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Título de la tesis:

“Implementation of Cognitive Radio for Wireless Sensor Networks in Congested IoT Environment”

Tesis presentada por:

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Resumen de la tesis (Abstract)

Nowadays, billions of smart objects are immersed in the communication world; sensing, interacting, and cooperating with each other to enable efficient services. That's why this work was divided in to three major IoT network related Cognitive Radio (CR). First, when we think about IoT, "classification" is a major challenge particularly if our technology is international level applicable. So, this limitation needs clear and deep analysis of the existing classification matrices and propose some future directions. That is why we decided to start our study by understanding the existing IoT classifications.

Second, results from our first research helped us to start a way how to implement CR in IoT. It is known that after the introduction of CR in IOT technology in communication, the hot research topics are: i) sensing, ii) Primary User Interference (PUI), iii) spectrum management, iv) security, v) spectrum sharing, and vi) environmental sensing. Among the listed, sensing and Primary User Interference are the bold ones. The base query for these two problems lays finding a means for which and what channel at a particular time is available and avoiding interference with Primary Users (PU).

Third and finally, we decided to study end-to-end delay, aiming to realize how much time it will take for a traffic load generated by a Mobile Node (MN) to reach Sink Node (SN), is a principal objective of most new trends in a Wireless Sensor Network (WSN). Most importantly, knowing the average minimum transmission time limit is a crucial piece of information in determining the future output of the network and the kind of technologies implemented. Here, what we did is take network load and transmission delay issues into account in estimating the Average Minimum Time Limit (AMTL) needed for a health operating cognitive WSN.

All techniques described in this work are implemented and resulted in a significant reduction of the target problems estimated around 10-30% reduction in average. Main limitations of Wireless Sensