooperative sensing reports and individual spectrum sensing. More details of the registration or release procedure is provided later in Section 3.3.

In all the previous discussion in this chapter dedicated cooperative nodes are considered for helping secondary users in order to reduce collisions shown in Figure 2.6. Although SU RX is a natural choice for cooperation besides performing reception for secondary user transmission. As secondary user transmitter communicates with its receiver SU RX in synchronous due to transmission of data frames. Therefore, SU RX is able to switch between cooperation and reception. Figure 3.4 depicts the cooperative nodes for SU TX. SU RX is shown acting as cooperative node which performs cooperative sensing as well as reception for secondary user transmitter. Additional dedicated cooperative nodes are C_j (j $\in$ 1..N-1), where N is the total number of cooperative nodes including SU RX associated with an SU TX.

As described in the start of this section, SU TX and the cooperative nodes switch among states (NO-COOP, REG-REL and COOP). Once at least one cooperative node (either SU TX or dedicated cooperative node) is registered with an SU TX, both cooperative node and SU TX switch to COOP state. In the COOP state, the cooperative nodes perform spectrum sensing and report their results to their related SU TX. Upon reception of sensing reports from the cooperative nodes, SU TX transmits data based upon its individual and cooperative sensing results. After illustration of the overall proposed design, the next section presents the protocols for sensing scheduling and cooperative sensing reports collection.

3.2 DETECTION PERFORMANCE ENHANCEMENT AND SENSING FREQUENCY ENHANCEMENT PROTOCOLS

The protocols *Detection Performance Enhancement* (DPE) and *Sensing Frequency Enhancement* (SFE) are based upon the idea proposed by Akyildiz et. al "Cooperative Spectrum Sensing in Cognitive Radio Networks: A Survey" in 2011 [5]. The proposed protocols (DPE and SFE) either improve detection performance or reduce effective sensing period at SU TX with the help of cooperative nodes respectively. An optimization is performed by improving detection performance and reducing effective sensing period simultaneously based upon primary user channel usage. But it is left for future work as this thesis analyzes DPE and SFE protocols for heterogeneous radio environments. The protocols describe how spectrum sensing reports from the cooperative nodes (dedicated or SU RX) are collected by SU TX and how secondary user data is transmitted based upon the cumulative reports (individual and cooperative) to minimize collisions with the primary user.

The idea of Detection Performance Enhancement protocol is to enhance the detection performance of SU TX by the cooperative nodes. This is achieved by fusing spectrum sensing results of secondary and cooperative nodes according to a fusion rule (*Data Fusion*). The thesis is limited to hard decision rules (OR, AND and MAJORITY) as described in Section 2.5. The idea of SFE protocol is to introduce more sensing events by the cooperative nodes between the individual sensing events performed at SU TX. Both ideas (improving detection performance or increasing sensing events) improve awareness of the surrounding radio environment for the secondary user which is the concept introduced by cognitive radio.

All the nodes are assumed to have radio device (introduced in next chapter) with a clock. The clock speed of each node is different due to crystal characteristics which is named as clock drift in this thesis. Therefore, a mechanism is developed to synchronize the cooperative nodes with SU TX. SU TX transmits BEACON frames on the dedicated control channel $Ch_{control}$ periodically with beacon period T_{BEACON} in both protocols. First DPE protocol is illustrated which is followed by an explanation of SFE protocol.

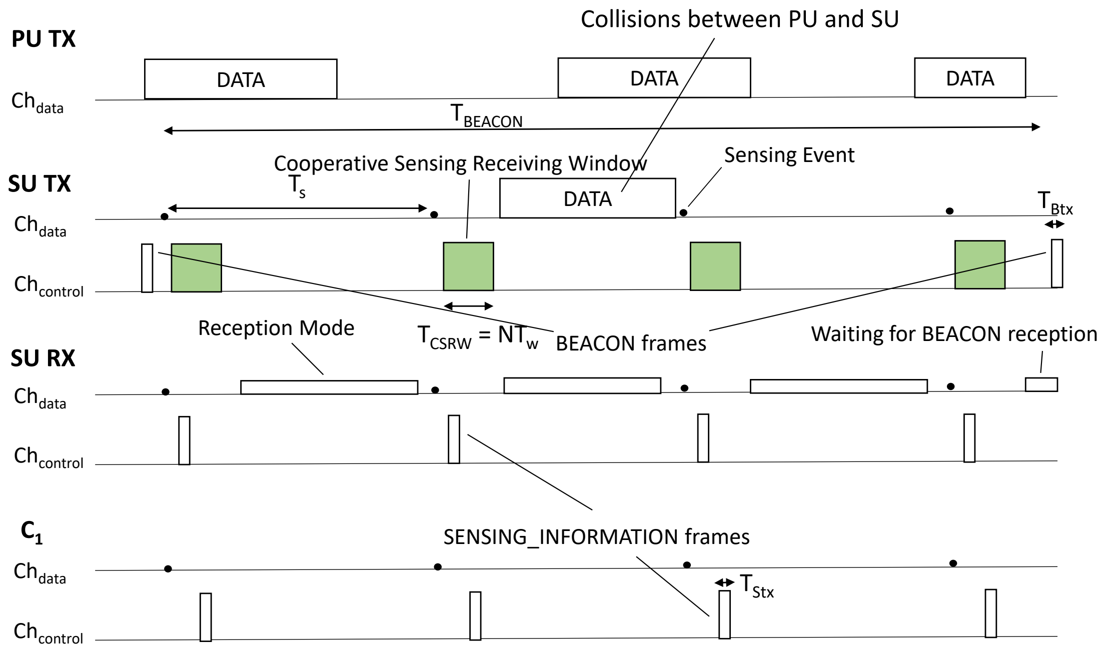

Figure 3.5 – *Detection performance enhancement (DPE) protocol*

3.2.1 DPE PROTOCOL

Figure 3.5 illustrates the DPE protocol with the cooperative nodes, SU RX and C_1. In this protocol, SU TX uses a Cooperative Sensing Receiving Window CSRW to receive the SENSING_INFORMATION frames sent by the cooperative nodes (*Sensing Scheduling* and *Control Channel and Reporting*). The time duration of this window is represented as T_{CSRW} = NT_w. Where N is the total number of cooperative nodes associated with a particular SU TX and T_w is time spent by SU TX on the control channel to receive one SENSING_INFORMATION frame. SENSING_INFORMATION frame contains the sensing result of spectrum sensing performed by cooperative node on the data channel Ch_{data}. Further details of all the frames defined in the protocols are given in Section 3.3.

SU TX performs individual spectrum sensing after T_s time which is called Sensing Period as stated by Akram et. al "Performance Evaluation Metric for Cooperative Sensing in Heterogeneous Radio Environments" in 2013 [49]. The cooperative nodes perform spectrum sensing with period of T_s and report their results to SU TX. After receiving SENSING_INFORMATION frames from the cooperative nodes, SU TX fuses result of its individual spectrum sensing with those of the cooperative nodes. If the cumulative decision of all the spectrum sensing results indicates that the data channel is free, SU TX transmits if there is data to send until the next sensing event otherwise SU TX does not transmit and waits for the next sensing event. There are two variants for the DPE protocol with SU RX or with the dedicated cooperative node. If SU RX is considered as cooperative node, DPE protocol differs with that of dedicated cooperative node C_1 in the following way. After sending sensing report to SU TX, SU RX switches to data channel

(*Reception Mode*) and is ready to receive data from SU TX. SU RX periodically switches to the control channel to receive expected BEACON frames. On the other hand, the cooperative node is free to do other tasks after it has sent the sensing report. Although Figure 3.5 shows only two cooperative nodes *SU RX* and C_1 associated with SU TX, the number of cooperative nodes are increased based upon the incurred overhead. More cooperative nodes at SU TX increase T_{CSRW} and decrease time for data transmission at SU TX. During CSRW, the control channel is occupied by SENSING_INFORMATION frames. Therefore addition of cooperative nodes imposes overhead on the control channel. The overhead $Overhead_{DPE}$ is due to SENSING_INFORMATION and BEACON frames and is given as follows:

$$Overhead_{DPE} = \frac{(N \times T_{Stx}) \times (\frac{T_{BEACON}}{T_s}) + T_{Btx}}{T_{BEACON}} \tag{3.1}$$

The terms T_{Stx} and T_{Btx} of Equation 3.1 represent the transmission times for SENSING_INFORMATION and BEACON frames respectively whereas $\frac{T_{BEACON}}{T_s}$ represents the number of sensing events between two consecutive BEACON frames. N incorporates SU RX if present with SU TX. After illustration of DPE protocol, in the next subsection details of the Sensing Frequency Enhancement protocol are illustrated.

3.2.2 SFE PROTOCOL

In this protocol, SU TX synchronizes cooperative nodes via periodic BEACON frames similar as that in the DPE protocol. Figure 3.6 illustrates the SFE protocol with both variants for SU RX and the dedicated cooperative node (C_1 for example). Similar to Detection Performance Enhancement protocol, sensing reports are collected on the dedicated control channel $Ch_{control}$ from the cooperative nodes by SU TX. In this protocol the spectrum sensing is performed by the cooperative nodes in between the individual spectrum sensing at SU TX rather than at the same time as that in DPE protocol (*Sensing Techniques* or *Scheduling*). The time duration for Cooperative Sensing Receiving Window in this case is T_w as only one SENSING_INFORMATION frame is collected at a time in this protocol. With DPE protocol, the transmission of DATA frames is performed upon the cumulative (individual and cooperative) spectrum sensing result. On the contrary in SFE protocol, the transmission of DATA frames are performed after the individual and cooperative spectrum sensing at SU TX. For illustration of experimental evaluation results in Section 6.1.3, Figure 3.5 and Figure 3.6 show the hidden node situation where SU TX alone with its individual spectrum sensing is not able to detect primary user transmission. The time duration between the cooperative (at SU RX, C_1 or any other possible C_j) and the individual spectrum sensing at SU TX is given by $\frac{T_s}{N+1}$ where N is the total number of cooperative nodes (including SU RX) associated with SU TX.

DATA consists of single or multiple frames for both primary and secondary user which are defined by PU Max Frame Size and SU Max Frame Size respectively. Both DPE and SFE protocols show the functionality how the sensing reports

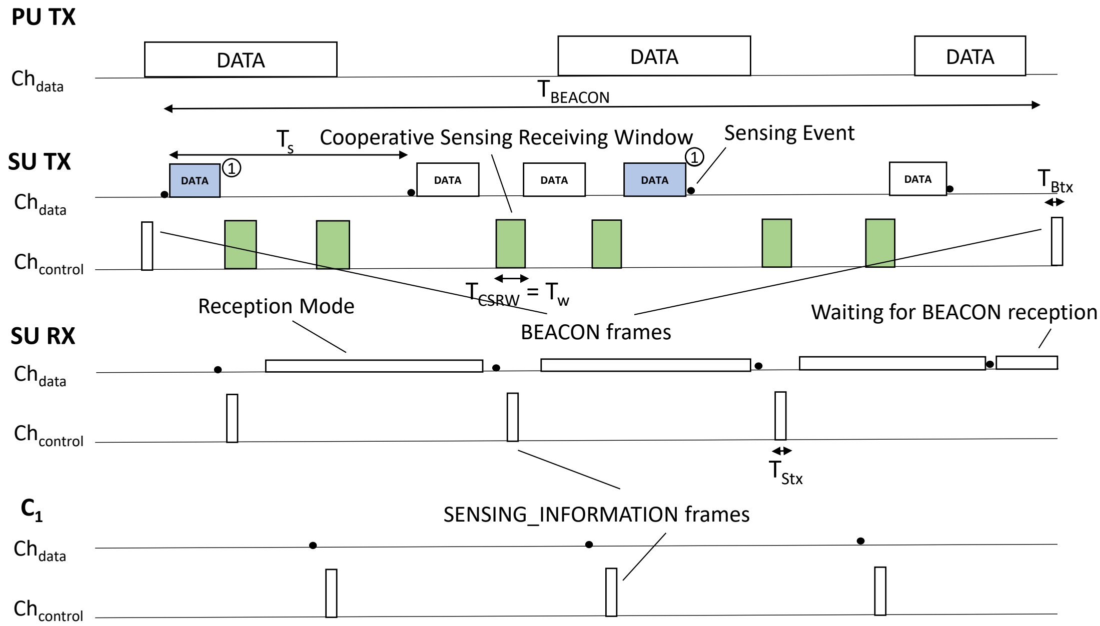

Figure 3.6 – *Sensing frequency enhancement (SFE) protocol*

from the cooperative nodes are collected by SU TX. They also illustrate how SU TX makes decision (either cumulative result or on individual and cooperative spectrum sensing results respectively) about transmission of data. This is in accordance with the cognitive cycle where each block of Figure 2.1 (Spectrum Analysis and Decision, Transmission) is part of the protocol design. DPE and SFE protocols are used during COOP state but cooperative nodes are selected for SU TX during REG-REL state. The next section presents a newly developed protocol, *Cooperative Node Selection Protocol* in this regard.

3.3 COOPERATIVE NODE SELECTION PROTOCOL

During REG-REL state, cooperative nodes are added (registered) or removed (released) at SU TX. The initial state of both SU TX and the cooperative nodes is NO-COOP as discussed already in Section 3.1. All the cooperative nodes listen to COOPNODE_REG_REL frame from SU TX on the control channel. As soon as the cooperative nodes receive COOPNODE_REG_REL frame from SU TX, both the cooperative nodes and SU TX enter REG-REL state. Before registration or release procedures are illustrated, Figure 3.7 and Figure 3.8 show the individual fields of the frames communicated during NO-COOP, COOP and REG-REL state.

Figure 3.7 shows the fields of all frame types exchanged during NO-COOP and COOP state of both secondary and cooperative nodes. COOPNODE_REG_REL frame is sent by SU TX on the control channel with period $T_{COOPNODE\_REG\_REL}$. FR_TYP field distinguishes the frame types on the control channel. SRC_ADD is the address of particular SU TX which transmits COOPNODE_REG_REL

COOPNODE_REG_REL

8 bit	16 bit	8 bit	8 bit	8 bit
FR_TYP	SRC_ADD	SPACE_AVAILABLE	PROT_TYP	T_s

BEACON

8 bit	16 bit	8 bit	Variable
FR_TYP	SRC_ADD	N	ADDRESS_LIST

SENSING_INFORMATION

8 bit	16 bit	16 bit	8 bit	8 bit	8 bit
FR_TYP	SRC_ADD	DEST_ADD	SENSING_RESULT	N	INDEX

Figure 3.7 – *Complete frames on the control channel during NO-COOP or COOP state*

frame. SU TX exploits SPACE_AVAILABLE field to inform the nearby cooperative nodes that SU TX desires more cooperative nodes in the system. There is a maximum limit for number of cooperative nodes with each SU TX due to involved overheads as discussed in the previous section. The associated cooperative nodes are informed about the type of protocol (DPE or SFE) by SU TX with PROTO_TYP field. T_s field is utilized by SU TX to inform the associated cooperative nodes regarding current sensing period. SU TX transmits BEACON frame during COOP state to synchronize the cooperative nodes. SU TX exploits the field N to inform all the associated cooperative nodes about total number of cooperative nodes registered to that SU TX. ADDRESS_LIST field contains the addresses of all the cooperative nodes registered at SU TX at any moment. The length of ADDRESS_LIST field is determined by the field N. SENSING_INFORMATION frame is sent by the cooperative node to its associated SU TX during COOP state containing the sensing result. The fields N and INDEX specify the position of the total number of cooperative nodes and the index position of that cooperative node with all the cooperative nodes. The field SENSING_RESULT holds the result of spectrum sensing result from the cooperative node. The cooperative nodes find their index in the DPE or SFE protocol with the help of ADDRESS_LIST and N field of BEACON frame of their associated SU TX. Furthermore, the lengths of the fields are specified with integer number of bytes (8 bit) and designed for the experimental evaluations for this thesis.

Figure 3.8 shows all the frames involved during registration or release procedures. All the frames (REGISTER_REQUEST_FROM_COOPNODE, ACK_REG_-TO_SUTX, REG_REQUEST_REJ_TO_COOPNODE, RELEASE_REQUEST-_FROM_COOPNODE, ACK_RELEASE_TO_COOPNODE) except ACK-_REG_TO_COOPNODE contain three fields (FR_TYP, SRC_ADD and DEST-_ADD). These fields help to identify the source and destination of the frame which are important for successful message exchange during REG_REL state of both SU TX and the cooperative nodes. Only ACK_REG_TO_COOPNODE frame has additional fields (N, T_s and PROTO_TYP) to inform the relevant cooperative nodes about the parameters of the protocol (DPE or SFE) used by

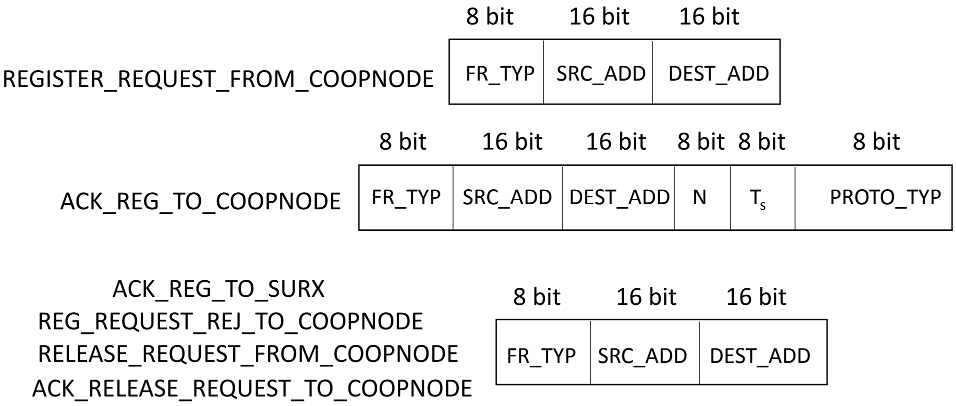

FIGURE 3.8 – *Complete frames on the control channel during REG-REL state*

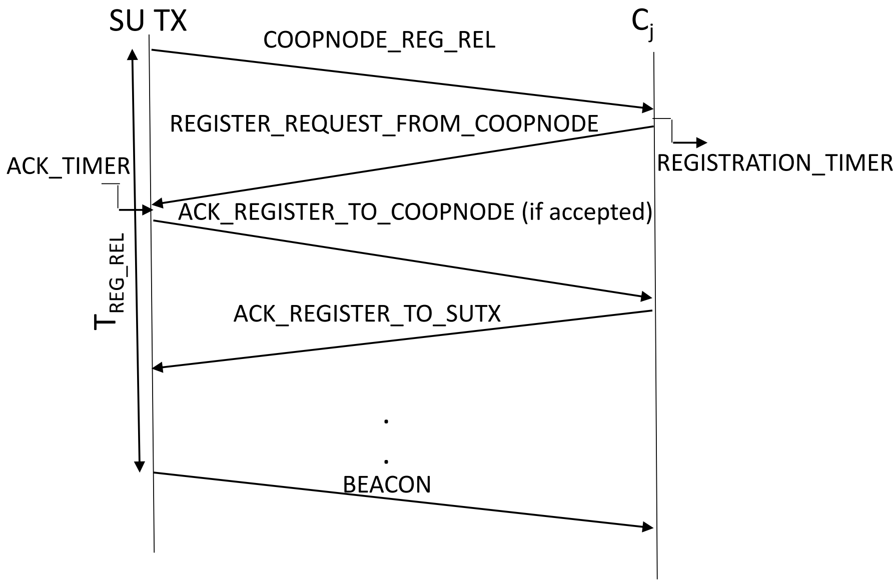

FIGURE 3.9 – *Registration procedure*

SU TX. Further illustration of the message exchange for all frames mentioned in this section is given in the following subsections.

3.3.1 REGISTRATION PROCEDURE

Figure 3.9 shows the registration procedure during REG-REL state among SU TX and the cooperative nodes. In NO-COOP state, the cooperative nodes perform individual spectrum sensing at data channel with sensing period, T_s and between sensing events the cooperative nodes switch to control channel to receive COOPNODE_REG_REL frame from SU TX. The purpose of performing spectrum sensing is that the cooperative nodes do not have to wait to perform another round of measurements to see whether they are useful for cooperation or not. The criterion for being useful is described with the help of thresholds later in this section. There is a SPACE_AVAILABLE field of COOPNODE_REG_REL (see previous subsection) frame sent by SU TX to inform the nearby cooperative nodes if that SU TX requires cooperative node at that time or not. Yang et. al in 2013 ("User Selection Based Cooperative Spectrum Sensing for Cognitive Radio Networks") show a criterion of PU busy detections and optimize the probability of false alarms. In that work, a training period detects the primary user activity. During the training period, the nodes which has high PU detection counts are selected. Consequently, performance with selective cooperative sensing is better as compared with non-selective cooperative sensing. Therefore, selecting best nodes for cooperation leads to efficient cooperative sensing due to involved overhead (see N in Equation 3.1). A similar method for node selection is part of the design in the proposed cooperative sensing protocols. The method in the form of protocol in the proposed design is different in a way that it also addresses the dynamic radio propagation effects (mobility aspects of the SU TX and the cooperative nodes) and no offline procedure (training) is used. The proposed design defines the mechanism to add or release the cooperative nodes dynamically considering the need by SU TX and the associated overheads of cooperative sensing. In the following, the proposed protocol is illustrated in detail.

As soon as, the cooperative node receives COOPNODE_REG_REL frame and SPACE_AVAILABLE is true, the cooperative node counts the number of times the data channel is detected busy from its own individual spectrum sensing. That counter value is divided by the total number of spectrum sensing events performed at the cooperative node to achieve a ratio r_{REG_REL}. If r_{REG_REL} is greater than a threshold ($Threshold_{REG}$ with value in range 0-1), the cooperative node sends REGISTER_REQUEST_FROM_COOPNODE to the respective SU TX. If $Threshold_{REG}$ is low, the probability that the relevant cooperative node is strong candidate is low although the cooperative node is easily registered to SU TX. If $Threshold_{REG}$ is high, the probability that the relevant cooperative node is a strong candidate is high but registration of cooperative node is difficult due to high threshold value. The selection of an appropriate value for $Threshold_{REG}$ depends upon the radio environment and mobility of SU TX and the cooperative nodes and therefore referred to Section 6.3.2 for implementation.

After transmission of REGISTER_REQUEST_FROM_COOPNODE frame, the cooperative node starts a timer (REGISTRATION_TIMER) in parallel for re-transmission attempts in case REGISTER_REQUEST_FROM_COOPNODE is not received by SU TX. When a new registration request arrives from a cooperative node, SU TX puts the address of that cooperative node in its inprocess registration list and sends ACK_REG_TO_COOPNODE to the respective cooperative node. SU TX maintains a timer ACK_TIMER for each inprocess cooperative node to retransmit the acknowledgment. If there are many offers from the multiple cooperative nodes, they are added in inprocess registration list at SU TX which are processed for registration according to the defined capacity at SU TX. A limit is imposed on maximum number of inprocess registration list due to maximum number of additional active cooperative nodes and limited number of available timers with the microcontroller. The maximum number of additional active co-operative nodes is selected based upon the overhead and the mobile environment. For evaluations performed in this thesis this number is set to 2 (excluding SU

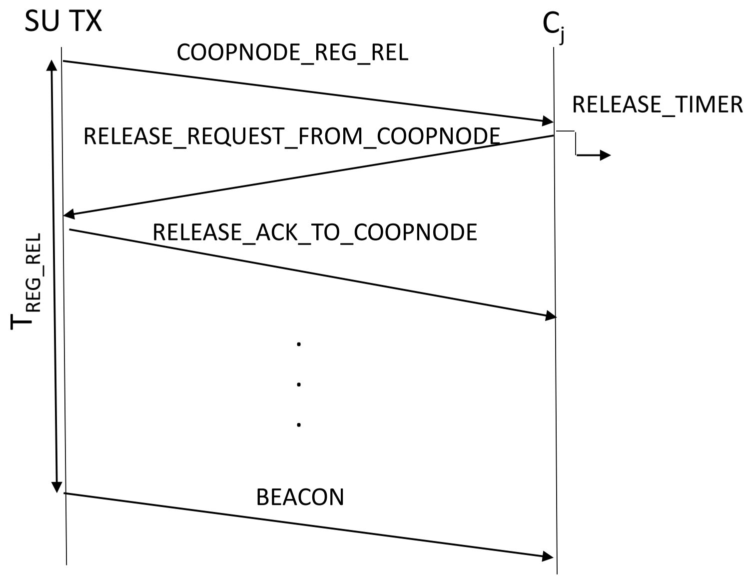

Figure 3.10 – *Release procedure initiated by C_j*

RX). If there is no room for new cooperative node in the inprocess registration list, SU TX sends REGISTER_REQUEST_REJECTED_TO_COOPNODE to the respective cooperative node. Figure 3.9 shows that inprocess registration list is refreshed after COOPNODE_REG_REL at SU TX and this list is refreshed repeatedly after $T_{COOPNODE\_REG\_REL}$ time. Upon reception of acknowledgment, the cooperative node sends ACK_REG_TO_SUTX to the respective SU TX which adjusts the DPE or SFE protocol (explained in next section) according to that. In this regard, the total number of cooperative nodes N is updated and the address of the cooperative node is added to the database of SU TX which adjusts the fields N and ADDRESS_LIST of BEACON frame. The field PROTO_TYPE is exploited to use a common protocol (DPE or SFE) by SU TX and the cooperative node. The cooperative node records the address of SU TX to which it is registered. The cooperative node sends spectrum sensing reports to SU TX with this address as destination. It is to be reminded that the ultimate decision for either to cooperate or not to cooperate is made by the cooperative node with the help of $Threshold_{REG}$.

3.3.2 Release procedure

The release procedure removes cooperative node from SU TX. The release procedure is initiated by SU TX or by the cooperative node. Figure 3.10 shows the release procedure initiated by the cooperative node. The cooperative node continuously records spectrum sensing results in COOP state for determining whether release procedure is to be performed or not. The resulting ratio r_{REG_REL} is having the same calculation as that for registration procedure. If r_{REG_REL} is lower than $Threshold_{REL}$, the release procedure is started as the cooperative node is no more useful for SU TX in this situation. Furthermore, it is another

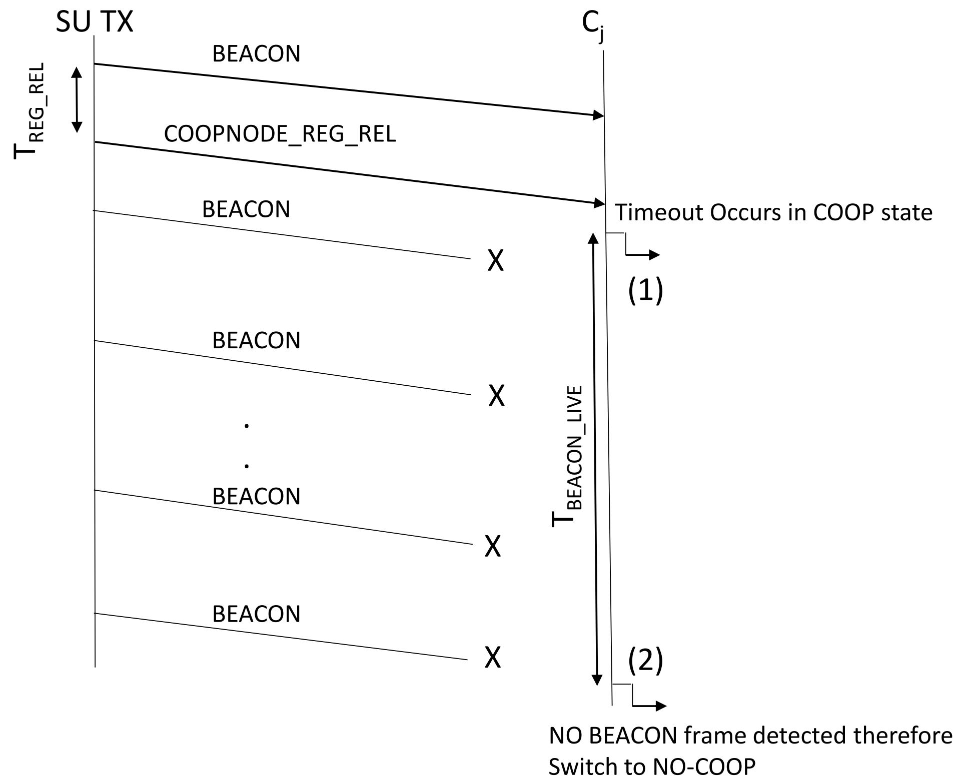

Figure 3.11 – *Release procedure initiated by C_j with T_{BEACON_LIVE}*

threshold besides $Threshold_{REG}$ which was discussed in the start of this section and was used for registration purposes. A low $Threshold_{REL}$ leads to stricter conditions for release of cooperative node whereas a high value leads to higher number of release procedures. If the r_{REG_REL} is lower than $Threshold_{REL}$, the cooperative node sends RELEASE_REQUEST_FROM_COOPNODE to SU TX and starts a timer RELEASE_TIMER for retransmission attempts. Upon reception of release request, SU TX removes the address from its database and sends RELEASE_ACK_TO_COOPNODE to the cooperative node. Figure 3.10 shows BEACON frame at the end of RELEASE_ACK_TO_COOPNODE frame which shows the assumption that SU TX has still at least one associated cooperative node.

There are situations in real radio environment where due to radio propagation effects, the cooperative node is not able to listen to SU TX. In this situation, the received BEACON frames at the cooperative nodes determine whether SU TX is in range or not. Figure 3.11 illustrates the release procedure with the help of BEACON frames. The cooperative node checks periodically with T_{BEACON_LIVE} time whether it has received any BEACON frame or not. At the timeout (1), the cooperative node C_j receives one BEACON frame and therefore stays in COOP state. At the next timeout (2), the cooperative node has not received any BEACON frame since the last timeout. BEACON frames are lost either due to radio propagation effects. Consequently, the cooperative node

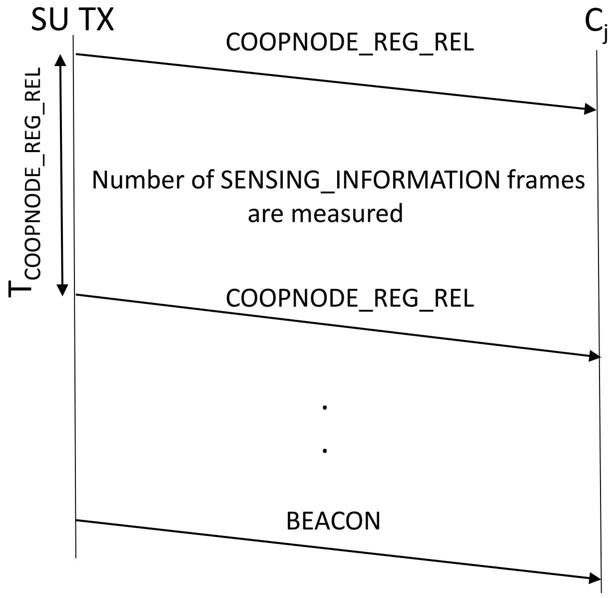

Figure 3.12 – *Release procedure initiated at SU TX*

switches to NO-COOP state and waits for next COOPNODE_REG_REL frame. The purpose of this functionality is that the cooperative node is able to serve other possible SU TX nearby rather than being associated to a SU TX to which it is no more useful.

Release procedure initiated by secondary user transmitter is shown in Figure 3.12. SU TX records the number of sensing reports (SENSING_INFORMATION frames) received from its associated cooperative nodes. A ratio r_{REL_SUTX} is calculated by dividing the received number of sensing reports by the total sensing events performed at SU TX for a particular cooperative node between two COOPNODE_REG_REL frames. If r_{REL_SUTX} is lower than $Threshold_{REL\_SUTX}$, SU TX removes its address from the field ADDRESS_LIST of the following BEACON frame. r_{REL_SUTX} is different than $r_{REL\_COOPNODE}$ as it considers only the number of sensing reports rather than considering the information contained in the sensing reports. After removal of the address of the cooperative node from ADDRESS_LIST field, in the next BEACON frame the cooperative node does not find its address in ADDRESS_LIST field and goes to NO-COOP state. If only one cooperative node is associated with SU TX, it is moved to NO-COOP state after removal of the cooperative node.

Similar to DPE and SFE protocols, the cooperative node selection protocol imposes overhead due to REG-REL state during which all communication messages (see start of this section) are exchanged among SU TX and the cooperative nodes on the control channel. This overhead is given as follows:

$$Overhead_{NODE\_SEL} = \frac{T_{REG\_REL}}{T_{COOPNODE\_REG\_REL}} \tag{3.2}$$

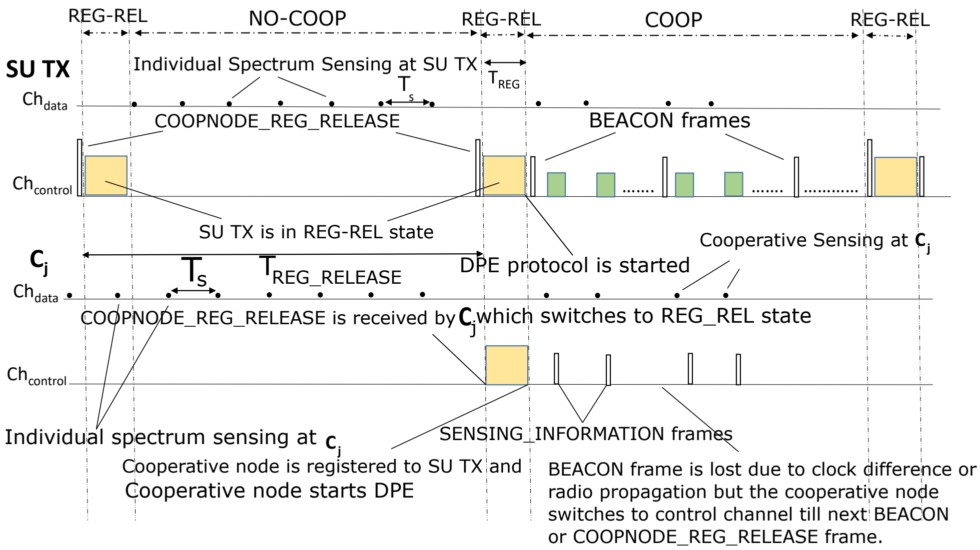

Figure 3.13 – *Extended view of the proposed cooperative sensing design*

Larger T_{REG_REL} time leads to larger time for registration or release procedure but it imposes larger overhead ($Overhead_{NODE\_SEL}$). Larger $T_{\mathrm{COOPNODE\_REG\text{-}\_REL}}$ leads to lower overhead but in high mobility environment the protocol is not predicted to perform well. Very low value of $T_{COOPNODE\_REG\_REL}$ is not recommended as it imposes high overhead on the system. Therefore appropriate values of T_{REG_REL} and $T_{COOPNODE\_REG\_REL}$ are desired to be chosen keeping in view the mobile environment, number of candidate cooperative nodes and the affordable overhead on the system. Overhead corresponds to the control channel usage for the cooperative node selection protocol but for analytical expression this is represented in terms of the time duration for REG-REL state at SU TX. The next section shows an extended view of the proposed design with DPE, SFE protocol along with various states.

3.4 FURTHER ILLUSTRATIONS

Figure 3.13 shows an extended illustration of Figure 3.1 which illustrates both the states and the details (spectrum sensing, BEACON and SENSING_INFORMATION frames etc.) of NO-COOP and COOP states. As discussed in Section 3.1, SU TX and the cooperative nodes are initially in NO-COOP state. SU TX transmits COOPNODE_REG_REL frame periodically. Initially both SU TX and C_j are not synchronized. Both SU TX and C_j perform individual spectrum sensing with sensing period, T_s. COOPNODE_REG_REL frames are sent periodically with period, $T_{COOPNODE\_REG\_REL}$. registration or release procedure occur during REG_REL state. The cooperative node, C_j switches to the control channel after performing individual spectrum sensing. As soon as the cooperative node receives COOPNODE_REG_REL frame from SU TX, it switches to REG_REL with SU TX. If the registration is successful in this REG_REL state, the cooperative node switches to COOP state with SU TX. DPE protocol is selected as an example.

SU TX collects spectrum sensing results from C_j and makes decision about transmission based upon its individual and cooperative spectrum sensing results. The purpose of COOPNODE_REG_REL frame is for registration and release of cooperative nodes. The purpose of BEACON is to synchronize SU TX and C_j so that the sensing reports are collected at SU TX at the specified time. Therefore, T_{BEACON} is always smaller than $T_{COOPNODE\_REG\_REL}$. Selection of a particular value for $T_{COOPNODE\_REG\_REL}$ is dependent upon the mobility level of nodes in the system and the overhead due to cooperative node selection protocol $Overhead_{NODE\_SEL}$. Whereas selection of T_{BEACON} is dependent upon maximum clock drift between any two nodes in the system. It is further shown in Figure 3.13 if a BEACON is lost due to clock drift or due to radio propagation effects. The cooperative node switches to the control channel till the next BEACON or COOPNODE_REG_REL frame is received. Or till the timeout for T_{BEACON_LIVE} timer occurs. The cooperative nodes are able to do other (own) tasks when they are not doing spectrum sensing, transmitting or receiving. As reception and transmission are independent tasks performed at the cooperative nodes.

Figure 3.14 illustrates addition of cooperative nodes (2) to SU TX whereas 1 cooperative node is not added as SU TX has limited capacity (inprocess registration list) during REG_REL state. In (a), COOPNODE_REG_REL frame is broadcast by SU TX with the SPACE_AVAILABLE field as 'true' which means that SU TX desires cooperative nodes. The nearby cooperative nodes (C_1, C_2 and C_3) in this example, find from their local spectrum sensing measurements that the ratio r_{REG_REL} is greater than $Threshold_{REG}$. Which means that all these nodes are useful for cooperation. Therefore, as shown in (b) all these nodes send REGISTER_REQUEST_FROM_COOPNODE frame to SU TX from which they received COOPNODE_REG_REL frame. SU TX receives the frames from C_2 and C_3 earlier than C_1. SU TX sends REG_REQUEST_REJ_TO_COOPNODE to C_1 due to limited capacity informing that SU TX is not able to accommodate during this REG_REL time. ACK_REGISTER_TO_COOPNODE frames are sent by SU TX individually each targeted for C_2 and C_3 as an acknowledgement (see (c)). C_2 and C_3 each responds with ACK_REGISTER_TO_SUTX to SU TX as shown in (d). This completes the registration procedure. As soon as timeout for REG_REL occurs, both SU TX and the cooperative nodes switch to COOP state. SU RX starts braodcasting BEACON frames. The registered cooperative nodes C_2 and C_3 get the information for sensing order from the fields (ADDRESS_LIST and N) of the BEACON frame as shown in (e). Upon reception of BEACON frame, both cooperative C_2 and C_3 transmit SENSING_INFORMATION frame destined for the respective SU TX in (f).

Figure 3.15 shows the removal of a cooperative node from SU TX. Initially in (a), it is shown that upon reception of COOPNODE_REG_REL frame two cooperative nodes (C_1 and C_2) are already registered to SU TX. But based upon the spectrum sensing measurements since last COOPNODE_REG_REL frame, $r_{REG\_REL} <$

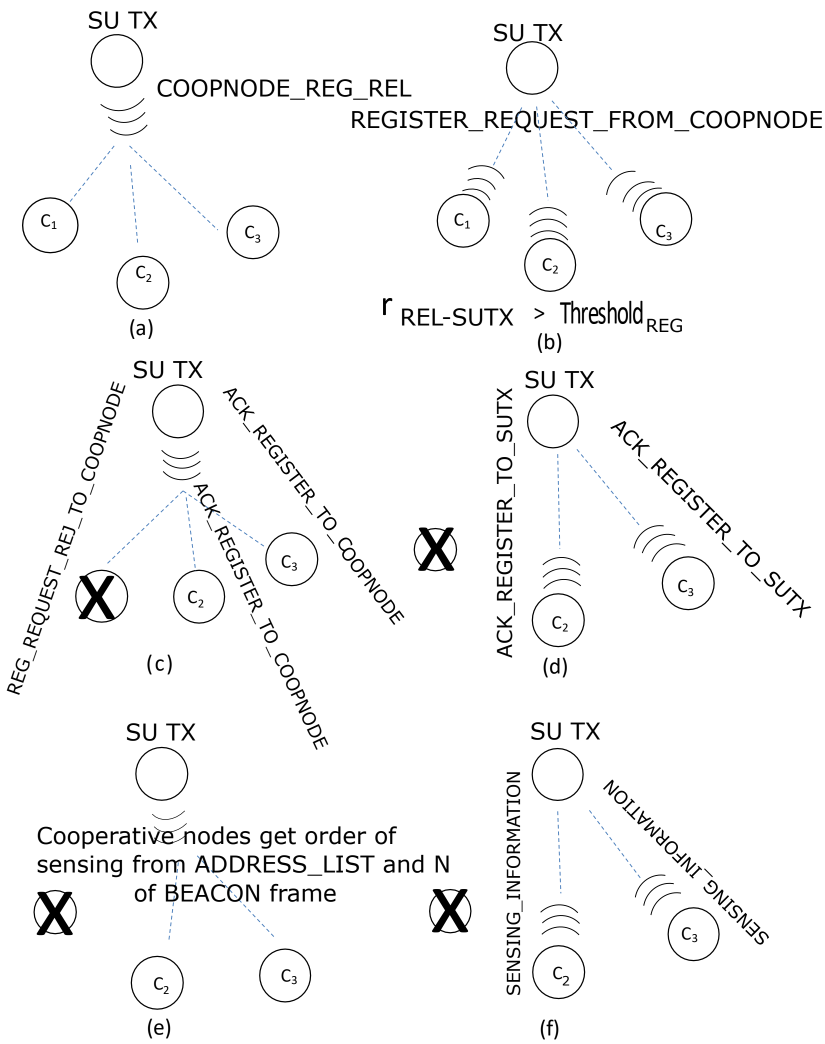

FIGURE 3.14 – *Illustration for addition of cooperative nodes to SU TX*

$Threshold_{REG\_REL}$ for C_1 which means that this node is not useful for SU TX. In (b), C_1 sends a message RELEASE_REQUEST_FROM_COOPNODE to SU TX for removal. Upon reception of this frame, SU TX responds to C_1 with RELEASE_ACK_TO_COOPNODE in (c). SU TX removes the address of C_1 from its list and in the next BEACON frame in (d), the ADDRESS_LIST field does not contain the address of C_1. Only C_2 responds with SENSING_INFORMATION frame in (e).

Figure 3.16 shows the removal of the cooperative node by SU TX. The removal of the cooperative node C_1 in this case completes in the the step (d). The time duration between two COOPNODE_REG_REL received frames at the cooperative node are considered in this removal procedure (see from (a) to (d)). It happens that not all the transmitted frames (SENSING_INFORMATION) from the cooperative node C_1 are received by SU TX. If the ratio calculation in the step (d) for C_1 comes out to be $< Threshold_{REL\_SUTX}$, the address of C_1

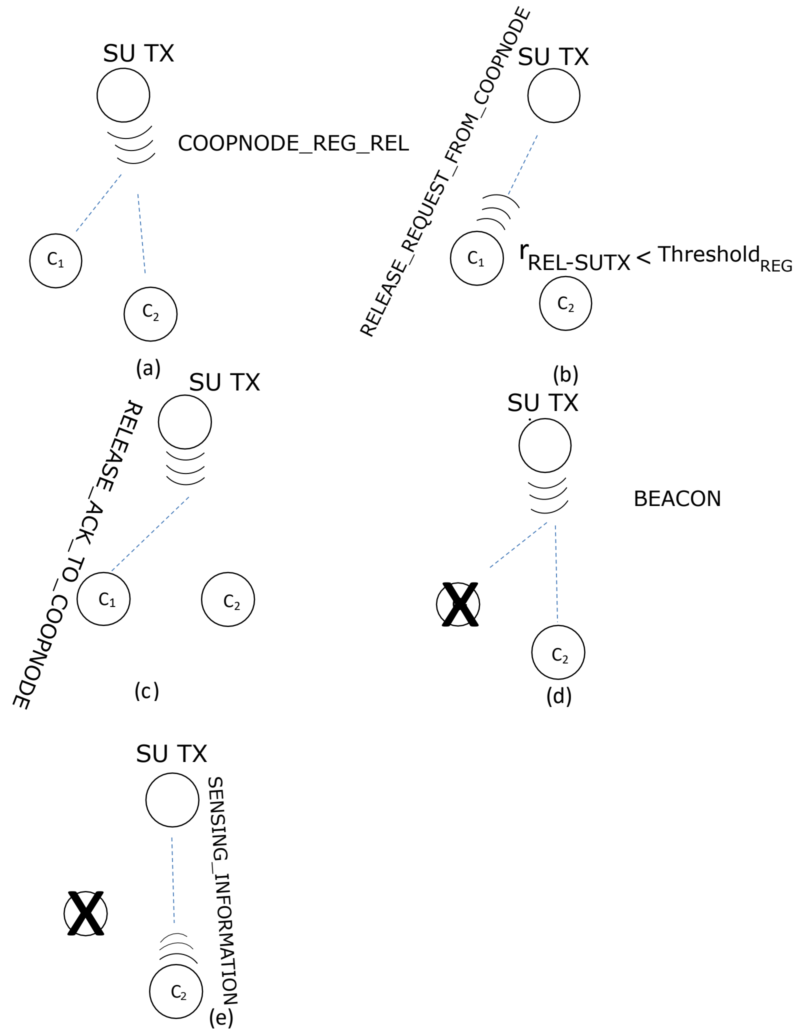

Figure 3.15 – *Illustration of removal of a cooperative node*

is removed from the list of SU TX as it is no more useful for SU TX. In the next step (e), C_1 does not receive its address in the ADDRESS_LIST field is therefore it moves to NO-COOP state to perform spectrum sensing measurements so that it is able to serve other nearby SU TX.

3.5 SUMMARY

The design described in this chapter is general which is valid for any radio technology supporting multiple channels. In later chapters, the approach is applied to heterogeneous radio environments. The proposed design exploits a dedicated control channel to get spectrum sensing results from the cooperative nodes to the secondary user. Furthermore, SU RX is also considered to be the cooperative node (besides dedicated ones) as it performs spectrum sensing. The design is associated with a list of parameters with both protocols. The parameters associated with DPE and SFE protocols are; beacon period T_{BEACON}, time duration

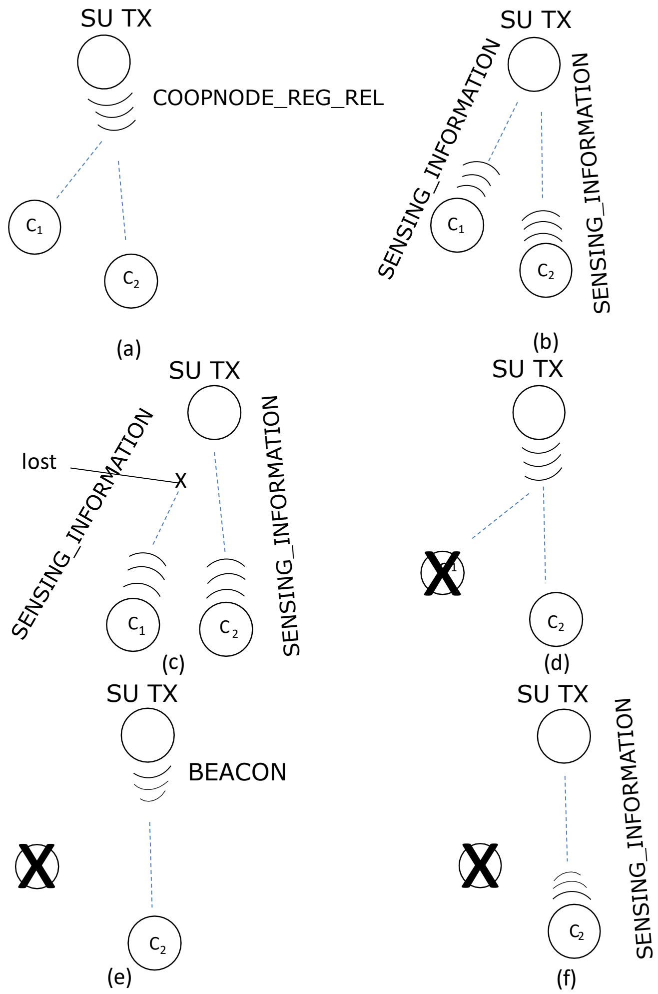

Figure 3.16 – *Illustration of removal of a cooperative node by SU TX*

for cooperative sensing receiving window for one cooperative node T_w, beacon frame transmission duration T_{Btx}, sensing information frame duration T_{Stx} and sensing period T_s whereas the parameters associated with the cooperative node selection protocol are; threshold for registration procedure $Threshold_{REG}$, threshold for release procedure at cooperative node $Threshold_{REL\_COOPNODE}$, threshold for release procedure at SU RX $Threshold_{REL\_SUTX}$ and timeout for beacon frame detection at the cooperative node T_{BEACON_LIVE}. The parameters; time period for REG-REL state T_{REG_REL} and time period for COOPNODE_REG_REL frame $T_{COOPNODE\_REG\_REL}$ relate to the overall system design. In the proposed cooperative sensing design, the cooperative nodes perform transmission of their spectrum sensing results and reception of BEACON and COOPNODE_REG_REL frames but they are able to do other (own) tasks as desired in the idle times. Therefore, the cooperative nodes do not spend 100% of time on cooperation but rather it depends upon T_{BEACON} and $T_{COOPNODE\_REG\_REL}$ values. The overheads with both DPE and cooperative node selection protocols of cooperative sensing are quantified. Furthermore, the frame structure for the messages between the cooperative nodes and SU TX are also illustrated with the help of examples. Before experimental and simulation evaluation results are presented, the next chapter describes the evaluation metric.

CHAPTER 4

EVALUATION METRIC

As discussed in Section 2.5, cooperative sensing addresses the imperfections, collisions with the individual spectrum sensing. But the cooperative sensing incurs overheads due to additional control channel usage. Therefore a new evaluation metric is required to be developed which considers both the benefits of reduction in collisions and the overheads whereas the special focus is on heterogeneous radio environments. The definition of the evaluation metric consists of two steps, first an evaluation metric (probability of error) is developed which provides an understanding about the fundamental difference regarding spectrum sensing between licensed and unlicensed bands, as the focus of this thesis is on heterogeneous radio environments. An analysis with probability of error provides an insight how spectrum awareness is improved by the sensing devices in heterogeneous radio environments both in existing and in future radio networks. Furthermore, theoretical investigations regarding DPE and SFE protocols are made with probability of error ignoring the overheads of cooperative sensing in the first step. After providing initial insight to the overall problem with the analysis, an improved version of evaluation metric called Effectiveness is developed in Section 4.2 which addresses the overheads associated with cooperative sensing and provides a criterion to evaluate system wide performance. This metric is required for evaluation of system wide performance with cooperative sensing. In the next section, first probability of error is defined, derived and discussed.

4.1 EVALUATION METRIC FOR SPECTRUM AWARENESS

As given in the introduction of this chapter, the metric probability of error provides a fundamental difference for spectrum sensing in unlicensed bands, heterogeneous radio environments and licensed bands. In order to define the metric, the selected parameters T_s, P_d, P_f and primary user traffic are considered as the purpose is consideration of fundamental difference between unlicensed and licensed bands. The other parameters of the proposed cooperative sensing design;

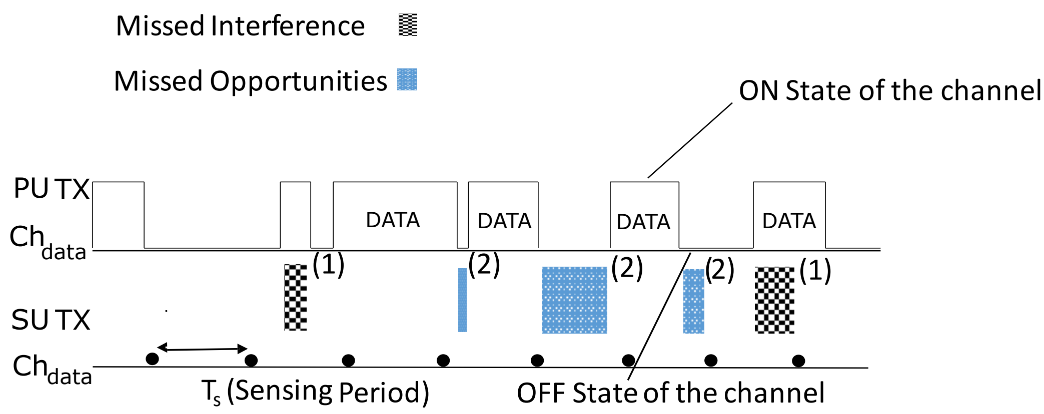

Figure 4.1 – *Missed interference and missed opportunity*

beacon period T_{BEACON}, time duration for cooperative sensing receiving window T_w, time duration for SENSING_INFORMATION frame T_{Stx}, time duration for BEACON frame T_{Btx}, time duration for REG-REL state T_{REG_REL}, time period for COOPNODE_REG_REL frame transmission $T_{COOPNODE\_REG\_REL}$, time period to check BEACON frames T_{BEACON_LIVE} and the thresholds for cooperative node selection protocol are not considered at this stage. The overhead of cooperative sensing is not incorporated yet. As discussed in Chapter 3, primary user transmits on the data channel. The primary user data traffic from PU TX is modeled as ON-OFF renewal process as described by David "Renewal Theory" in 1962 [14]) and is illustrated in Figure 4.1. This is state of the art in this field as shown by Xue et. al "Optimization of Periodic Channel Sensing by Secondary Users in Cognitive Radio Network" in 2010 [76] and by Kim et. al "Efficient Discovery of Spectrum Opportunities with MAC Layer Sensing in Cognitive Radio Networks" in 2008 [24]. In heterogeneous radio environments, primary user is seen as interferer from the secondary user perspective. Therefore, the term interferer is used in this context. During OFF time secondary user has an opportunity to send and during ON state interference occurs if the ON state is not detected by the secondary user or sensing device. The ON and OFF states of the channel are associated with the T_{ON} and T_{OFF} times respectively.

Referring to Figure 4.1, two terms are introduced; *Missed Interference* (1) and *Missed Opportunity* (2). Consider the scenario where an opportunity (OFF state) is discovered by the sensing device of SU TX. Until the next sensing event, all opportunities are explored but there is a chance that sensing device misses interference if primary user appears in the meanwhile. This event is named as missed interference. Now a scenario is considered where interference (ON state) is detected by the sensing device. Until the next sensing event, there is a chance that ON state disappears and an opportunity occurs which is missed during these two sensing events. This event is named as missed opportunity. Furthermore, missed opportunity and missed interference are mutually exclusive events during two sensing events as they do not occur simultaneously. The parameters ON and OFF times, sensing period T_s and detection performance P_d, P_f of a sensing device are selected for analysis ignoring overheads. T_s is defined as the time interval between two sensing events as described in Section 2.4. The detection performance of a sensing device is modeled as a random process with two parameters; probability of detection P_d and probability of false alarm P_f as introduced in Section 2.2. For the proposed model, sensing duration T_d is assumed to be small compared to dynamics of primary user traffic pattern. Duty cycle, u is defined as a fraction of time in which channel is in ON state,

$$u = \frac{E[T_{ON}]}{E[T_{ON}] + E[T_{OFF}]} \tag{4.1}$$

where $E[T_{ON}]$ and $E[T_{OFF}]$ represent the expected values for the duration of ON and OFF states of the channel. In the next step, probability of missed opportunity P_{mo} and probability of missed interference P_{mi} are calculated which are the basic components of P_{err} for spectrum sensing in heterogeneous radio environments.

4.1.1 DERIVATION

In order to calculate P_{mo} and P_{mi} average time of interference and opportunities are studied during the sensing period, T_s. The work of Kim and Shin "Efficient Discovery of Spectrum Opportunities with MAC-layer Sensing in Cognitive Radio Networks" in 2008 [24] is considered as a base for the calculations. First, the definitions and terms are introduced. $T_c^O(t)$ (c = 0,1) defines average time of opportunities on the channel during (t_s, $t_s + t$) whereas c represents the sample collected by the sensing device at time t_s. $T_c^I(t)$ (c = 0,1) defines average time of interference accordingly, whereas $\tilde{T}_c^I(t)$ represents the average time of interference during (t_s, $t_s + t$) in the special case when state transition occurs at t_s. Figure 4.2 shows the time duration of interferences during (t_s, $t_s + t$) for various possible scenarios. For example, Figure 4.2 (i), (ii) shows the time duration of interferences, $T_0^I(t)$ during (t_s, $t_s + t$) if the sensing device finds opportunity (c = 0) at the sensing instant, t_s. From (i), it is seen that there are no interferences until the next sensing event at ($t_s + t$), therefore $T_0^I(t) = 0$ for that scenario. From (ii), it is seen that the interferer appears earlier than the next sensing event. For this scenario the time duration of interference is dependent on the average time of interference in the time $(t - \tilde{x})$ until the next sensing event. Therefore, $T_0^I(t) = \tilde{T}_1^I(t - \tilde{x})$ for this scenario. The average time of interference during (t_s, $t_s + t$) if the sensing device finds the opportunity at t_s, $T_0^I(t)$ is given by

$$T_0^I(t) = \int_0^t \frac{\mathbb{F}_{T_{OFF}}(\tilde{x})}{E[T_{OFF}]} \tilde{T}_1^I(t - \tilde{x}) d\tilde{x} \tag{4.2}$$

$\mathbb{F}_{T_{ON}}(\tilde{x})/E[T_{ON}]$ and $\mathbb{F}_{T_{OFF}}(\tilde{y})/E[T_{OFF}]$ are probability density functions of the remaining time in ON and OFF state from t_s respectively. Similarly, the expressions for $T_1^I(t)$, $\tilde{T}_0^I(t)$, $\tilde{T}_1^I(t)$ are written as follows:

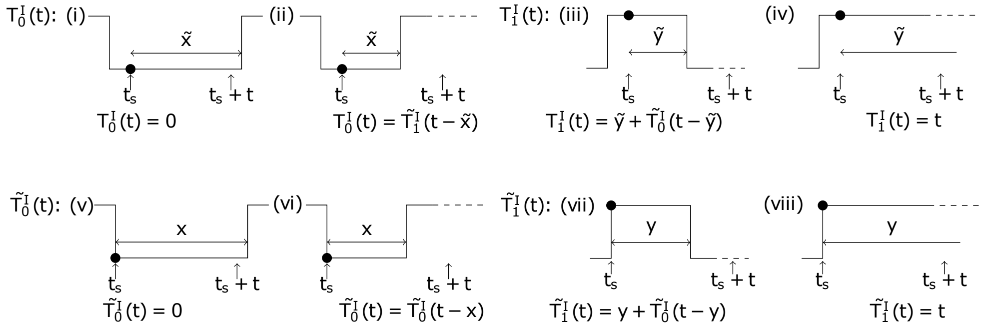

FIGURE 4.2 – *Illustration of $T_c^I(t)$ and $\tilde{T}_c^I(t)$, $\tilde{x}/\tilde{y}$*

$$T_1^I(t) = \int_0^t \frac{\mathbb{F}_{T_{ON}}(\tilde{y})}{E[T_{ON}]}(\tilde{y} + \tilde{T}_0^I(t - \tilde{y}))d\tilde{y} + t\int_t^\infty \frac{\mathbb{F}_{T_{ON}}(\tilde{y})}{E[T_{ON}]}d\tilde{y} \tag{4.3}$$

$$\tilde{T}_0^I(t) = \int_0^t f_{T_{OFF}}(x)\tilde{T}_0^I(t - x)dx \tag{4.4}$$

$$\tilde{T}_1^I(t) = \int_0^t f_{T_{ON}}(y)(y + \tilde{T}_0^I(t - y))dy + t\int_t^\infty f_{T_{ON}}(y)dy \tag{4.5}$$

where $f_{T_{ON}}(x)$ and $f_{T_{OFF}}(y)$ are probability density functions of durations for ON and OFF states of the channel respectively. In case the transition occurs at t_s, x/y is used instead of $\tilde{x}/\tilde{y}$. In order to calculate $T_c^O(t)$, Figure 4.3 is referred and the calculations are performed as done for $T_c^I(t)$. Whereas for $T_c^O(t)$, the expressions $T_0^{O*}(s)$ and $T_1^{O*}(s)$ are obtained from the work of Kim et. al "Efficient Discovery of Spectrum Opportunities with MAC Layer Sensing in Cognitive Radio Networks" in 2008 [24],

$$T_0^O(t) = \int_0^t \frac{\mathbb{F}_{T_{OFF}}(\tilde{x})}{E[T_{OFF}]}(\tilde{x} + \tilde{T}_1^O(t - x))d\tilde{x} + t\int_t^\infty \frac{\mathbb{F}_{T_{OFF}}(\tilde{x})}{E[T_{OFF}]}d\tilde{x} \tag{4.6}$$

$$T_1^O(t) = \int_0^t \frac{\mathbb{F}_{T_{ON}}(\tilde{y})}{E[T_{ON}]}\tilde{T}_0^O(t - \tilde{y})d\tilde{y} \tag{4.7}$$

$$\tilde{T}_0^O(t) = \int_0^t f_{T_{OFF}}(x)(x + \tilde{T}_1^O(t - x))dx + t\int_t^\infty f_{T_{OFF}}(x)dx \tag{4.8}$$

$$\tilde{T}_1^O(t) = \int_0^t f_{T_{ON}}(y)\tilde{T}_0^O(t - y)dy \tag{4.9}$$

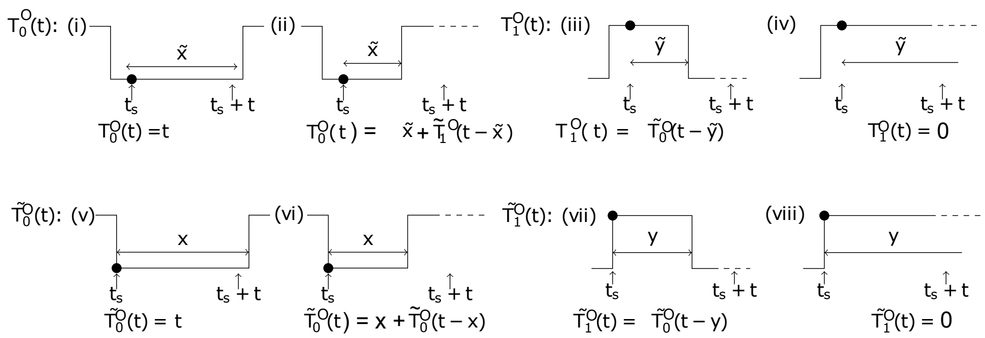

FIGURE 4.3 – *Illustration of $T_c^O(t)$ and $\tilde{T}_c^O(t)$, $\tilde{x}/\tilde{y}$*

Laplace Transformation solves for $T_0^I(t)$ and $T_1^I(t)$ and their respective expressions are written in terms of their Laplace Transforms $T_0^{I*}(s)$ and $T_1^{I*}(s)$,

$$T_0^{I*}(s) = \frac{\mathbb{F}^*_{T_{OFF}}(s)}{E[T_{OFF}]s^2} \frac{f^*_{T_{ON}}(0) - f^*_{T_{ON}}(s)}{1 - f^*_{T_{ON}}(s) f^*_{T_{OFF}}(s)} \tag{4.10}$$

$$T_1^{I*}(s) = \frac{1}{E[T_{ON}]s^2} \left[\mathbb{F}^*_{T_{ON}}(0) - \mathbb{F}^*_{T_{ON}}(s) \frac{1 - f^*_{T_{OFF}}(s) f^*_{T_{ON}}(0)}{1 - f^*_{T_{OFF}}(s) f^*_{T_{ON}}(s)} \right] \tag{4.11}$$

Similarly, Laplace Transformation calculates $T_0^{O*}(s)$ and $T_1^{O*}(s)$ as follows:

$$T_0^{O*}(s) = \frac{1}{E[T_{OFF}]s^2} \left[\mathbb{F}^*_{T_{OFF}}(0) - \mathbb{F}^*_{T_{OFF}}(s) \frac{1 - f^*_{T_{OFF}}(0) f^*_{T_{ON}}(s)}{1 - f^*_{T_{OFF}}(s) f^*_{T_{ON}}(s)} \right]$$

$$T_1^{O*}(s) = \frac{\mathbb{F}^*_{T_{ON}}(s)}{E[T_{ON}]s^2} \frac{f^*_{T_{OFF}}(0) - f^*_{T_{OFF}}(s)}{1 - f^*_{T_{OFF}}(s) f^*_{T_{ON}}(s)}$$

The terms $P_c^I(t)$ $(c = 0{,}1)$ and $P_c^O(t)$ $(c = 0{,}1)$ are defined as probability of interference and probability of opportunity during $(t_s,\, t_s + t)$ respectively where a sample c is collected by the sensing device at t_s. These terms are calculated as follows:

$$P_c^I(t) = \frac{T_c^I(t)}{t} \tag{4.12}$$

$$P_c^O(t) = \frac{T_c^O(t)}{t} \tag{4.13}$$

Finally P_{mo} and P_{mi} are function of P_d, P_f and T_s in the following:

$$P_{mo}(T_s, P_f, u) = u \cdot P_1^O(T_s) \cdot (1 - P_f) + (1 - u) \cdot P_0^O(T_s) \cdot P_f \tag{4.14}$$

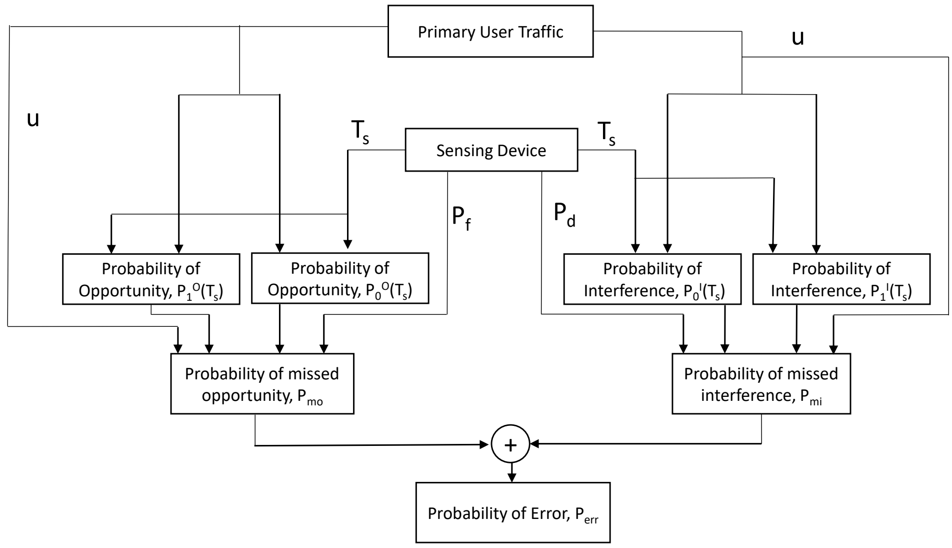

FIGURE 4.4 – *Calculation of* P_{err}

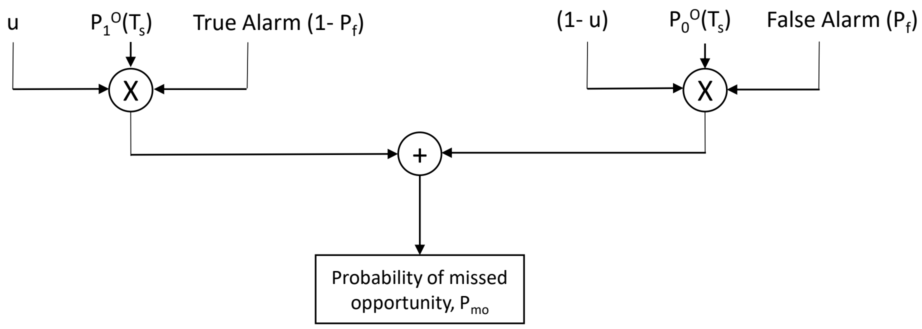

FIGURE 4.5 – *Calculation of* P_{mo}

$$P_{mi}(T_s,P_d,u) = u \cdot P_1^I(T_s) \cdot (1-P_d) + (1-u) \cdot P_0^I(T_s) \cdot P_d \tag{4.15}$$

whereas primary user traffic pattern influences the terms; u, $P_c^O(T_s)$ and $P_c^I(T_s)$. For heterogeneous radio environments each radio has equal right to access the radio spectrum. Therefore, missed opportunity is as important as missed interference. Consequently, the goal of optimum spectrum sensing is to minimize the probability of missed interference and the probability of missed opportunity. Therefore, the metric for spectrum sensing in heterogeneous radio environments P_{err} Probability of Error is defined as follows:

$$P_{err}(T_s,P_d,P_f,u) = P(mo \cup mi) = P_{mo}(T_s,P_f,u) + P_{mi}(T_s,P_d,u) \tag{4.16}$$

where missed opportunity mo and missed interference mi are mutually exclusive events. P_{err} serves as new evaluation metric for spectrum awareness in heteroge-

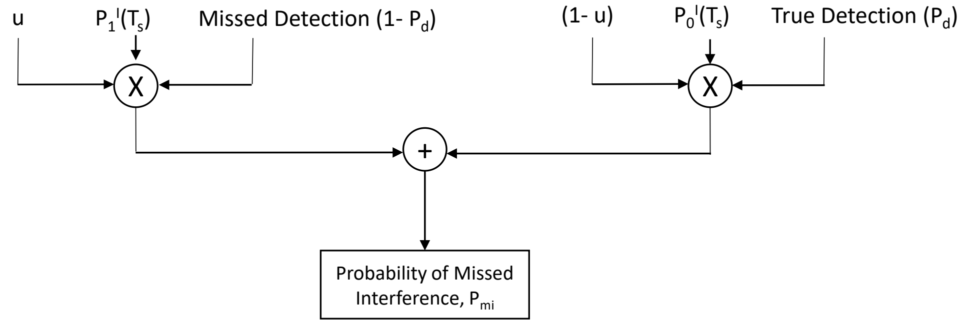

FIGURE 4.6 – *Calculation of P_{mi}*

neous radio environments which considers both P_{mo} and P_{mi} whereas in licensed bands only P_{mi} is considered. This provides the fundamental difference between evaluation criterion between licensed and unlicensed bands. If probability of error decreases, spectrum awareness is improved for the radio and vice versa. For an optimum spectrum sensing scheme, P_{err} should be minimized. Figure 4.4, Figure 4.5 and Figure 4.6 illustrate the calculation of P_{err} with the help of individual quantities P_{mo} and P_{mi}. The related equations are Equation 4.14, Equation 4.15 and Equation 4.16 for calculations of P_{mo}, P_{mi} and P_{err} respectively. Three parameters P_d, P_f and T_s are associated with the sensing device. The primary user traffic is associated with T_{ON} and T_{OFF} times and the duty cycle, u is calculated from these times using Equation 4.1. Probability of missed opportunity is the sum of two quantities. If ON state is observed, probability of missed opportunity is calculated by weighting the probability of opportunity $P_1^O(T_s)$ with u and *True Alarm* (1-P_f). On the contrary if OFF state is observed, Probability of Missed Opportunity is calculated by weighting the probability of opportunity $P_0^O(T_s)$ with (1-u) and *False Alarm* P_f. Probability of missed interference is the sum of two quantities. If OFF state is observed, probability of missed interference is calculated by weighting the probability of interference $P_0^I(T_s)$ by the corresponding weights ((1-u), *True Detection* P_d). On the contrary if ON state is observed, probability of missed interference is calculated by weighting the probability of interference $P_1^I(T_s)$ with the corresponding weights u , *Missed Detection* (1-P_d). The probability of error P_{err} is finally the sum of probability of missed opportunity and probability of missed interference.

After P_{err} is derived, the next subsection provides analysis with single user and shows influence of parameters; T_s, u, P_d and P_f. The purpose of evaluation is to show how these parameters influence P_{mi} and P_{mo} and to show that in heterogeneous radio environments P_{err} is the right metric. It is to be reminded here that the additional parameters T_{BEACON}, T_w, T_x and the thresholds related to the proposed cooperative sensing design are not considered for P_{err} as the purpose of this metric to show fundamental difference between licensed and unlicensed bands and no overheads related with cooperative sensing are considered.

Table 4.1 – *Parameter settings for Figure 4.7 and Figure 4.9*

P_d (%)	P_f (%)	Duty cycle of PU (%)
poor (80)	**high** (35)	Low (9.1), Medium (50) and High (90.9)

4.1.2 EVALUATION IN SINGLE USER SCENARIOS

Table 4.1 describes the parameter settings for analysis with single user. Two types of values for detection performance (P_d, P_f) are taken from a curve for the AWGN channel proposed by Ghasemi et. al "Opportunistic Spectrum Access in Fading Channels through Collaborative Sensing" in 2007 [18]. ($P_d = 80\%$, $P_f = 0.01\%$) represents **poor** probability of detection whereas ($P_d = 99.9\%$, $P_f = 35\%$) represents **high** probability of false alarm. It is to be noted that the hidden node scenario is not specified yet with reference to P_d and is discussed later in Section 5.3 after consideration of real radio propagation conditions. Exponentially distributed ON and OFF times for PU's traffic pattern are used as done by Xue et. al "Optimization of Periodic Channel Sensing by Secondary Users in Cognitive Radio Network" in 2010 [76] and by Kim et. al "Efficient Discovery of Spectrum Opportunities with MAC Layer Sensing in Cognitive Radio Networks" in 2008 [24]. Three exemplary scenarios are selected for the duty cycle of primary user traffic; Low (9.1%), Medium (50%) and High (90.9%) to show the trends of P_{mo}, P_{mi} and P_{err}. Figure 4.7 shows the results for a single sensing device's detection performance measured with the metric P_{err} and its components P_{mo} and P_{mi}. On the x-axis, the ratio $\frac{T_s}{E[T_{OFF}]}$ is shown which increases from left to right. To increase $\frac{T_s}{E[T_{OFF}]}$ there are two options; For a fixed value of $E[T_{OFF}]$ sensing period T_s is increased or alternatively for a fixed value of sensing period T_s, $E[T_{OFF}]$ is decreased. In this way, the impact of PU's traffic pattern as well as that of the sensing period is analyzed simultaneously. Figure 4.7(a), (b) show the case where detection probability of the sensing device is poor (80%). Figure 4.7(c), (d) show the case for high false alarm probability (35%).

In Figure 4.7, T_s increases from left to right, P_{err} increases i.e. as a longer sensing period increases both probability of missed opportunity P_{mo} and probability of missed interference P_{mi}. $E[T_{OFF}]$ and $E[T_{ON}]$ decreases simultaneously due to fixed duty cycle for a curve if we move from left to right in Figure 4.7, consequently P_{err} increases. As with larger $E[T_{OFF}]$ and $E[T_{ON}]$, the sensing device achieves better information about actual state of channel due to lower dynamics of the PU's activity. In other words, the switching from ON to OFF or OFF to ON state of the channel is at slower rate with larger $E[T_{OFF}]$ and $E[T_{ON}]$ times.

A poor detection probability of the sensing device influences probability of missed interference as shown in Equation 4.15 whereas a high false alarm probability influences probability of missed opportunity as shown in Equation 4.14. A poor detection probability increases P_{mi} severely if duty cycle of PU is high as shown in Figure 4.7(b). This is because the channel is mostly in ON state and the sensing device misses most of the interference due to poor detection probability. On the contrary, a high false alarm probability leads to a greater number of missed opportunities if the channel is mostly in OFF state (low duty cycle) as

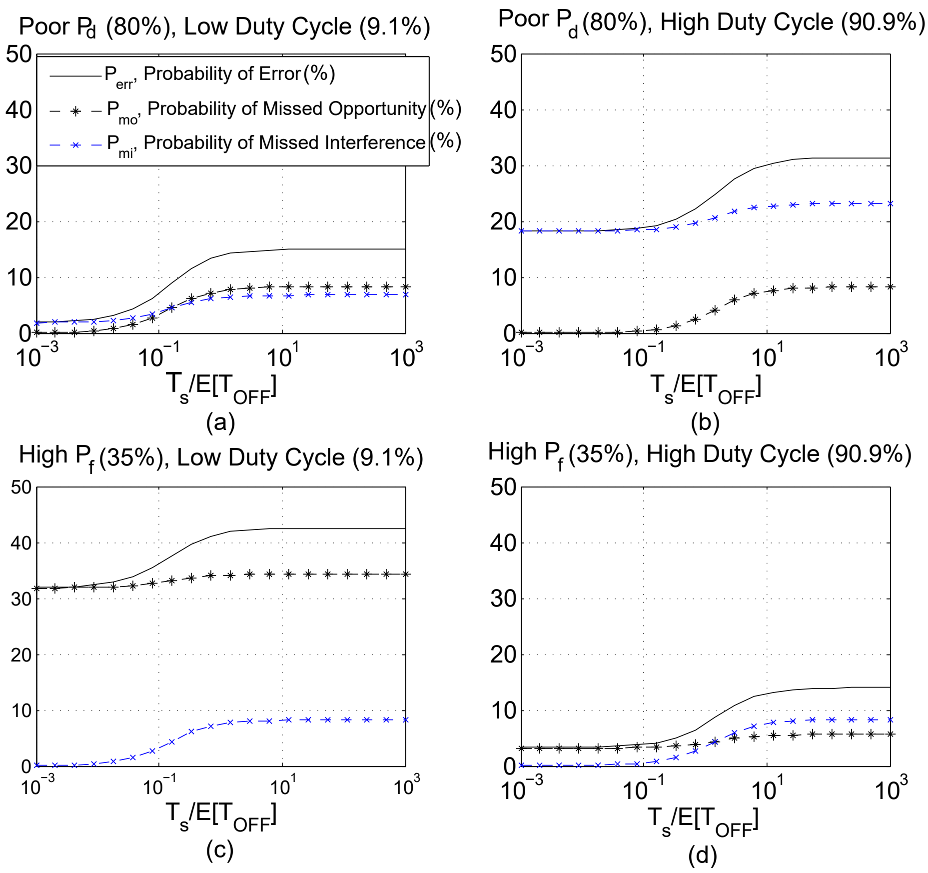

FIGURE 4.7 – *Comparison of evaluation metrics*

shown in Figure 4.7(c).

The goal of spectrum or cooperative sensing in licensed bands where we assume only a single cooperative radio transmission is to increase spectrum utilization while having an interference constraint imposed by primary user. This is achieved by keeping P_{mi} below a certain threshold while minimizing P_{mo}. Figure 4.7 shows that in one situation P_{mi} is much higher than P_{mo} (see (b)) whereas in another situation P_{mo} is dominant (see (c)). In the other two cases (see (a) and (d)), curves for P_{mo} and P_{mi} cross each other. As in heterogeneous radio environments, the goal is to optimally improve spectrum awareness. This is not achieved if only P_{mi} or alternatively only P_d is considered. For example the following works consider only P_d for cooperative sensing as used in licensed bands (described in Section 1.3). Alshamrani et. al "A Cooperative MAC with Efficient Spectrum Sensing Algorithm for Distributed Opportunistic Spectrum Networks" in 2009 [7]. Biswas et. al "Cooperative Shared Spectrum Sensing for Dynamic Cognitive Radio Networks" in 2009 [53]. Hoseini et. el "An Optimal Algorithm for Wideband Spectrum Sensing in Cognitive Radio Systems" in 2010 [64]. Park et. al "Performance of Joint Spectrum Sensing and MAC Algorithms for Multichannel Opportunistic Spectrum Access Ad Hoc Networks" in 2011 [33]. Consequently, both metrics P_{mi} and P_{mo} need to be considered with equal weight.

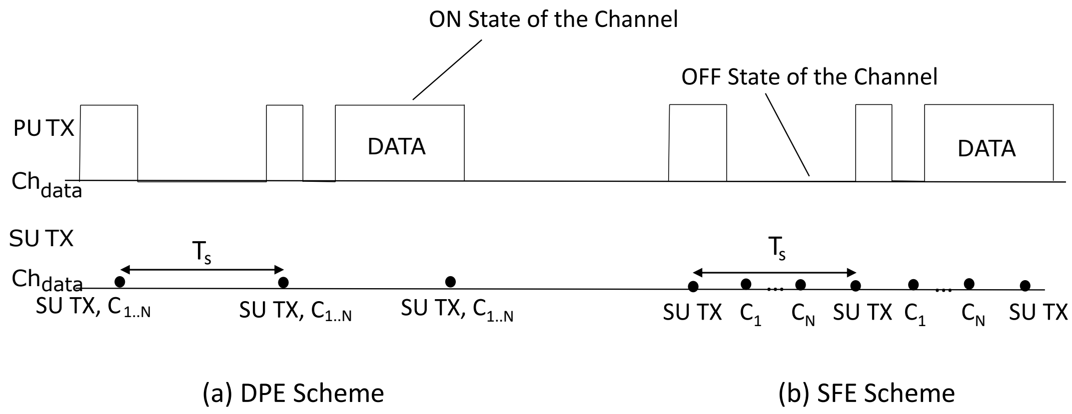

FIGURE 4.8 – *The schemes based upon DPE and SFE protocols*

This demonstrates the advantage of using P_{err} as a performance evaluation metric for spectrum sensing in heterogeneous radio environments and hence provides the fundamental difference between evaluation metrics in licensed and unlicensed bands. In the next subsection, DPE and SFE schemes are evaluated with P_{err} which are based upon the concept introduced by Akyildiz et. al "Cooperative Spectrum Sensing in Cognitive Radio Networks" in 2011 [5]. The purpose of evaluation of DPE and SFE schemes is to provide theoretical analysis with P_{err} ignoring the overheads.

4.1.3 EVALUATION OF DPE AND SFE

According to Equation 4.14 - Equation 4.16, P_{err} is influenced by two major factors; (a) detection performance of the sensing device and (b) sensing period. These two factors are the basis of DPE and SFE protocols which address the overheads associated with cooperative sensing. Consequently, spectrum awareness is improved in two basic approaches either via selecting appropriate fusion rule or via adjusting sensing period of cooperative nodes. It is to be reminded here that the purpose of evaluations in this subsection is to evaluate the concept behind DPE and SFE protocols which were described in Section 3.2. Figure 4.8 shows both DPE and SFE schemes. The sensing period, T_s is between two individual spectrum sensing events at SU TX. Whereas the cooperative nodes C_j (including SU RX) assist SU TX in DPE scheme by fusing individual and cooperative sensing results. The effective sensing period, T is equal to the sensing period of individual sensing period T_s with DPE scheme.

$$T = T_s$$

Different fusion rules are evaluated in DPE scheme as shown by Ghasemi et. al "Opportunistic Spectrum Access in Fading Channels through Collaborative Sensing" in 2007 [18] and are described in the following;

$$P_d = F_d(SU\,TX, C_1, C_2 \ldots C_N)$$

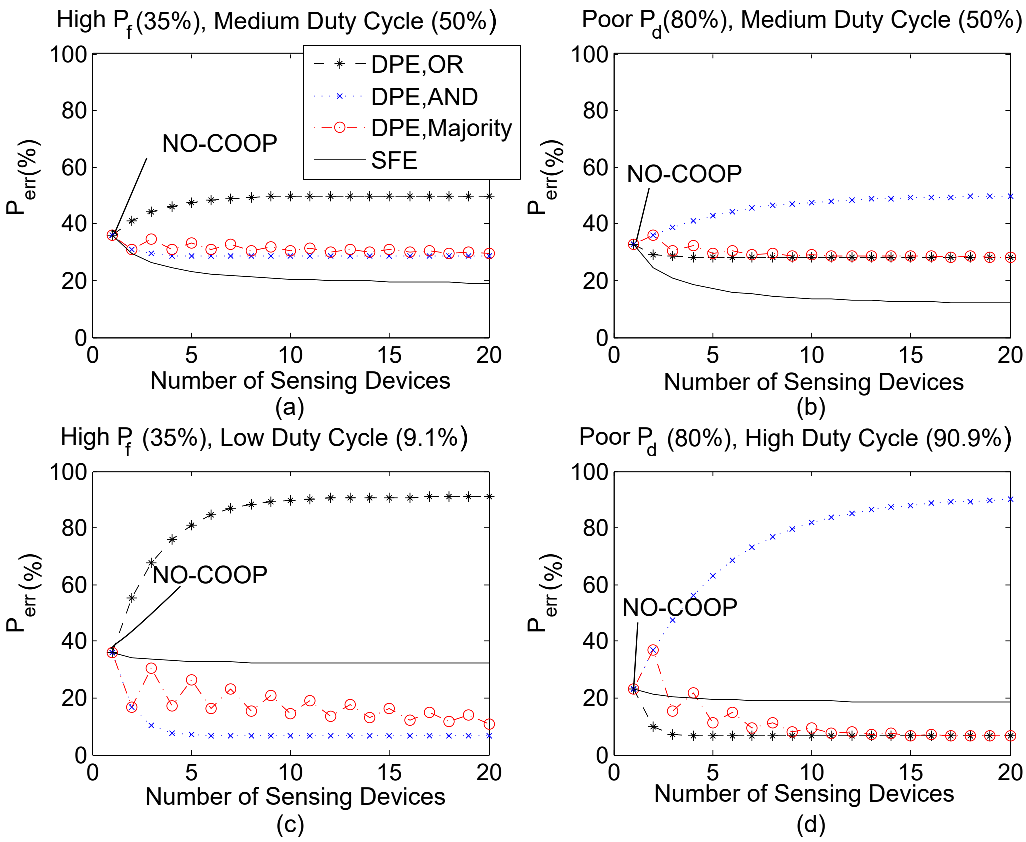

FIGURE 4.9 – *Performance of DPE and SFE, sensing devices include both SU TX and the cooperative nodes C_j (including SU RX), $E[T_{ON}] = T_s$*

$$P_f = F_f(SU\,TX, C_1, C_2 \ldots C_N)$$

where $F_d(SU\,TX, C_1, C_2 \ldots C_N)$ and $F_f(SU\,TX, C_1, C_2 \ldots C_N)$ represent the joint detection probability and joint false alarm probability for SU TX and the co-operative nodes with a certain fusion rule. For SFE scheme, T_s represents the sensing period between two sensing events at SU TX whereas T represents the effective sensing period between any neighboring nodes; for example, between SU TX and C_1. The SFE scheme adjusts the sensing period respectively according to the work of Yucek et. al in 2009 "A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications"[47] and is described in the following,

$$T = \frac{T_s}{N+1}$$

while the joint P_d and P_f are the same as those for individual spectrum sensing. The effective sensing period, T is reduced by a factor of $\frac{1}{N+1}$ which is similar to the SFE protocol discussed in Section 3.2. The effective sensing period, T and the joint P_d and P_f values are inserted into Equation 4.14 - Equation 4.16 to calculate P_{err} for both schemes so that their performance is evaluated.

The same parameter settings (see Table 4.1) are used again as an example. The performance of DPE and SFE schemes is shown in Figure 4.9. On the x-axis, the number of sensing devices are varied which includes both spectrum sensing performed at SU TX and at the cooperative nodes C_1-C_N. The results for individual spectrum sensing at SU TX (NO-COOP) are shown if the number of sensing devices is 1. Although NO-COOP represents a state with the proposed cooperative sensing design where SU TX performs individual spectrum sensing. It is assumed that all the sensing devices have identical detection performance whereas more complex cases are left for analysis for future research work. For consideration of hidden node scenario, detection probability of 80% is selected similar to the results shown in Figure 4.7. Although more realistic values are taken for evaluations in the next chapters. For DPE scheme, three fusion rules are distinguished OR, AND and Majority. The results are shown with increasing number of sensing devices. An optimum scheme achieves a low P_{err} in all the scenarios and becomes better the more devices cooperate ignoring the overheads with the current study. For medium duty cycle in Figure 4.9(a) and (b), P_{err} of SFE is lower than DPE. For medium duty cycle, the dynamics of PU's activity is high compared to low and high duty cycle. As in SFE scheme, sensing devices take turns thereby decreasing effective sensing period and the performance improves with each additional sensing device. Figure 4.9(c) and (d) show that SFE scheme provides only moderate performance improvement in case the duty cycle is low or high.

The performance of DPE scheme varies depending on fusion rule. In general, DPE scheme aims for improving performance in case the detection performance of the individual sensing device is poor. AND rule decreases joint detection probability as well as joint false alarm probability. On the contrary, OR rule increases joint detection probability as well as joint false alarm probability. AND rule performs best in case individual false alarm probability is high and duty cycle is low as shown in Figure 4.9(c). Although AND rule decreases joint detection probability its impact on P_{err} is not so severe due to low duty cycle. Therefore, the result is a significant performance improvement due to decrease in joint false alarm probability. OR rule performs best in case individual detection probability is poor and duty cycle is high as shown in Figure 4.9(d). Although OR rule increases joint false alarm probability in this case but due to high duty cycle its impact on P_{err} is not so severe. Therefore, this results in a significant performance improvement due to increase in joint detection probability. The performance of Majority rule lies in between OR and AND rules in all cases. If the performance of both DPE and SFE is compared with NO-COOP, it is seen that SFE always performs better as compared with NO-COOP. This is due to the reason that with SFE scheme addition of sensing devices always decreases effective sensing period which leads to decrease in P_{err} as overheads are ignored. Whereas the performance of DPE scheme in comparison with NO-COOP varies depending upon the fusion rule and the duty cycle of primary user.

Summarizing the comparison, we see in Figure 4.9 that none of the existing cooperative sensing scheme is optimal for all scenarios as none of them provides lowest P_{err} with increasing number of cooperative nodes. Even more important is the fact that an optimal scheme for one scenario does not work at all in other scenarios. e.g. The DPE AND scheme is optimal in Figure 4.9(c) but the worst candidate in Figure 4.9(d). We conclude that the evaluation metric P_{err} in this section provides a good fundamental difference between licensed and unlicensed bands, furthermore it provides a good general insight for using cooperative sensing for future radio networks and even future radio technologies. The purpose for evaluation of DPE and SFE scheme with P_{err} is to show the theoretical limits gained by cooperative sensing ignoring the overheads although it is expected that limited number of cooperative nodes are useful due to incurred overheads. The overheads associated with cooperative sensing are due to synchronization, control channel establishment, cooperative node selection. Therefore in the next section, a revised evaluation metric *Effectiveness* is proposed which addresses also the overheads for cooperative sensing.

4.2 EVALUATION METRIC FOR SYSTEM WIDE PERFORMANCE

Effectiveness considers two factors; first one is related with effective data channel utilization by both primary and secondary users and the second factor is related with the wastage due to collisions between PU and SU and the control channel usage overhead. The aim of an efficient cooperative sensing design is to improve effective data channel utilization and decrease wastage. P_{err} provides a metric for improving spectrum awareness but when cooperative sensing is applied with any radio technology, collisions in the networks are decreased and furthermore the cost (overhead) to decrease the collisions is to be low. Figure 4.10 shows the details of the improved evaluation metric (Effectiveness) and their individual parts. The goal of any cooperative sensing design is to perform efficient radio bandwidth (data channel) usage with minimal overhead. Therefore, in the proposed metric *Effectiveness*, data channel utilization is quantified in terms of primary and secondary user goodputs as the proposed cooperative sensing design consists of DATA frames in Figure 3.5 and Figure 3.6. Whereas the overheads are quantified with the help of frame transmissions on the control channel. PU N_{rx} and SU N_{rx} are total received data bytes at PU RX and SU RX respectively during the complete experiment or simulation time T_e whereas PU N_{tx} and SU N_{tx} are the total transmitted data bytes at PU TX and SU TX respectively during the experiment or simulation time. Throughput and Goodput are defined as follows:

$$Throughput = \frac{N_{tx}}{T_e} \tag{4.17}$$

$$Goodput = \frac{N_{tx} - N_{lost}}{T_e} \tag{4.18}$$

Where 'N_{lost}' is the total number of bytes which are lost or collided during the experiment or simulation run. In this regard, preamble and CRC are not part of the transmitted or received frames. Preamble provides synchronization and CRC detects the integrity of the received frames. Goodput ratios PU $Goodput_r$, SU $Goodput_r$ are calculated by Equation 4.19 and Equation 4.20 where PU

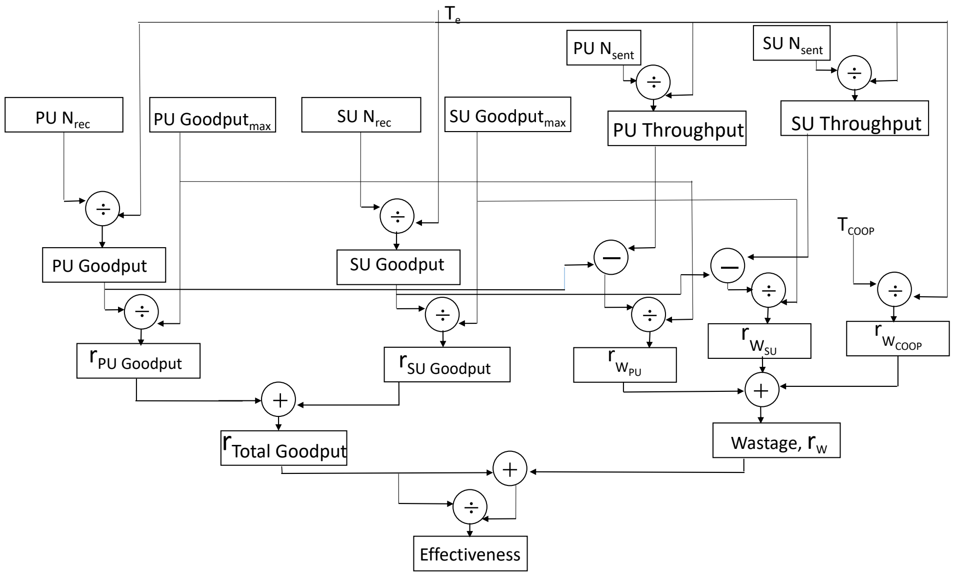

FIGURE 4.10 – *Evaluation metric for system wide performance for cooperative sensing in heterogeneous radio environments*

$Goodput_{max}$ and SU $Goodput_{max}$ are the reference maximum possible primary and secondary user goodputs respectively. For example, in the experimental setup (see Chapter 5), PU $Goodput_{max}$ and SU $Goodput_{max}$ are $\approx$ 250 kbps and 500 kpbs respectively.

$$r_{PU\,Goodput} = \frac{PU\,Goodput}{PU\,Goodput_{max}} \tag{4.19}$$

$$r_{SU\,Goodput} = \frac{SU\,Goodput}{SU\,Goodput_{max}} \tag{4.20}$$

In heterogeneous radio environments or unlicensed frequency bands, a fair spectrum usage is important, where each radio device has equal right to access the radio bandwidth. Therefore, both primary and secondary user goodput are equally important in the system. Furthermore, it is discussed in Section 4.1.1 that in contrary to the licensed bands missed interference and missed opportunity are equally important in heterogeneous radio environments. Therefore, $r_{Total\,Goodput}$ is defined which is related with effective data channel utilization as follows:

$$r_{Total\,Goodput} = r_{PU\,Goodput} + r_{SU\,Goodput} \tag{4.21}$$

In the next step, calculations for the second part (wastage) of the evaluation metric are performed. Due to collisions between primary and secondary user transmission, radio bandwidth is wasted both at PU TX and SU TX which is calculated as follows:

$$r_{W_{PU}} = \frac{PU\,Throughput - PU\,Goodput}{PU\,Goodput_{max}} \tag{4.22}$$

$$r_{W_{SU}} = \frac{SU\ Throughput - SU\ Goodput}{SU\ Goodput_{max}} \tag{4.23}$$

Where $r_{W_{PU}}$ and $r_{W_{SU}}$ represent the radio bandwidth wasted due to collisions at PU TX and SU TX respectively. Collisions that occur are counted twice as wastage as both transmitters of PU and SU waste energy during the transmission. Radio bandwidth is wasted due to transmission of BEACON and SENSING_INFORMATION frames (overhead) at SU TX and the cooperative nodes which is calculated as follows:

$$r_{W_{COOP}} = \frac{T_{COOP}}{T_e} \tag{4.24}$$

Where the ratio, $r_{W_{COOP}}$ represents the bandwidth wasted due to BEACON and SENSING_INFORMATION frames at SU TX and cooperative nodes. T_{COOP} is time duration of all BEACON and SENSING_INFORMATION frames transmitted on the control channel during the experiment or simulation duration, T_e. It is reminded here that Equation 3.1 presents the overhead (in analytical expression) for DPE protocol but Equation 4.24 shows the calculations of the overhead for both DPE and SFE protocol during experiment or simulation run (empirical method). Note that $r_{W_{PU}}$ and $r_{W_{SU}}$ attribute to the bandwidth wasted on the data channel whereas $r_{W_{COOP}}$ attributes to the bandwidth wasted on the control channel. The total bandwidth wastage, W is calculated as follows:

$$r_W = r_{W_{PU}} + r_{W_{SU}} + r_{W_{COOP}} \tag{4.25}$$

Finally, the system performance is defined in terms of Effectiveness which is the ratio between the Total Goodput and the Total Goodput plus all wastage r_W and is given as follows:

$$Effectiveness = \frac{r_{Total\ Goodput}}{r_{Total\ Goodput} + r_W} \tag{4.26}$$

The goal of any cooperative sensing design is to improve Effectiveness thereby improving efficient spectrum utilization and reducing collisions in heterogeneous radio environments. Effectiveness gives equal weightage to both quantities $r_{PU\,Goodput}$ and $r_{SU\,Goodput}$ as the focus of thesis is on heterogeneous radio environments as described in Chapter 1. This aspect is discussed in the initial metric P_{err} which gives equal weightage to both P_{mo} and P_{mi}. Although no evaluation or analysis has been performed yet with Effectiveness.

4.3 SUMMARY

In this chapter, two evaluation metrics are presented which are applicable for heterogeneous radio environments. The first metric, probability of error ignores the overheads associated with cooperative sensing whereas the other one, Effectiveness considers system wide performance evaluation with cooperative sensing incoporating also the overheads. The theoretical analysis performed with probability of error P_{err} provides problem awareness to developing individual or cooperative sensing schemes with the selected parameters sensing period T_s, ON time of PU T_{ON}, OFF time of PU T_{OFF}, detection probability P_d, false alarm probability P_f. The parameters are selected ignoring the overheads regarding cooperative sensing. Effectiveness evaluates system wide performance of cooperative sensing in heterogeneous radio environments. Effectiveness considers both the advantage gained (reduction of collisions) by cooperative sensing as well as the overheads associated with cooperative sensing. Both probability of error and Effectiveness are general evaluation metrics which serve to evaluate performance of individual and cooperative sensing protocols. Before the evaluations are performed for cooperative sensing, the next chapter presents the experimental setup and initial validation results. The single user results with individual spectrum sensing are shown where physical layer aspects are studied in detail. The physical layer aspects are frame level transmissions, receptions, collisions and radio propagation conditions. As the proposed design involves MAC layer design therefore, physical layer aspects also need to be investigated.

CHAPTER 5

EXPERIMENTAL SETUP AND VALIDATIONS

In the previous chapter evaluation metrics are discussed for individual and cooperative spectrum sensing. Before evaluations of the proposed cooperative sensing design are performed with Effectiveness, first the experimental setup including the type of nodes (fixed or portable) and the radio devices involved are presented in this chapter. In the second step, a single user and predictable small scale scenario is selected. The experimental results for this single user scenario are compared with the analytically predicted ones. In this way, physical layer and frame level transmissions of the experimental setup are studied in detail. Detection probability is an important parameter for evaluation of cooperative sensing. In the last step, measurement results for detection probability are shown by performing a number of experiments in the indoor environment of the institute in contrast to Section 4.1.2 where the values of detection probability are taken from the exemplary simulation analysis. As simulations lack consideration of realistic values for detection probability and false alarm probability. Therefore, finding realistic values for detection and false alarm probability is an important research question for evaluation of cooperative sensing. Experiments are performed and a methodology is developed to determine both detection and false alarm probability in indoor radio environment of the institute. Although heterogeneous radio environments involve IEEE 802.11, IEEE 802.15.4 and IEEE 802.15.4, the experimental setup supports IEEE 802.15.4 radio devices which means that physical layer frames of IEEE 802.15.4 are considered in the experiment. In the following, details of the testbed are described.

5.1 TESTBED

Evaluation of cooperative sensing involves management of experiments with distributed wireless nodes. In this regard testbed is helpful in managing and performing experiments with distributed nodes in real world environments. WISEBED testbed as described by Akram et. al "A Reusable and Extendable Testbed for

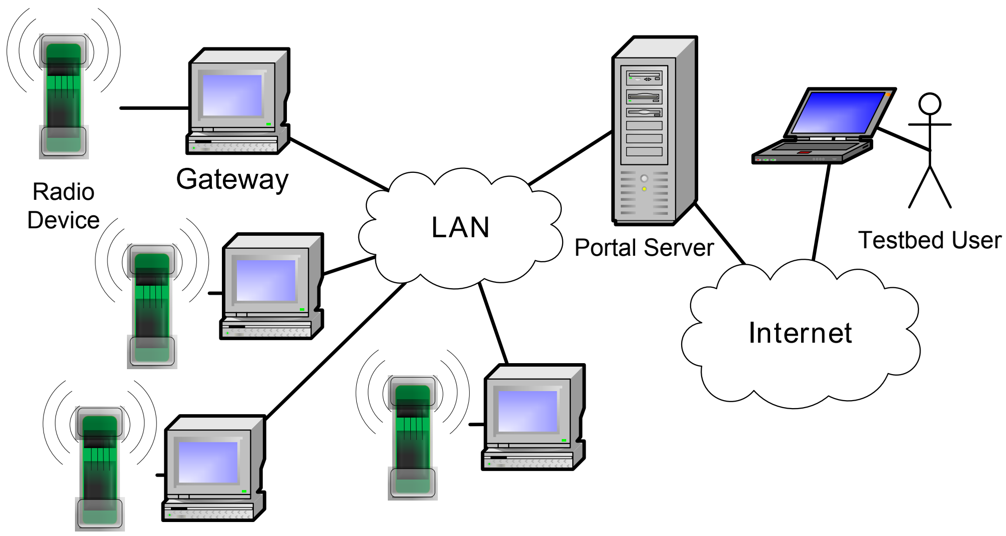

Figure 5.1 – *Architecture of WISEBED testbed*

Implementation and Evaluation of Cooperative Sensing" in 2013 [50] performs and evaluates cooperative sensing experiments. Figure 5.1 shows conceptual overview of the testbed with *Testbed User*, *Portal Server*, *Radio Device* and *Gateway*. Testbed user sends programs, retrieves results and analyzes them on a local computer. Portal server is the central system which coordinates the request from testbed user and sends commands to the relevant entities via gateways to the radio device. Radio device RD1, RD2 ... RD6 consists of a microcontroller with a radio chip. Further detail of the radio device is given in the next section. There are two kinds of gateway devices (fixed and portable gateway). Fixed gateway along with the radio device called *Stationary Testbed Node* is deployed in the institute with Ethernet cable to the Internet. Exemplary stationary testbed nodes deployed in the institute are shown in Figure 5.2. A portable gateway with a radio device called Mobile Testbed Node is depicted in Figure 5.3. Portable devices are attached to a mobile robot which enables them to drive autonomously along the floor. The portable gateway supports WLAN to connect to the network infrastructure. Experiment output e.g. results and debug messages is transmitted from the radio device (the details shown later in Figure 5.5) via the serial interface to the gateway and forwarded to the portal server. From the portal server it is transmitted to the user. For testbed output processing the user connects to the portal server with a Java program and retrieves the output for each individual radio device.

There are various mechanisms of the testbed; authentication and authorization, reservation, experiment deployment, experiment control, and result retrieval. User authentication and authorization restrict access to the testbed to registered users exclusively. This is important especially when the testbed is available via the Internet. Reservation ensures that the current user has the testbed or parts of it e.g. subset of radio device exclusively claimed for its experiment. Experiment deployment allows the testbed user to deploy an experiment on the reserved radio devices even from a remote location. Experiment control includes stopping

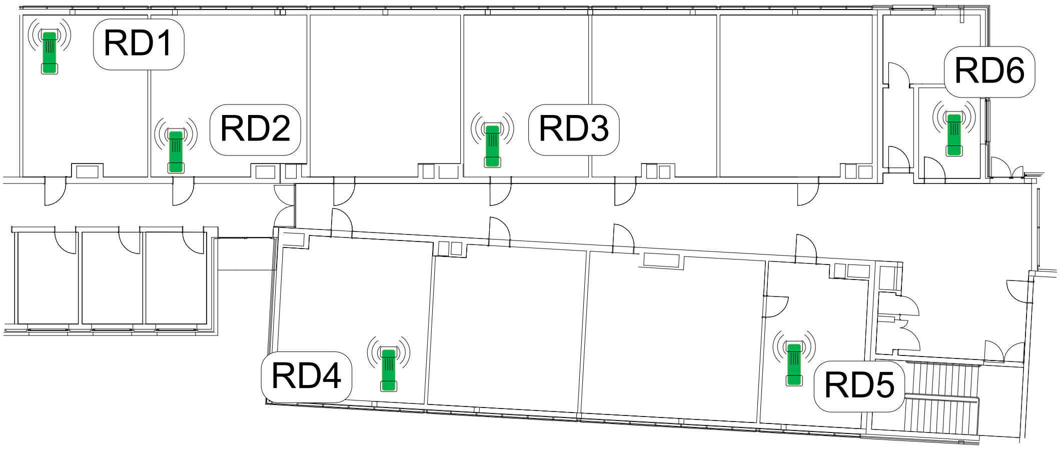

Figure 5.2 – *Stationary testbed nodes in the institute*

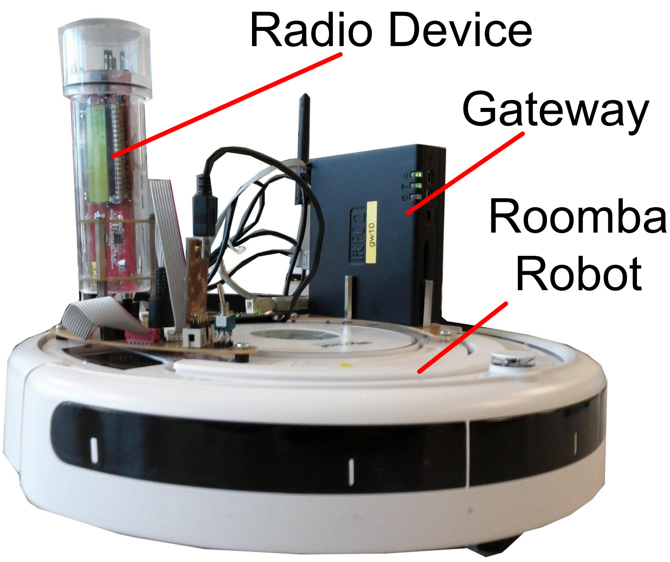

Figure 5.3 – *Mobile testbed node*

or resetting the experiment. Finally result retrieval includes getting debug or final results at the end of experiment. Execution of an experiment with the testbed is illustrated by an example. First the user connects to the portal server and reserves the testbed. In the second step, the user transfers the software and experiment configuration to the portal server. The portal server reliably transfers the software and configuration to the gateways where it finally resides on the radio device. Testbed provides shell scripts which serve as user interface. The proposed cooperative sensing design is implemented on the IEEE 802.15.4 equipped radio devices shown in the next section.

Figure 5.4 – *Radio device (TRISOS sensor node)*

5.2 RADIO DEVICE

WISEBED testbed incorporates all kinds of radio platforms. This thesis considers IEEE 802.15.4 equipped radio devices for implementation of primary, secondary and cooperative nodes and presents experimental evaluation results with a number of stationary and mobile scenarios. Whereas the general discussion is performed via simulations.

Figure 5.4 shows an outer view of the radio device *TRISOS* available in the COSA center of excellence. Whereas the internal hardware details of the radio device and its interface with the gateway are shown in Figure 5.5. The radio device consists of an AT86RF231 RF chip and an ATxmega128A1 microcontroller besides other peripherals, for example LED and display module (LCD). The radio device uses RF chip for the evaluation of the cooperative sensing experiments whereas LED and LCD modules serve the purpose of debugging and result retrieval of the experiments. The RF chip is a 2.4 GHz low power transceiver. It is compliant to IEEE 802.15.4, even though implementations and evaluations consider only physical layer functionality. In the RF chip, an integrated hardware supported energy detector engine performs spectrum sensing for the secondary user. The hardware of the RF chip updates the Received Signal Strength Indicator (RSSI) value every 2us and stores it in a register. Secondary and cooperative users utilize this RSSI value to report the outcome of spectrum sensing event. Both secondary and cooperative users transmits this RSSI value in the SENSING_RESULT field (see Figure 3.7 and Section 3.3) of the SENSING_INFORMATION frame for sensing report. Other types of spectrum sensing methods cyclostationary detection and matched filter shown in Section 2.2 are not considered for evaluation in this thesis. As the RF chip of the radio device supports only built in energy detection using RSSI measurements. Offset-QPSK (O-QPSK) is the modulation scheme and different standard and non-standard data rates 250 kbps up to 2 Mbps are selected. Different data rates distinguish primary and secondary users in the experiments. As a consequence, evaluation is performed for both successful primary and secondary user receptions from the experimental data. Furthermore, this is used to validate the testbed where shorter frames are used on the secondary user side as sensing period is to be lower than T_{ON} for successful individual or cooperative sensing. Further details of validation scenario are described in the next section. The RF chip is controlled via SPI interface by the microcontroller. Furthermore, the microcontroller passes the transmitted or received data and the spectrum sensing results to the testbed.

The radio device is connected to the gateway via two interfaces in two directions, from gateway via JTAG interface for programming and to the gateway via RS232

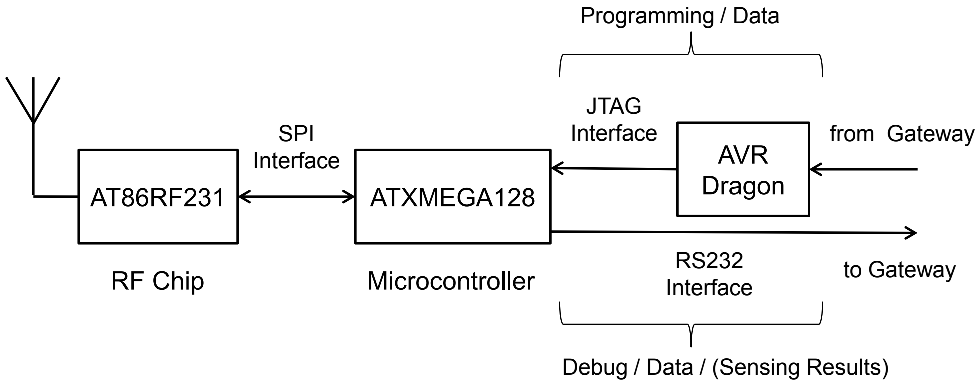

Figure 5.5 – *Hardware details of the radio device along with its interface to the gateway*

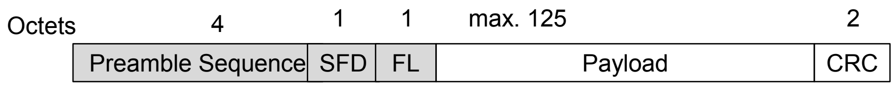

Figure 5.6 – *Physical layer frame format of IEEE 802.15.4*

for debugging and transferring results. Experimental output (e.g. results and debug messages) is transmitted from the radio device via the serial interface to the gateway and from there transmitted to the portal server (see Figure 5.1).

Primary and secondary user transmit the same frame format (see Figure 5.6) in different data rates. The header of physical layer frame consists of preamble sequence, Start Frame Delimiter (SFD) and Frame Length (FL). Therefore, receivers distinguish frames of primary user from those of secondary user by the data rate and frame length in this evaluation. The implementation of the proposed cooperative sensing design is performed on the radio devices in software. Before performing long term measurement series, the correct implementation is debugged. For real time debugging, the radio device also contains a debug pin and a pin for DAC (Digital to Analog Convertor) output. With the debug pin, the radio device flexibly monitors timing of various parameters during run time of the experiment and controlled via the software. The results of the spectrum sensing is transferred to the DAC for further debugging. Both pins serves as an input of an oscilloscope in order to validate the software and analyze the measurement results during the experiment in real time. An additional software utility (API) is developed to control the transmission parameters of the radio devices easily and quickly. The corresponding parameters are: (IEEE 802.15.4 compliant) RF channel, transmission power, frame length, wait time between two consecutive frames and data rate. The API enables monitoring of successful transmission and reception of the corresponding frames additionally. Furthermore, with the help of API the radio channel activity is displayed on the LCD of the radio device. This is helpful for debugging and monitoring of the experiments.

Figure 5.7 shows the radio channels used by IEEE 802.15.4. As described in Section 1.1, there are other standards (WLAN and Bluetooth) operating in

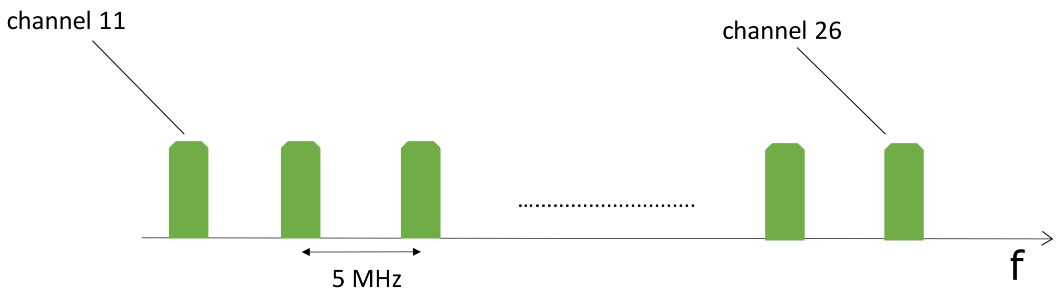

Figure 5.7 – *IEEE 802.15.4 radio channels at 2.4 GHz*

heterogeneous radio environments but the testbed exploits IEEE 802.15.4 radio devices. There are 16 channels available with IEEE 802.15.4 as described by Thanh-Dien et. al in 2011[38]. The spacing between the two radio channels is 5 MHz although neighboring channels affect the reception. In the evaluations maximum 3 radio channels are used at a time which correspond to data, control and synchronization channel. *start* node synchronously starts the experiments on the synchronization channel. All the nodes listen on synchronization channel for the starting frame. Before evaluations for the proposed cooperative sensing design are shown, first testbed is validated with the help of a predictable small scale scenario.

5.3 VALIDATION WITH SINGLE USER SCENARIO

In this section, the testbed is validated with the help of measurements so that the details of the testbed scenarios are understood with fine details. A simple single user predictable scenario is selected so that the experimental results are easily validated with analytical calculations. In this way, it is ensured that the primary and secondary user transmissions and collisions occur as expected or not. The details are understood on the individual frame level regarding what happens if frames from primary and secondary user collide. Furthermore, measurements are useful to study the real radio propagation conditions. The next subsection describes the single user implementation algorithm along with scenario setup.

5.3.1 SCENARIO DESCRIPTION AND IMPLEMENTATION

Figure 5.8 shows the scenario for validation of the testbed. The locations of primary and secondary nodes are shown and cooperative nodes are not added in the scenario yet. The purpose is to see how collisions occur in the primary and secondary user transmissions. SU TX performs spectrum sensing and opportunistic transmissions while PU TX sends data with certain duty cycle and without performing spectrum sensing. The detection probability of spectrum sensing performed by SU TX is 100% in the validation scenario as the purpose of the scenario is to understand the experimental setup and that the primary and secondary user transmissions occur as expected. PU TX is a stationary testbed node whereas mobile testbed nodes are used by PU RX, SU TX and SU RX. PU RX is placed at a position where it receives all the primary user transmissions but

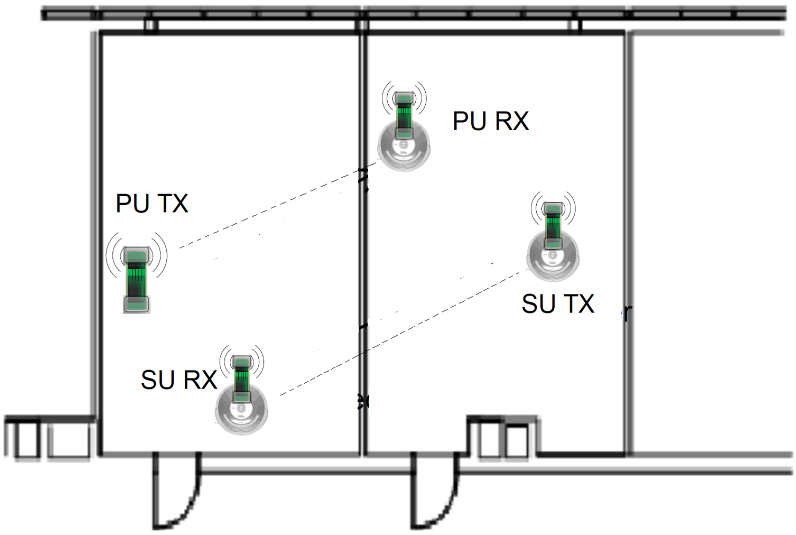

Figure 5.8 – *A predictable small scale validation scenario in the institute*

is strongly interfered by concurrent SU transmissions. Similarly, SU RX is placed at a position where it receives all the secondary user transmissions but is strongly interfered by concurrent primary user transmissions. The purpose of developing this scenario is to understand the collisions and successful transmissions at the frame level so that hidden node scenarios are defined later and the performance of cooperative sensing is analyzed. In the setup shown in Figure 5.8, the received power level of primary and secondary user transmissions at PU RX are -80 dBm and -60 dBm respectively. As -80 dBm is lower than -60 dBm, the concurrent secondary user transmission at PU RX corrupts the primary user receptions at PU RX severely. Similar is the case with SU RX. These signal strengths are measured with the help of an API. The testbed nodes are placed in different rooms in order to achieve the desired received power levels at PU RX and SU RX.

Figure 5.9 shows the flowchart of the algorithm implemented at SU TX whereas Figure 5.10 shows primary and secondary user transmissions on air in the scenario. As described in the previous paragraph, there is no cooperative sensing involved as the purpose is only to validate the testbed and understand the complete system with individual spectrum sensing NO-COOP at SU TX. PU TX uses deterministic T_{ON} and T_{OFF} times as an example in order to model the channel usage pattern from primary user as it was easy to implement. T_{ON} represents the time where the data channel is busy due to primary user transmission whereas T_{OFF} represents the time where the data channel is not occupied by the primary user.

In the following, the hardware implementation details of the individual spectrum sensing algorithm NO-COOP is described. PU TX transmits during T_{ON} time and switches the state of its RF chip to TRX_OFF during T_{OFF} time in order to save energy and avoid influence of SU transmissions. SU TX performs spectrum sensing with RSSI measurements. Before sensing is performed, SU TX has to switch the

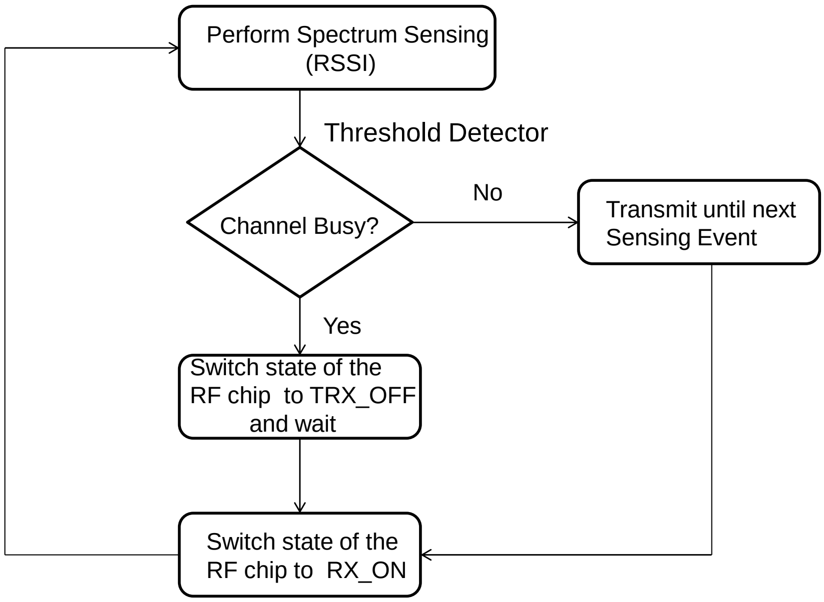

FIGURE 5.9 – *Flow chart for the individual spectrum sensing NO-COOP algorithm implemented in SU TX in the validation scenario*

state of its RF chip to RX_ON to read a valid RSSI value. Performing an RSSI measurement requires 10μs time which is required to transfer the RSSI value from the RF chip to the microcontroller of the radio device. This time is defined as sensing duration, T_d (see Figure 5.10) which is negligible for the measurement results (0.1ms) as compared with the frame size of IEEE 802.15.4. This time is considered in the experimental evaluation results in the next chapter. Although generalization on this time is not discussed as it is hardware or technology specific. During sensing, if the measured value is greater than a threshold, SU TX assumes the data channel as busy and switches the state of its RF chip to TRX_OFF in order to save energy and avoid influence of primary user transmission (see Figure 5.9 and ③ in Figure 5.10), as the RF chip neither receives nor transmits during TRX_OFF state. $T_{RX_{ON}}$ is the time to switch the state of the RF chip of the radio device from TRX_OFF to RX_ON state.

During spectrum sensing if the measured value is less than a threshold, SU TX assumes the data channel as free and transmits a frame until the next sensing event (see Figure 5.9 and ①, ② in Figure 5.10). Transferring data frame from the microcontroller to the RF chip of the radio device takes approximately T_{SPI} (0.14ms) time during which no signal on the air is observed. SU TX performs spectrum sensing with sensing period, T_s as discussed in Section 3.2. As described earlier, primary and secondary transmitted frames are distinguished by data rate and frame length field of IEEE 802.15.4 physical layer frame as shown in Figure 5.6. In order to elaborate this, In the experiments, primary and secondary user corrupt each others frame in case of concurrent transmission, therefore CRC Field (see Figure 5.6) of the received frame serves as a check for correct reception of the complete frame at PU RX and SU RX. Therefore, in the rest of the thesis;

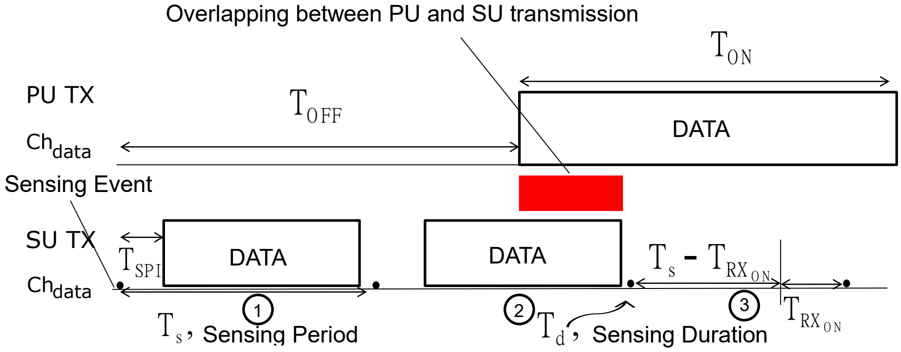

Figure 5.10 – *Primary and secondary user transmissions in the validation scenario*

wherever received frame is mentioned in the experimental results it is to be considered as correctly received frame determined by CRC field. Further details of implementations of PU RX and SU RX is given in Appendix A.

Table 5.1 shows the parameter settings for the validation scenario. Deterministic T_{ON} and T_{OFF} times are considered for primary user traffic. As an example, single setting of primary user traffic T_{ON} = 4ms and T_{OFF} = 4ms is considered as the purpose is only to validate the testbed. Primary user transmits data at 250 kbps whereas secondary user transmits data opportunistically at 500 kbps. The main reason behind this is that for the validation results shown later in this section, primary user needs to contain longer frames as compared with those of secondary user. The size of secondary user frame determines the sensing period. The sensing period is to be smaller than primary user frames. Otherwise, secondary user frames will have collisions (unpredictable) with primary user frames and the experimental results are not easy to compare with the analytical or empirical calculations. As stated earlier, the purpose of these experiments is to investigate what happens on the frame level if primary and secondary user transmissions collide in the testbed scenario with each at their respective receivers. The results shown in the current section consider only single frame transmission for primary user whereas more detailed study is presented in Chapter 6 and Chapter 7. Several values of T_s are analyzed in the evaluation. The minimum value of T_s in the validation setup is determined by Equation 5.1. $T_{Preamble\_SFD\_FL}$ stands for transmission time for Preamble, SFD and FL fields of IEEE 802.15.4 frame. All these fields (6 Bytes) are transmitted at 250 kbps resulting in total duration of (0.192ms). This time is necessary while transmitting any payload size of secondary user frame. T_{SPI} is the time to transfer the frame from the microcontroller to the RF chip (0.14ms) which the secondary user has to wait for transmission of any payload size and is due to hardware constraint. $T_{payload_{min}}$ represents the transmission time for minimum payload (1 Byte for data, 2 Bytes for CRC). This payload (3 Bytes) is transmitted at 500 kbps and is of duration (0.04ms). The total time summing up of $T_{Preamble\_SFD\_FL}$, T_{SPI} and $T_{payload_{min}}$ according to Equation 5.1 leads to 0.372ms. Although secondary user is able to sense with the times < 0.372ms but the RF chip is not able to successfully transmit frames with this high frequency as it requires to send Preamble, SFD, FL, payload and

TABLE 5.1 – *Parameter settings for the validation scenario NO-COOP*

T_{ON} (ms)	T_{OFF} (ms)	T_s (ms)	P_d (%)	P_f (%)
4	4	0.5, 1.25, 2	100	0

TABLE 5.2 – *Parameter settings (cont..) for the validation scenario NO-COOP*

N	PU Technology	SU Technology	T_e (s)
0	IEEE 802.15.4 (250 kbps)	IEEE 802.15.4 (500 kbps)	500

T_{SPI} time to transfer the data from microcontroller to the RF chip.

$$T_{s(min)} = T_{Preamble\_SFD\_FL} + T_{SPI} + T_{payload_{min}} \tag{5.1}$$

The maximum value of T_s in the validation setup is determined by Equation 5.2. Where $T_{Preamble\_SFD\_FL}$ value is same (0.192ms) as that for $T_{s(min)}$. The maximum payload $T_{payload_{max}}$ is 125 Bytes along with 2 Bytes of CRC and is transmitted at 500 kbps which leads to 2.04ms time. T_{SPI} is same (0.14ms) as that for $T_{s(min)}$ and is therefore independent of the data rate. Therefore summing up all three quantities $T_{Preamble\_SFD\_FL}$, $T_{payload_{max}}$ and T_{SPI} leads to $T_{s(max)}$ = 2.36ms.

$$T_{s(max)} = T_{Preamble\_SFD\_FL} + T_{SPI} + T_{payload_{max}} \tag{5.2}$$

Three values of T_s are selected (0.5ms, 1.25ms and 2ms) for analysis of the validation scenario. These values are selected in a way that they are $> T_{s(min)}$ and $< T_{s(max)}$. Furthermore, only limited number of values (well distinguished within the allowed range) are selected as performing large number of experiments with unpredictable radio conditions is also not easy. For each measurement run, both PU TX and SU TX wait for a *start* frame which is sent by another testbed node besides those shown in Figure 5.8. During each measurement run of T_e = 500s, PU TX sends approximately 60000 frames, each with a duration of 4ms. T_e represents the time duration for measurement, experiment or simulation run and is used throughout the thesis. As SU TX transmits opportunistically, the number of frames sent by SU TX in the experiment run varies. Overlapping primary and secondary user transmissions corrupt each others frames at their respective receivers. Spectrum sensing performed by SU TX helps to reduce collisions at the receivers thereby decreasing loss in primary user transmissions and increasing successful secondary user transmissions. In the following, an analysis is performed to compute the ratios of the received frames per transmitted ones for primary and secondary nodes for the parameter settings described in this subsection.

5.3.2 VALIDATION RESULTS

P_d is 100% for all measurement runs. Therefore, SU TX transmits during T_{OFF} and remains in idle state in T_{ON}. SU TX performs K_s sensing events during T_{OFF} which is described by the following,

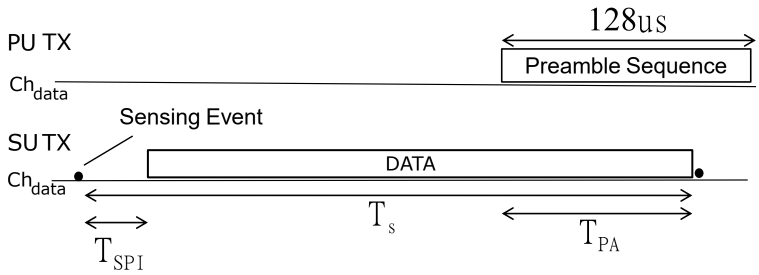

Figure 5.11 – *Successful reception of primary user transmissions due to preamble*

$$K_s = \frac{T_{OFF}}{T_s} \tag{5.3}$$

SU TX sends K_s frames on the average in (T_{ON} + T_{OFF}) time as detection probability is assumed to be 100%, therefore no transmission is performed during T_{ON}. Additionally, there is only one frame during one T_s. Therefore, K_s represent the number of frames as well as the number of sensing events during T_{OFF}.

It is shown in Figure 5.10 (see 2) that 1 out of K_s SU transmitted frames collides with PU frame during (T_{ON} + T_{OFF}) time and gets corrupted. Therefore, the ratio of the received frames with respect to the transmitted frames for the secondary user, r_{su} is calculated as follows;

$$r_{su} = \frac{N_{RX}}{N_{TX}} = \frac{(K_s - 1)}{(K_s)} \tag{5.4}$$

N_{RX} and N_{TX} represent total SU received and transmitted frames respectively during the experiment duration T_e = 500s. Very large value for T_e is not selected in the real world scenarios because it is difficult to maintain the same radio conditions for larger time durations. Very small values of T_e are not selected because statistically sound results are of interest. In the next step the ratio of received frames with respect to the transmitted frames for primary user, r_{pu} is considered. As explained before in this section, PU TX transmits one frame of T_{ON} = 4ms duration which is always collided by one transmitted frame of SU TX. But some of the transmitted frames of PU TX which overlap partly with those of SU TX are still received successfully by the primary user receiver. This is due to the preamble of the frames. The preamble synchronizes the receiver with the transmitter. Even if the first part of the preamble is corrupted due to interference, the receiver is able to synchronize to the transmitter and receive the rest of the frame correctly as shown in Figure 5.11.

The preamble is transmitted at 250 kbps therefore the total transmission time of the preamble is 128μs. The start of transmission from PU TX and SU TX are synchronized with the help of another *start* node. After they start transmitting they do not remain synchronized as the radio devices of PU TX and SU TX have a microcontroller with a clock drift. As described earlier in this section, the transmission time of one SU frame always overlaps with that of the PU frame

Table 5.3 – *Successful receptions with $P_d = 100\%$, $T_{PA} = 100us$*

Sensing Period, T_s	Primary User, r_{pu}		Secondary User, r_{su}	
	Actual	Expected	Actual	Expected
0.5 ms	25%	20%	89%	87%
1.25 ms	7.75%	8%	70%	69%
2 ms	6.4%	5%	54%	50%

in ($T_{ON} + T_{OFF}$) time. But the overlapping transmission times vary during the experiment as the radio devices of the PU TX and SU TX do not remain synchronized during the whole measurement run. The overlapping transmission times between PU and SU are equally probable in the range from 0 to T_s during the measurement run. The maximum overlapping transmission time between PU and SU is given as T_{PA}. Therefore, the ratio of the received frames with the transmitted ones for the primary user r_{pu} is written as,

$$r_{pu} = \frac{T_{PA}}{T_s} \tag{5.5}$$

The average value for T_{PA} is measured and is $\approx 100\mu$s and is used for calculation of analytical values which are discussed later.

Table 5.3 shows r_{pu} and r_{su} determined via measurements in case the detection probability is 100%. The actual values are the ones found via measurement whereas the expected values are the ones which are analytically calculated from Equation 5.4 and Equation 5.5. Maximum of receptions are seen with (r_{pu} = 25%, r_{su} = 89%) with the shortest sensing period, T_s = 0.5ms as reducing sensing period improves spectrum awareness leading to lower collisions. On the contrary, minimum of successful receptions are seen (r_{pu} = 6.4%, r_{su} = 54%) with the largest sensing period, T_s = 2ms as increasing sensing period reduces spectrum awareness leading to more collisions. In the next subsection, a procedure to determine P_d is defined and outcome of the real world measurements for the detection probability is presented which is an important investigation regarding evaluation of the proposed cooperative sensing design. As the purpose of using cooperative sensing is to overcome the hidden node situation where secondary user is not able to detect primary user transmission. In this regard, P_d is the determining parameter for hidden node scenario.

5.3.3 DETECTION PROBABILITY IN REAL RADIO ENVIRONMENT

In Section 4.1.2, various values of P_d and P_f are taken from the simulation analysis performed by Ghasemi et. al "Opportunistic Spectrum Access in Fading Channels through Collaborative Sensing" in 2007 [18] but they lack consideration of real radio propagation environment. P_f is not considered (although its value is 0% from measurements) in this thesis as P_d defines hidden node scenario which is in the scope of this thesis for evaluation of the proposed cooperative sensing design. Therefore in order to calculate detection probability P_d during a

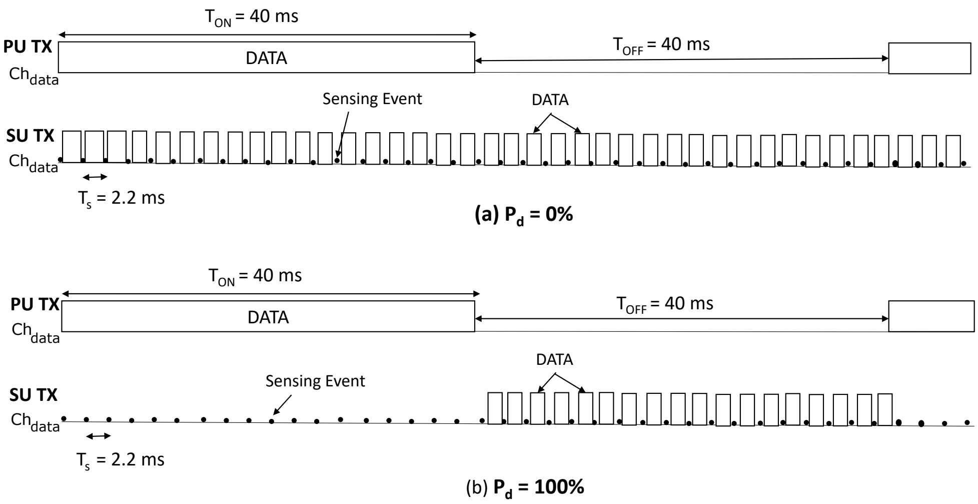

FIGURE 5.12 – *Two extreme situations (P_d = 0%, 100%) for determining P_d during a measurement run*

measurement run, the following experimental settings and procedure is adopted so that real world values for P_d are investigated.

Figure 5.12 shows the selected settings for determination of P_d in the indoor radio environment of the institute. T_{ON} = 40ms and T_{OFF} = 40ms are selected for the calculations as they are long enough for resulting a fixed value for P_d as T_e = 500s as done before in this chapter. T_s is selected to be 2.2ms as it is fast enough to detect the primary user traffic pattern. Furthermore, this time is long enough as compared with T_{SPI} so that there is minimal gap from SU side and the results are predicted easily from the calculations. PU and SU use IEEE 802.15.4 with 250 kbps and 500 kbps respectively as used earlier in this chapter. Figure 5.12 (a) shows PU and SU radio transmission along with spectrum sensing events with P_d = 0%. Whereas Figure 5.12 (b) shows PU and SU radio transmission along with spectrum sensing events with P_d = 100%. As two extremes are selected as an example for illustration. The expected total number of SU transmitted frames N_{TX} for any measurement run is given as follows, provided that P_d is assumed 100% (see Figure 5.12 (b) for explanation).

$$N_{TX} = \frac{T_{OFF} \times T_e}{(T_{ON} + T_{OFF}) \times T_s} \tag{5.6}$$

Where SU TX transmits during T_{OFF} and does not transmit during T_{ON}. As due to perfect detection performance (P_d = 100%), SU TX finds the channel as busy during spectrum sensing and stops transmission. N_{TX} is taken as reference for calculation of P_d in any experiment run. Therefore, P_d is calculated as follows;

$$P_d = 1 - \frac{(N_{TX}^{P_d} - N_{TX})}{N_{TX}} \tag{5.7}$$

where $N_{TX}^{P_d}$ is the total number of SU transmitted frames in a measurement run for any value of P_d. N_{TX} is calculated analytically from Equation 5.6 while $N_{TX}^{P_d}$ is obtained from the experiments. $N_{TX}^{P_d}$ is always greater than N_{TX}. In case $N_{TX}^{P_d} = N_{TX}$, P_d becomes 1 which means secondary user does not transmit due to perfect spectrum sensing. In case $N_{TX}^{P_d} = 2\ N_{TX}$, P_d becomes 0 which means secondary user transmits during T_{ON} time due to imperfect spectrum sensing. Therefore $N_{TX}^{P_d}$ increases with a decrease in P_d. These two extreme situations are shown in Figure 5.12 as described earlier in this section. A number of scenarios are evaluated with three values of P_d. The API of the software developed for the radio device (for RSSI measurement) measures approximate power level of PU transmissions. Developing a scenario for $P_d = 0\%$ or 100% is easier if SU TX is placed at a far distant location from PU TX or quite close to the PU TX respectively. But developing a scenario for a desired value of P_d in the range ($0\% < P_d < 100\%$) is not trivial in the indoor radio environment. As there are many rooms in the institute and walls of various rooms which leads to fading and shadowing situation as described in Section 2.3. SU TX (mobile testbed node) is placed at various positions in the institute where the power levels ($\leq$ -90 dBm) of PU TX were quite close to the threshold used by SU TX for spectrum sensing. Afterward, the same configuration is loaded on PU TX, SU TX and SU RX as discussed earlier. Three measurement runs are performed for such positions of SU TX. Equation 5.7 calculates the detection probability in these experiments. Different values for P_d are obtained; $P_{d1} = 53\%$, $P_{d2} = 47\%$ and $P_{d3} = 90\%$. These values were very rare to find. Hence as stated earlier ($0\% < P_d < 100\%$) are very rare in real indoor environment. The hidden node scenario is described as a situation where $P_d \approx 0$ and is considered in all the later evaluations of the proposed cooperative sensing design in Chapter 6 and Chapter 7.

5.4 SUMMARY

This chapter discussed the testbed infrastructure. It is demonstrated how primary and secondary users are setup with IEEE 802.15.4 radio devices for stationary and mobile scenarios. A single user validation scenario with individual spectrum sensing NO-COOP is presented in order to investigate the testbed and see the transmissions at frame level. An important finding is that it is not necessary that the whole preamble of the physical layer frame is received correctly rather if part of it is corrupted, the corresponding receiver is still able to receive it successfully. It is shown how detection probability is determined in the experiments which is an important parameter regarding evaluation of the proposed design in the heterogeneous radio environments. Various measurement runs are performed in the indoor environment of the institute which show that the situations where detection probability is greater than 0% and less than 100% are not very common. Rather, detection probability P_d is either ≈ 0 or 100% in the indoor radio environment. In the next chapter, performance evaluation of the proposed cooperative sensing design is presented in a number of stationary and mobile scenarios which is important for developing a realistic model and analysis.

CHAPTER 6

EXPERIMENTAL EVALUATION

In the previous chapter, the investigations were performed on the frame level with individual spectrum sensing with perfect detection probability but the scope of this thesis is on situations where wireless transmitters are not able to detect the concurrent radio transmissions from other devices. Therefore, this chapter presents evaluation results for the proposed cooperative sensing design for the situations where $P_d = 0\%$ (hidden node scenario). The proposed cooperative sensing design is evaluated in real radio propagation conditions rather than with simulations. Evaluation of cooperative sensing with real radio propagation is important to develop a realistic simulation model. Stationary scenario is evaluated with dedicated cooperative nodes initially to compare DPE and SFE protocols. A scenario *PU and SU Collision* is selected in a way that it provides best improvement in Effectiveness with cooperative sensing (COOP) as compared with individual spectrum sensing (NO-COOP). In the next step, evaluation for cooperative sensing is performed in a number of stationary scenarios in order to show usefulness of the proposed design with low, medium and high duty cycles of primary user traffic. Finally, evaluations are performed with exemplary mobile scenarios to show performance with additional cooperative node as well. In the evaluation results, the symbols NO-COOP and COOP refer to individual and cooperative sensing respectively rather than the states described in Section 3.1. For the experimental evaluation, NO-COOP refers to the state of the proposed cooperative sensing design where COOPNODE_REG_REL frames are sent but no cooperative nodes are available in the surrounding area.

First in the next section, evaluations are shown for stationary scenarios with dedicated cooperative nodes so that the performance of DPE and SFE protocols is compared.

6.1 EVALUATIONS WITH DEDICATED COOPERATIVE NODES

Cooperative node selection protocol is not evaluated in the stationary scenarios as there is no mobility involved in the scenarios and the dedicated cooperative node is registered in the initial phase which is not shown in the description and all the nodes are assumed to be in COOP state of the proposed cooperative sensing design. The purpose of evaluation is to demonstrate the performance comparison of DPE and SFE protocols in real world scenario. In the next subsection, settings of the scenario *PU and SU Collision* is described.

6.1.1 SCENARIO DESCRIPTION

Figure 6.1 shows the details of the scenario with all the nodes involved. PU TX, SU TX, PU RX, SU RX and C_1 use mobile testbed nodes whereas C_2 and *start* use fixed testbed nodes. Although no mobility is involved in a measurement run, the purpose of using mobile testbed nodes in this scenario is that they are portable and can be placed at any desired location whereas fixed testbed nodes have fixed positions in the institute. In stationary scenario, cooperative node selection protocol is not discussed as the aim is to evaluate DPE and SFE protocols. WISEBED testbed does not ensure synchronized start of software on the testbed nodes, therefore a dedicated synchronization channel is utilized which is different than data and control channels to synchronize start of the experiments. *start* node sends the starting frame on the synchronization channel. The software running on the radio devices is synchronized to this starting frame. SU TX in the current setup is in a room where radio conditions are not good. Therefore, nodes relay the start frame sent by the *start* node. The experiment duration, T_e is managed by the local timers of the radio devices.

In the following, the placement of testbed nodes is described. SU TX is placed at a location where it does not detect the transmission from PU TX. Detection probability $P_d \approx 0$ for hidden node scenario. The cooperative nodes C_1 and C_2 are placed at the locations where they detect primary user transmission ($P_d \approx 100\%$) whereas both cooperative nodes communicate successfully in both directions with SU TX. SU RX is placed at location where it receives secondary user transmission but simultaneous transmission from primary user corrupts the reception of secondary user transmission. Similarly PU RX is placed at a location where it receives primary user transmission but simultaneous secondary user transmission corrupts the reception of primary user transmission. The placement of PU RX and SU RX is done in a similar way as shown for the validation scenario in Section 5.3.1. The purpose of evaluation of this scenario *PU and SU Collision* is that the amount of collisions occurring in the system is maximum due to hidden node scenario and cooperative sensing provides significant performance improvement. Therefore, for comparison and evaluation purposes this scenario *PU and SU Collision* is investigated in detail this and in the next chapter.

The placement of testbed nodes according to the requirements specified here is not trivial as the radio channel conditions in the indoor environment is not very predictable. As discussed in Section 2.3, the radio environment is determined by

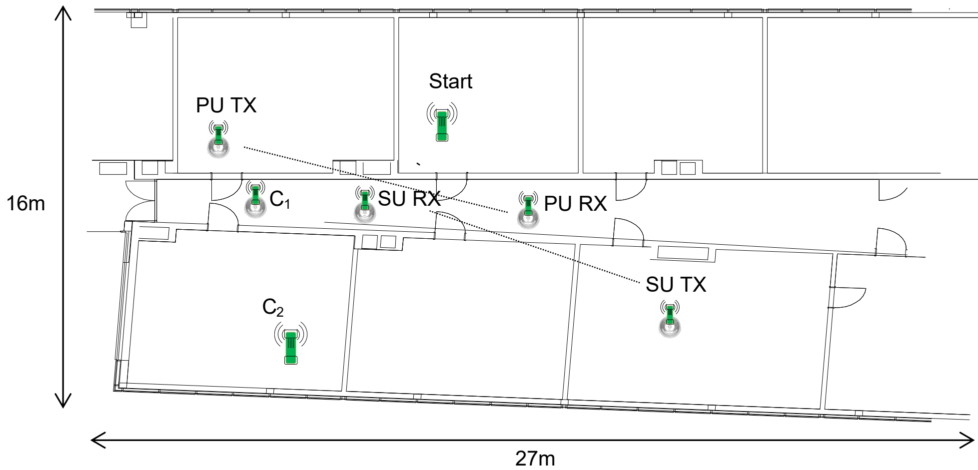

FIGURE 6.1 – *Stationary scenario in hidden node situation PU and SU Collision*

various phenomena free space loss, multipath fading and shadowing. There are many walls in the indoor environment and the radio signals reflect and attenuate from these walls and various kinds of objects or reflectors in the surrounding environment leading to unpredictable radio environment. As reproducibility of the experiments is most important to allow the comparison between different implementations and settings, the measurements are performed in evenings to ensure a minimum number of movements of people on the floor and avoid additional unpredictable interferer like WLAN and Bluetooth. As discussed in Section 5.3.3, values of 0% $<P_d<$100% are not common in indoor radio environment. In other words, in the indoor radio environment the values for P_d are either 0% or 100% most of the time whereas other values are very rare. Therefore, hidden node situation between PU TX and SU TX is associated with $P_d \approx 0\%$. P_f is ≈ 0.5 % in real measurements and is therefore not discussed in the rest of the thesis. Furthermore, cooperative nodes are placed at locations where $P_d \approx 100\%$. In the next subsection, the experimental settings for various parameters of the proposed cooperative sensing design DPE and SFE protocols are described.

6.1.2 EXPERIMENTAL SETTINGS

Table 6.1 and Table 6.2 show the experimental settings for the scenario described in this section. For the measurement results presented here, the experiment duration T_e for a single run is set to 500s. This value is selected as larger times make it difficult to maintain stable radio conditions in the indoor radio environment which vary strongly by the passage of even a human being in the scenario. Very small value for T_e is not selected as the results are not statistically sound otherwise. The maximum value of clock drift among two radio devices is 0.5s per 100s or 0.5% for the testbed nodes mentioned in Section 5.1. This value is an important parameter as it influences the beacon period and *Cooperative Sensing Receiving Window*. T_w is the time duration of Cooperative Sensing Receiving Window (CSRW) for one cooperative node either for DPE of SFE protocol. For multiple cooperative nodes, the time duration for CSRW T_{CSRW} = N T_w for DPE protocol whereas $T_{CSRW} = T_w$ for SFE protocol as discussed in Chapter 3.

The values for T_{BEACON} = 100ms and T_w = 2.4ms are taken by hit and trial which ensures more than 98% successful reception of SENSING_INFORMATION frames at SU TX in the setup. The frame duration (T_{Btx} and T_{Stx}) of BEACON and SENSING_INFORMATION is 1ms in the current setup and is taken as an example. Besides all communication among SU TX and the cooperative nodes is performed at 250 kbps in this and even in later evaluations. This data rate for control channel was chosen as an example as the purpose of experimental evaluation was to make the protocol work in real radio propagation environment.

The system is investigated for $T_s < T_{ON}$. The situation for $T_s > T_{ON}$ is not interesting as sensing period should be small enough to capture the dynamics of the primary user traffic. This aspect has been indicated in Figure 4.7, where it is shown that for $\frac{T_s}{E_{TOFF}} = 10^{-1}$ P_{err} reaches approximately minimum value (19 %out of maximum of 32% see Figure 4.7 (a)). P_{err} always decreases with decrease in T_s when the overheads associated with cooperative sensing are ignored. Whereas Effectiveness does not always decrease due to increase in overheads with decrease in T_s. Larger T_{ON} and T_{OFF} require larger T_e in order to get good statistics. On the contrary smaller values of T_{ON} and T_{OFF} require smaller values of T_s which is difficult to achieve due to minimum frame size limits of IEEE 802.15.4. Therefore T_{ON} = 40ms and T_{OFF} = 40ms is selected and the system is analyzed for values of T_s = 10ms, 20ms, 30ms and 40ms. A more detailed analysis for T_s, T_{ON} and T_{OFF} is performed in the next chapter.

The medium duty cycle (50%) for the primary user traffic is selected whereas other duty cycles are considered in the later part of this chapter with SU RX. The reason behind selection of 50% is that for low duty cylce we are not always able to see significant performance improvement as compared to NO-COOP. Higher duty cycle requires large T_e in order to get good statistics. IEEE 802.15.4 channels 21, 22 and 25 are selected for data, control and synchronization channel respectively in the measurements. These channels are selected because WLANs operating in the same area do not use these frequencies. The maximum time duration of IEEE 802.15.4 physical layer frame is 4.2ms (PU Technology = IEEE 802.15.4 with 250 kbps) and 2.2ms for the secondary user (SU Technology = IEEE 802.15.4 with 500 kbps). N = 1,2 as the performance is shown with both 1 and 2 dedicated cooperative nodes C_1, C_2. SU RX does not cooperate with SU TX for the evaluations in this section. This is due to the reason that using dedicated cooperative nodes C_1, C_2 gives us more freedom regarding placement of nodes and ease of finding the desired scenario *PU and SU Collision*.

Multiple frames are used by primary and secondary users in various experimental settings to achieve larger T_{ON} times as compared with individual frame size (see DATA for both primary and secondary user in Figure 3.5 and Figure 3.6). It is to be reminded here that the cooperative node selection protocol is not part of the evaluation in this section although the cooperative nodes C_1 and C_2 are registered with this protocol and are not released from SU TX during the experiment. In the next subsection, the results of the scenario *PU and SU*

TABLE 6.1 – *Parameter settings for Figure 6.1-Figure 6.6, evaluation of DPE and SFE*

T_{ON} (ms)	T_{OFF} (ms)	T_s (ms)	T_w (ms)	T_{Btx}, T_{Stx} (ms)	T_{BEACON} (ms)
40	40	10,20,30,40	2.4	1	100

TABLE 6.2 – *Parameter settings (cont..) for Figure 6.1-Figure 6.6*

N	PU Technology	SU Technology	T_e (s)
1,2	IEEE 802.15.4 (250 kbps)	IEEE 802.15.4 (500 kbps)	500

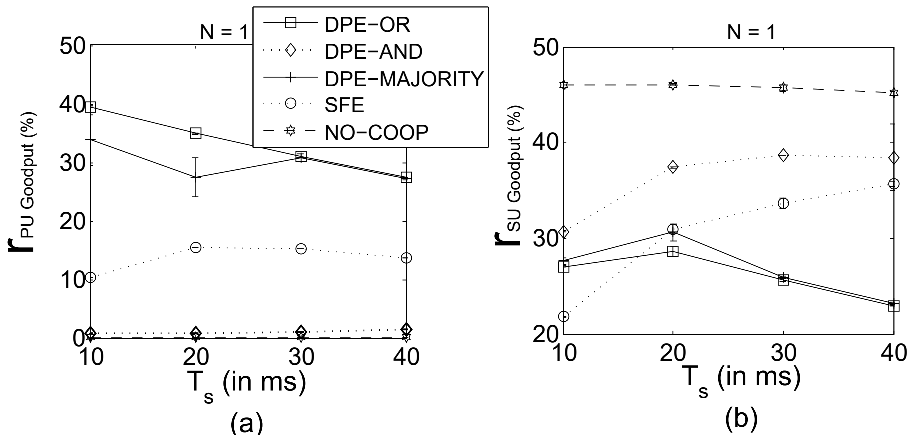

FIGURE 6.2 – *Primary and secondary user goodput with dedicated cooperative node C_1*

Collision (hidden node scenario) are presented.

6.1.3 RESULTS

Figure 6.2 shows the primary and secondary user goodput $r_{PU\ Goodput}$ and $r_{SU\ Goodput}$ calculated from Equation 4.19 and Equation 4.20 both with individual spectrum sensing NO-COOP as well as with cooperative sensing DPE and SFE protocol. All the results are shown with confidence level of 95% [11]. With NO-COOP, primary user goodput is 0%. In this case, all primary user transmissions are corrupted due to concurrent secondary user transmissions as SU TX is not able to detect primary user transmissions in the hidden node scenario. Note, that the maximum achievable primary user goodput in this setup is 50% as the duty cycle for primary user transmission is 50%. Secondary user goodput is maximum for NO-COOP (see Figure 6.2(b)) as there is no Cooperative Sensing Receiving Window ($T_{CSRW} = 0$) and BEACON frame transmissions with individual spectrum sensing. T_{CSRW} is the time associated with COOP state during which no useful data transmission is performed for the secondary user. During this time, SU TX collects spectrum sensing reports (SENSING_INFORMATION frames) from the cooperative nodes.

Cooperative sensing improves the primary user goodput but secondary user goodput is decreased. In the next step, the performance of the proposed cooperative sensing protocols DPE, SFE is discussed. The performance of DPE protocol

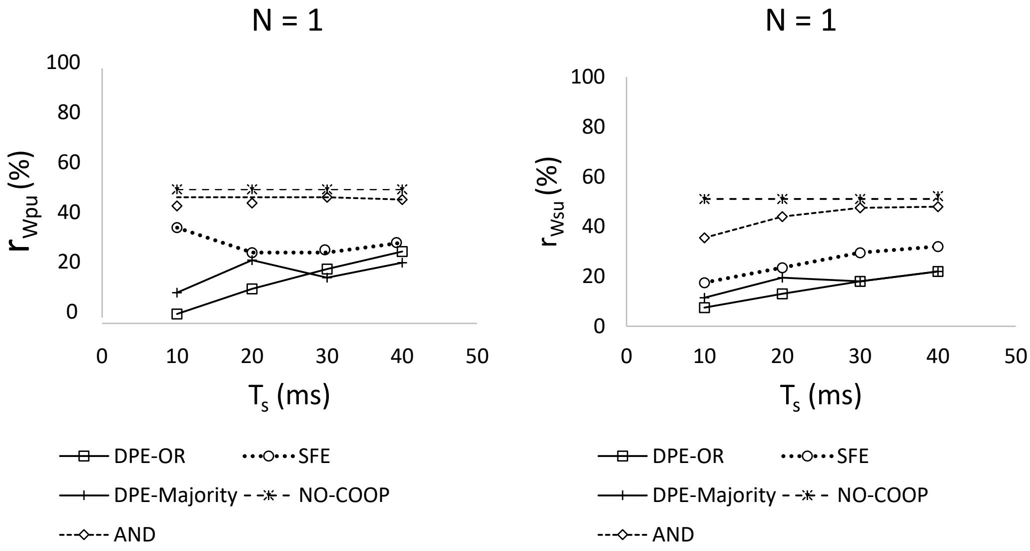

FIGURE 6.3 – *Wastage for primary and secondary user $r_{W_{PU}}$, $r_{W_{SU}}$*

varies according to the fusion rule. There is a large increase from 0% to 40% in primary user goodput due to the OR fusion rule. Due to high cumulative detection probability, SU TX is able to detect the primary user transmissions leading to lower number of collisions. There is decrease from 45% to 25% in the secondary user goodput due to CSRW and high cumulative detection probability for this fusion rule. A very small decrease in the secondary user goodput from 45% to 38% is seen with AND fusion rule. This is due to Cooperative Sensing Receiving Window. A small increase from 0% to 5% in the primary user goodput with AND fusion rule is associated with T_{CSRW} again. As AND fusion rule does not help to improve the cumulative detection probability leading to higher number of collisions but small percentage of primary user transmission are not corrupted as secondary user does not transmit during T_{CSRW}. The performance of the MAJORITY fusion rule is close to the OR fusion rule. With SFE protocol we see medium level increase from 0% to 20% in primary user goodput but medium level decrease from 45% to 30% in secondary user goodput.

Figure 6.3 and Figure 6.4 show the evaluation results for wastage r_W. The wastage for primary user traffic $r_{W_{PU}}$ is 50% for NO-COOP as all the primary user transmissions are corrupted by the concurrent secondary user transmission in hidden node situation. $r_{W_{PU}}$ is low 10%-15% for DPE protocol OR and Majority as cumulative detection probability is improved which reduces collisions and protects primary user transmission. The performance with DPE-AND is comparable to NO-COOP as there is no improvement in cumulative detection probability thereby affecting primary user transmission severely. The performance of SFE protocol is worse with $r_{W_{PU}} = 35\%$ as additional transmission of frames (see ① in Figure 3.6) leads to higher collisions between primary and secondary user transmission. The wastage for secondary user traffic $r_{W_{SU}}$ is 54% for NO-COOP. Due to hidden node situation, SU TX transmits all the time because it is

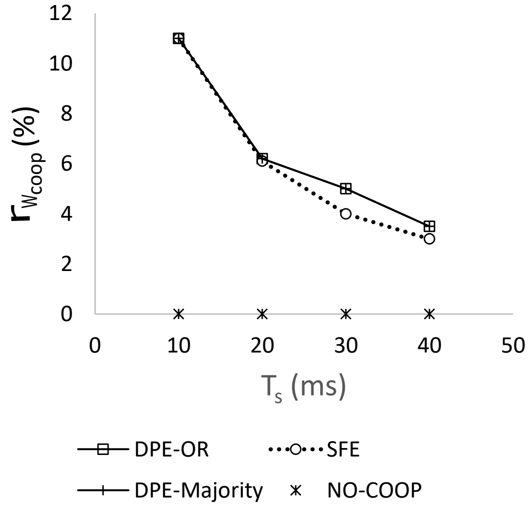

Figure 6.4 – *Wastage on the control channel* $r_{W_{COOP}}$

unaware of primary user transmission but 50% of the time it is collided by primary user transmission which leads to $r_{W_{SU}} = 54\%$. As the duty cycle of primary user traffic is 50%. The range of values for $r_{W_{SU}}$ is quite low 20% for DPE protocol OR and Majority as SU TX avoids transmitting upon correctly detecting primary user transmission thereby reducing the wastage due to collisions. DPE-AND does not perform well as cumulative detection probability is not improved, therefore the performance is comparable with NO-COOP. Although $r_{W_{SU}}$ for SFE protocol is lower than NO-COOP but still higher than DPE (OR and Majority) protocol. Additionally, $r_{W_{PU}}$ and $r_{W_{SU}}$ both increase with increase in sensing period, T_s for DPE protocol as the collisions increase in the system. Therefore, lower T_s is always preferred but it also imposes higher overhead on the channel which is discussed in the following.

The third kind of wastage is on the control channel ($r_{W_{COOP}}$). Figure 6.4 shows the wastage $r_{W_{COOP}}$ for both NO-COOP and cooperative sensing DPE and SFE. There is no wastage on the control channel with NO-COOP as individual spectrum sensing at SU TX does not require any control channel usage. $r_{W_{COOP}}$ decreases with increase in T_s with cooperative sensing DPE and SFE. For example, $r_{W_{COOP}}$ is 12% for T_s = 10ms whereas $r_{W_{COOP}}$ is 5% for T_s = 30ms. This is due to the reason that $r_{W_{COOP}}$ is directly dependent upon the number of BEACON and SENSING_INFORMATION frames. An increase in T_s decreases number of SENSING_INFORMATION frames which decreases $r_{W_{COOP}}$. After presenting the individual parts of the metric (Effectiveness) with N = 1 using dedicated cooperative node C_1, in the following evaluation of DPE, SFE and NO-COOP is performed in terms of Effectiveness for increasing number of cooperative nodes.

Figure 6.5 shows Effectiveness which includes both effective spectrum utilization and wastage as calculated in Equation 4.26 for the system having different number of cooperative nodes N = 1,2. It is shown that the performance of NO-COOP is bad 30% but the performance of DPE-AND is worst <30% for both N =

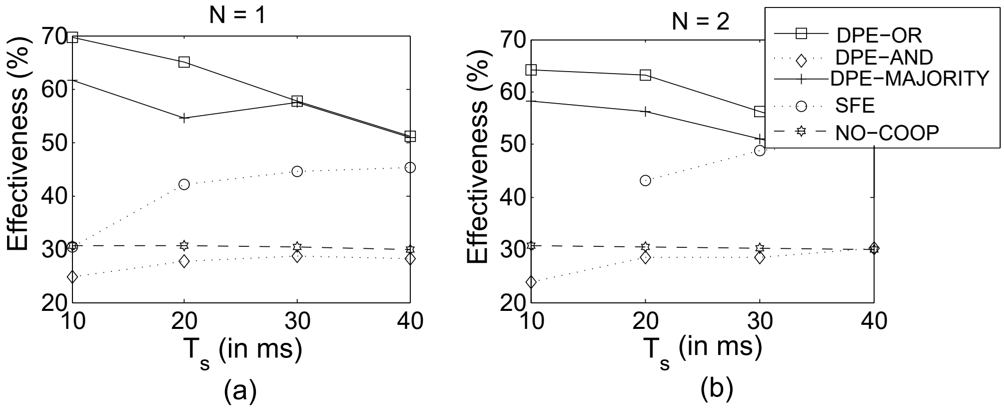

FIGURE 6.5 – *Effectiveness with increasing number of cooperative nodes*

TABLE 6.3 – *Summary of performance considering T_s = 30 ms*

	$r_{PU\ Goodput}$	$r_{SU\ Goodput}$	Effectiveness
DPE-OR	high (33%)	medium (25%)	high (59%)
DPE-AND	poor (1%)	medium (38%)	worst (28%)
DPE-MAJORITY	high (33%)	medium (38%)	high (58%)
SFE	medium (16%)	medium (33%)	medium (45%)
NO-COOP	worst (0%)	high (46%)	poor (30%)

1 and 2. As DPE-AND does not provide any performance improvement in $r_{Total\ Goodput}$ rather it imposes only additional wastage $r_{W_{COOP}}$. Furthermore, the performance difference with different number of cooperative nodes is minimal as PU TX is hidden to SU TX. Therefore the individual spectrum sensing at SU TX allows the transmission of data in any case (see AND rule in Section 2.5) which leads to collisions in the system. DPE OR and Majority outperform all others because the number of collisions are least for these protocols which leads to higher $r_{Total\ Goodput}$ and lower wastage r_W. The performance of SFE protocol is inferior as compared to DPE protocol because it incurs additional collisions due to transmissions performed by 1 as shown in Figure 3.6.

Table 6.3 summarizes the findings described in this subsection. In brief DPE-OR and DPE-Majority has high Effectiveness among all the categories as the primary user goodput $r_{PU\ Goodput}$ is best among all the settings. Secondary user goodput $r_{SU\ Goodput}$ is medium for cooperative sensing DPE and SFE protocols as the extra sensing effort from the cooperative nodes reduces collisions with primary user but due to Cooperative Sensing Receiving Window secondary user is not able to transmit data for T_{CSRW} time. $r_{SU\ Goodput}$ is high with NO-COOP as $T_{CSRW} = 0$ in this case and all secondary user transmissions are received by SU RX which do not collide with primary user transmission. All the primary user transmission is corrupted with NO-COOP. Therefore $r_{PU\ Goodput}$ is worst with this setting.

Figure 6.5 shows the system performance with an increasing number of cooperative nodes from N = 1 to N = 2. The outcome is that rather than improvement a decrease in Effectiveness is seen with the addition of another cooperative node to SU TX (see for DPE-OR with N = 1 Effectiveness = 70% whereas for DPE-OR with N = 2, Effectiveness = 65%). This is because additional cooperative node N = 2 does not help significantly in reduction of collisions in the current scenario. As P_d is = 100% for C_1, the scenario is stationary and the cooperative node C_1 is able to detect perfectly the primary user transmission. Therefore additional cooperative node C_2 does not provide any further benefit rather it imposes additional overhead $r_{W_{COOP}}$ in the system. The concept of additional cooperative node for DPE protocol is useful in those scenarios where the first cooperative node is not able to detect primary user transmission due to radio propagation effects etc. For SFE protocol, an improvement for example; from 48% to 53% for T_s = 40ms is seen with second cooperative node which indicates that there is potential for performance improvement with SFE protocol with increasing number of cooperative nodes. For T_s = 10ms and N = 2, CSRW increases for SFE protocol that no time is left for transmission for secondary user after collecting sensing reports from the cooperative nodes, therefore this setting is not evaluated.

In the next step, the influence of type of primary user traffic is studied. The parameter settings for these results are the same as those in Table 6.1 and Table 6.2. The performance is shown with deterministic and randomly distributed T_{ON} and T_{OFF} times for primary user traffic. Randomly distributed T_{ON} and T_{OFF} times are calculated by the following C code snippet.

,

```

float calculate_time(int average_ON_OFF_time){
    double rnd = (double) rand() / (RAND_MAX + 1.0);
    return -logf(1.0 - rnd) * averagetime;

}
```

ALGORITHM 6.1 – *main.c file for getting random time for T_{ON} and T_{OFF}*

The function calculate_time (float average_ON_OFF_time) returns the T_{ON} or T_{OFF} time to be used in the implementation run each time the function is called. average_ON_OFF_time represents the average value of T_{ON} and T_{OFF} time for the primary user. rand() is the function of C standard library which returns a pseudo random number in the range of 0 to RAND_MAX with uniform distribution. Whereas RAND_MAX is a constant whose default value varies between implementations but it is granted to be at least 32767. A natural logarithm function is used in this regard as an exemplary function to return the ON or OFF time at the point of iteration when the function is called. If T_{ON} is calculated, the frame(s) are prepared to be sent to the air by PU TX based upon T_{ON} time. Finally, they are sent on air by the RF chip one by one. The random ON and OFF time distributions are taken due to ease of implementation and as an example. Whereas, the other random distributions (for example exponential as done in Section 4.1.2) is not considered in experiments due to complexity of implementation.

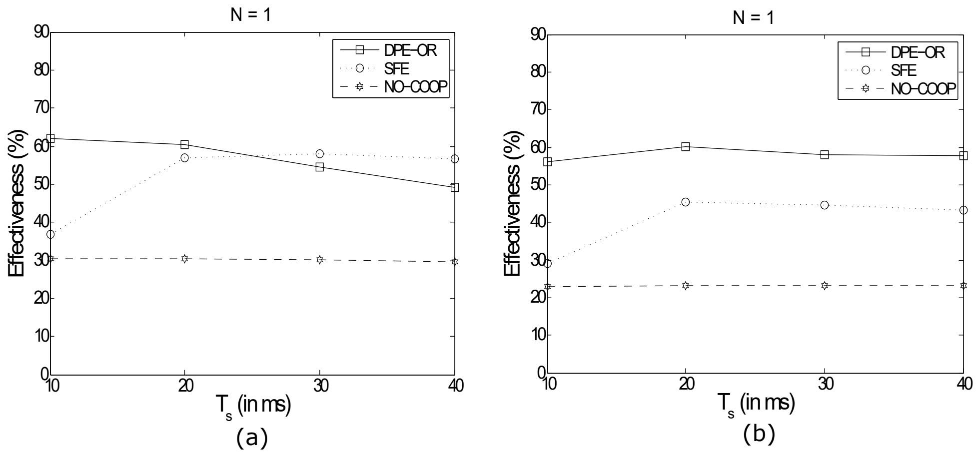

FIGURE 6.6 – *Performance with deterministic (a) and exponential (b) primary user traffic*

Figure 6.6 shows the results with deterministic (a) and randomly (b) distributed primary user traffic. The results show that Effectiveness with deterministic traffic is much better than that when randomly distributed traffic is considered for primary user. As random distributed traffic is probabilistic, therefore primary user transmitted frames are not quite strictly in succession as that with deterministic traffic. Therefore, there is a comparatively higher probability that secondary user or cooperative node detects the empty spaces between randomly space primary user frames. Consequently, the probability of collisions with randomly distributed primary user traffic is higher as that with deterministic primary user traffic. Although the difference is not visible significantly with DPE protocol but it is more prevalent with NO-COOP (see 30% for deterministic traffic as compared with 23% for randomly distributed traffic).

The conclusion of discussion of this section is that the performance improvement with DPE protocol (OR and Majority) is much better than that with SFE protocol. Therefore in the rest of discussion in this thesis, DPE protocol is analyzed in detail. The detailed analysis is performed in a wide range of real world scenarios so that the performance of cooperative sensing is evaluated. Then later in the thesis a realistic model is developed and recommendations for application of cooperative sensing are provided. In order to show further evaluation for DPE protocol for real world scenarios, SU RX is taken as cooperative node as well. As SU RX is a first natural choice for cooperative node. Therefore, evaluations with SU RX are performed first in a wide range of scenarios even by varying the duty cycle of primary user traffic. These evaluations are followed by further evaluations in the later section where additional dedicated cooperative node are also added in the system to see the performance change even in mobile scenarios.

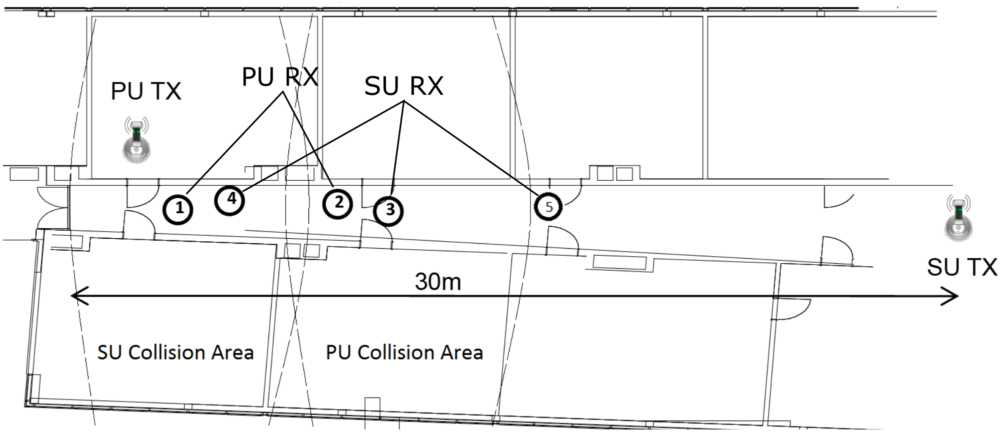

FIGURE 6.7 – *Scenarios where SU RX acts as cooperative node*

6.2 EVALUATIONS WITH SU RX AS A COOPERATIVE NODE

Secondary user receiver is a candidate for cooperative node as discussed in Figure 3.4. Although SU RX acting as a cooperative node reduces the requirement of additional cooperative nodes by one, it imposes additional constraint on the performance. For example; if the BEACON frame is lost the secondary user receiver is not able to receive the DATA frames transmitted by SU TX. Due to loss of BEACON frames, SU RX stays at the control channel to wait for next BEACON and therefore not able to receive DATA frames from SU TX. Regarding analysis, in this section a detailed study is performed regarding topology of different nodes and placement of SU RX related to the other nodes PU TX and SU TX. The evaluation with dedicated cooperative nodes were performed in a scenario *PU and SU Collision* which provides comparison of DPE and SFE protocols. In all other scenarios, the performance gain if any with cooperative sensing is lower than that with the scenario *PU and SU Collision*. In this section, the focus of evaluation is on various kinds of scenarios with SU RX rather than comparison of DPE, SFE and NO-COOP as the comparison is already studied in the previous section. Furthermore, the impact of primary user traffic pattern is studied so that the gain achieved with cooperative sensing is evaluated. In all the scenarios PU TX transmission is hidden ($P_d = 0\%$) to SU TX as in the previous section. The next subsection describes the scenarios in detail.

6.2.1 SCENARIO DESCRIPTION

In the previous section, only one scenario PU and SU Collision was selected whereas in this section a more detailed scenarios are considered so that performance of cooperative sensing is studied in various situations with different primary user traffic and in the end system level recommendations are provided. Figure 6.7 shows the selected locations as 5 circles for PU RX and SU RX in the floor. The position of PU TX and SU TX is fixed in all the scenarios. The selection of these scenarios is based upon the collision areas so that a detailed study with topology using SU RX is performed. Two zones are named i.e. PU Collision Area and SU Collision Area. In PU Collision Area, primary user transmission is collided by concurrent secondary user transmission at PU RX and primary user frames are corrupted. This happens if received power level of secondary user transmission at PU RX is high enough to corrupt the primary user transmitted frames at PU RX. On the contrary, in SU Collision Area secondary user transmission is collided by concurrent primary user transmission at SU RX and secondary user frames are corrupted due to comparatively higher power levels of PU TX transmitted frames at SU RX. Although these areas are not determined very precisely. Based upon measurements several scenarios are specified in Table 6.4 with placement of the primary and secondary user receivers. In all scenarios, primary user transmission is hidden to SU TX. The selection of the scenarios is based upon the collision areas, e.g. collisions occurring at PU RX and SU RX and the goal of evaluation is to see how much performance improvement is shown by cooperative sensing in each type of scenario.

In the scenario *No Collision*, there are no collisions with the primary and secondary user transmissions at their respective receivers. The relevant positions of PU RX and SU RX are ① and ⑤ respectively. As PU RX is quite close to PU TX and outside PU Collision Area, concurrent secondary user transmission has no influence on primary user transmission. SU RX is quite close to SU TX and outside of SU Collision Areas. Therefore, collisions occur neither at PU RX nor at SU RX.

In the scenario *PU Collision*, primary user transmission is corrupted at PU RX with the concurrent secondary user transmission but secondary user transmission is not corrupted at SU RX because of concurrent primary user transmissions. The relevant positions of PU RX and SU RX are (②, ⑤) respectively. As PU RX is in PU Collision Area therefore primary user frames are corrupted because of concurrent secondary user transmission. SU RX is again outside of SU Collision Areas and therefore secondary user transmitted frames are correctly received. Furthermore, in both *No Collision* and *PU Collision* scenarios, SU RX is not able to detect primary user transmissions PU TX is hidden to SU RX along with SU TX.

In the scenario *PU Collision Improvement*, PU RX is at the same position as that in *PU Collision* but SU RX is now in a position to detect primary user transmission. The relevant positions of PU RX and SU RX are (②, ③) respectively. In this situation, the difference with the scenario *PU Collision* is that SU RX is nearer to PU TX and is able to detect primary user transmission so that SU RX acting as cooperative node is able to improve the system performance.

In the scenario *PU and SU Collision*, both primary and secondary user transmissions are corrupted at PU RX and SU RX by concurrent secondary and primary user transmission respectively. The relevant positions of PU RX and SU RX are (②, ④). In this situation, primary and secondary user receivers are in PU and SU Collision Areas respectively. This leads to corruptions of primary and secondary user transmitted frames at PU RX and SU RX respectively. SU RX is nearer to PU TX and is able to perfectly detect primary user transmission and thus is able to improve performance with cooperative sensing.

Table 6.4 – *Placement of PU RX and SU RX*

Scenario Description	PU RX	SU RX
No Collision	1	5
PU Collision	2	5
PU Collision Improvement	2	3
PU and SU Collision	2	4
SU Collision	1	4

In the last scenario *SU Collision*, secondary user transmission is corrupted at SU RX by concurrent primary user transmission but primary user transmitted frames are not corrupted at PU RX due to secondary user transmission. The relevant positions of PU RX and SU RX are (①, ④). In this scenario, PU RX is close to PU TX and secondary user transmission is not able to corrupt primary user transmission but SU RX is in SU Collision Area and concurrent primary user transmission corrupts secondary user transmitted frames. The scenario *PU and SU Collision* is similar to the one discussed in Figure 6.1. Therefore, it is expected that the scenario *PU and SU Collision* provides high performance gain for cooperative sensing (DPE protocol) as compared with NO-COOP. In the next subsection, the experimental settings for the scenarios are described.

6.2.2 EXPERIMENTAL SETTINGS

As discussed in Section 2.3, the radio environment has multiple radio propagation effects (fading, shadowing and free space loss). Therefore, the experiments are performed mostly in the mornings and evenings when movement of people is limited on the selected floor. Movement of people creates significant but random effects that do not allow for comparison of measurements. Experiment Duration, T_e = 1000s is selected for each run of the experiment to make sure that sound statistics are obtained. The results (Figure 6.2-Figure 6.6) shown in previous section had confidence level of 95% and have multiple runs (>5). Therefore, shorter T_e = 500s was justified. But the scenarios shown in this section have multiple positions and proper management of nodes for different experiments was cumbersome which led to select higher T_e = 1000s and shorter number of runs as it was difficult to maintain same radio conditions and well defined collision areas. The parameters T_{BEACON}, T_w, T_{Btx} and T_{Stx} have the same values 100ms, 2.4ms and 1ms as that used in previous section. Where these parameters represent beacon period, time duration for CSRW for one cooperative node, transmission time for BEACON and SENSING_INFORMATION frames respectively. As only SU RX is able to act as cooperative node in the scenarios, therefore N = 1 in the current setting. Although Figure 6.5 shows decrease in Effectiveness with increase in sensing period. We select T_s = 30ms as an example for further experimental evaluation in this chapter. The reason behind selection of this value was that we were able to see noticable real time activity for primary and secondary user transmission on the LCD module for the radio device shown in Figure 5.4. Additionally, lower T_s < 10ms are also not selected as these lead to higher overheads. In the previous section, only one kind of primary user traffic pattern is considered to evaluate performance of DPE and SFE protocols and But

Table 6.5 – *Parameter settings for Figure 6.7-Figure 6.9*

T_s (ms)	T_w (ms)	T_{Btx}, T_{Stx} (ms)	T_{BEACON} (ms)
30	2.4	1	100

Table 6.6 – *Parameter settings (cont..) for Figure 6.7-Figure 6.9*

N	PU Technology	SU Technology	T_e (s)
1	IEEE 802.15.4 (250 kbps)	IEEE 802.15.4 (500 kbps)	1000

in this section three settings for duty cycle of primary user traffic, 9%;50%;91% (low, medium and high respectively) are used as shown in Table 6.7. The purpose of this setting is to demonstrate the impact of primary user traffic on Effectiveness. Additionally, $T_s = 30$ms is considered for evaluation in this section and even in the next section. This sensing period is selected as an example. As compared to 10ms and 20ms, larger number of secondary user frames are seen on API of the radio device which ease real time visualization of primary and secondary user transmissions on the air. Randomly distributed T_{ON} and T_{OFF} times are used for the primary user in this setting as done by Kim et. al "Efficient Discovery of Spectrum Opportunities with MAC Layer Sensing in Cognitive Radio Networks" in 2008 [24]. Larger values of T_{ON} and T_{OFF} are not selected to achieve the same duty cycle as the experiment duration is not enough to get statistically sound results. It is shown earlier that DPE protocol is not able to capture the dynamics of primary user traffic if T_{ON} is smaller than T_s. Very low values of T_{ON} are not selected to achieve the same duty cycle (50% and 90%) of primary user traffic as T_s has to be lower than T_{ON}. Effectiveness is small with very low values of T_s due to overhead of $r_{W_{COOP}}$. Table 6.5 and Table 6.6 show experimental settings for the scenario described in the previous subsection. The measurements are performed with the two settings regarding cooperative sensing. In the first setting NO-COOP, SU TX performs spectrum sensing with $T_s = 30$ms and there is no cooperation from SU RX. In the second setting (SU RX$_{(DPE)}$) secondary user receiver acts as a cooperative node. The same value of $T_s = 30$ms is selected for both settings to compare their performance. It is to be reminded here that SU RX passes through cooperative node selection protocol in REG_REL state and once SU RX is registered to SU TX as cooperative node, the release procedure is disabled so that the performance in COOP is analyzed. Otherwise, SU TX is not able to receive until SU RX switches to the COOP state.

The movement of people is avoided during the experiments but still radio conditions change which ultimately changes the performance with each run of the experiment for the scenarios. Therefore the results are shown for a single run as the radio conditions are unpredictable. Still single runs impose some outliers in the measurements but experimental evaluation has its limitations with reproducibility. The results allow for a qualitative comparison and indicate some quantitative effects. Besides earlier in previous section results with several runs for a particular scenario are shown with 95% confidence level which increases confidence for the measurements. The main problem with the measurements is unpredictable radio conditions which model the real world scenarios but limit

TABLE 6.7 – *Mean values of T_{ON} and T_{OFF} times for primary user traffic*

duty cycle	T_{ON}	T_{OFF}
9%	4 ms	40 ms
50%	40 ms	40 ms
91%	40 ms	4 ms

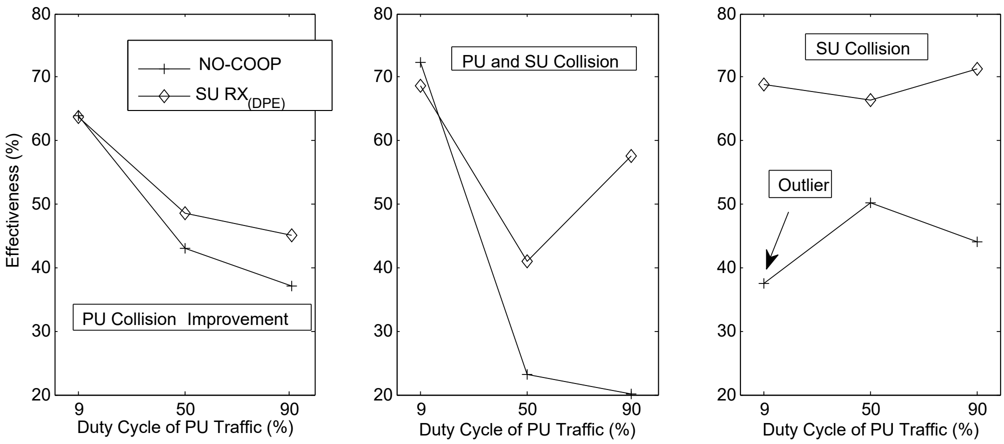

FIGURE 6.8 – *Scenarios where cooperative sensing increases overall performance*

the reproducibility. This realistic environment is weighted much higher than reproducibility because confidence for a real-world usage is gained and the proper functionality of a protocol is understood with unpredictable effects. The next subsection presents the evaluation results for the scenarios described in this section.

6.2.3 RESULTS

Figure 6.8 shows the results for scenarios where cooperative sensing improves effectiveness for the system. An increasing effectiveness is seen with cooperative sensing in scenarios PU Collision (Improvement), PU and SU Collision and SU Collision specially for high duty cycle of primary user traffic. Effectiveness with the scenario PU and SU Collision is maximum (40%) with 90% duty cycle of PU Traffic as collisions happen both at PU RX and SU RX and these are reduced with cooperative sensing. An outlier is seen here for 9% duty cycle with NO-COOP for SU Collision scenario as SU RX is far away from SU TX which leads to lower receptions due to changing radio conditions e.g. due to movement or other dynamics in the system.

Figure 6.9 shows the results for the scenarios No Collision and PU Collision where cooperative sensing does not increase the performance as compared with individual spectrum sensing. In these scenarios SU RX is not able to detect primary user transmission and consequently does not help in reduction of collisions if there are any. In the scenario No Collision, a small decrease for example 8% decrease with duty cycle 50% is seen in Effectiveness with cooperative sensing which is partially attributed to the overheads $r_{W_{COOP}} = 3\%$ and $Overhead_{NODE\_SEL} =$

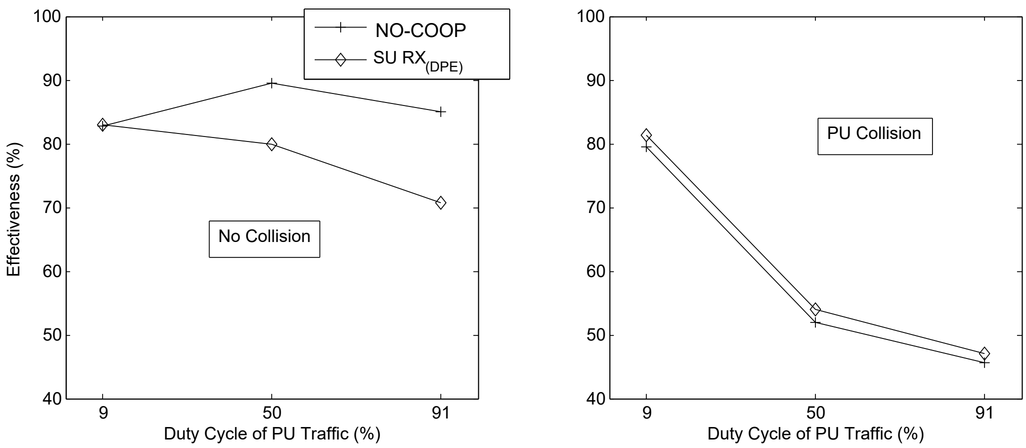

Figure 6.9 – *Scenarios where cooperative sensing does not improve performance*

2% of cooperative sensing besides radio propagation effects. But in the scenario PU Collision decrease in Effectiveness is seen for both settings NO-COOP and SU RX$_{(DPE)}$ with an increase in duty cycle of primary user traffic. As SU RX is not able to detect primary user transmission, cooperative sensing does not help in this scenario at all.

The outcome of this evaluation shows that the DPE protocol performs better if primary user traffic is high and as a consequence the advantage of cooperative sensing comes when the primary user traffic is high. Cooperative sensing imposes only overhead in the system if the primary user traffic is low. The purpose of cooperative sensing is to reduce collisions described in Section 2.4 but with overhead on the control channel. Additionally, Cooperative Sensing Receiving Window CSRW reduces the useful time for secondary user transmission as during this time sensing reports are collected from the cooperative nodes by SU TX. As described in Section 6.1.3 on Page 90, only DPE protocol is discussed in the rest of thesis whereas SFE protocol is left for future work. It is shown that SU RX is not able to detect primary user transmission all the time. Therefore in the next section, the performance with additional cooperative node C_1 is shown.

6.3 EVALUATIONS IN MOBILE SCENARIOS

In order to demonstrate performance of the proposed cooperative sensing design specially cooperative node selection protocol in mobile environment, two exemplary scenarios are conceptualized and evaluated. The selection of the scenarios is done in a way that the performance of both SU RX and C_1 acting as cooperative node is studied and compared. Furthermore, selection of the parameters T_{REG_REL}, $T_{COOPNODE\_REG\_REL}$, T_{BEACON_LIVE}, $Threshold_{REL\_SUTX}$, $Threshold_{REG}$, $Threshold_{REL\_COOPNODE}$ in the mobile scenarios are demonstrated in the real world radio environment. These parameters are time durations for registration or release procedure, time period for COOPNODE_REG_REL frames, time period to check for BEACON frames, threshold for releasing a cooperative node at SU TX, threshold for registering a cooperative node at SU

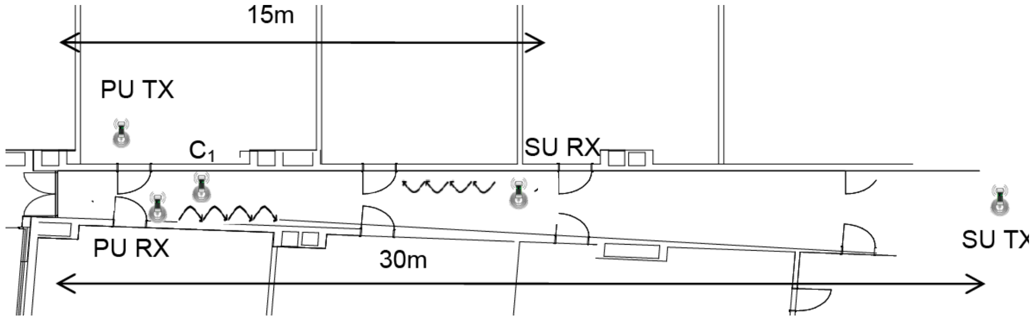

Figure 6.10 – *Mobile scenario PURX-SURX-away PU RX and SU RX remain away from each other during the whole experiment run*

TX, threshold for releasing from SU TX at the cooperative node respectively. In the previous section, the scenarios were stationary and each scenario belonged to one collision area which was difficult to reproduce as the collision areas do not have sharp boundaries due to unpredictable radio propagation effects in the environment. On the contrary, in this section PU RX and SU RX move in these scenarios so that they pass through different collision areas and the scenarios are easily reproduced which is important for improving the confidence of the results. The transmission of PU TX is hidden to SU TX in all the scenarios. In the next subsection, the mobile scenarios are explained with the help of diagrams.

6.3.1 scenario description

Figure 6.10 and Figure 6.11 show the initial placement of the nodes and movement of PU RX and SU RX. Both PU TX and SU TX are stationary in all the scenarios. One additional stationary cooperative node C_1 is introduced in the scenarios. As reproducibility is difficult to achieve for comparison of various settings, mobile testbed nodes are used to generate reproducible movements. In mobile scenario "PURX-SURX-away", both PU RX and SU RX follow a rectangular path of length $\approx$ 15m while remaining away from each other during the experiment. Whereas in mobile scenario "PURX-SURX-close", PU RX and SU RX stays quite close with each other during the experiment duration due to their starting positions. The purpose of selection with these two positions (away and close) is that the two extremes are selected considering the radio environment. In the next subsection, experimental settings of the mobile scenarios is described.

6.3.2 experimental settings

Table 6.8 and Table 6.9 show the values of the related parameters of the proposed cooperative sensing design for the results shown in this section. Experiments are performed in each scenario with three different settings. In the first setting NO-COOP, neither of the nodes SU RX and C_1 act as cooperative nodes and SU RX performs only reception for SU TX transmissions. In the second setting $SURX_{(DPE)}$, C_1 again remains switched off but SU RX acts as a cooperative node N = 1. In the third setting C_1 added, C_1 is added in the system and both

TABLE 6.8 – *Parameter settings for Figure 6.10-Figure 6.13*

T_s (ms)	T_w (ms)	T_{Btx}, T_{Stx} (ms)	T_{BEACON} (ms)
30	2.4	1	100

TABLE 6.9 – *Parameter settings (cont..) for Figure 6.10-Figure 6.13*

N	PU Technology	SU Technology
1,2	IEEE 802.15.4 (250 kbps)	IEEE 802.15.4 (500 kbps)

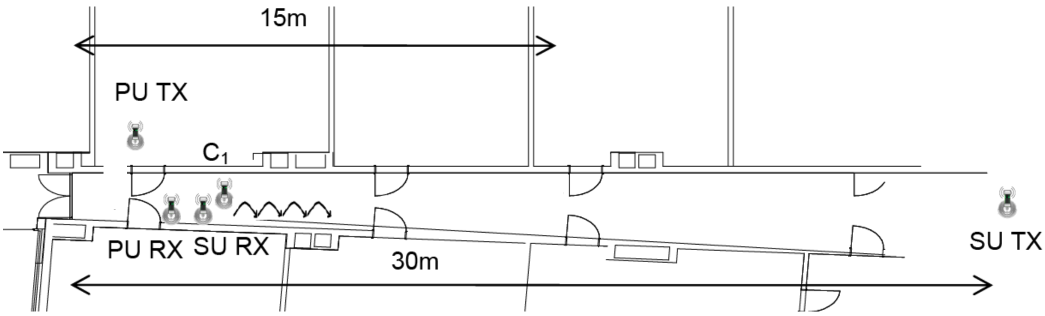

FIGURE 6.11 – *Mobile scenario PURX-SURX-close PU RX and SU RX remain quite close to each other during the whole experiment run*

nodes SU RX and C_1 act as cooperative nodes N = 2. Each experiment run is repeated twice Run 1 and Run 2 as the larger number of runs requires similar radio environment which is difficult to maintain and is affected by even a moving human being. The values for the parameters T_s, T_{BEACON}, T_w, T_{Btx} and T_{Stx} are 30ms, 100ms, 2.4m and 1ms which are the same as those used in the previous sections of this chapter. We select this exemplary setting as the purpose of the evaluation is to evaluate cooperative sensing in mobile scenario rather than impact of various parameters on performance. The technologies mentioned for primary and secondary user are the same described in previous section PU Technology = IEEE 802.15.4 with 250 kbps, SU Technology = IEEE 802.15.4 with 500 kbps. An exemplary higher value 50% of duty cycle for primary user traffic is selected as the proposed cooperative sensing protocols provide performance gain with higher primary user traffic as investigated in the previous section. Furthermore, randomly distributed T_{ON} and T_{OFF} times are considered in the evaluations as done in previous section.

In the next step, selection of the parameters T_{REG_REL}, $T_{COOPNODE\_REG\_REL}$, T_{BEACON_LIVE} are shown in Table 6.10 and are discussed. All the nodes communicate with each other with carrier sensing during T_{REG_REL} time which is the time duration of REG-REL state of the cooperative sensing design. T_{REG_REL} = 100ms is selected which is sufficient for handling two cooperative nodes for registration or release procedure. Furthermore, once SU RX is registered it is not released from the system as it performs reception. As far as $T_{COOPNODE\_REG\_REL}$ is concerned, higher value of $T_{COOPNODE\_REG\_REL}$ imposes less $Overhead_{NODE\_SEL}$ but it does not handle high mobility of coop-

Table 6.10 – *Parameter settings (cont..) for Figure 6.10-Figure 6.13, evaluation in mobile scenarios*

T_{REG_REL} (ms)	$T_{COOPNODE\_REG\_REL}$ (s)	T_{BEACON_LIVE} (s)
100	5	10

erative nodes very well. Additional cooperative node C_1 is stationary but SU RX is mobile with very low speed of 0.120m/s. This value was selected so as to have stable movement of testbed nodes along the specified path. A reasonable value based upon the measurements of $T_{COOPNODE_REG_REL} = 5$s is selected which leads to an overhead of 2% (see Equation 3.2) for the cooperative node selection protocol. This value was selected based upon measurements and the distances of PU TX, SU TX from the cooperative nodes. As C_1 is stationary SU RX is mobile and the only random parameter in this setting is the radio channel. The distances from PU TX, SU TX to the cooperative nodes strongly affect the radio channel conditions between transmitting device to the receiving device. For example, with small distances the straight path (1) shown in Figure 2.4 is dominant and the fluctuations of the radio signal at the receiving end are minimal. As described in Section 3.3, the cooperative node C_1 in this case checks whether the associated SU TX is still in the range T_{BEACON_LIVE} and its value is 10s in the experiments. This value is selected as C_1 is stationary in the setup and SU TX is in range of it. Very low values for T_{BEACON_LIVE} lead to more release and registration procedures for a particular cooperative node. Very high values lead to unnecessary association of a particular cooperative node with SU TX if BEACON frames are not received by the cooperative node.

In the final step, the thresholds introduced in Section 3.3 $Threshold_{REG}$, $Threshold_{REL\_COOPNODE}$ and $Threshold_{REL\_SUTX}$ are discussed (shown in Table 6.11). $Threshold_{REG}$ represents the threshold for registration to SU TX by the cooperative node. Lower value of $Threshold_{REG}$ leads to large number of registration procedures but its higher value incurs lesser number of registrations. $Threshold_{REL\_SUTX}$ and $Threshold_{REL\_COOPNODE}$ represent the threshold for releasing the cooperative node at SU TX and the threshold for releasing from SU TX at the cooperative node. Smaller values of $Threshold_{REL\_SUTX}$ and $Threshold_{REL\_COOPNODE}$ introduce lesser number of release procedures whereas larger values of these thresholds introduce larger number of release procedures. The value of these thresholds are selected based upon the mobility level of various nodes and the expected intensity of primary user traffic. The value (by hit and trial) for all these thresholds is 0.15 so that the number of registration or release procedures is small (for example less than 5). Experiment duration, $T_e = 1000$s for all the experiments as that in previous section as the number of runs for a particular experiment is small (2) as compared to that in Section 6.1.2. The number of rectangular rounds each PU RX and SU RX traverses during the experiment run in both mobile scenarios is 3. The speed of ≈ 0.120m/s for PU RX and SU RX is selected and the nodes move in curved paths rather than straight paths as the floor of the institute where the nodes move is not flat. Therefore curved paths lead to reproducible movement of the nodes. Furthermore, the total estimated distance transversed during the complete

Table 6.11 – *Parameter settings (cont..) for Figure 6.10-Figure 6.13, evaluation in mobile scenario*

$Threshold_{REL\_SUTX}$	$Threshold_{REG}$	$Threshold_{REL\_COOPNODE}$	T_e (s)
0.15	0.15	0.15	1000

experiment run is 120m (speed $\times$ T_e = 0.120m/s $\times$ 1000s). The circumference of the rectangular path is $\approx$ 36m which consists of Length (15m,15m) and Width (3m, 3m). Furthermore, SU RX is added to SU TX according to the cooperative node selection protocol but the release procedure is disabled for SU RX. This functionality is not added to the implementations and evaluation with such aspect is left for future work as the purpose was just to show the performance of SU RX acting as cooperative node in mobile scenario.

6.3.3 RESULTS

Before the results are explained, first a number of quantities (see Table 6.13) are defined. *Busy Detections* is the ratio of SENSING_INFORMATION frames which report the data channel as busy to the total SENSING_INFORMATION received frames at a particular cooperative node. *# Registrations* represents the number of registrations performed during the whole experiment run. *# Registrations* is greater than 1 if the cooperative node is released from SU TX either initiated from C_1 or SU TX. *Beacons Sent* is the ratio of actual BEACON frames sent by SU TX over the maximum amount that is possible for transmission during the experiment duration. *Beacons Received* is the ratio of successfully received BEACON frames at the cooperative node (SU RX or C_1) with those transmitted at SU TX. Table 6.13 presents the individual quantities for first run of the experiments for both mobile scenarios. Table 6.15 shows measurement results for components of Effectiveness for both scenarios for experiment run 1. This in combination with Table 6.13 helps to explain the results of mobile scenarios. The components of Effectiveness are $r_{Total\ Goodput}$, Wastage in primary user transmission $r_{W_{PU}}$, Wastage in secondary user transmission $r_{W_{SU}}$, Wastage on the control channel $r_{W_{COOP}}$ (see Section 4.2). $r_{W_{COOP}}$ does not exist for NO-COOP as there is no usage of control channel in this state of the proposed cooperative sensing design. It is to be reminded here that NO-COOP refers to individual spectrum sensing or NO-COOP state of the proposed cooperative sensing alternatively. The only difference between simple NO-COOP with NO-COOP state is that with NO-COOP state, COOPNODE_REG_REL frame transmission is there.

Figure 6.12 shows the performance for the mobile scenario PURX-SURX-away. In this case, Effectiveness is 45%, 51% and 59% for NO-COOP, SU RX$_{(DPE)}$ and C_1 added settings respectively for the experiment run 1. Although Effectiveness is already improved (5% margin as compared with NO-COOP) with SU RX$_{(DPE)}$ setting, a performance improvement (14% margin as compared with NO-COOP) is seen with the additional cooperative node C_1. This is because C_1 is stationary and quite near to PU TX, therefore it informs SU TX continuously about PU TX activity (*Busy Detections* (C_1) = 60%) whereas SU RX is mobile and is not in a

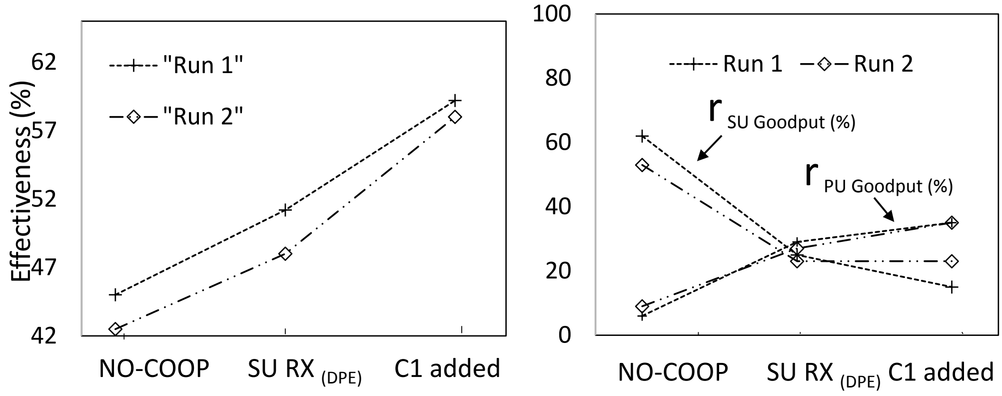

Figure 6.12 – *Results for the mobile scenario PURX-SURX-away*

position to detect primary user transmissions all the time (*Busy Detections* (SU RX) = 44%). Primary user goodput $r_{PU\ Goodput}$ is improved from 7% to 30% and 38% with both SU $\text{RX}_{(DPE)}$ and C_1 added settings respectively for experiment run 1. As both SU RX and C_1 informs SU TX about primary user transmissions at the right times which are not detectable by SU TX itself due to hidden node scenario. Secondary user goodput $r_{SU\ Goodput}$ is decreased from 61% for NO-COOP to 23% and 12% with SU $\text{RX}_{(DPE)}$ and C_1 added settings respectively for experiment run 1. As correct detection of primary user transmission helps SU TX to reduces collisions but secondary user transmits less data in this scenario either because of CSRW or primary user detections. The release procedure for SU RX is disabled as it has to perform reception continuously for SU TX. Therefore the number of registrations for SU RX is 1 with both settings SU $\text{RX}_{(DPE)}$, C_1 added. On the contrary, the number of registrations for C_1 is 2 in this case. This means that during the experiment run, C_1 is released once and is registered again with SU TX. *Beacons Sent* is 92% and 86% for SU $\text{TX}_{(DPE)}$ and C_1 added respectively which is less than 100% for both settings. This is due to the overhead of T_{REG_REL}, clock drift, non zero duration (1ms) of BEACON frames and *# Registrations* $(C_1) = 2$ which attribute to the release procedure during the experiment. *Beacons Received* (SU RX) for both settings SU $\text{TX}_{(DPE)}$ and C_1 added is 84% and 88% respectively and is less than *Beacons Received* (C_1) which is 95%. The reason behind this is that SU RX is moving during the whole experiment and receives comparatively less number of BEACON frames sent by SU TX. On the contrary C_1 is stationary and is able to receive BEACON frames with comparatively higher percentage.

Figure 6.13 shows the performance for the mobile scenario PURX-SURX-close, here Effectiveness is 50%, 46% and 62.5% for NO-COOP, SU $\text{RX}_{(DPE)}$ and C_1 added setting respectively for experiment run 1. The behavior of primary and secondary user goodputs are similar to the evaluation results for the mobile scenario PURX-SURX-away. Primary user goodput $r_{PU\ Goodput}$ is improved from 10% to 23% and 35% with both SU $\text{RX}_{(DPE)}$ and C_1 added settings respectively for experiment run 1. In this scenario, SU TX gets more information with SU RX and C_1 about primary user transmissions at the right times which SU TX

Table 6.12 – *Measurement results related to DPE Protocol for experiment run 1, mobile scenario PURX-SURX-away*

	SU RX$_{(DPE)}$	C_1 added
Busy Detections (SU RX)	44%	47%
Busy Detections (C1)	N.A.	60%
# Registrations (SU RX)	1	1
# Registrations (C1)	N.A.	2
Beacons Sent	92%	86%
Beacons Received (SU RX)	84%	88%
Beacons Received (C1)	N.A.	95%

Table 6.13 – *Measurement results related to DPE Protocol for experiment run 1, mobile scenario PURX-SURX-close*

	SU RX$_{(DPE)}$	C_1 added
Busy Detections (SU RX)	33%	29%
Busy Detections (C1)	N.A.	60%
# Registrations (SU RX)	1	1
# Registrations (C1)	N.A.	1
Beacons Sent	92%	88%
Beacons Received (SU RX)	88%	90%
Beacons Received (C1)	N.A.	99%

Table 6.14 – *Details of components of effectiveness for experiment run 1, mobile scenario PURX-SURX-away*

	NO-COOP	SU RX$_{(DPE)}$
Effectiveness	45%	51%
$r_{Total\ Goodput}$	67%	55%
$r_{W_{PU}}$	44%	20%
$r_{W_{SU}}$	38%	28%
$r_{W_{COOP}}$	N.A.	4%

alone is not able to get itself due to hidden node scenario. Secondary user goodput $r_{SU\ Goodput}$ is decreased from 63% for NO-COOP to 30% and 15% with SU RX$_{(DPE)}$ and C_1 added settings for experiment run 1. The reason behind this is the same CSRW and PU TX detections as described for mobile scenario PURX-SURX-away. *Beacons Sent* have similar values, 92% and 88%

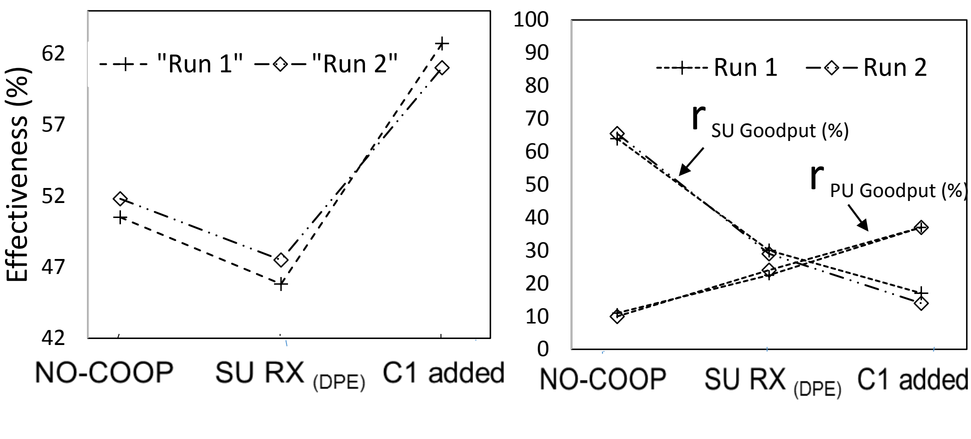

Figure 6.13 – *Results for the mobile scenario PURX-SURX-close*

Table 6.15 – *Details of components of effectiveness for experiment run 1, mobile scenario PURX-SURX-close*

	NO-COOP	SU RX$_{(DPE)}$
Effectiveness	50%	46%
$r_{Total\ Goodput}$	75%	53%
$r_{W_{PU}}$	38%	27%
$r_{W_{SU}}$	36%	31%
$r_{W_{COOP}}$	N.A.	4%

for SU RX$_{(DPE)}$ and C_1 added respectively as those for the mobile scenario PURX-SURX-away. *Beacons Received* for SU RX and C_1 are 88% and 99% respectively. The comparatively lower value for SU RX is due to its mobility in the experiment as explained for the mobile scenario PURX-SURX-away. The quantities *# Registrations* (SU RX) and *# Registrations* C_1 are 1 for this mobile scenario as no release procedure is observed for C_1 in this scenario.

Busy Detections (SU RX) is 33% which is lower as compared with that 44% in the mobile scenario PURX-SURX-away. The comparatively lower value of *Busy Detections* (SU RX) is one source of lower Effectiveness for SU RX$_{(DPE)}$ as compared with NO-COOP. As with comparatively higher value of *Busy Detections* (SU RX) corresponds to large number of busy channel detections enabling SU TX to avoid collisions with the primary user transmission. Table 6.15 explains this effect with the help of measurement results for components of Effectiveness for NO-COOP and SU RX$_{(DPE)}$ for both mobile scenarios. The first observation is that Effectiveness with NO-COOP for mobile scenario PURX-SURX-away is 45% which is already less than that (50%) for mobile scenario PURX-SURX-close. The one reason behind this is $r_{Total\ Goodput}$ which is 8% lower for the mobile scenario PURX-SURX-away as compared with the mobile scenario PURX-SURX-close. The other reason behind this is $r_{W_{PU}}$ which is 6% higher for the mobile scenario PURX-SURX-away as compared with the mobile scenario PURX-SURX-close. $r_{W_{COOP}}$ does not exist for NO-COOP. The second observation is that Effectiveness with SU RX$_{(DPE)}$ is lower 5% for the mobile scenario PURX-SURX-close as compared with the PURX-SURX-away. The one reason behind this is $r_{W_{PU}}$ which is 7% higher for the mobile scenario PURX-SURX-close as compared with the PURX-SURX-away. $r_{W_{SU}}$ is comparatively higher for the mobile scenario PURX-SURX-close. $r_{W_{COOP}}$ is same for both the cases 4% as the parameter settings of the DPE protocol is same both the scenarios. The main reason for comparatively higher $r_{W_{PU}}$ and $r_{W_{SU}}$ for the mobile scenario PURX-SURX-close attributes to low *Busy Detections* (SU RX) = 33% as compared with that 44% for the mobile scenario PURX-SURX-away. Furthermore, comparatively lower value of $r_{W_{SU}}$ for cooperative sensing in general is not only because of collisions between primary and secondary user transmissions but due to loss of BEACON frame receptions at SU RX during the experiment. As SU RX is not able to receive secondary user transmitted frames if it does not receive BEACON frames during COOP state (see Figure 3.5 on Page 36). As a result of the analysis in this section, although SU RX relaxes the need for additional cooperative node but it is not necessary that it provides superior performance as compared with NO-COOP. The purpose of evaluation for mobile scenarios is that how we select the parameters for a particular situation. The next section provides a detailed summary of the findings concluded from this chapter.

6.4 SUMMARY

The outcome of the evaluations of the proposed cooperative sensing design with IEEE 802.15.4 radio devices is that cooperative sensing improves the performance where SU TX alone is not able to detect primary user transmissions. Three kinds of scenarios are conceptualized; stationary scenario with dedicated cooperative node C_1, stationary scenarios with SU RX acting as cooperative node and mobile scenarios with both SU RX and C_1 acting as cooperative nodes. The proposed design consists of two kinds of protocols; DPE, SFE and cooperative node selection protocols. In the first kind of scenario (stationary scenario with dedicated cooperative nodes), DPE and SFE protocols are evaluated and compared. In the second kind of scenarios (stationary scenario with SU RX acting as cooperative node) only DPE protocol is evaluated with different primary user traffic patterns. In the last step, the third kind of scenarios are shown in order to demonstrate cooperative node selection protocol along with appropriate selection of the parameters related to the proposed cooperative sensing design. The scenario PU and SU Collision serves as a benchmark to evaluate the proposed cooperative sensing design and compares performance of cooperative sensing with individual spectrum sensing as it provides best possible gain with cooperative sensing. Another outcome is that DPE protocol (OR and Majority rule) performs better than SFE protocol although SFE protocol indicates performance improvement with additional cooperative nodes but the detailed evaluation and discussion of SFE protocol is beyond the scope of this thesis.Therefore, in the rest of the thesis DPE protocol is investigated further. The stationary scenarios with SU RX and mobile scenarios with SU RX and C_1 show further evaluation for the proposed cooperative sensing design (DPE and cooperative node selection protocol) in the real world radio environment. The results show that for low primary user traffic, cooperative sensing does not provide any performance gain. The main performance gain with cooperative sensing is reached for high primary user traffic with greater than 50% duty cycle in the current setup. Therefore the mobile scenarios are evaluated with 50% duty cycle only. The outcome of further evaluation shows that the performance with SU RX acting as cooperative node improves in one of the two mobile scenarios. In one mobile scenario, the performance with SU RX acting as cooperative node is inferior to NO-COOP. The reason behind this is that SU RX is not always in a position to detect primary user transmission due to mobility. Additionally, if SU RX does not receive BEACON frames, it is not able to receive any data from SU TX till the next successfully received BEACON. Therefore, the overhead is more than the advantage gained by cooperative sensing in that scenario. Although with C_1, the performance is always better in both mobile scenarios as it is stationary and is always able to detect primary user transmission and cooperative sensing performs better as compared to individual spectrum sensing. It is found via measurements that the maximum number of cooperative nodes at SU TX should be limited to 1 or 2 (see Figure 6.5) due to overheads associated with cooperative sensing.

While addressing hidden node problem, exposed node problem is encountered. A situation occurs where the cooperative nodes (SU RX or additional cooperative node) detect primary user transmission but there are no collisions at PU RX or at SU RX. The exposed node problem is not addressed in this thesis and left for future work as the focus of this thesis is on hidden node problem.

The collision areas are important parameters (see Section 6.2) in deciding whether to do cooperative sensing. They depend upon the radio propagation environment and the radio technologies and therefore need to be investigated before cooperative sensing is applied to the network. PU Collision Area is the area where PU transmitted frames are corrupted by concurrent SU transmission whereas SU Collision Area is the area where SU transmission is corrupted by concurrent PU transmission. If PU and SU Collision areas are small, cooperative sensing is not recommended. The cooperative sensing is no more helpful in this situation as there are no significant collisions and only overheads are imposed on SU TX due to cooperative sensing. For example, Figure 6.8 and Figure 6.9 present the results for the scenarios where cooperative sensing either improves the performance or does not improve performance respectively. Although collision areas in these scenarios are fixed but the placement of the nodes PU RX and SU RX is changed to see how much improvement is seen with cooperative sensing as compared with individual spectrum sensing. The outcome is that in the best case, the improvement with cooperative sensing is seen from 7% to 40% (see Figure 6.8 (a) and (b)). The collision areas are determined by the power levels of primary and secondary user transmitters and the radio environment and therefore not in the control of the designers. An alternative to finding collision areas first and then deciding for cooperation or not is to detect collisions in adaptive manner. The detailed discussion is left for designers and implementers of cooperative sensing and is also open to research.

The overhead due to $Overhead_{NODE\_SEL}$ is small 2% and is not considered in the later part of this thesis. The other part of the overhead $r_{W_{COOP}}$ for DPE and SFE changes from 10% to 4% for sensing period of 10ms to 40ms. The value of sensing period is not to be a very low as it increases $r_{W_{COOP}}$ in the system. As the outcome of this chapter is provide the insight for usage of cooperative sensing in real radio propagation but the experimental setup considered has its limitation regarding general study of cooperative sensing in heterogeneous radio environments. For example fixed values for beacon period T_{BEACON}, time duration for cooperative sensing receiving window T_w, time duration for BEACON frame T_{Btx} and time duration for SENSING_INFORMATION frame T_{Stx} are used in the experimental evaluation using IEEE 802.15.4. Heterogeneous radio environments include IEEE 802.15.4, IEEE 802.11 and IEEE 802.15.1. In order to answer the questions regarding usage of cooperative sensing for heterogeneous radio environments, a simulation model is proposed in the next chapter. An analysis is performed to provide recommendations for application of cooperative sensing for heterogeneous radio environments for various primary user traffic and the PU and SU technology. Scalability aspects are described briefly and the performance of DPE protocol is compared with RTS/CTS and busy tone techniques.

CHAPTER 7

OPTIMIZATIONS, SCALABILITY AND COMPARISON

In the previous chapters (Chapter 5 and Chapter 6), the focus was on evaluation of individual and cooperative spectrum sensing with real world scenarios. The purpose of the evaluation in real world scenarios was to get base for the realistic model for cooperative sensing for system wide performance evaluation. The stationary and mobile scenarios in the previous chapter provide real world evaluation of the proposed cooperative sensing design, but they have limited range of the parameters beacon period T_{BEACON}, time duration to receive sensing report T_w, sensing period T_s, time duration for SENSING_INFORMATION frame T_{Btx}, T_{Stx}, duration of ON state T_{ON}, duration of OFF state T_{OFF}, PU Technology and SU Technology with the testbed. Therefore, a simulation model is required which is analyzed for broad range of described parameters for providing recommendations for application of cooperative sensing in general for heterogeneous radio environments. Section 7.1 shows the influence of the parameters on Effectiveness and also presents the optimum values of the parameters with the help of a simulation model. Optimum sensing period and maximum Effectiveness for various duty cycles are shown. Additionally, the influence of the parameters; beacon period T_{BEACON}, time duration to receive sensing report T_w, sensing period T_s, time duration for BEACON frame T_{Btx}, time duration for SENSING_INFORMATION frame T_{Stx}, PU Technology, SU Technology are studied in detail. In the next section, performance of cooperative sensing in presence of Bluetooth interferer is also elaborated. Finally, a discussion is made to provide recommendations for application of cooperative based upon the model and analysis which was impossible based upon the experimental evaluation only. The proposed cooperative sensing design is also for multiple primary, secondary and cooperative nodes but in Chapter 6 evaluations are performed only with single primary and secondary nodes. In this regard, Section 7.4 presents an overview for further research for scalability aspects of the proposed cooperative sensing

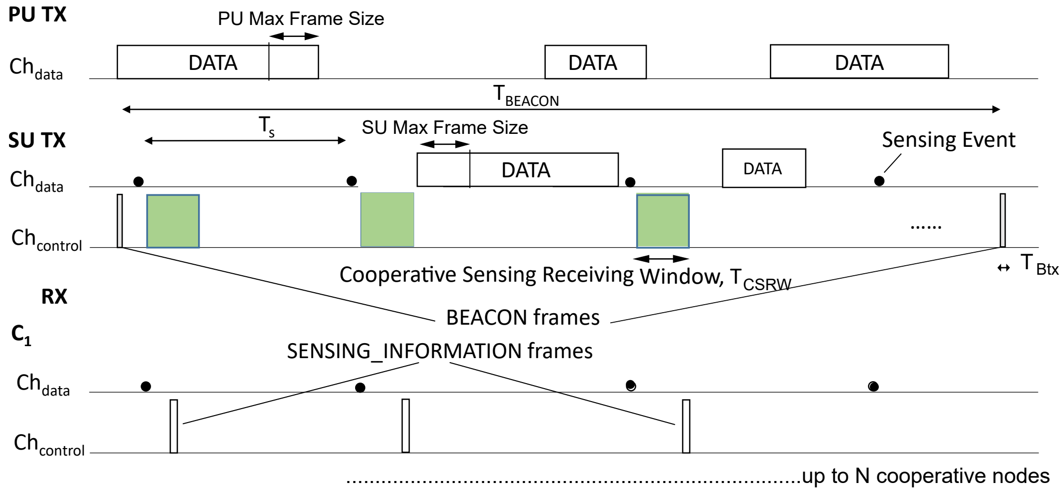

Figure 7.1 – *Parameters for simulation model for the DPE protocol*

design. As discussed in Section 1.1, the goal of this thesis is to reduce collisions in heterogeneous radio environments with cooperative sensing. Section 7.5 compares the proposed cooperative sensing design with techniques like RTS/CTS and Busy Tone to reduce collisions in heterogeneous radio environments. The next section shows the influence on Effectiveness for general range of parameters of the proposed cooperative sensing design which was not possible with the experimental evaluation.

7.1 SIMULATION ANALYSIS

Simulations are performed based upon a model. The model is developed based upon the measurements performed for the scenario PU and SU Collision discussed in Figure 6.1. The reason behind selection of this scenario is twofold; the first and major reason is that the scenario provides the best performance gain with cooperative sensing as compared with individual spectrum sensing. The second reason is that the measurement results are more reliable (see Section 6.1.3) for this scenario as compared with the mobile scenarios (see Section 6.3). The measurement results for this scenario are validated with the simulation results. First the simulation model is elaborated in the next subsection which is followed by the definition of the optimum terms E_{max}, $T_{s(optimum)}$ and finally their relevant values for the selected simulation scenarios are discussed.

7.1.1 MODEL

As described in Section 6.4, DPE (OR and Majority rule) protocol performs better than SFE protocol therefore DPE protocol is taken as reference for further discussion in this chapter and further discussion on SFE protocol is left for future work. Figure 7.1 shows the parameters of the simulation model of the proposed

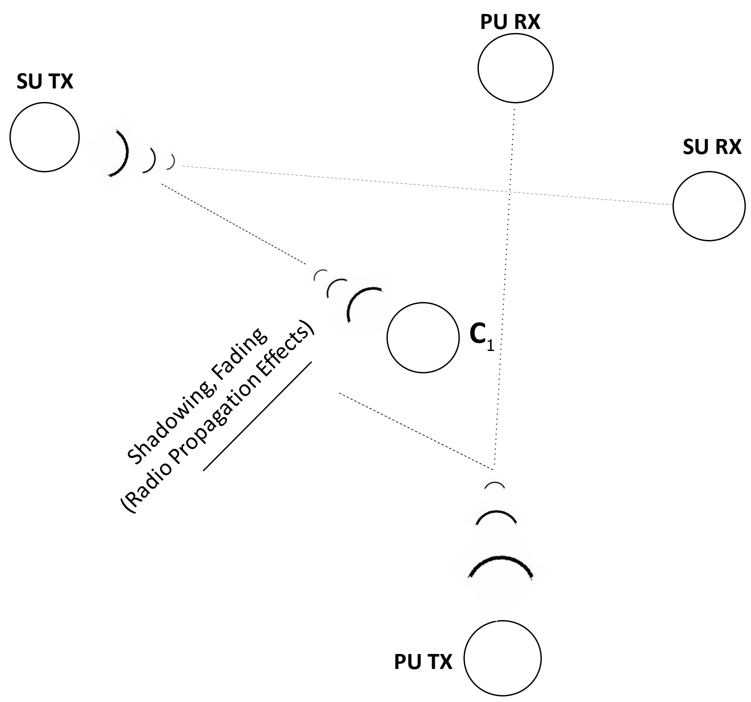

Figure 7.2 – *Topology for the simulation setup under consideration*

cooperative sensing design. Only dedicated node C_1 is considered as the focus of this chapter is to analyse the impact of broad range of parameters rather than studying topology of nodes and radio propagation effects. In this regard, an exemplary topology of various nodes involved are illustrated in Figure 7.2. The topology includes PU TX, SU TX and their respective receivers PU RX and SU RX and the dedicated cooperative node C_1. Figure 7.1 is same as Figure 3.5 except that only C_1 is considered instead of SU RX and C_1.

The parameters PU Technology and SU Technology are modeled by defining the maximum frame size of their transmitted frames (PU Max Frame Size and SU Max Frame Size). Furthermore concurrent transmission of primary and secondary user transmission always corrupt the frames at their respective receivers as also described in Section 6.1.1. The model for primary, secondary and cooperative nodes shown in Figure 7.1 is implemented with MATLAB simulation software. There are three arrays ($transmission$, $start-index$ and $end-index$) which are maintained in MATLAB each for primary and secondary user. The $transmission$ array holds the ON or OFF state of the data channel at a particular time instant according to T_{ON} and T_{OFF} times for the complete simulation time. The resolution of the time is taken as 0.01ms which is sufficient to obtain statistically sound results. Very high resolution of simulation time is not considered as it increases the simulation time. The $start-index$ and $end-index$ arrays hold the starting and ending of transmitted frame times respectively for primary or secondary user. First the $transmission$, $start-index$ and $end-index$ arrays for primary user are filled up according to T_{ON} and T_{OFF} times. Spectrum sensing is performed with sampling of the $transmission$ array

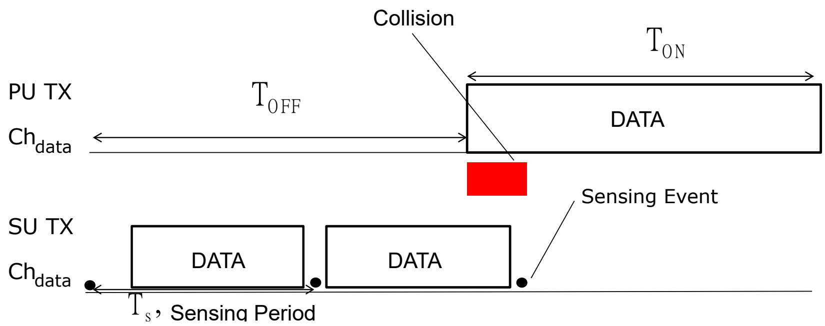

FIGURE 7.3 – *Graphical representation of contents of transmission array for PU and SU for simulations*

with T_s sensing period. Figure 7.3 illustrates the graphical representation for the contents of *transmission* arrays for PU and SU. As said earlier, the simulation resolution time is taken 0.01ms which results in statistically sound results. The representation shown considers perfect detection probability with NO-COOP for illustration purposes although hidden node scenario is investigated both with individual and cooperative sensing in this chapter. In case the collision occurs for a particular frame transmission for SU, the corresponding start and end index of frame of SU as present in $start - index$ and $end - index$ arrays are compared with corresponding *transmission* array.

The cooperative nodes are synchronized with their associated SU TX, but primary and secondary user transmissions are not synchronized. In order to model the asynchronous primary and secondary user transmissions, a range of offset values is taken for secondary user transmission for each particular setting of T_s. The offset is applied from 0 to T_s as the results are expected to repeat after T_s. T_{BEACON} is also considered in the model in order to calculate the exact timings of spectrum sensing event. The outcome of the spectrum sensing result is used to fill up secondary user *transmission*, $start - index$ and $end - index$ arrays. If the result of spectrum sensing is '1', it means that data channel is busy otherwise it is free for secondary user transmission. While filling up *transmission*, $start - index$ and $end - index$ arrays for secondary user, Cooperative Sensing Receiving Window times are also taken into consideration. Finally, Effectiveness is calculated as follows.

Referring to Equation 4.18 and Equation 4.19 in Section 4.2, primary user goodput $r_{PU\ Goodput}$ is calculated by summing up the transmission durations of primary user frames in the $start - index$ and $end - index$ arrays which do not overlap (collide) with the secondary user transmissions (*transmission* array). The total duration of the successful primary user transmissions is divided by the simulation time, T_e as $r_{PU\ Goodput}$ represents a ratio. Similarly referring to Equation 4.18 and Equation 4.20, secondary user goodput $r_{SU\ Goodput}$ is calculated by summing up the durations of secondary user transmitted frames in the $start - index$ and $end - index$ arrays which do not overlap (collide) with the primary user transmissions (*transmission* array). The total duration of the successful secondary user transmissions is divided by the total simulation time, T_e

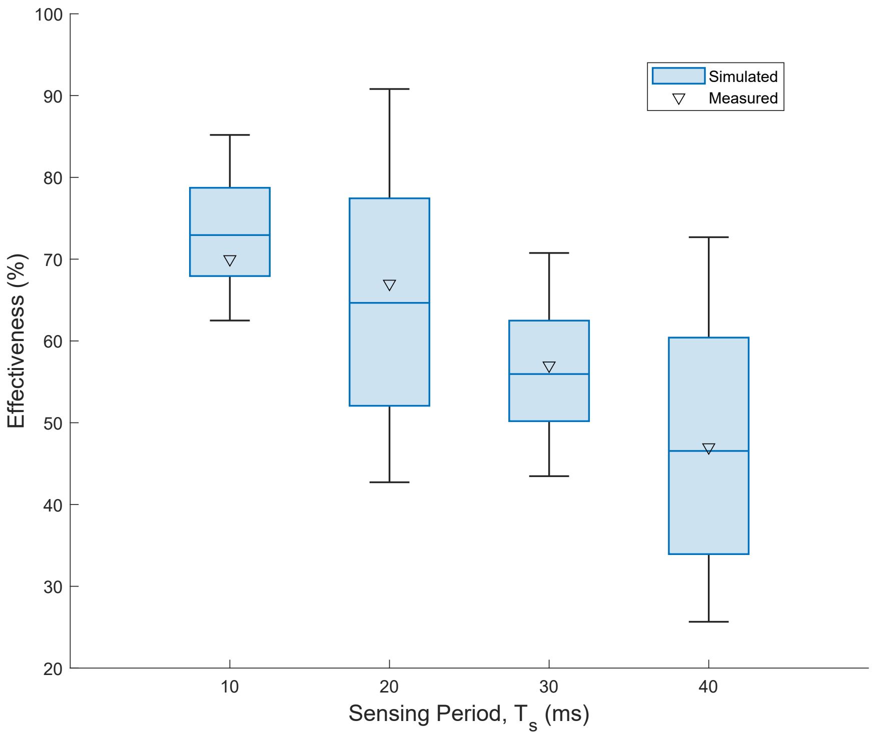

FIGURE 7.4 – *Comparison of measurement and simulation results*

as $r_{SU\ Goodput}$ represents a ratio. In order to calculate $r_{W_{PU}}$ and $r_{W_{SU}}$, throughput is calculated by summing up transmission durations in the $start - index$ and $end - index$ arrays of primary or secondary users and then dividing the sum by the simulation time, T_e. Finally Equation 4.22 and Equation 4.23 calculate $r_{W_{PU}}$ and $r_{W_{SU}}$. $r_{W_{COOP}}$ (see Equation 4.24) is calculated by weighting the BEACON and SENSING_INFORMATION frames by T_{Btx} and T_{Stx} respectively and finally the total sum is divided by the simulation time, T_e. All the wastages are ratios and are dimensionless quantities. Effectiveness is finally calculated according to Equation 4.26.

Before a detailed simulation analysis of the proposed cooperative sensing design is performed, the simulation results are shown with the same experimental setting as those in Section 6.1.2 to validate the proposed model. All the values for the parameters are selected same to the ones used in Section 6.1.2 in order to have fair comparison for validation. The simulation time is selected as 500s which is also the experiment duration used in Section 6.1.2. T_{ON} = 40ms and T_{OFF} = 40ms is selected and the system is analyzed for values of T_s = 10ms, 20ms, 30ms and 40ms. T_{BEACON} = 100ms and T_w = 2.4ms and N = 1. As in experimental evaluation, the start of experiment is always synchronized which is not realistic in real wireless networks. Therefore, offsets are taken to show the results which are useful in real networks. One change here is that results for simulation are provided with different offsets to secondary user transmission for a particular value of T_s. The results are therefore shown with Boxcharts. This continues in all the results presented in later part of this section. Figure 7.4 compares the measurement results with simulation results of DPE (OR fusion rule) protocol for one cooperative node. Effectiveness for various T_s is shown which clearly indicates that the simulation results closely match with the experimental ones. As described before, the simulation results have boxchart as variation in offset from 0 to T_s leads to variation in Effectiveness for a particular sensing period. But the measured values (70%, 68%, 58%, 47%) are close to the average values (72%, 67%, 57%, 47%) for the sensing periods 10ms, 20ms, 30ms, 40ms respectively. The average is considered as the measured values are also represented with average values. The following factors are ignored as they increase complexity of the simulations although their influence on the results is minimal.

- There is a small jitter present in the system which is not included in the model and therefore is not implemented exactly in the simulations.
- The time during which frame is transferred to the RF chip from the micro controller of the radio device. T_{SPI} is also not modeled in the simulations both for primary and secondary nodes.
- In the simulations, it is assumed that the primary or secondary user frames are always corrupted in case of concurrent transmission but in measurements this does not happen all the time as radio channel conditions vary with time and it is difficult to maintain perfectly the same scenario situation.
- Detection probability for the cooperative node C_1 is assumed 100% in the simulations whereas in reality it is $\approx$ 100% (99%).
- In measurements, SENSING_INFORMATION frames are collected approximately 98% of the time. whereas in the simulations these frames are assumed to be collected 100% of the time. This difference is one aspect which makes the simulation results different to the measurements. Furthermore, no data is available to see the real time reception of SENSING_INFORMATION frames in the experiments.

In this section, the results have been shown with selected values of T_s and Effectiveness is shown for individual values of T_s in order to validate the developed model. In the following a detailed simulation analysis of the proposed cooperative sensing design is performed to provide recommendations for using cooperative sensing in heterogeneous radio environments as stated in Section 1.2. In the next subsection, optimization goals are defined. Based upon these goals Section 7.1.3 shows the impact of the parameters; beacon period T_{BEACON}, time duration for BEACON frame T_{Btx}, time duration for SENSING_INFORMATION frame T_{Stx}, time duration for cooperative sensing receiving window for one cooperative node T_w, time duration for ON state of channel T_{ON}, time duration for OFF state of channel T_{OFF}, PU Technology, SU Technology for the proposed cooperative sensing design.

7.1.2 OPTIMIZATION GOALS

In the previous chapter and from Figure 7.4, it is evident that the performance of cooperative sensing in terms of Effectiveness is dependent on the sensing period. Therefore, the goal of optimization is to maximize Effectiveness by changing the

Table 7.1 – *Parameter settings for Figure 7.5-Figure 7.7 for illustration of E_{max} and $T_{s(optimum)}$*

T_w (ms)	T_{Btx}, T_{Stx} (ms)	T_{BEACON} (ms)	Duty Cycle
1.8,1	1	1000	25%

Table 7.2 – *Parameter settings (cont...) for Figure 7.5-Figure 7.7 for illustration of E_{max} and $T_{s(optimum)}$*

N	PU Technology	SU Technology	T_e(s)
1	IEEE 802.15.4 (250 kbps)	IEEE 802.15.4 (250 kbps)	100

sensing period. In this regard two new terms E_{max}, $T_{s(optimum)}$ are defined which are elaborated later in this subsection. The performance of cooperative sensing is visualized with these terms by varying the values for the parameters; beacon period T_{BEACON}, time duration for BEACON frame T_{Btx}, time duration for SENSING_INFORMATION frame T_{Stx}, time duration for cooperative sensing receiving window for one cooperative node T_w, time duration for ON state of channel T_{ON}, time duration for OFF state of channel T_{OFF}, PU Technology, SU Technology for the proposed cooperative sensing design.

In the next step, an exemplary curve is presented to illustrate the newly introduced terms E_{max}, $T_{s(optimum)}$. Table 7.1 and Table 7.2 show the parameter settings for the curve presented in Figure 7.5. The curve illustrates the dependence of performance of cooperative sensing with T_s. PU and SU Technology is IEEE 802.15.4 with 250 kbps. This is different to the evaluations performed in Chapter 5 and Chapter 6 where secondary user was using 500 kbps. The purpose was to have shorter frames on the secondary user side in order to ease the requirement on T_s to be less than T_{ON} (see Page 75). T_{BEACON} is taken 1000ms whereas T_w is 1.8ms, T_{Btx} and T_{Stx} = 1ms, N = 1 (as system works also with one cooperative node). The values for T_{BEACON} and T_w are different to that in the previous chapter because it is assumed that crystal clocks are considered which results in lower clock drifts. More detailed impact of T_{BEACON} and T_w on Effectiveness is studied later in this section. Simulation time of 100s is sufficient in this case as statistically sound results are obtained as is seen from the length of the bar of each individual value (see Figure 7.5).

Effectiveness increases with the sensing period T_s = 4ms to 13.8ms and decreases from 14.3ms onwards. In order to explain this behavior, the individual components $r_{TotalGoodput}$, $r_{PUGoodput}$, $r_{SUGoodput}$ and $r_{W_{coop}}$, $r_{W_{PU}}$, $r_{W_{SU}}$ of Effectiveness are shown in Figure 7.6 and Figure 7.7 respectively. $r_{PUGoodput}$ always decreases with increase in sensing period T_s. This is similar behavior observed in experimental evaluations in Figure 6.2 on Page 85. As an increase in T_s leads to decrease in spectrum awareness or increase in P_{err} as shown in Figure 4.7 on Page 59 and discussed in Section 4.1.2. $r_{SUGoodput}$ increases with increase in sensing period T_s initially upto T_s = 18.8ms and later starts decreasing. For lower sensing period, N $\times$ T_w time (see Figure 3.5) limits secondary user transmissions as secondary user is not able to transmit during Cooperative Sensing Receiving Window. For higher sensing period, collisions increase in the system due to

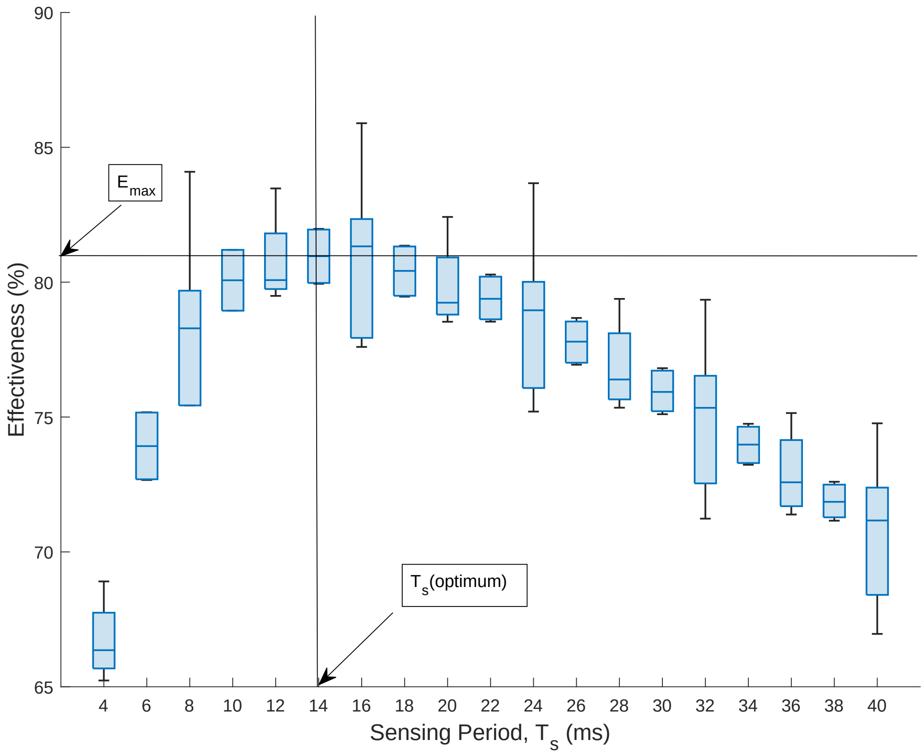

FIGURE 7.5 – *Illustration of E_{max} and $T_{s(optimum)}$*

decrease in spectrum awareness leading to decrease in $r_{SUGoodput}$. This is similar behavior shown in Figure 6.2 although only four sampling points of sensing period are available from experiments as the purpose of evaluation was to get problem awareness for usage of cooperative sensing in real radio propagation environment. $r_{TotalGoodput}$ increases up to $T_s = 18.8$ms and later decreases with further increase in T_s. $r_{W_{PU}}$ and $r_{W_{SU}}$ always increase with increase in sensing period T_s. As collisions increase in the system with increase in T_s due to decrease of spectrum awareness. Summarizing, the increasing trend of Effectiveness up to 14ms is due to decreasing trend of $r_{W_{COOP}}$ as well as increasing trend of $r_{TotalGoodput}$. The maximum value of Effectiveness is represented as E_{max} and the relevant T_s value at which this occurs is represented as $T_{s(optimum)}$. For Figure 7.5, E_{max} and $T_{s(optimum)}$ are 82% and 14ms respectively. In the next subsection, E_{max} and $T_{s(optimum)}$ are shown for various duty cycles of primary user traffic, PU and SU Technology and the parameters T_{BEACON}, T_w, T_{Btx} and T_{Stx}. A new term (Burst length, L) is defined for primary user traffic as follows;

$$L = \frac{T_{ON}}{PU\ Max\ Frame\ Size} \tag{7.1}$$

Where $PU\ Max\ Frame\ Size$ is the maximum frame size for PU Technology. The purpose of introducing this new term is that the performance of cooperative sensing be analyzed in terms of number of primary user frames in succession and independent of technology. The simulation time is taken to be $T_e = 100$s so that statistically sound results are obtained. The number of cooperative

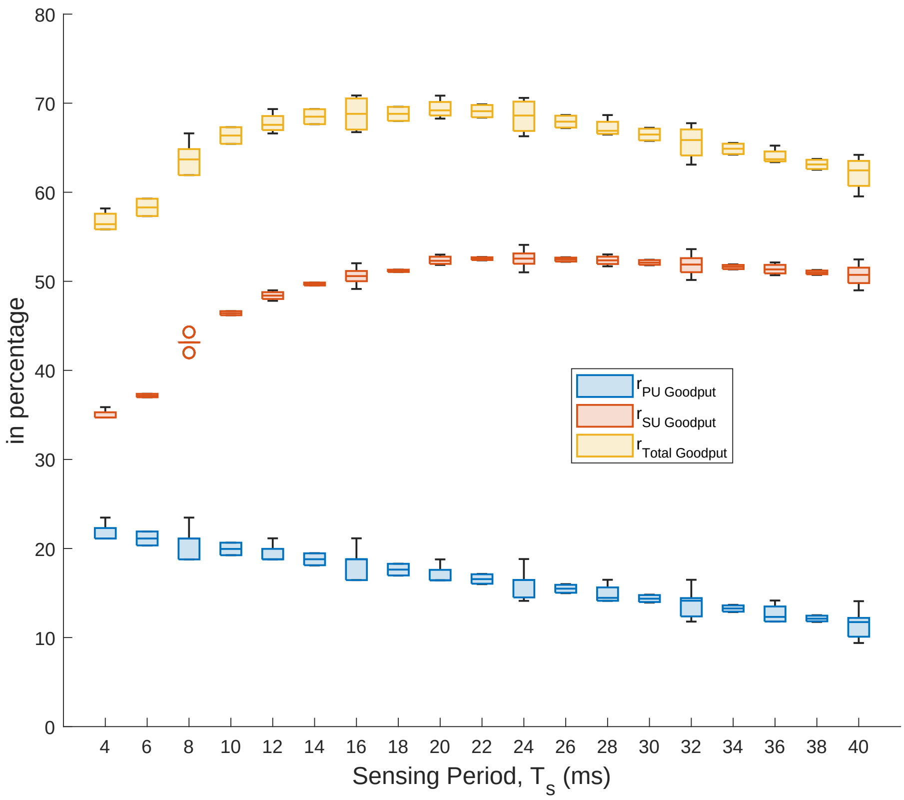

Figure 7.6 – *Illustrations of goodputs* $r_{Total\ Goodput}$, $r_{PU\ Goodput}$, $r_{SU\ Goodput}$

nodes taken in the setup is N = 1 for all the results whereas only a dedicated node is considered as the purpose is to study influence of parameters rather than real propagation conditions and mobility. Furthermore, whenever COOP is mentioned it refers to DPE protocol with the OR fusion rule. Whereas NO-COOP refers to the individual spectrum sensing at SU TX exclusively. Furthermore, COOPNODE_REG_REL frames associated with the proposed design are not addressed in the simulation model as it is overhead for addressing mobility aspects and is about 2% from the experiments for mobility speed of 0.120m/s. For higher speeds, the overhead for COOPNODE_REG_REL frames also needs consideration. Therefore, mobility aspects are not considered in the simulations as the focus of analysis in this section on analyzing the performance of DPE protocol and its parameters. The next subsection describes the simulation results with the model discussed in Section 7.1.1.

7.1.3 Results

In this subsection, simulation results are presented by selecting IEEE 802.15.4, 250 kbps, duty cycle of primary user traffic (25%, 50% and 75%), time duration for Co-operative Sensing Receiving Window for one cooperative node T_w (1.2ms, 1.8ms, 2.1ms and 2.4ms), time duration for BEACON and SENSING_INFORMATION frames T_{Btx} and T_{Stx} (0.3ms, 1ms), time period for BEACON frame transmissions T_{BEACON} (100ms, 500ms, 1000ms). Later in this subsection results are

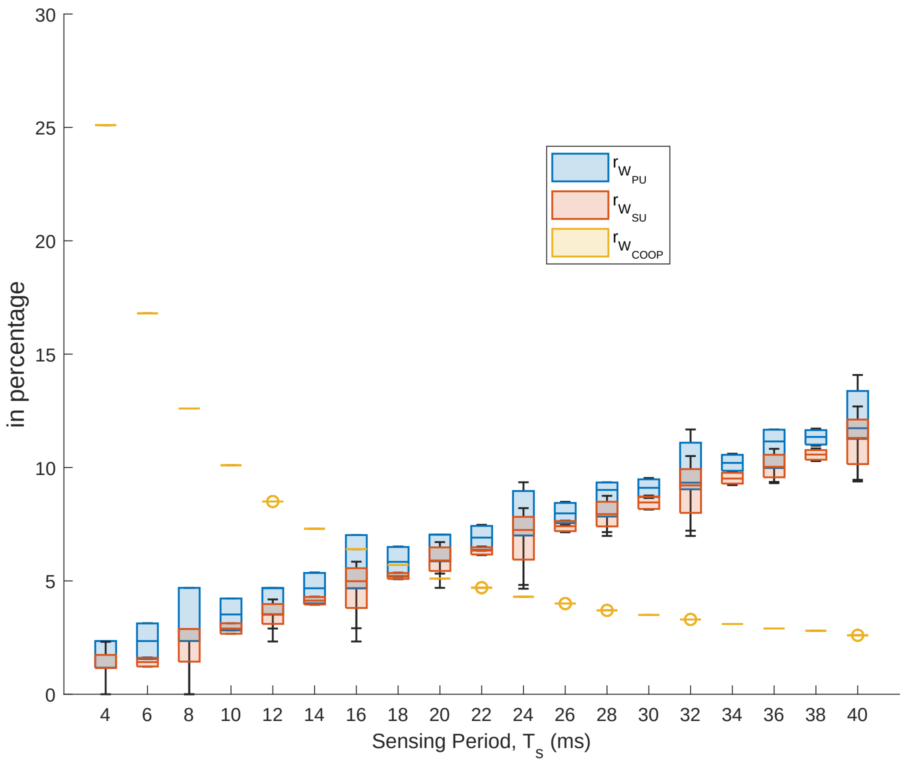

Figure 7.7 – *Illustration of wastages $r_{W_{PU}}$, $r_{W_{SU}}$, $r_{W_{coop}}$*

shown by changing PU technology with IEEE 802.11g having 54 Mbps. This is contrary to the evaluations performed in previous chapter where the variation in parameters is fixed (IEEE 802.15.4 for both primary and secondary user side, T_w = 2.4ms, T_{BEACON} = 100ms, T_{Btx} and T_{Stx} = 1ms) due to experimental setup. In the simulation analysis, the selection of primary and secondary user technology is based upon the concept that maximum and minimum frame sizes are selected out of the available technologies in heterogeneous radio environments (described in Section 1.1).

$$T_{max\_frm\_size} = T_{Preamble} + T_{payload} \tag{7.2}$$

The maximum frame size for IEEE 802.15.4 with 250 kbps data rate is 4.2ms and is calculated by Equation 7.2. The payload in this case consists of 125 Bytes and 2 Bytes for CRC and is transmitted at 250 kbps. Whereas the maximum frame size for IEEE 802.11g with 54 Mpbs data rate is 0.4ms and is calculated by Equation 7.2. The payload in this case 2346 Bytes and is transmitted at 54 Mbps. IEEE 802.11g is selected as another technology as the purpose is only to see another extreme (0.4ms) in the maximum frame size as compared with IEEE 802.15.4 having 4.2ms frame. Three values of duty cycles are selected. Figure 6.8 and Figure 6.9 show that 9% duty cycle is not interesting as cooperative sensing does not perform better than NO-COOP. Therefore duty cycle of 25%, 50% and 75% is selected. Considering duty cycle of 0% and 100%, there are no collisions in the system and the data channel is completely occupied by either secondary or by

Table 7.3 – *Parameter settings for Figure 7.8 for illustration of influence of T_{BEACON} and T_w*

T_w (ms)	T_{Btx}, T_{Stx} (ms)	T_{BEACON} (ms)
2.4, 2.1, 1.8	1	100, 500, 1000

Table 7.4 – *Parameter settings (cont...) for Figure 7.8 for illustration of influence of T_{BEACON} and T_w*

N	PU Technology	SU Technology	T_e(s)
1	IEEE 802.15.4 (250 kbps)	IEEE 802.15.4 (250 kbps)	100

Table 7.5 – *Parameter settings for Figure 7.9-Figure 7.12 exhibiting impact of duty cycle of PU*

T_w (ms)	T_{Btx}, T_{Stx} (ms)	T_{BEACON} (ms)
1.8	1	1000

the primary user respectively. Effectiveness is $\approx$ 100% in this case. T_w depends upon the clock drift among SU TX and the cooperative nodes as well as the time duration (T_{Btx} and T_{Stx} of BEACON and SENSING_INFORMATION frames). Therefore selection of T_w for a particular scenario is done in combination with T_{Btx} and T_{Stx}. The scenario under investigation is still the hidden node scenario described in Figure 6.1.

The first investigation is regarding influence of clock drift and its relation to T_{BEACON} and T_w. The x-axis shows burst length (L) which is the number of primary user frames sent during T_{ON} time in succession and is also defined in Equation 7.1. The y-axis shows E_{max} which is the maximum Effectiveness achieved for all possible T_s values for the described setup and is also defined in Section 7.1.2. The discussion in the previous chapter has shown that the testbed setup has clock drift of 0.5% which leads to T_{BEACON} = 100ms and T_w = 2.4ms. In case the radio device use a microcontroller which has crystal, the clock drifts are reduced and resultantly the constraint on maximum T_{BEACON} is reduced leading to higher allowed value. Correspondingly, T_w is reduced. Two additional settings (T_{BEACON} = 500ms, T_w = 2.1ms and T_{BEACON} = 1000ms and T_w = 1.8ms) (please see Table 7.3 and Table 7.4) are investigated to see the influence of clock drift among radio devices. Figure 7.8 shows E_{max} for three selected settings. The results show that the influence is negligible although T_{BEACON} = 100ms and T_w = 2.4ms has comparatively low E_{max} (please see the corresponding boxchart). Therefore, lower the clock drift the better system performance although the influence is negligible.

In the next step, influence of primary user traffic is shown with 25%, 50% and

Table 7.6 – *Parameter settings (cont...) for Figure 7.9-Figure 7.12 exhibiting impact of duty cycle of PU*

N	PU Technology	SU Technology	T_e(s)
1	IEEE 802.15.4 (250 kbps)	IEEE 802.15.4 (250 kbps)	100

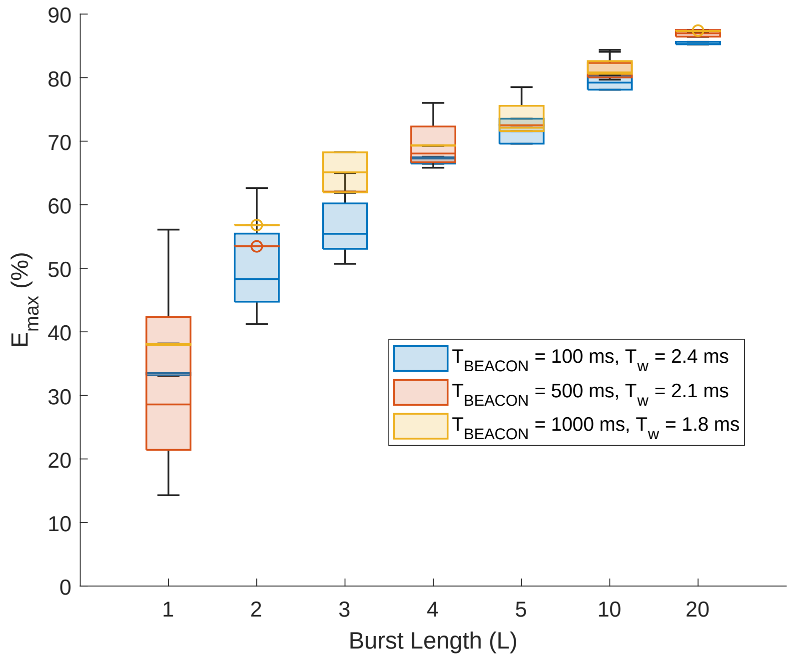

FIGURE 7.8 – *Influence of T_{BEACON} and T_w on system performance*

75% duty cycle. A comparison with NO-COOP is also presented to show the usefulness of cooperative sensing for system performance. Figure 7.9-Figure 7.11 shows evaluation of cooperative sensing as compared with individual spectrum sensing for various duty cycles. The performance of the system is evaluated for various duty cycles when primary and secondary nodes using the same technology (IEEE 802.15.4 with 250 kbps). Table 7.5 and Table 7.6 show the values of the parameters considered for simulations. $T_{BEACON} = 1000$ms in all the figures as it has been discussed earlier that higher value of T_{BEACON} is recommended if the clock drift of relevant radio devices allows it. The x-axis shows burst length (L) and the y-axis depicts E_{max} similar to previous figure in this subsection.

With increase in burst length, the performance of cooperative sensing increases significantly. For example E_{max} increases from 38% to 88% for burst length from 1 to 20 for 25% duty cycle. Similarly, E_{max} increases from 24% to 85% for burst length from 1 to 20 for 50% duty cycle. Whereas for 75% duty cycle, E_{max} increases from 41% to 71% for burst length from 1 to 20. The median value of the boxchart is used in the description unless otherwise mentioned. The performance increase with an increase in burst length is a similar phenomenon shown in Figure 4.7 where an increase in $\frac{E[T_{OFF}]}{T_s}$ or $\frac{E[T_{ON}]}{T_s}$ leads to reduction in P_{err} for a particular duty cycle. Therefore, larger T_{ON} or T_{OFF} times for a particular duty cycle results in lesser collisions in the system which shows better E_{max}.

The performance margin with cooperative sensing COOP as compared with NO-COOP improves with higher duty cycle (please see margin of $E_{max} = 28\%$, 47% and 52% for 25%, 50% and 75% duty cycles respectively for burst length of 10). This is due to the reason that for NO-COOP increase in duty cycle, the number

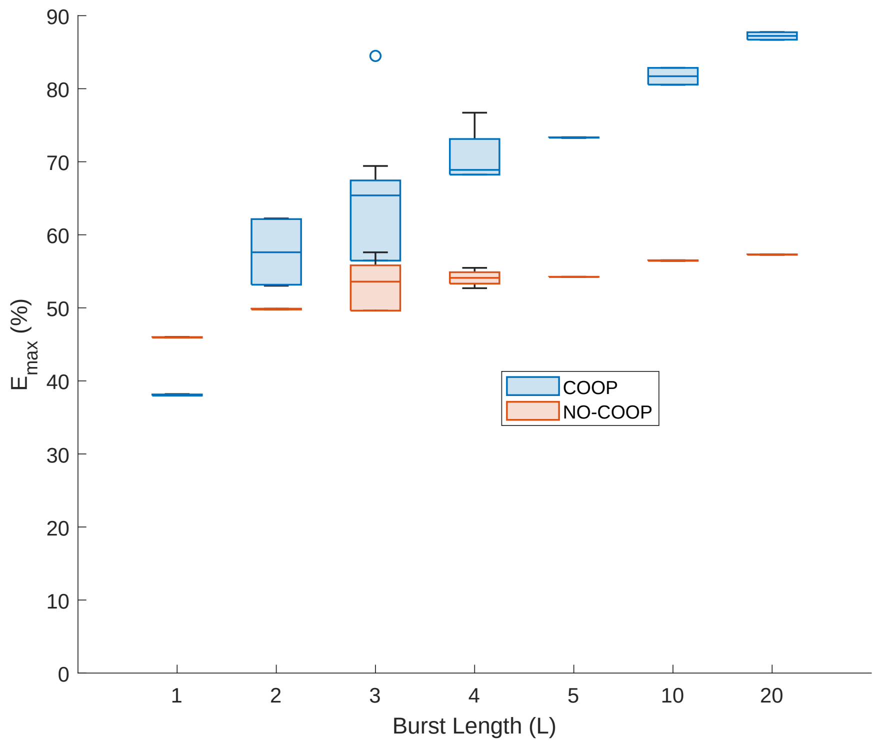

FIGURE 7.9 – *Maximum Effectiveness E_{max} for duty cycle = 25%, SU = IEEE 802.15.4 with 250 kbps*

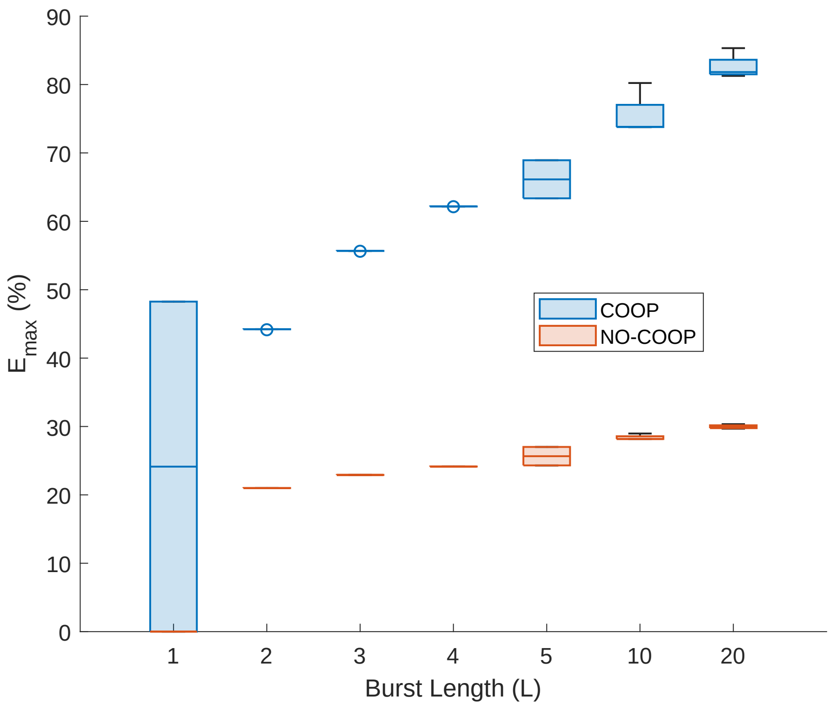

FIGURE 7.10 – *Maximum Effectiveness E_{max} for duty cycle = 50%, SU = IEEE 802.15.4 with 250 kbps*

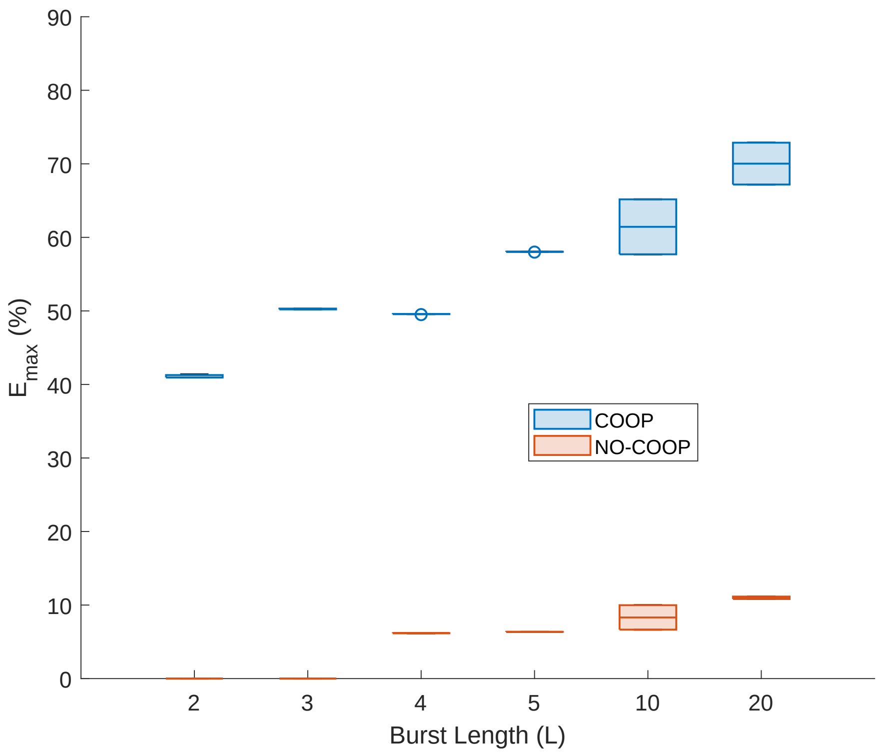

FIGURE 7.11 – *Maximum Effectiveness E_{max} for duty cycle = 75%, SU = IEEE 802.15.4 with 250 kbps*

of collisions in the system increase due to undetectable (hidden node scenario) primary user frames. With low duty cycle (25%), the performance of NO-COOP is even better by 8% as compared to COOP for burst length of 1. In this situation, the number of collisions in the system are low and cooperative sensing is not much useful in this situation as it only imposes overhead on the system. An investigation regarding duty cycle is done in Section 6.2. Although the results in that section are not statistically sound enough (due to radio propagation effects) but they provide qualitative comparison of performance with various duty cycles. For duty cycle of 75%, there are no results for burst length of 1. As T_{OFF} is 1.4ms and for successful cooperative sensing T_s needs to be less than T_{ON} = 4.2ms and T_{OFF} = 1.4ms which is not possible due to the chosen T_w = 1.8ms.

The related $T_{s(optimum)}$ times are shown in Figure 7.12 and are explained in the following. The purpose of presenting these results is to illustrate the impact of duty cycle of primary user traffic on the optimum sensing period. The results show that $T_{s(optimum)}$ increases with an increase in burst length. For example; for 25% duty cycle from 3ms to 18ms for burst length from 1 to 20, for 50% duty cycle from 2ms to 12ms for burst length from 1 to 20 and for 75% duty cycle from 3ms to 10ms for burst length from 2 to 20. With increase in burst length, the optimum value of $T_{s(optimum)}$ is increased. The reason behind this is that with larger burst length (T_{ON} or T_{OFF} times), the sensing device is able to capture

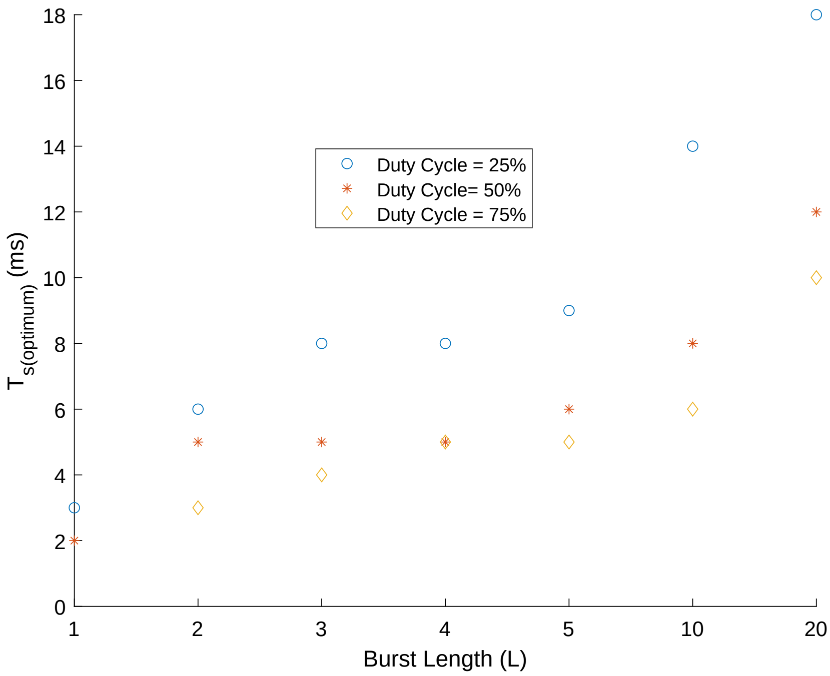

FIGURE 7.12 – *Optimum sensing period $T_{s(optimum)}$ for various duty cycles, SU = IEEE 802.15.4 with 250 kbps*

TABLE 7.7 – *Parameter settings for Figure 7.13 demonstrating the impact of PU Technology on system performance*

T_w (ms)	T_{Btx}, T_{Stx} (ms)	T_{BEACON} (ms)	Duty Cycle (%)
1.8	1	1000	25

TABLE 7.8 – *Parameter settings (cont...) for Figure 7.13 demonstrating the impact of PU Technology on system performance*

N	PU Technology	SU Technology	T_e(s)
1	IEEE 802.11g, IEEE 802.15.4	IEEE 802.15.4	100

actual channel state of primary user even with higher sensing period. Therefore, E_{max} is achieved for higher sensing period. Another aspect which is apparent from Figure 7.12 is the impact of duty cycle on the optimum sensing period. With comparatively higher duty cycle, corresponding T_{OFF} time decreases for a particular burst length which leads to lower optimum sensing period as collisions increase in the system with comparatively higher sensing periods. Therefore, E_{max} is achieved with lower $T_{s(optimum)}$ times.

In the next step, the impact of primary user technology on system performance is studied. As heterogeneous radio environments include both IEEE 802.15.4 and IEEE 802.11 besides IEEE 802.15.1 (which is discussed in next section). As in previous chapter only IEEE 802.15.4 is used therefore in this section IEEE 802.11 is also applied on primary user side to see the impact of shorter frames on system performance. Table 7.7 and Table 7.8 show the related parameter settings.

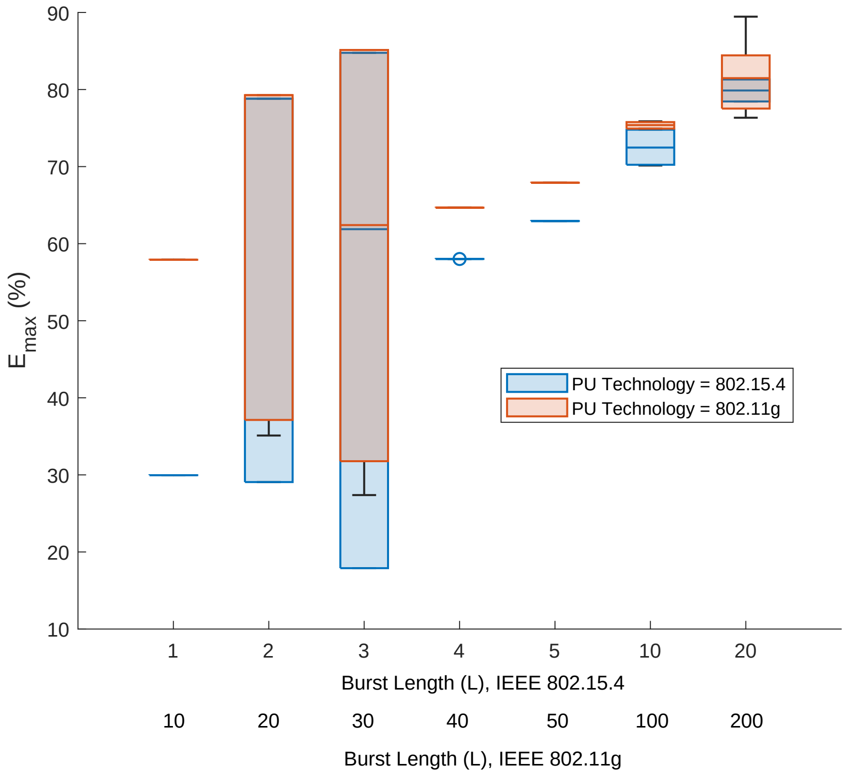

Figure 7.13 – *Impact of radio technology on PU side for 75% duty cycle*

All the parameters are taken same as the ones for Figure 7.9-Figure 7.12 as the purpose is to show only influence of changing radio technology on the primary user side (IEEE 802.15.4 and IEEE 802.11g). Duty cycle of 75% is taken as this is the case where maximum influence is expected if primary user technology is changed.

Figure 7.13 shows the impact of primary user technology. The maximum frame size for IEEE 802.11g is 0.4ms whereas for IEEE 802.15.4, it is 4.2ms. Therefore, on x-axis two types (IEEE 802.15.4 and IEEE 802.11g) of burst lengths are mentioned. The results show that the technology having shorter frames (IEEE 802.11g) has slightly better performance. As an example; for burst length of 5, IEEE 802.11g has E_{max} of 69% where IEEE 802.15.4 has E_{max} of 64%. It is to be noted here that the burst length of 50 or more for IEEE 802.11 is very unlikey in realistic scenarios but the purpose here is only to demonstrate the comparison of performance of IEEE 802.15.4 and IEEE 802.11. As an additional note, 802.11n uses the concept of frame aggregation which is an additional functionality to improve channel utilization [15]. Frame aggregation further increases the burst length for primary user. It has been shown already in this section that with increase in burst length, performance of cooperative sensing improves in the system. Therefore, frame aggregation has an additional benefit regarding system wide performance improvement for cooperative sensing.

So far in all the discussion, control frames with data rate of 250 kbps of IEEE 802.15.4 are used but regarding generalization an investigation is also required to

Table 7.9 – *Parameter settings for Figure 7.14 illustrating impact of control frame durations*

T_w (ms)	T_{Btx}, T_{Stx} (ms)	T_{BEACON} (ms)	Duty Cycle (%)
1.8, 1.2	1, 0.3	1000	25

Table 7.10 – *Parameter settings (cont...) for Figure 7.14 illustrating impact of control frame durations*

N	PU Technology	SU Technology	T_e(s)
1	IEEE 802.15.4 (250 kbps)	IEEE 802.15.4 (250 kbps)	100

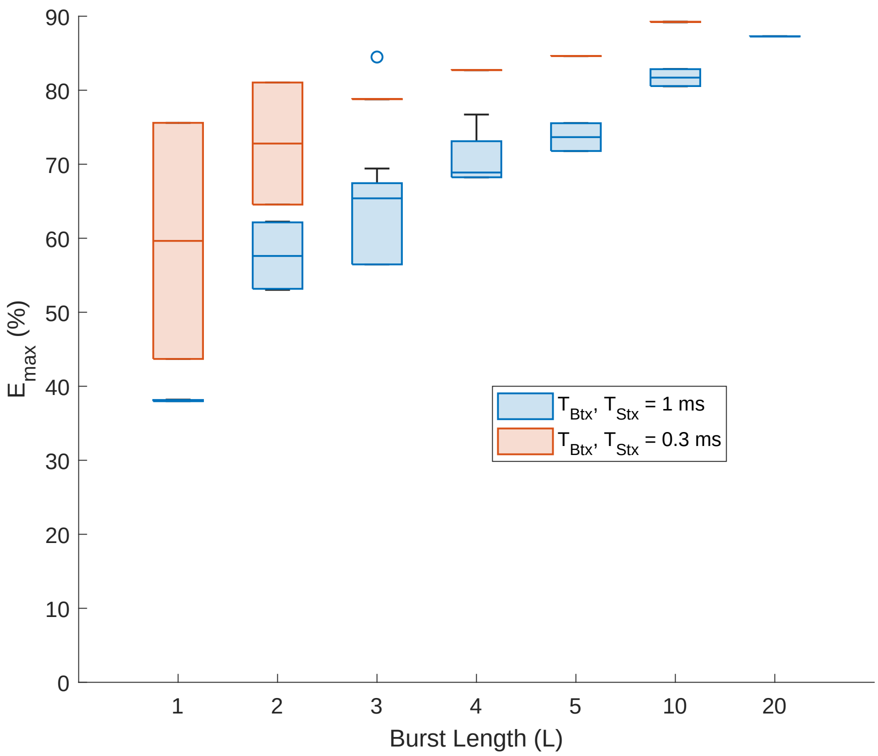

Figure 7.14 – *Influence of control channel frame duration*

demonstrate the impact of transmission durations on the control channel. In the following, two different frame durations for the control information are considered in order to see the impact of control channel usage. Table 7.9 and Table 7.10 show the related parameter settings. All the parameters are taken same as the ones for Figure 7.9-Figure 7.12 except T_w, T_{Btx} and T_{Stx}. Two set of values (0.3ms and 1ms) for T_{Btx} and T_{Stx} are taken whereas related values for T_w are 1.2ms and 1.8ms which are taken as an estimate depending upon the control frame durations. Figure 7.14 shows the impact of control frame durations on system performance. The results show that shorter frame durations lead to higher E_{max}. As an example; for burst length of 5, E_{max} is 85% and 73% for T_{Btx} = 0.3ms and T_{Btx} = 1ms respectively.

Table 7.11 – *Parameter settings for Figure 7.15-Figure 7.17 illustrating cooperative sensing evaluation with Bluetooth interferer*

T_w (ms)	T_{Btx}, T_{Stx} (ms)
0.4, 0.1	0.2, 0.05

Table 7.12 – *Parameter settings (cont...) for Figure 7.15-Figure 7.17 illustrating cooperative sensing evaluation with Bluetooth interferer*

T_{BEACON} (ms)	N	SU Technology	T_e(s)
1000	1	IEEE 802.15.4, IEEE 802.11g	100

The results in this section show that types of clocks used for microcontroller influence the performance although not significant. It is suggested that crystal clocks are used for the microcontrollers of the radio devices. The use of cooperative sensing is useful specially for high duty cylce ($> 50\%$) as with lower duty cycle overheads with cooperative sensing supercede the gain in terms of reduction of collisions in hidden node scenario. These findings are also found in the previous chapter from experimental evaluation. Furthermore, the results show that the technology having shorter frames or alternatively with higher data rates performs better with cooperative sensing. In the last step, it is seen that higher the data rate used on the control channels results in better system performance because of lower overhead on the control channel. So far in this section, analysis of cooperative sensing with IEEE 802.15.4 and IEEE 802.11g is performed but heterogeneous radio environments include not only IEEE 802.15.4, IEEE 802.11g but also IEEE 802.15.1. Therefore, in the next section application aspects of cooperative sensing in presence of Bluetooth interferers are discussed.

7.2 PERFORMANCE WITH BLUETOOTH

The third technology to be considered in the ISM bands is IEEE 802.15.1 (Bluetooth). The medium access utilized by Bluetooth is frequency hopping and time slots. The hopping rate is 1600 per second. In [51], Akash et al. elaborates the channel occupation with IEEE 802.15.4, IEEE 802.11g and IEEE 802.15.1 as all of them are part of heterogeneous radio environments. The ISM frequency range is from 2400 to 2485 MHz. The bandwidth for a single channel with IEEE 802.15.1 is 1 MHz. The bandwidth for IEEE 802.15.4 is 5 MHz whereas it is 22 MHz for IEEE 802.11g. Therefore, on the average two channels of IEEE 802.15.1 collide with one channel of IEEE 802.15.4 whereas 11 channels of IEEE 802.15.1 collide with one channel of IEEE 802.11g. While selecting the control channel for cooperative sensing, it should be ensured that there are no other overlapping channels within the same or other technology so that control channel information is not corrupted for successful cooperative sensing.

In [32], Pooja provides a comprehensive survey of Bluetooth technology. The standard suggest to use multislot mechansim for master and slave configuration as desired by the user application. As an example, 1,3 and 5 slots [80] for Bluetooth interferer as primary user is considered. The corresponding slot durations are

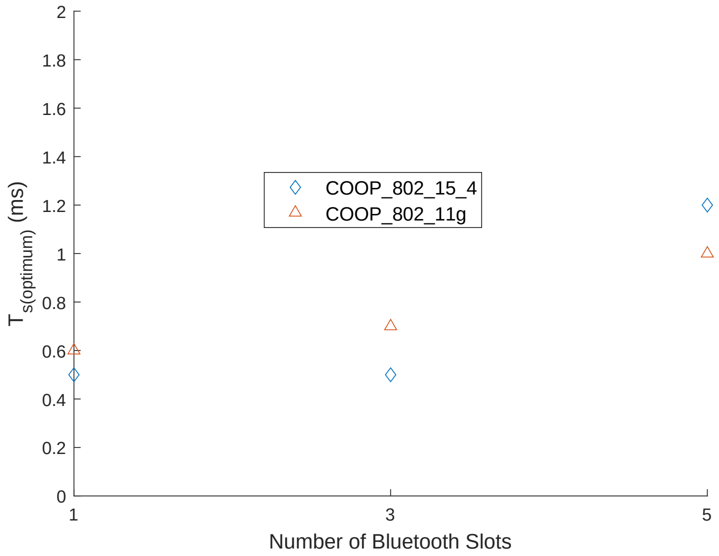

FIGURE 7.15 – *Sensing period for avoiding collision with Bluetooth*

0.625ms, 1.88ms and 3.125ms. The duty cycles for Bluetooth traffic for 1,3 and 5 slots are 0.0625%, 0.125% and 0.3125 % respectively. As explained previously in this chapter and in the previous chapter, cooperative sensing is not useful if the duty cycle of primary user traffic is low. Rather cooperative sensing imposes overhead in terms of control channel usage. Considering the Bluetooth interferers, the duty cycle is very low for 1,3 and 5 slots settings. Therefore, applying cooperative sensing to avoid collisions in presence of Bluetooth interferer is not recommended. But if it is still highly desired that the collision with Bluetooth interferer needs to be avoided, in the following recommended sensing periods and the related Effectiveness and wastage for primary user traffic is described. Figure 7.15-Figure 7.17 show the results for usage of cooperative sensing for IEEE 802.15.4 and IEEE 802.11g on secondary user side whereas Table 7.11 and Table 7.12 show the related parameter settings. For IEEE 802.15.4, BEACON and SENSING_INFORMATION frame durations (T_{Btx}, T_{Stx}) are taken as 0.2ms. 2000 kbps data rate is considered for communication on the control channel as higher data rate leads to shorter frame durations and less overhead. Additionally, minimum allowed sensing period is also reduced which allows the cooperative sensing to work even for 1 slot setting for Bluetooth. For successful cooperative sensing, T_s is required to be less than T_{ON} and T_{OFF}. Therefore, 0.4ms is the minimum sensing period with IEEE 802.15.4 for cooperative sensing to work. For IEEE 802.11g, each T_{Btx} and T_{Stx} times are taken as 0.05ms. 54 Mbps is taken for communication on the control channel as well as for data channel. The minimum allowed sensing period with IEEE 802.11g is 0.1ms. Higher sensing period is favoured because it involves less overhead due to smaller number of transmissions on the control channel. But at the same time, collisions also increase in the system due to decrease in spectrum awareness.

Figure 7.15 shows the recommended sensing periods if IEEE 802.15.4 or IEEE 802.11g are used on the secondary user side. Based upon simulation analysis,

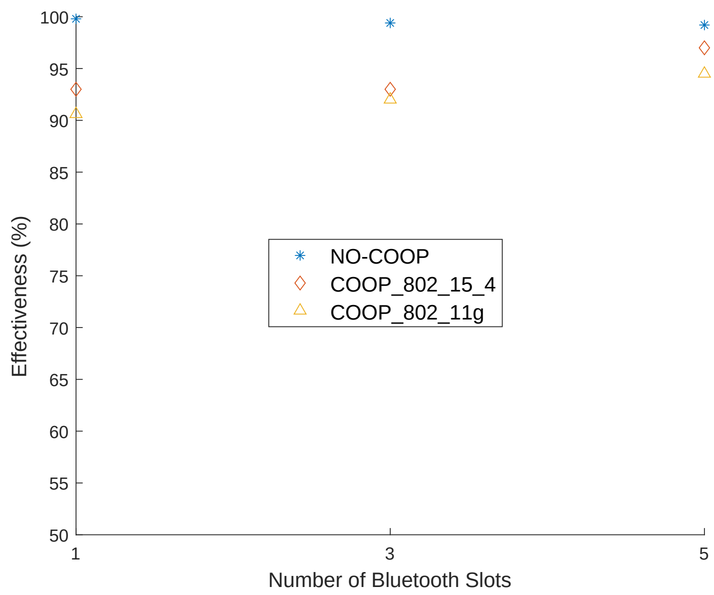

Figure 7.16 – *Comparison of performance with NO-COOP and cooperative sensing with Bluetooth transmissions*

0.5ms, 0.55ms and 1.2ms are the sensing periods which is selected for IEEE 802.15.4 for successful cooperative sensing for 1,3 and 5 slots respectively. For IEEE 802.11g, 0.6ms, 0.7ms and 1.1ms are the sensing periods recommended for slot 1, 3 and 5 respectively for successful cooperative sensing. It is to be reminded again that cooperative sensing is not of much benefit considering heterogenous radio environments in terms of system wide performance for very low duty cycle of primary user traffic. The analysis shown in this section demonstrates the use of cooperative sensing to avoid collisions with Bluetooth transmission at the cost of higher overhead due to low sensing periods.

Figure 7.16 shows the related effectiveness for NO-COOP and COOP with IEEE 802.15.4 and IEEE 802.11g. Effectiveness for NO-COOP is $\approx$ 100%, as there is no overhead involved. Additionally, the collisions (wastages) are minimal in the system due to very low duty cycle. Effectiveness with IEEE 802.15.4 and IEEE 802.11g on the secondary user side is in the range of 90%-96%. The lower value (less than 100%) for Effectiveness is due to overhead on the control channel for both IEEE 802.15.4 and IEEE 802.11g.

Figure 7.17 shows the primary user (Bluetooth) wastages for the sensing periods shown in Figure 7.15 for NO-COOP, IEEE 802.15.4 and IEEE 802.11g on the secondary user side. For NO-COOP, primary user wastage $r_{W_{PU}}$ is 0.06%, 0.18% and 0.31% for Bluetooth slots 1, 3 and 5 respectively. Whereas for IEEE 802.15.4 and IEEE 802.11g, $r_{W_{PU}}$ is in the range 0.04% to 0.2%. The reduction in primary user wastages is due to cooperative sensing. With individual spectrum sensing NO-COOP, secondary user transmitter is not able to detect primary user transmission due to hidden node which leads to higher primary user wastage. A recent version of Bluetooth technology with low energy (BLE) is surveyed in [21]. BLE also uses frequency hopping and the time slots although the connection

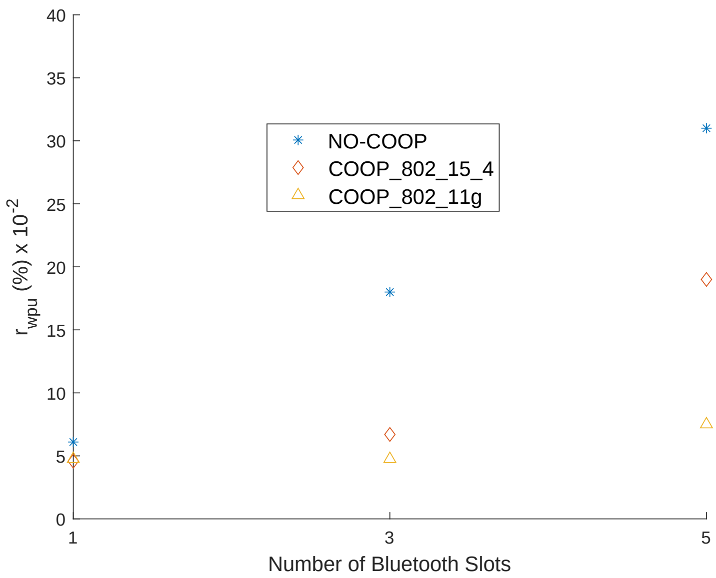

FIGURE 7.17 – *Wastage in primary user transmission for Bluetooth interferer*

time is shorter than classical Bluetooth technology. Therefore, the discussion for classical Bluetooth is also applicable to BLE as the duty cylce of Bluetooth traffic is also very low.

The discussion in this section shows that cooperative sensing is not of significant advantage in case of Bluetooth interferers (either BLE or the classical Bluetooth). The reason behind this is that cooperative sensing improves the performance in case of hidden node scenarios. If the duty cycle of primary user traffic is very low as is the case with Bluetooth, reduction in collisions in hidden node scenario is not significant with cooperative sensing. Rather overhead on the control channel limits the performance improvement. Even the performance with cooperative sensing is inferior than individual spectrum sensing in terms of Effectiveness. But if it is highly desired that Bluetooth transmissions are to be protected from the collisions, sensing period should be lower than the Bluetooth slot durations. Too much lower values are also not selected as it increases overhead on the control channel. Therefore, optimum sensing periods are also shown for IEEE 802.15.4 and IEEE 802.11g in the presence of different slot numbers for Bluetooth. In the next section, a summary of the findings from simulation analysis is presented.

7.3 DISCUSSION

In the previous sections a detailed simulation analysis of the proposed cooperative sensing design has been performed which is not possible with the experimental setup. The DPE protocol with OR fusion rule is selected for analysis as it performs better than SFE protocol as concluded in the previous chapter. It is to be reminded that cooperative node selection protocol is not part of discussion in the simulation analysis performed as the relevant parameters for the cooperative node selection protocol depends upon the radio environment and the mobility of the nodes in the system. Furthermore, the detailed analysis for SFE protocol is out of the scope of this thesis. Some of the findings have overlapping as with those found with real world evaluations (see Section 6.4) and evaluations with P_{err} (see Section 4.1.2). For example, the performance margin in terms of Effectiveness of cooperative sensing as compared with individual spectrum sensing improves with an increase in duty cycle in hidden node situation.

The performance of cooperative sensing improves with increase in burst length which is similar to decrease in P_{err} due to increase in $\frac{E[T_{ON}]}{T_s}$ or $\frac{E[T_{OFF}]}{T_s}$ keeping the same duty cycle as observed in Figure 4.7. On the contrary, the analysis also shows new findings which are explained in the following. Performance of cooperative sensing improves initially with T_s and later decreases due to increase in number of collisions in the system. Low Effectiveness with small T_s is attributed to high overhead because of large number of BEACON and SENSING_INFORMATION frames. Therefore, the curve for Effectiveness is convex shaped with respect to T_s. This leads to introduction of two kinds of new terms Maximum Effectiveness E_{max} and Optimum Sensing Period $T_{s(optimum)}$. The optimum sensing period increases with increase in burst length. The reason behind this is that with increase in burst length, T_{ON} also increases which leads to higher $T_{s(optimum)}$ for obtaining Maximum Effectiveness. As a matter of fact, in heterogeneous radio environments considered the application traffic varies which leads to dynamic primary user traffic pattern. If the recommended optimum sensing periods are used, the burst length are approximately estimated by the results of individual and cooperative sensing results. Finally, the sensing period are adjusted accordingly based upon the estimated primary user traffic. In this way, dynamic primary user traffic is coped with by adjusting operating sensing period based upon traffic estimation.

The parameter T_w has dependency with T_{Btx} and T_{Stx}. Lower values of T_w, T_{Btx} and T_{Stx} leads to higher E_{max} as the overhead $r_{W_{COOP}}$ on the system is reduced which leads to higher E_{max} value. Another outcome is that the technology having shorter frames provides better system performance as the probability of collisions in the system is reduced if shorter frames are used in the system. The maximum allowed beacon period T_{BEACON} is determined by the clock drift of the radio devices as well as the control channel frame durations. It is recommended that crystal clocks for the radio devices are selected so that the constraint on T_{BEACON} is relaxed and higher corresponding values are possible in the system. As the results show that E_{max} is comparatively higher for larger T_{BEACON} times.

Cooperative sensing is useful in heterogeneous radio environments if primary user traffic is high. For low or very low duty cycle of primary user traffic, cooperative sensing is not useful. Although the system parameters are to be carefully selected in order to apply cooperative sensing for very low duty cycle of primary user traffic. The results show that cooperative sensing with IEEE 802.15.4 and IEEE 802.11g on secondary user side reduces primary user wastage for Bluetooth although there is an overhead involved. Furthermore, it is not possible to use Bluetooth on secondary user side. As the approach used by Bluetooth is frequency hopping and time slots which makes it impossible to use the related cooperative sensing protocols within the Bluetooth.

The findings from simulation study complements the investigations made in previous chapter as the focus of simulation study is on generality and optimization of performance. On the contrary the focus of experimental study was on evaluation of the proposed cooperative sensing design in real radio propagation environment with mobility as well. The simulation study in this section along with the conclusions provided in Section 6.4 completes the recommendations for use of cooperative sensing for heterogeneous radio environments. The cooperative sensing is designed for multiple primary, secondary and cooperative nodes but the findings and analysis described so far in this thesis considers only single primary, secondary and cooperative nodes. Although a detailed scalability analysis requires a thorough investigation from simulation or experimental perspective. The next section briefly guides the future research directions for analysis regarding scalability aspects of the proposed cooperative sensing design.

7.4 SCALABILITY ASPECTS

The focus of this section is on scalability aspects of the proposed cooperative sensing design with multiple primary and secondary nodes. The proposed cooperative sensing design utilizes dedicated control channel for exchange of sensing information and synchronization among SU TX and the cooperative nodes. The scope of the thesis targets heterogeneous radio environments, therefore multiple channels available in this band (for example; 16 channels for IEEE 802.15.4, 3 in IEEE 802.11g [84]) are considered. In order to generalize the radio channels, primary, secondary and cooperative nodes, the following notations are considered. There are X radio channels, M primary users, K secondary users and N cooperative nodes. In order to address the organization of secondary users with the available radio channels two approaches (centralized and decentralized) are proposed. These approaches are based upon the concept that multiple secondary users share either data channel or the control channel respectively. In the next subsections both approaches are briefly explained.

7.4.1 CENTRALIZED APPROACH

In this approach, secondary users are suggested to follow master slave configuration and the secondary users share the data channel while using a dedicated control channel. The master node coordinates the transmission among the slave nodes and share the data channel in this way. In the following, the centralized approach for DPE protocol is explained. Secondary User Master Transmitter $SU\,TX_M$ sends BEACON frames according to DPE protocol whereas Secondary User Slave Transmitters $SU\,TX_{S_j}$ follow BEACON frames transmitted by $SU\,TX_M$. where 'j' ϵ 1...K-1.

$SU\,TX_M$ collects spectrum sensing reports from the cooperative nodes $C_1..C_N$ or from any receiver of secondary user slave transmitter. Figure 7.18 shows the concept behind the centralized approach. $SU\,TX_M$ coordinates the sharing of data and control channel among various slave secondary users. The receivers of slave secondary users $SU\,TX_{S_j}$ listen to BEACON frames and also act as

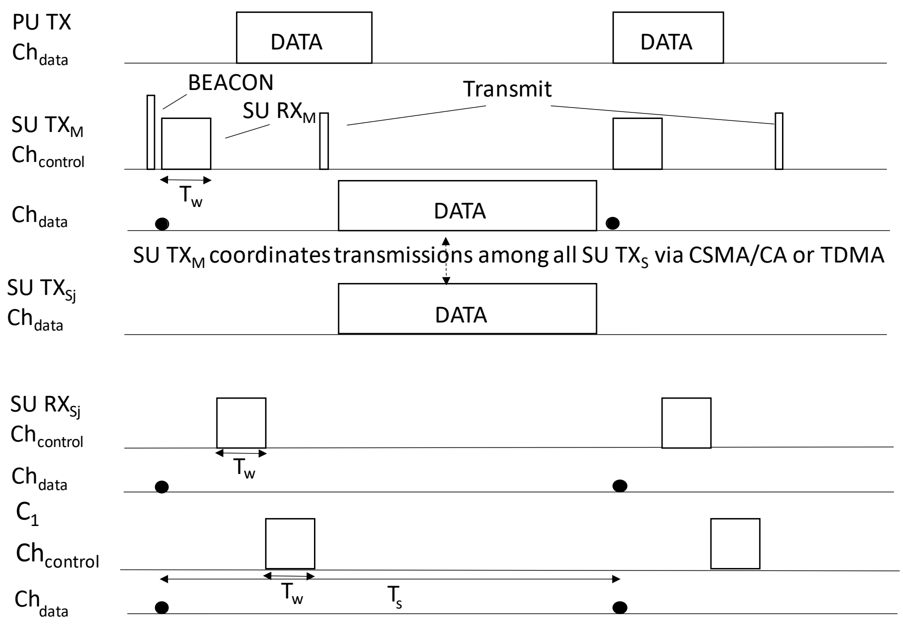

Figure 7.18 – *DPE protocol with centralized approach during COOP state*

cooperative nodes based upon the defined criteria (discussed in Section 3.3 and Section 6.3). Additionally dedicated cooperative nodes $C_1..C_N$ also help $SU\,TX_M$ in the radio environment. Although only C_1 is shown to be added to $SU\,TX_M$ in the DPE protocol. The selection of additional cooperative node is determined by cooperative node selection protocol as described in Section 3.3. After collection of cooperative sensing reports, $SU\,TX_M$ sends $Transmit$ frame until next sensing event if the result of cumulative decision declares data channel to be free for transmission. The associated $SU\,TX_S$ starts transmission based upon reception of $Transmit$ frame. The data channel is shared among master and slave secondary users via Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as described by Younus et. al "Performance Analysis of CSMA/CA in Wireless Local Area Network" in 2015 [44] or Time Division Multiple Access (TDMA) as described by Falconer et. al "Time Division Multiple Access Methods for Wireless Personal Communications" in 1995 [17]. With BEACON frame the slave secondary users are informed regarding the configuration in this regard. In TDMA based sharing, slots are allocated in the data channel by the master to the slaves with dedicated resources whereas in CSMA/CA based approach secondary users share the data channel via spectrum sensing on the transmitter side. Selection of Secondary User Master Transmitter is also another problem. In the first simple approach, it is fixed in the protocol whereas in the second approach a dedicated protocol is required for the selection purposes which also need investigation. SFE protocol is also extended similar to DPE protocol. The only difference is that in SFE protocol the receiver of slave secondary users decreases the sensing period rather than detection performance. In the next subsection, decentralized approach is discussed.

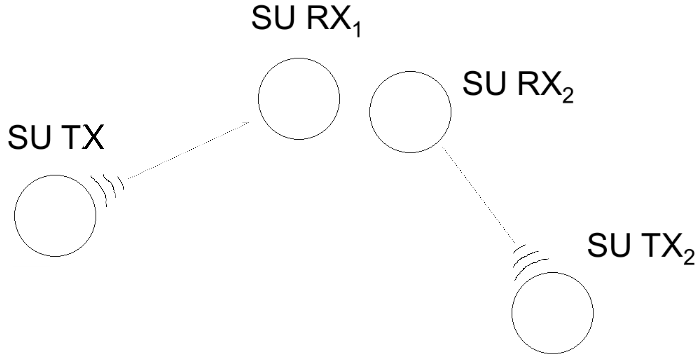

Figure 7.19 – *SU RX as cooperative node with decentralized approach*

7.4.2 DECENTRALIZED APPROACH

In this approach a pair of secondary user transmitter and receiver share the control channel for sensing information exchange whereas the data is transmitted on their respective data channels. Each secondary user transmitter and receiver pair transmit data on a separate data channel whereas control channel is shared among them for sensing information exchange. Therefore, collisions occur on the control channel due to overlapping of BEACON and SENSING_INFORMATION frames from different secondary users. Figure 7.19 shows the situation where two secondary user transmitter and receiver pairs are shown. They share the control channel for sensing information exchange whereas a separate data channel is used by each pair of secondary user transmitter and receiver. Primary users are not shown in Figure 7.19 as the purpose is to illustrate SU TX and SU RX pairs in decentralized approach. $SU\ RX_1$ and $SU\ RX_2$ act also as cooperative nodes for their respective secondary user transmitters $SU\ TX_1$ and $SU\ TX_2$. DPE protocol involves BEACON and SENSING_INFORMATION frames among SU TX and its cooperative nodes. In this approach, BEACON and SENSING_INFORMATION frames collide among SU TXs and SU RXs. On the contrary, there are no collisions on the control channel with centralized approach as the decision to transmit or not is made collectively by multiple users. Although detailed analysis is outside the scope of this thesis.

In the start of this section, multiple channel and multiple primary, secondary and cooperative users are considered. Regarding primary users, each primary user transmits on separate data channel. If the primary users are separated well apart, the same data channel is used for data transmission by them. As far as secondary users are considered, both centralized and decentralized approaches play role in this regard. Two cases are discussed in the following: In the first case, the number of radio channels (X) >the number of primary and secondary user (max(M, K)) which is trivial as there are plenty of radio resources in this situation. Decentralized approach is more favorable in this situation as centralized approach limits the secondary user goodput as it is shared among secondary users which use the same control channel. The second case is more interesting where the number of radio channels are limited and primary and secondary users are more in number (X <min(M, K)). M-X primary users share the data channel with the

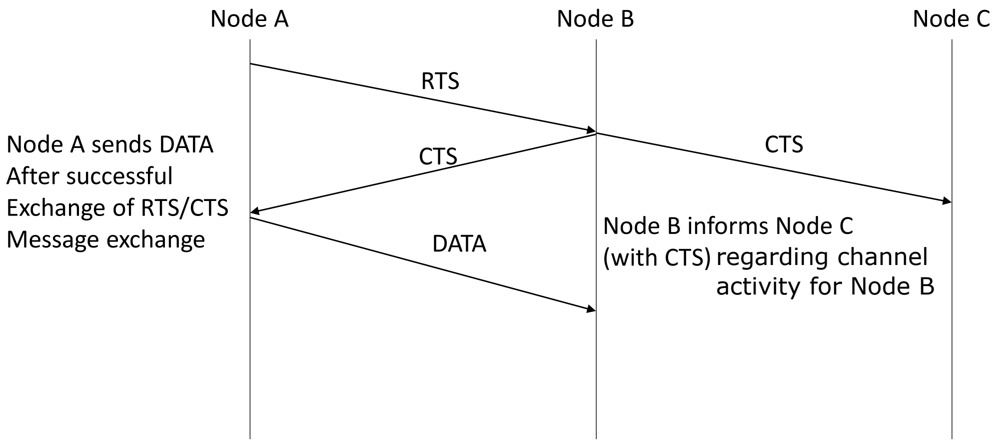

Figure 7.20 – *RTS and CTS illustration*

other primary users on average. Therefore the primary users have to be spatially apart to share the same data channel. The number of cooperative nodes are at least equal to number of secondary users. The number of control channels are also specified depending upon the number of secondary users and available number of radio channels. Each cooperative node present in the system listens on one of the specified control channel. Secondary users are also aware of the list of specified control channels. In the next step, the process of entering and leaving the system by secondary users are explained in more detail. If a new secondary user transmitter $SU\,TX_j$ (j ϵ 1..K) is switched on it searches for BEACON and SENSING_INFORMATION frames on one of the available specified control channel. If it does not find any BEACON and SENSING_INFORMATION frame on any one of the specified control channel, it starts transmitting COOPNODE_REG_REL frame and looks for any potential cooperative node in the neighboring area and finally cooperative nodes are associated with it. If another secondary user transmitter $SU\,TX_l$ (l ϵ 1..K, l $\neq$ j) enters the system and finds BEACON and SENSING_INFORMATION frames on one of the available control channel, it registers itself to $SU\,TX_j$ and becomes a slave node to it and communicates according to the centralized approach. If any SU TX in the system does not find BEACON and SENSING_INFORMATION frames on the control channel, it starts transmitting its own COOPNODE_REG_REL and look for possible cooperative nodes in the nearby area. In summary, the process is completely autonomous and both centralized and decentralized approaches are adopted by the secondary users. It is also a new multiple access protocol as radio resources are shared by primary and secondary users. After description and analysis of the proposed cooperative sensing design, the next section presents comparison of the proposed cooperative sensing design with other techniques to solve hidden node problem.

7.5 COMPARISON WITH RTS/CTS AND BUSY TONE

In this section existing techniques to reduce collisions in wireless networks are studied and their results are compared with those of the proposed cooperative sensing design. The first technique is Request to Send (RTS) and Clear to Send (CTS) message exchange as shown by Kaur et. al "An Implementation and Analysis of RTS/CTS Mechanism for Data Transfer in Wireless Network" in 2015 [23] and by Weinmiller et. al "Analyzing RTS/CTS Mechanism in the DFWMAC Media Access Protocol for Wireless LANs" in 1995 [42]. Figure 7.20 illustrates the RTS/CTS message exchange among three nodes. Node A wants to transmit data to Node B but Node C is not able to hear the transmissions from Node A. The consequence of this is that collisions occur at Node B if Node C transmits concurrently with Node A. This problem is solved by RTS/CTS message exchange before the actual data transmission at Node A. RTS message is first sent by Node A to show its intention to transmit data to Node B. Upon reception of RTS message, Node B informs (with CTS message) all neighboring nodes (Node C in this case) that no other transmission is allowed in its vicinity as Node A is going to transmit DATA frame. As soon as RTS/CTS message exchange is completed, Node A starts sending DATA frame which reduces collisions in the system. In the next step, the application of RTS/CTS message in heterogeneous radio environments is considered as the scope of this thesis is heterogeneous radio environments.

Figure 7.21 shows an example of RTS/CTS technique in heterogeneous radio environment. SU TX sends RTS frame. Upon successful reception of RTS frame, SU RX replies with CTS frame. When CTS frame is successfully received by SU TX, DATA frame is sent. RTS/CTS message is exchanged before a new DATA frame is sent by SU TX. In the heterogeneous radio environments, both RTS and CTS messages are sent on the data channel. If any of the messages (RTS or CTS) is collided by the primary user frames, a back off (also shown in Figure 7.21) counter is used in the simulations in order to reduce the number of transmissions for RTS/CTS. Without back off mechanism, primary user transmission is always hit by RTS or CTS message which makes RTS or CTS technique an ineffective approach to reduce collisions in heterogeneous radio environments. RTS/CTS messages are sent on the data channel therefore, the term wastage $r_{W_{rts-cts}}$ is an overhead in this case. The overhead term for cooperative sensing has been used with the usage of control channel previously. But with RTS/CTS, the term $r_{W_{rts-cts}}$ represents the overhead or wastage on the data channel. Although usage of control channel is also another alternative for RTS and CTS message exchange, but it imposes further overhead on the control channel. Before presenting evaluation results of RTS/CTS technique, another technique Busy Tone is explained first and later the comparison of these techniques is presented with the proposed cooperative sensing design. Cooperative node selection protocol is not considered while comparing these approaches. The evaluation and comparison for mobile scenarios is outside the scope of this thesis.

Another method of reduction of collisions and a solution to hidden node problem is busy tone as described by Videv "Guided Research Final Report" [40]. Busy Tone suggests using two channels; data channel and the control channel similar

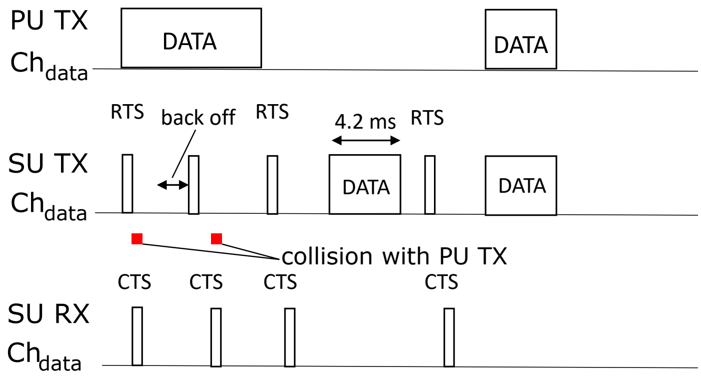

Figure 7.21 – *Use of RTS/CTS message exchange in heterogeneous radio environments*

to the proposed cooperative sensing design. In this scheme, the receiver generates busy tone signal on the control channel upon reception of a frame at data channel to inform other nearby nodes that some nearby transmitter has transmitted data to it and data channel is busy at the moment. On the transmitter side, the nodes before transmitting the data checks on the control channel if it is free from other transmissions. Figure 7.22 shows the implementation details of busy tone for the heterogeneous radio environments. SU RX keeps on performing spectrum sensing and if channel activity is found on the data channel, busy tone frame is transmitted on the control channel. The busy tone frames are separated by the time intervals (0.5ms in the current simulation setup) which are due to performing spectrum sensing by SU RX and are shown in Figure 7.22. SU TX keeps on checking the control channel. If there is no channel activity or no busy tone frame is received on the control channel, data frame of 4.2ms (due to IEEE 802.15.4) is sent by SU TX on the data channel. Similar to RTS/CTS message exchange, the evaluation for the busy tone is also performed for the hidden node scenario with PU and SU Collision case. For evaluation purposes, the same evaluation metric (Effectiveness) is considered for RTS/CTS and Busy Tone. The overhead $r_{W_{bt}}$ is the percentage of the control channel usage due to busy tone frames. The messages for RTS/CTS scheme are the individual RTS and CTS messages on the data channel. Therefore the overhead for RTS/CTS schemes are the accumulated RTS/CTS messages whereas for Busy Tone scheme, the overhead is due to the busy tone frame transmissions on the control channel.

In the following simulation results for RTS/CTS, Busy Tone and COOP are presented. Where COOP represents the proposed cooperative sensing design (DPE with OR fusion rule). The results are presented for 25%, 50% and 75% duty cycles to show the impact of primary user duty cycle on the performance. The selection of the duty cycles is performed similar to the results shown in Section 7.1.3. The other simulation settings are described as follows; PU Technology = IEEE 802.15.4 with 250 kbps, SU Technology = IEEE 802.15.4 with 250 kbps. The same technology on both primary and secondary user sides is used as an example which is same as the ones shown in Section 7.1.3. COOP settings are same as the one considered in Section 7.1.3; $T_{BEACON} = 1000$ms, $T_w = 1$ms, $T_{Btx} = 1$ms,

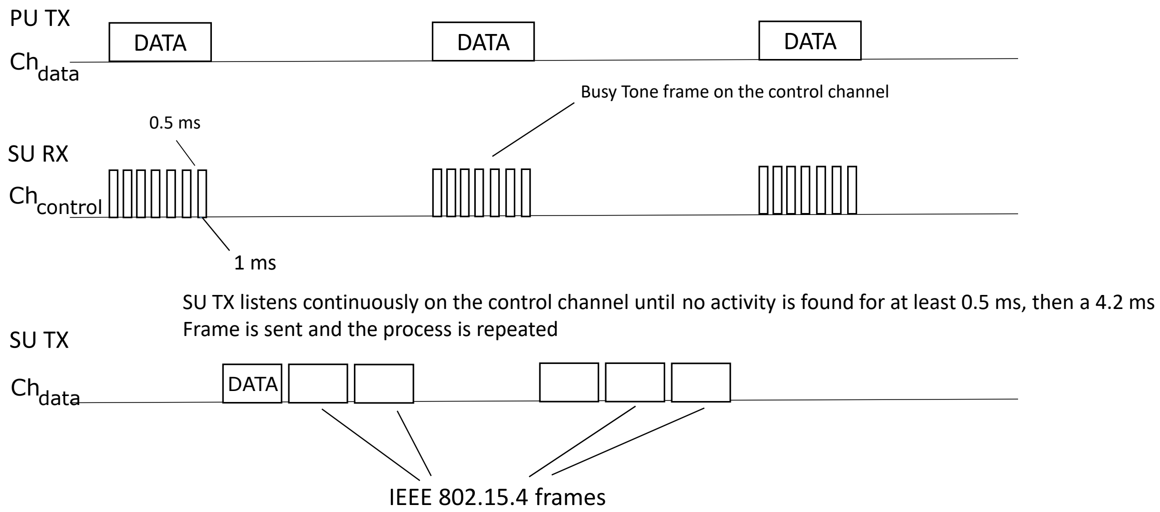

FIGURE 7.22 – *Use of Busy Tone in heterogeneous radio environments*

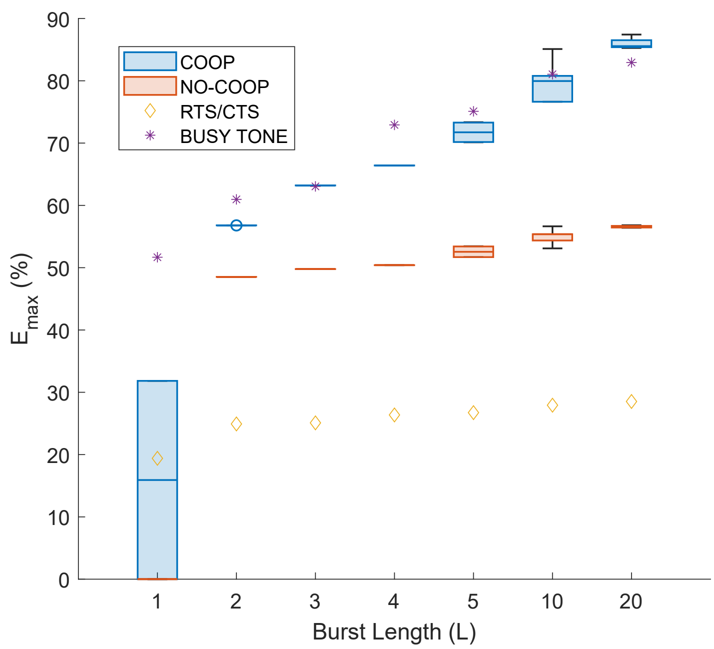

FIGURE 7.23 – *Comparison of Busy Tone, RTS/CTS, COOP and NO-COOP for 25% duty cycle*

T_{Stx} = 1ms, N = 1. These settings are selected as an example to show comparison with RTS/CTS and Busy Tone. The transmission times for RTS/CTS and Busy Tone frames are taken as 1ms (see Figure 7.21 and Figure 7.22) similar to the control channel messages (BEACON and SENSING_INFORMATION frames) used in cooperative sensing.

Figure 7.23-Figure 7.25 shows the performance NO-COOP, COOP, RTS/CTS and Busy Tone for 25%, 50% and 75% duty cycles. The results show that the

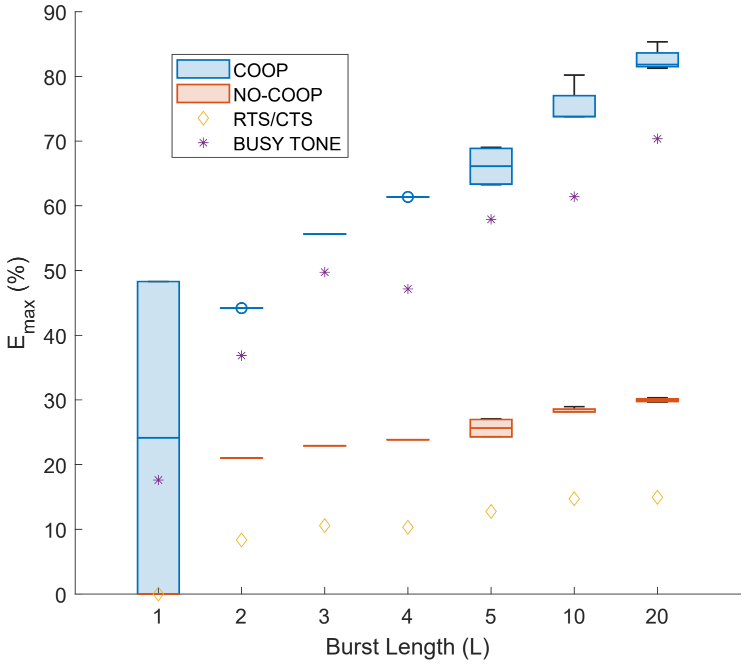

FIGURE 7.24 – *Comparison of Busy Tone, RTS/CTS, COOP and NO-COOP for 50% duty cycle*

performance for RTS/CTS is inferior to all the other approaches (NO-COOP, COOP, Busy Tone). The reason behind this is that the overhead of RTS/CTS message exchange before actual data transmission is high. Therefore, there is an additional waste $r_{W_{rts-cts}}$ on the secondary user side. The primary user traffic is also collided by RTS/CTS message exchange which involves additional waste on primary user side due to RTS/CTS messages. The additional waste is high specially with high duty cycle of primary user traffic (please see for RTS/CTS, Effectiveness of less than 10% for 75% duty cycle). Therefore, RTS/CTS approach is favourable if primary user traffic is low. The performance of Busy Tone is comparable to COOP for low duty cycle but becomes poor as the duty cycle of primary user traffic is increased in the system. This is due to large number of busy tone frame transmissions on the control channel which is attributed to the waste $r_{W_{bt}}$.

In summary, it is concluded that the performance of Busy Tone technique in heterogeneous radio environments is better than RTS/CTS technique whereas cooperative sensing performs best due to low overheads and better collision reduction in the system. Although, it has been seen that for low duty cycle Busy Tone turns out to be performing comparable to the cooperative sensing. Similarly, it is also predicted that RTS/CTS perform comparable to Busy Tone if control channel is used for RTS/CTS message exchange and duty cycle is low but additional resource of control channel is required for such purpose. The poor performance of in band RTS/CTS messages is due to collisions with primary user traffic. The scalability discussion of all these existing techniques is still left for future work.

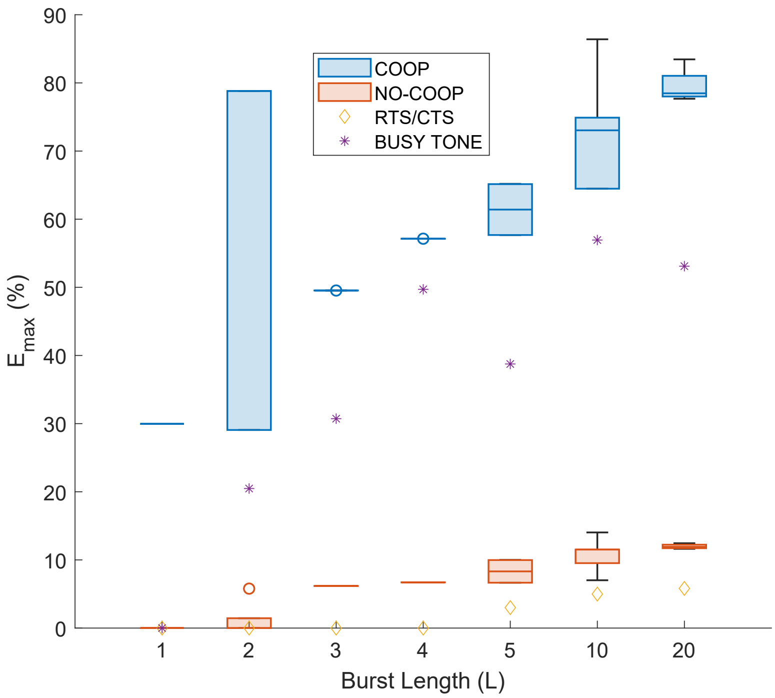

FIGURE 7.25 – *Comparison of Busy Tone, RTS/CTS, COOP and NO-COOP for 75% duty cycle*

In the next section, recommendations are provided for use of cooperative sensing in heterogeneous radio environments. The conclusions are drawn based upon the investigations performed from the previous and current chapters.

7.6 RECOMMENDATIONS

In the following, recommendations for use of cooperative sensing are described.

- The first recommendation is that maximum 1 or 2 cooperative nodes are sufficient for successful cooperative sensing as additional cooperative nodes impose overhead on the system (see Chapter 6 and Figure 6.5).
- Collision areas should be investigated before applying cooperative sensing. As discussed in Section 5.3.1 and Section 6.2, collision areas depend upon radio propagation conditions and the power levels of primary and secondary user transmissions. A hit and trial method is used to see the rough estimate of collision areas. Although radio conditions might vary but with getting rough estimate of collision areas we are able to predict whether cooperative sensing is worth to do (besides other factors). If there are no significant collisions in spite of hidden node, cooperative sensing is not needed.
- Cooperative sensing is recommended to be used specially for duty cycle of greater than 50% as the benefit (reduction in collisions) gained with cooperative sensing is higher as compared with the involved overheads. Additionally, for larger burst length greater than 5 the advantage of

cooperative sensing is more prevalent, although the primary user traffic is not in control in dynamic heterogeneous radio environments (see Section 6.2 and Section 7.1.3).

- Although clock drift among various nodes in the system have minimal influence, it is recommended that crystal clocks are used with the microcontrollers of the radio devices (see Section 7.1.3). As an example, the beacon period of 1000ms for synchronization purposes are used for IEEE 802.15.4 if crystal clocks are assumed to be used by secondary and cooperative users.
- It is recommended that the technology having shorter frames are used on the primary user side in the system as it results in better system performance (see Section 7.1.3). IEEE 802.11 has shorter frames as compared with those of 802.15.4. As far as, 802.15.4 is concerned it supports different data rates. The RF chip AT86RF231 for IEEE 802.15.4 supports various data rates; 250 kbps, 500 kbps, 1000 kbps and 2000 kbps. Therefore, higher the data rate; lower the possible frame durations which leads to improved system performance with cooperative sensing. Therefore, it is recommended to use 2000 kbps for IEEE 802.15.4 and to use 54 Mbps for 802.11 for primary user.
- It is also recommended that higher data rate on the control channel is used so that the overhead on the system is reduced which results in better system performance (see Section 7.1.3). As an example, 2000 kbps is recommended for IEEE 802.15.4 whereas 54 Mbps is recommended for IEEE 802.11g.
- Use of cooperative sensing is recommended for Bluetooth interferer if the Bluetooth frames need to be protected from collision. Otherwise cooperative sensing is not suggested to be used in such systems (see Section 7.2).
- The selection of appropriate thresholds for cooperative node selection protocol are shown for low speed (0.120m/s) scenarios. Therefore, it is recommended that for other speeds, the thresholds are adjusted according to the discussion in Section 6.3 (see Section 6.3.2).
- It is recommended to use adaptive approach by secondary users in case of unknown primary user traffic. The primary user is predicted if the recommended sensing periods for the lowest duty cycle are used initially. The operating sensing period can be adjusted based upon the estimated primary user traffic (see Section 7.1.3 for optimum sensing period for various burst lengths).

7.7 SUMMARY

The outcome of the discussion in this chapter is to provide recommendations for use of cooperative sensing in heterogeneous radio environments. A model is developed based upon the real world scenario in Chapter 6. The optimization goals for the proposed cooperative sensing design are defined and simulation results are shown by varying different parameters (duty cycle of PU traffic, primary and secondary user technology, beacon period T_{BEACON}, time duration for BEACON frame T_{Btx}, time duration for SENSING_INFORMATION frame T_{Stx}, time duration for cooperative sensing receiving window T_w) from the proposed cooperative sensing design. The results show that the performance gain with cooperative sensing improves with an increase in burst length of primary user transmissions. Furthermore a technology having shorter frames have better Effectiveness than those with longer frames. Additionally, optimum sensing periods are also shown with the help of number of diagrams. Later scalability aspects of the proposed cooperative sensing design are explained briefly as the detailed analysis is beyond the scope of this thesis. A comparison with other techniques (RTS/CTS and Busy Tone) is also performed. So far, the focus of all discussion is on usage of cooperative sensing in heterogeneous radio environments. In this regard, Effectiveness is taken as an evaluation criterion for successful cooperative sensing while reducing collisions in the system with minimum overhead. But no example in the field has been shown yet where the proposed design is able to improve performance of the network. In the next chapter, one of the potential application for the proposed cooperative sensing design is discussed in detail.

CHAPTER 8

APPLICATION

In all the previous discussions in this thesis, the focus has been on applying cooperative sensing in heterogeneous radio environments. The aim of cooperative sensing has been on reduction of collisions with minimum involved overhead. The overhead includes the control frames (BEACON and SENSING_INFORMATION) for DPE or SFE protocol and the control frames are the frames involving registration and release procedures for cooperative node selection protocol. Effectiveness has been used as the evaluation criterion for cooperative sensing in both real world as well as in simulation analysis for providing guidelines and recommendations. But from the application point of view, a communication network needs to meet quality of service requirements. This aspect has not been addressed in the previous chapters. In this chapter, the focus is on using cooperative sensing meeting quality of service requirements where acknowledgments are considered both on primary and secondary user side. In this regard one exemplary application is envisaged from the existing literature. The application in the medical field is selected as an example. The next section motivates the medical field application which is followed by typical requirements from medical field. Later a testbed evaluation scenario is illustrated which also includes acknowledgements of data frames. In the next step, results are shown with the evaluation scenario. Finally the chapter ends with a short summary.

8.1 MOTIVATION

The health care sector is interested in advanced Information Communication Technology (ICT) systems to efficiently administer the healthcare delivery for a range of services as described by Kurtinaityt "E-Health- The Usage of ICT Developing Health Care System" in 2007 [2]. Advanced ICT systems will be able to deliver healthcare to patients in hospitals, medical centers and in their homes and workplaces thus offering cost savings and improving the quality of life of patients. Khan et. al "Wireless Body Area Networks for Medical Applications" in 2010 [3] analyze the requirements for the medical applications and describe possible infrastructures for the hospitals. Various proposals of MAC protocols for the medical field are described in this article. For example, three protocol configurations are suggested; TDMA, Polling and CSMA. In order to implement these protocols a central fixed architecture is suggested in that article which coordinates and manages the radio resources among various nodes in the system. The next section describes the typical communication requirements.

8.2 APPLICATION REQUIREMENTS

In this section, the application requirements for a scenario in Intensive Care Unit (ICU) is described and later the proposed DPE protocol is adapted (parameter selection and inclusion of acknowledgments) accordingly to meet these requirements. Paksuniemi et. al "Wireless Sensor and Data Transmission needs and Technologies for Patient Monitoring in the Operating Room and Intensive Care Unit" in 2006 [69] describe the data rate requirements for the medical applications specially in ICU after collecting data by interviewing various doctors in the hospital. Table 8.1 summarizes application requirements in the medical field. ECG has highest data rate of 18 kbps if three electrodes are considered. Whereas the data rate for all other sensors; Blood pressure noninvasive, Blood pressure invasive, PAP, CVP, Photoplethysmography, Cardiac output, Body Temperature is 1.44, 1.2, 1.2, 1.2, 1.44, 0.48, 0.0024 kbps respectively. The cumulative data rate for all the sensors sums up to 25 kbps if three electrodes are assumed. On the contrary, the cumulative data rate for all the sensors is 79 kbps if twelve electrodes are considered. As ECG data rate reaches up to 18 x 4 (72 kbps) if twelve electrodes are considered. Therefore, the data rate requirement is found to be from 25 to 79 kbps depending upon the number of electrodes of ECG. Besides high reliability of 100%, there is also a maximum latency requirement of 500ms.

Two kinds of patients are treated in the hospitals which are attributed to primary and secondary users. The first one is in critical situation (ICU) while the other one is in less critical situation. The patients which are in critical situation are classified as the primary users whereas the less critical patients are classified as the secondary users. Primary user demands high reliability which is described later whereas secondary users accommodate packet loss and variation in latency. Furthermore staff users are able to request or send information of patients. The staff users also correspond to the secondary users as their information communication with the patients is not very critical as compared to that for the patients in ICU.

The next section elaborates the evaluation scenario. The scenario is selected in a way to demonstrate the usage of cooperative sensing from application point of view. Acknowledgements are used in order to provide the reliability of transmission for both primary and secondary user. Two kinds of primary user traffic are considered to meet data rate requirement of 25 and 79 kpbs for the application. Although more detailed evaluations are suggested before use of cooperative sensing in the field but the evaluation scenario presented in the next section is sufficient for demonstrate the usage of cooperative sensing in the field from application point of view.

Table 8.1 – *Typical requirements for medical applications [70]*

Parameter	Standard Sensor or Method	Bit Rate 12 bits A/D
Blood Pressure Noninvasive	Strain Gage integrated on silicon, cuff auscultation	1.44 kb/s
Blood pressure invasive	Strain Gage integratedon silicon	1.2 kb/s
Pulmonary artery pressure (PAP)	Strain gage integrated on silicon	1.2 kb/s
CVP, Central venous pressure	Strain gage integrated on silicon	1.2 kb/s
ECG (3,5 or 12 electrodes)	Skin electrodes	18 kb/s 3 electrodes
Photoplethysmography	Two photodiodes	1.44 kb/s
Cardiac output	Thermodilutio	0.48 kb/s
Body Temperature	Thermistor thermocouple	0.0024 b/s

8.3 EVALUATION SCENARIO

So far, regarding evaluation of the proposed cooperative sensing design in heterogeneous radio environment one directional communication (from SU TX to SU RX) is addressed. But in real wireless networks, acknowledgments are part of the protocol for ensuring reliability of the wireless transmission at the MAC layer. The proposed metric (Effectiveness) has been considered in evaluation for all the scenarios and even for simulation results without acknowledgments. The application demands support for acknowledgments for both primary and secondary users in order to provide reliability of the transmission. In this regard, the proposed metric (Effectiveness) is considered to measure effective channel utilization and the wastage W among primary and secondary users but the quality of service parameters are studied with acknowledgments. In order to evaluate the system with acknowledgments further analysis is performed. Although in previous chapter, an analysis is performed from general perspective considering various technologies IEEE 802.15.4, IEEE 802.11 and IEEE 802.15.1. In the following, a special real world scenario with IEEE 802.15.4 is selected based upon ease to demonstrate the usefulness of the proposed design. Only secondary user transmissions corrupt the reception at the primary user receivers in the scenario selected. It is shown later that cooperative sensing reduces these collisions at the primary user and therefore decreases loss in primary user transmitted frames as well as improves goodput.

Figure 8.1 shows the modified DPE protocol with dedicated cooperative node C_1 with acknowledgment both for primary and secondary users. All the functionality of the DPE protocol is same except addition of acknowledgment frame from the receivers of primary and secondary users. The analysis shown for acknowledgment uses the same experimental setup discussed in Chapter 5 although now the purpose of evaluation is to show usage of the proposed design in real wireless networks.

The same experimental setup shown in Section 5.3 is utilized, therefore primary user transmits at 250 kbps whereas the secondary user transmits at 500 kbps.

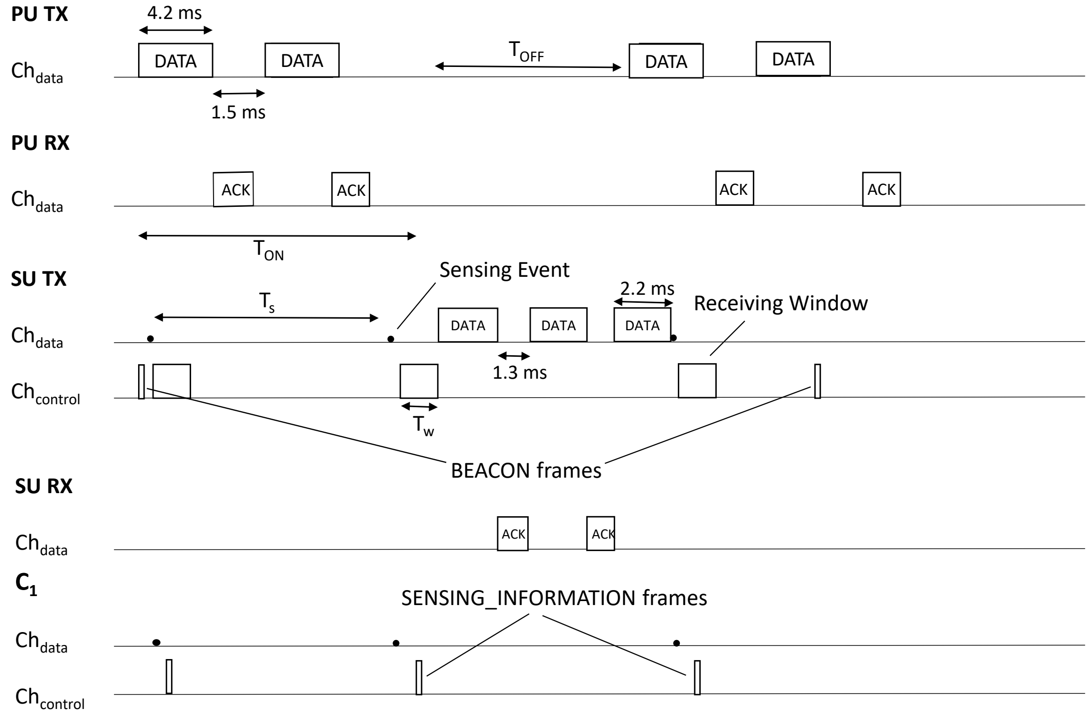

Figure 8.1 – *DPE protocol with acknowledgments both for primary and secondary users*

Primary user uses frame size of 4.2ms for data from PU TX to PU RX. The time duration for reception of acknowledgment is 1.5ms which is a bit more than assumed (1ms time for transmission of ACK frame). It should be noted here that the RF chip also supports usage of acknowledgement from IEEE 802.15.4. Although in this work, new messages are defined for the acknowledgements as an example in the proposed cooperative sensing design rather than using acknowledgement frame from IEEE 802.15.4 standard. 0.5ms time is allocated for reception of ACK and transferring the data to microcontroller and initializations of the RF chip and microcontroller (see Section 5.3 and Figure 5.10). Therefore, 1.5ms time is reserved for reception of acknowledgment ACK frame at PU TX. On the secondary user side, the frame size of 2.2ms for data is used from SU TX to SU RX (as secondary user transmits at 500 kbps). For the acknowledgment ACK frame, 1.3ms (shorter than primary user due to high transmission rate) is reserved at SU TX for its reception. Acknowledgments are considered for both primary and secondary users in order to provide reliability for the transmission due to possible collisions or possible radio propagation effects as discussed in Section 2.3. Figure 8.2 shows the evaluation scenario with acknowledgment added to the DPE protocol. All the nodes PU TX, SU TX, SU RX, PU RX and C_1 are placed at the appropriate places whereas *start* node synchronously starts the experiments. The dedicated cooperative node C_1 is placed near to PU TX and PU RX so as to detect the primary user transmissions either from transmitter or from receiver. Furthermore SU RX only serves the purpose of reception for SU TX and not cooperating in this scenario. This is due to the reason that the

Table 8.2 – *Parameter settings for Table 8.6-Table 8.8 for illustrating the application*

T_w (ms)	T_{Btx}, T_{Stx} (ms)	T_{BEACON} (ms)
2.4	1	100

purpose of evaluation is to demonstrate the usage of cooperative sensing and C_1 is enough for such demonstration.

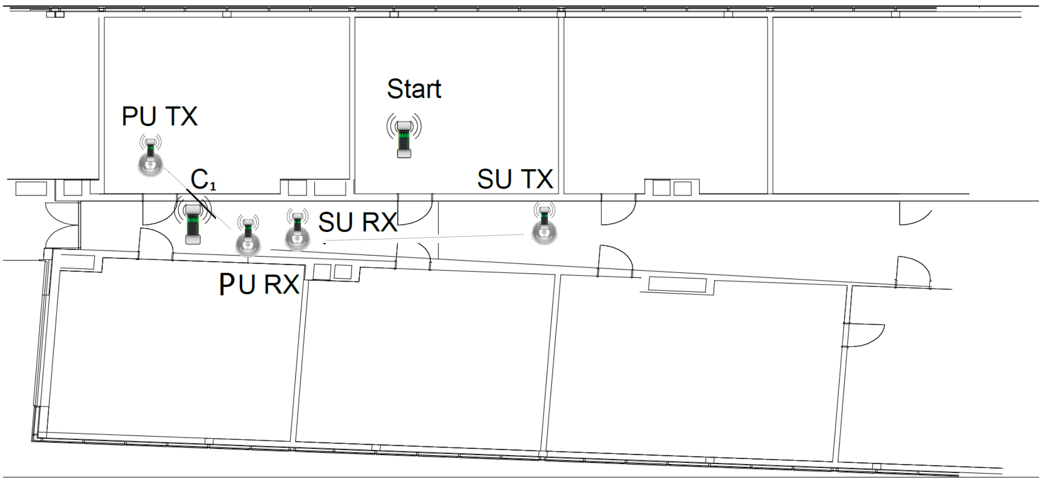

Figure 8.2 – *Evaluation scenario with acknowledgments*

Table 8.2-Table 8.5 show the parameter settings for the results presented in the next section. While selecting the optimum parameters for a particular application a detailed simulation analysis is recommended but for demonstration of cooperative sensing usage in the field, the parameter settings and the results of Section 6.1 are taken for analysis of results.

Time duration for Cooperative Sensing Receiving Window T_w, time duration for BEACON frame T_{Btx}, time duration for SENSING_INFORMATION frame T_{Stx}, beacon period T_{BEACON}, PU Technology, SU Technology, experiment duration T_e and N have same values; 2.4ms, 1ms, 1ms, 100ms, IEEE 802.15.4 with 250 kbps, IEEE 802.15.4 with 500 kbps, 500s and 1 as used in Section 6.1.2. T_s is selected as 30ms as done in Section 6.2. The other parameters of the proposed cooperative sensing design are T_{REG_REL}, $T_{COOPNODE\_REG\_REL}$, T_{BEACON_LIVE}, $Threshold_{REL\_SUTX}$ and $Threshold_{REG}$, $Threshold_{REL\_COOPNODE}$ and their values are 100ms, 5s, 10s, 0.15, 0.15, 0.15 respectively. The values used are same as the ones used in Section 6.3 as similar radio propagation environment are expected. No mobility of nodes is involved in the scenario under consideration.

Previous discussion of cooperative sensing (see Section 7.3) shows that the advantage of cooperative sensing is significant when primary user duty cycle is high. But low duty cycle of primary user traffic also provides more margin for retransmissions for primary user and more opportunities for secondary user transmission. Additionally, there are two kinds of application data rate requirement; 25 kbps and 79 kbps which depend upon the number of electrodes used for ECG. In this regard, two types of duty cycles are considered keeping in view

Table 8.3 – *Parameter settings (cont...) for Table 8.6-Table 8.8 for illustrating the application*

N	PU Technology	SU Technology	T_e (s)
1	IEEE 802.15.4 (250 kbps)	IEEE 802.15.4 (500 kbps)	500

Table 8.4 – *Parameter settings (cont..) for Table 8.6-Table 8.8 for illustrating the application*

T_{REG_REL} (ms)	$T_{COOPNODE\_REG\_REL}$ (s)	T_{BEACON_LIVE} (s)
100	5	10

Table 8.5 – *Parameter settings (cont..) for Table 8.6-Table 8.8 for illustrating the application*

$Threshold_{REL\_SUTX}$	$Threshold_{REG}$	$Threshold_{REL\_COOPNODE}$
0.15	0.15	0.15

two types of application data rate requirement. Therefore only two settings (low and medium duty cycles) are shown for the considered scenario. The low duty cycle is associated with T_{ON} = 40ms and T_{OFF} = 200ms where the burst length is approximately 10 for primary user. This duty cycle is considered keeping in view 25 kpbs data rate. The low duty cycle (20%) correspond to effective data rate of 50 kbps without acknowledgements and ignoring preamble and CRC. The acknowledgements are taken as 1.5ms for 4.2ms data frame. As a result is 26% is used for acknowledgements which further decreases the achievable data rate but the maximum achievable data rate is still above than 25 kbps which meets the requirement. For medium duty cycle, T_{ON} = 40ms and T_{OFF} = 40ms are chosen where the burst length is also 10 for the primary user. The medium duty cycle (50%) leads to effective data rate of 125 kbps without acknowledgements and ignoring preamble and CRC. The achievable data for this setting turns out to be 90 kbps which is higher than the application data rate of 79 kbps. The actual data rate in a particular scenario is less than the achievable data rate because of packet loss of radio propagation and preamble and CRC.

The next section presents the evaluation results. The performance is evaluated with three settings; without presence of secondary user, in presence of secondary user and with cooperative sensing. It is shown how cooperative sensing copes with the hidden node situation, reduces collisions and resultantly meets the application requirements in terms of data rate as well as latency. Scalability aspects are briefly discussed.

8.4 RESULTS

Table 8.6 and Table 8.8 show the results of evaluation with low and medium duty cycle of primary user traffic. The first column consists of quantities: primary user goodput - PU Goodput (Kpbs); secondary user goodput - SU Goodput (kbps); average latency for primary user transmitted frames - PU Latency (ms); average latency for secondary user latency - SU Latency (ms); primary user packet loss

Table 8.6 – *Performance with T_{ON} = 40ms and T_{OFF} = 200ms for application data rate of 25 kbps*

	Without SU	With SU (NO-COOP)	DPE with C_1
PU Goodput (kbps)	36.6	18.9	35.3
SU Goodput (kbps)	N/A	89.9	105
PU Latency (ms)	4.35	25.6	6.4
SU Latency (ms)	N/A	3.6	2.8
PU Packet Loss (%)	0.24	3.6	1
SU Packet Loss (%)	N/A	18.9	0

Table 8.7 – *Calculation of Effectiveness for the results of Table 8.6*

	$r_{PUGoodput}$ (%)	$r_{SUGoodput}$ (%)	$r_{W_{PU}}$ (%)	$r_{W_{SU}}$ (%)	$r_{W_{coop}}$ (%)	*Effectiveness* (%)
NO-COOP	11.4	30.6	42	0	N/A	50
COOP	19.7	33.6	3	0	5	87

- PU Packet Loss (%); secondary user packet loss - SU Packet Loss (%). The evaluations are performed with three different settings. In the second column, the results are shown when secondary user is not present in the system and no collisions are possible in the system. Whereas in the third column results are shown with secondary user transmission as the secondary user transmission collides with the primary user transmission (NO-COOP). In the last column, results are shown if cooperative sensing (DPE protocol with the acknowledgments) is applied. Table 8.7 and Table 8.9 show the calculated Effectiveness values from the measured results according to Equation 4.26 mentioned on Page 65. The calculation of $r_{PUGoodput}$ is done using Equation 4.19 where PU Goodput is taken as 1.5 × (PU Goodput (kbps) entry in Table 8.6 and Table 8.8). The factor 1.5 is considered as the PU Goodput (kbps) is measured excluding primary user acknowledgments. $PU\,Goodput_{max}$ is 250 kbps. Similarly Equation 4.20 calculates $r_{SUGoodput}$. The term SU Goodput is taken as 1.3 × (SU Goodput (kbps) entry in Table 8.6 and Table 8.8). The factor for secondary user acknowledgments is 1.3. $SU\,Goodput_{max}$ is 500 kbps. The calculation of $r_{W_{PU}}$ is performed based upon PU packet loss and PU latency entries in Table 8.6 and Table 8.8. PU latency (ms) indicates the retransmission attempts implicitly for the primary user frames. The difference between the values for DPE with C_1 and NO-COOP shows the primary user lost frames because of collisions from secondary user transmissions. Although radio propagation is another source for loss in primary user receptions. In the considered scenario, only primary user transmission is collided and corrupted by secondary user transmission. As the purpose is to show the performance with acknowledgments, additionally we are interested in the primary user goodput to meet the application requirement. In Figure 6.1 on Page 83, the main purpose with the scenario PU and SU Collision was to evaluate best performance gain of cooperative sensing and compare the proposed cooperative sensing design (DPE and SFE protocols), where both primary and secondary transmissions are collided by each other.

The outcome of the measurement results is that for low duty cycle with T_{OFF} = 200ms (see Table 8.6), primary user goodput is 36 kbps when no secondary user is present in the system. When secondary user also enters the system, primary user goodput is reduced to 18.9 kbps due to collisions. With the introduction of cooperative node, collisions are reduced and primary user goodput is restored to 35.3 kbps. In this way, with low duty cycle of primary user traffic cooperative sensing is able to meet the requirements for the medical applications if 3 electrodes are used for ECG. The average packet loss rate for PU and SU for the setting (DPE with C_1) is 1% and 0% respectively. This is slightly higher than that 0.24% and 0% for the setting Without SU but lower than that (3.6% and 18.9%) for the setting NO-COOP. The average latency for PU and SU for the setting DPE with C_1 is 6.4ms and 2.8ms. This is slightly higher than that (4.35ms and 2.2ms) for the setting Without SU but lower than that (25.6ms and 3.6ms) for the setting NO-COOP. Secondary user goodput is 178 kbps in absence of primary user transmission (not shown in Table 8.6 and Table 8.8) although slight decrease in SU Goodput is observed 105 kbps when secondary user reduces collisions with primary user transmission with the help of the cooperative node. Average PU latency = 6.4ms which is also comparatively higher than when SU TX is working standalone 4.35ms. Besides PU packet loss is 1% which is minimal in this case due to the cooperative node C_1. This decrease is due to collisions which occur between primary and secondary user transmission. Retransmission attempts are considered for primary and secondary users. The higher retransmission attempt count decreases packet loss at the cost of increase in average latency. On the contrary lower retransmission attempt count decreases average latency but the packet loss is increased in the system. Although impact of various number of retransmission attempts is not discussed in this thesis and is left for designers and future work. The retransmission attempts are set to 16 for both Primary and Secondary User transmissions as an example. Therefore PU Latency reaches to 25.6ms when secondary user transmission interferes with the primary user transmission which is quite low as demanded (500ms) by the application. SU Latency is not much affected as primary user transmission is not in a position to corrupt the secondary user transmission. Therefore, no significant change in SU Latency is observed even in presence of concurrent primary and secondary user transmission. In realistic scenarios, primary user transmission also corrupts the receptions for the secondary user. As described earlier in this section, the purpose of analysis in this chapter is to illustrate usage of cooperative sensing in wireless networks from application point of view.

Effectiveness improves with cooperative sensing by a margin of 37% as compared with individual spectrum sensing NO-COOP. The major reason behind poor *Effectiveness* 50% with NO-COOP is due to high retransmission attempts due to collisions from secondary user. The purpose of providing high T_{OFF} due to low duty cycle is two-fold. The first purpose is that primary user traffic is provided a reliability with retransmissions. Whereas the second purpose is to provide sufficient opportunity to the secondary user transmission.

In the next step, 12 electrodes considered for ECG resulting in application data rate of 79 kbps. As discussed in the previous section, medium duty cycle is considered in Table 8.8 where T_{ON} and T_{OFF} are taken as 40ms. In this case, primary user goodput is comparatively high 94.7 kbps for the setting (Without SU) which reduces slightly to 76.9 kbps with the setting DPE with C_1 and concurrent transmission with secondary user. PU Goodput is quite low 19.1 Kpbs as expected for the setting NO-COOP. Although primary user goodput is

TABLE 8.8 – *Performance with T_{ON} = 40ms and T_{OFF} = 40ms for application data rate of 79 kbps*

	Without SU	With SU (NO-COOP)	DPE with C_1
PU Goodput (kbps)	94.7	19.1	76.9
SU Goodput (kbps)	N/A	79.9	43.2
PU Latency (ms)	4.25	26.7	6
SU Latency (ms)	N/A	4.4	3.6
PU Packet Loss (%)	0	8	0.82
SU Packet Loss (%)	N/A	19.1	0

increased from 35.3 kbps to 76.9 kbps with increase in duty cycle but secondary user goodput is also decreased from 105 kbps to 43.2 kbps for the setting DPE with C_1. PU Goodput in presence of SU (NO-COOP) is quite low (19.1 Kpbs) as expected due to high collisions in the system. Primary user goodput is 94.7 kbps when no secondary user is present in the system which meets the requirements for the medical applications in case 12 electrodes are used for ECG. When secondary user also enters the system, primary user goodput is reduced to 18.9 kbps due to collisions. With the introduction of cooperative node, collisions are reduced and primary user goodput is restored to 76.9 kbps which is quite close (79 kbps) to what the application demands from the system. The average packet loss rate for PU and SU for the setting DPE with C_1 is 0.82% and 0% respectively. This is slightly higher than that (0% and 0%) for the setting Without SU but lower than that (8% and 19.1%) for the setting NO-COOP. The average latency for PU and SU for the setting DPE with C_1 is 6ms and 3.2ms. This is slightly higher than that (4.25ms and 2.2ms) for the setting Without SU but lower than that (26.7ms and 4.4ms) for the setting NO-COOP. Higher duty cycle leads to higher primary user goodput but the secondary user goodput is also decreased. But the average latencies and packet loss rates are quite similar even with change in duty cycle. *Effectiveness* improves with cooperative sensing by a margin of 42.6% as compared with individual spectrum sensing NO-COOP.

The outcome of the discussion is that both low and medium duty cycles suffice the requirement of medical field if 3 or 12 electrodes are used respectively with the system. In the next step, scalability aspects regarding the considered medical application are highlighted as currently the evaluation has been on single user scenario. Two approaches are suggested in this thesis regarding the proposed cooperative sensing design in Section 7.4; centralized and decentralized. In a centralized approach, data channel is shared among multiple secondary users. If it is assumed that secondary users employ TDMA approach, this leads to SU goodput $<\frac{105}{K}$ and $\frac{43.2}{K}$ on the average for low and medium duty cycles respectively. Where 'K' represents the number of secondary users sharing a data channel. As each TDMA utilizes a slotted mechanism to allocate the radio bandwidth to the secondary users. SU Latency is also increased for a single secondary user (K * 2.8) ms and (K * 3.6) ms for low and medium duty cycle respectively. As the TDMA slots are divided among all secondary users leading to higher average SU latency per secondary user. A detailed analysis of scalability for the considered application is beyond the scope of this thesis. As the purpose of this chapter is to demonstrate how cooperative sensing is useful for real wireless network.

TABLE 8.9 – *Calculation of Effectiveness for results of Table 8.8*

	$r_{PUGoodput}$ (%)	$r_{SUGoodput}$ (%)	$r_{W_{PU}}$ (%)	$r_{W_{SU}}$ (%)	$r_{W_{coop}}$ (%)	*Effectiveness* (%)
NO-COOP	10.6	25.5	40	0	N/A	47.4
COOP	43	13.8	1	0	5	90

8.5 SUMMARY

Summarizing the discussion, in this chapter the use of cooperative sensing for the medical application is elaborated. In this regard, Effectiveness provides indication only in terms of reduction of collisions and the involved overhead. The application requires data rate of 25 and 79 kbps with 500ms latency if 3 or 12 electrodes for ECG are used. This is met by selecting T_{ON} = 40ms, T_{OFF} = 200ms and T_{ON} = 40ms, T_{OFF} = 40ms respectively. It is shown that individual spectrum sensing is not able to meet this requirement from data rate point of view but cooperative sensing meets the data rate requirement as well as primary user latency.

In the next chapter, conclusions are drawn from all the discussions throughout the chapters and an outlook is also presented highlighting the future research direction.

CHAPTER 9

CONCLUSIONS AND OUTLOOK

Cooperative sensing has proved to be the promising technique for reducing interference and collisions in hidden node scenarios. The investigations have shown that cooperative sensing works if either IEEE 802.15.4 or IEEE 802.11 is used on secondary user side. While on primary user side any technology; IEEE 802.15.4, IEEE 802.11 or IEEE 802.15.1 is used although cooperative sensing does not perform well in presence of Bluetooth technology.

In order to apply cooperative sensing to heterogeneous radio environments, modeling is performed with primary and secondary user with hidden node. The goal is specified as reduction of collisions between primary and secondary user at their respective receivers. The proposed design uses dedicated control channel to get spectrum sensing results from the cooperative nodes to the secondary user. The overheads with DPE, SFE and cooperative node selection protocols of cooperative sensing are quantified in the thesis. For analysis purpose, two evaluation metrics are presented in this thesis which are applicable for heterogeneous radio environments. The first metric, probability of error ignores the overheads associated with cooperative sensing whereas the other metric Effectiveness considers system wide performance.

IEEE 802.15.4 is taken as an exemplary experimental setup. In this regard, the investigatations on the frame level transmissions and collisions with individual spectrum sensing in testbed scenarios present new findings. The major finding is that the whole preamble is not necessary for synchronization at the receiver of IEEE 802.15.4 frames. If part of preamble (25% for IEEE 802.15.4) is corrupted, the receiver is still able to receive the frames correctly. Another set of investigations was the determination of detection probability in the real world scenario which is important for evaluation of cooperative sensing. In previous research all values for detection probability are considered in simulations and analysis but the testbed evaluation have shown different findings. The outcome is that detection probability of $\approx 0\%$ or 100% is more common in the indoor environment where some rare values (53%, 47% and 90%) were also found in the measurements. As described in the start that cooperative sensing provides benefit when the secondary user is not able to detect transmissions from the primary user (hidden node situation). Therefore, hidden node scenario is defined as where $P_d \approx 0$ for SU TX.

Further evaluation with testbed scenarios with cooperative sensing presents new findings. The first outcome is that DPE (OR, Majority) performs better (Effectiveness of 65%) than all other cooperative sensing protocols (DPE-AND and SFE) ($\leq$ 50%). The increase in number of cooperative nodes does not influence the performance as one cooperative node which is able to detect primary user transmission is enough. It is recommended that 2 cooperative nodes be available so that if one is not in a position to detect primary user transmission the other one is helpful in that situation. Although cooperative node selection protocol also addresses this issue in a dynamic radio environment. Further evaluation in stationary scenarios with secondary user receiver acting as cooperative node shows that secondary user receiver provides performance gain of 40% specially with high duty cycle (91%) with burst length of 10 for primary user traffic, if both concurrent primary and secondary user transmissions collide at their respective receivers (PU and SU Collision scenario). Evaluation in mobile scenarios demonstrates the use of cooperative node selection protocol in mobile environment. The selection of the remaining threshold parameters for registration and release of cooperative nodes; T_{REG_REL}, $T_{COOPNODE\_REG\_REL}$, T_{BEACON_LIVE}, $Threshold_{REL\_SUTX}$, $Threshold_{REG}$, $Threshold_{REL\_COOPNODE}$ for the proposed cooperative sensing design is demonstrated. The results show that secondary user receiver improves the performance from 42% to 48% in one of the mobile scenario while the dedicated cooperative node C_1 further improves the performance up to 59%. The conclusions from these scenarios is that the cooperative node near to primary user activity is in a better position to assist secondary user and improve *Effectiveness* to much larger extent.

In the next step, the scenario PU and SU Collision is considered and a simulation analysis is presented for broader range of the parameters (sensing period, beacon period, cooperative sensing receiving window, beacon and sensing information frame durations and burst length) for the proposed design. This analysis was not possible with experimental setup as it is not easy to change the parameters in the hardware and see its influence. Therefore, a model is developed based upon the PU and SU Collision scenario. Two terms, maximum effectiveness E_{max} and optimum sensing period $T_{s(optimum)}$ are defined. The values for these two terms are shown considering the related parameters; beacon period, cooperative sensing receiving window, beacon and sensing information frame duration and burst length. The results show that with increase in burst length, E_{max} increases and the number of collisions are reduced in the system. The optimum sensing period also increases with increase in burst length of primary user. An increase in duty cycle of primary user traffic improves the performance margin of cooperative sensing as compared with individual spectrum sensing. The impact of primary user technology is that the technology having shorter frame sizes provides better system wide performance in terms of *Effectiveness*. Two exemplary technologies (IEEE 802.15.4 and IEEE 802.11g) from the considered heterogeneous radio environments are used in the simulation setup to show the performance. Clock drifts of the radio devices have negligible influence on the performance although crystal clocks are recommended to be able to use all the sensing periods with best performance.

The proposed cooperative sensing design is also valid for multiple primary and secondary users. Although no analysis results are provided in this thesis for scalability but two approaches (centralized and decentralized) are suggested in this regard. Additionally comparison of the proposed cooperative sensing design is also performed with other technologies like RTS/CTS, Busy tone. The results show that the performance of the proposed design is better than both RTS/CTS and busy tone. The performance of busy tone approach lies in between that of cooperative sensing and RTS/CTS. The main reason behind this is that with busy tone approach the overhead (busy tone frames on the control channel) is quite high as compared with that of cooperative sensing specially with high duty cycle. On the contrary, with RTS/CTS approach in band control messages collide with primary user traffic too often which leads to high wastage of primary user transmission. This results in poor performance of RTS/CTS technique for heterogeneous radio environments.

Usage of cooperative sensing in the medical field also shows promising results. The goal in heterogeneous radio environments is to minimize collisions with minimum overhead. But application requirements are also considered while applying cooperative sensing in the field. As an example, two kinds of data rates (25 kbps and 79 kbps) are considered while 500ms latency from application is considered. Additionally, the proposed design supports acknowledgements both on primary and secondary user side without any significant change in the design. The results show that cooperative sensing achieves not only the net data rate of 35.3 kbps and 76.9 kbps respectively for desired application requirements, but also maintains the PU latency in the evaluation scenario turns out to be 6.4ms and 6ms for 25 kbps and 79 kbps respectively which is quite below than the application latency requirement of 500ms. The purpose of evaluation is to provide an insight how cooperative sensing is applied in the field. Although a more thorough evaluation and analysis (more scenarios) is suggested for future research before using that in the field.

9.1 FUTURE RESEARCH DIRECTIONS

The investigations made in this thesis has a scope of single primary and single secondary user. But a detailed research regarding scalability is a potential research topic. Simulation study as well as real world evaluation are both candidate methodologies for analyzing scalability aspects. For centralized approach, selection of master node is again another topic of research in this regard.

The focus of this thesis is on evaluation of Detection Performance Enhancement protocol although Sensing Frequency Enhancement protocol also needs to be investigated as evaluations performed from simulation perspective in Chapter 4 indicates performance improvement with SFE scheme in selected scenarios. The SFE protocol is favored in situations where all cooperative nodes have perfect detection probability and DPE-OR protocol does not improve performance with addition of cooperative nodes in the system. In such situation, SFE protocol is a candidate to be researched where effective sensing period is decreased with the incorporating additional cooperative nodes. Therefore, selecting either SFE or DPE according to radio environment or topology needs investigation.

The implementation of the proposed cooperative sensing design with IEEE 802.15.4 setup leads to 4% overhead with each cooperative node therefore the proposed design with thresholds works well in the radio environment where detection probability is either 0% or 100%. In this thesis, the investigations are performed with only 1 or maximum 2 cooperative nodes with hard decision fusion rule. A cooperative node selection mechanism along with soft decision fusion rules and their real world evaluations is also a potential research topic.

The scope of this thesis is on 2.4 GHz band and the related technologies whereas the other bands are considered for future work. In this thesis, only medical field application is discussed and the evaluations are performed concerning for single primary, secondary and cooperative users. Scalability issues are again future research topics for the application. For example, how to coordinate data and control information transmission among secondary users and cooperative nodes with centralized and decentralized approach is still open research question. consideration of multiple primary users along with multiple secondary and cooperative users also needs thorough investigation.

Industry is switching to wireless devices fast removing the wires in the area in operation. But due to proliferation of wireless devices, the wireless transmissions are prone to interference and losses. Specially in control applications, reliability of radio transmission is highly desired. The proposed cooperative sensing design is also useful in this situation and detailed investigations are required in this regard as well.

APPENDIX A

IMPLEMENTATIONS AND THE RELATED SOURCE CODE

In the following C code snippets shows the selected parts of implementations of PU RX with the radio nodes. A.1 lists the software program for PU RX. In the experimental evaluations, primary user is assumed to send data at 250 kbps while secondary user transmits at 500 kbps. As already explained in Section 5.3, the main reason for that is secondary user requires shorter frames than primary user therefore secondary user uses higher data rates. Primary and secondary user transmitted frames are detected by PU RX as the preamble part of the physical layer frame is transmitted at 250 kbps data rate. Therefore a problem occurs when the SFD field of secondary user frame is detected by PU RX. As the actual frame duration of a secondary user frame is lower than what is perceived by PU RX. For example, if a secondary user frame having payload of 120 Bytes is detected by the RF Chip of PU RX. The frame duration of secondary user frame on air is 2.112ms whereas the frame duration of the detected frame is perceived to be 4ms by PU RX. Therefore the RF Chip of PU RX remains in BUSY_ON state for 4ms and therefore for 1.89ms the RF Chip of PU RX is not able to detect or receive any other frames. In order to solve this problem, FL field of IEEE 802.15.4 physical layer frame is used to distinguish between primary and secondary user frames in the current experimental setup. Once secondary user frame is distinguished or detected, the RF chip of PU RX is immediately reset and switched to RX_ON state so that the transceiver is able to receive the frames onwards. The length of secondary user frames is specified in each transmission in the current setup. rx_start_ISR() is interrupt service routine which is called when SFD is detected by the RF chip of PU RX and is defined at hal_set_rx_start_event_handler. frame_length variable is already updated when this ISR is called and PU RX reads FL field of received IEEE 802.15.4 frame. If FL turns out to be belonging to secondary user, a boolean variable incorrect_reception is made *true*. The main() program initializes the RF Chip and other I/O peripherals necessary also for debugging. Later, the program waits for a synchronization frame on synch channel for a synchronized start of experiments among all the involved nodes. Once the synchronization frame is received by PU RX, the program uses a while loop to continuously read (rf_receive_data()) the buffer allocated for receive bytes of the RF Chip. During the experiment if secondary user frame is detected by PU RX, it is immediately identified by rx_start_ISR() and is corrected at line numbers 163-172 where the state machine of the RF is enforced to reset and then later on moved to RX_ON.

```
1
2  // I/O and some additional headers files are included.
3
4  int main()
5  {
6          /* The following method helps to initialize the
7          * parameters for necessary I/O, local
8          * and global variables, data rate is also specified
9          * here whether it is primary or secondary user receiver
10         * (PU RX or SU RX). */
11
12         init();
13         tat_set_operating_channel(synch_channel);
14         rf_config_data_rate(rf_RATE_250KBPS);
15         /* Wait for the Synch Frame on synch channel
16         * which is different than data or control channel. */
17         while(true){
18            uint8_t rbuf[255];
19            uint8_t size = 255;
20            rf_state_type staterec;
21            staterec=rf_receive_data(&size, rbuf);
22            if(staterec == rf_SUCCESS){
23                  /* Upon successful reception of Synch Frame
24                  * Timer for Complete Experiment Time,
25                  * Te is set now */
26               clk_set_timer(false, experiment_duration,
27                     timer_callback, MSEC);
28                     break;
29            }
30         }
31         rf_init();
32         /* clears the receiver buffer due to reception
33         * of frames @ synch channel */
34
35         tat_set_operating_channel(data_channel);
36         rf_config_data_rate(rf_RATE_250KBPS);
37         tat_set_trx_state(RX_ON);
38         /* Interrupt Handler is defined for SFD detection
39         * of IEEE 802.15.4 physical layer frame */
40         hal_set_rx_start_event_handler(rx_start_ISR );
41         application();
42 }
43 void application{
44
45   // some further local variable intializations
```

```
  /* now the code snippet for ignoring 500 kbps
        *data rate frame (primary user frame) when the
        *receiver is tuned to receive primary user frames.*/
        while(true){
          uint16_t datarate = getdatarate(data_rate);
  /* If current data rate is 250 kbps (Primary User
        * Receiver) and 500 kbps (Secondary User) data frame
        * is received at PU RX receiver.*/

     if(incorrect_reception && (getdatarate(data_rate) == 250)){
              /* reset the transceiver as the RF chip moves
              * to BUSY_RX state when preamble for IEEE 802.15.4 frame
              * is received by the chip. Therefore the state machine
              * of the transceiver is reset so that the transceiver
              * does not stay in BUSY_RX more than expected. */
             tat_reset_state_machine();
                  tat_set_trx_state(RX_ON);
             incorrect_reception = false;
          }
   /* The transceiver again gets ready for next reception of
   *  primary user frames which could have been blocked
        *  because of preamble reception
        *      of secondary user frames */

          uint8_t rbuf[255];
          uint8_t size = 255;
          rf_state_type staterec;
          staterec=rf_receive_data(&size, rbuf);
          if(staterec == rf_SUCCESS){
             numreceived_bytes+= size;
                 coopnode_data_frame data_frame;
                 data_frame = *(coopnode_data_frame*)&rbuf;
                 if(stop_experiment){
                    uint16_t experiment_time =
                                        (experiment_duration/1000L);
        /* Output to Testbed Gateway which can further route
        * the data to the Testbed User or Alternatively,
        * printf has been configured for TRISOS node output */
                       while(1);
                       return;    // return to the main function
                 }
          }
}
```

```

//  Timer for Complete Experiment Time, Te

static void timer_callback(void){
        stop_experiment = true;
        led_switchOff(led_1);
}
/* INCORRECT_RECEIVED_FRAME_SIZE can be used to set at
* an appropriate number for Secondary User frames, Furthermore
* rx_start_ISR is called when SFD is detected and framelength
* is available to be read by the microcontroller*/
void rx_start_ISR(uint32_t const isr_timestamp,
uint8_t const frame_length){
        if(frame_length == INCORRECT_RECEIVED_FRAME_SIZE)
                        incorrect_reception = true;
}
```

Algorithm A.1 – *main .c file for PU RX*

LIST OF ABBREVIATIONS AND NOMENCLATURE

Acronyms

$SUTX_M$ Secondary User Master Transmitter

$SUTX_s$ Secondary User Slave Transmitter

ACK Acknowledgment

API Application Programming Interface

AWGN Additive White Gaussian Noise

BLE Bluetooth Low Energy

BP Band Pass

CDMA Code Division Multiple Access

COOP Cooperative Sensing or Cooperative Sensing state

CRC Cyclic Redundancy Check

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

CSRW Cooperative Sensing Receiving Window

CTS Clear to Send

DAC Digital to Analog Convertor

DPE Detection Performance Enhancement

ECG Elektro Cardiogram

FDMA Frequency Division Multiple Access

FPGA Field Programmable Gate Array

FSPL Free Space Path Loss

ICT Information Communication Technology

IoT Internet of Things

ISM Industrial Scientific and Medical Band

JTAG Joint Test Action Group

LAN Local Area Network

LCD Liquid Crystal Display

LED Light Emitting Diode

MAC Medium Access Control

MIMO Multiple Input Multiple Output

OFDM Orthogonal Frequency Division Multiplexing

PU Primary User

PU RX Primary User Receiver

QPSK Quadrature Phase Shift Keying

REG-REL Registration Release state

RFC Request for Comments

RSSI Received Signal Strength Indicator

RTS Request to Send

SDR Software Defined Radio

SFD Start of Frame Delimiter

SFE Sensing Frequency Enhancement

SNR Signal to Noise Ratio

SPI Serial Peripheral Interface

SU Secondary User

SU RX Secondary User Receiver

SU TX Secondary User Transmitter

TDMA Time Division Multiple Access

USRP Universal Software Radio Peripheral

Nomenclature

c speed of light, 2.99792458×10^8

E_{max} Maximum Effectiveness

L Number of primary user frames sent during ON state of data channel

N Number of cooperative nodes in the system

$Overhead_{DPE}$ Overhead due to DPE protocol

$Overhead_{NODE\_SEL}$ Overhead due to cooperative node selection protocol

P_d Detection probability

P_f False alarm probability

P_{err} Probability of error

P_{mi} Probability of missed interference

P_{mo} Probability of missed opportunity

r_W Ratio for total wastage

$R_y^\alpha(\tau)$ Cyclic auto correlation function

$r_{PUGoodput}$ Ratio of primary user goodput during experiment or simulation run with the maximum possible primary user goodput

$r_{SUGoodput}$ Ratio of secondary user goodput during experiment or simulation run with the maximum possible secondary user goodput

$r_{TotalGoodput}$ Ratio for total primary and secondary user goodput

$r_{W_{COOP}}$ Ratio for wastage on the control channel

$r_{W_{PU}}$ Ratio for wastage for primary user transmission

$r_{W_{SU}}$ Ratio for wastage for primary user transmission

$S_y^\alpha(f)$ Spectral correlation density

T_d Sensing duration

T_e Time duration for experiment or simulation run

T_s Sensing period

T_w Time duration for Cooperative Sensing Receiving Window for one cooperative node

T_{BEACON_LIVE} Time duration to check for BEACON frames at the cooperative node

T_{BEACON} Time duration between two consecutive BEACON frames

T_{Btx} Transmission time for BEACON frame

$T_{COOPNODE\_REG\_REL}$ Time duration between two consecutive COOPNODE_REG_REL frames

T_{CSRW} Time duration for Cooperative Sensing Receiving Window for DPE or SFE protocol for any N

T_{OFF} Time duration of OFF state of the data channel

T_{ON} Time duration of ON state of the data channel

T_{REG_REL} Time duration of REG-REL state

$T_{RX_{ON}}$ Time duration to switch the state of the RF chip of the radio device from TRX_OFF to RX_ON state

$T_{s(optimum)}$ Optimum sensing period

T_{SPI} Time duration for transferring of frames from the microcontroller to the RF chip

T_{Stx} Transmission time for SENSING_INFORMATION frame

$Threshold_{REG}$ Threshold used for registration of cooperative node (range is from 0 to 1)

$Threshold_{REL\_COOPNODE}$ Threshold used for release of cooperative node initiated at the respective cooperative node (range is from 0 to 1)

$Threshold_{REL\_SUTX}$ Threshold used for release of cooperative node initiated at SU TX (range is from 0 to 1)

u Duty cycle of primary user traffic

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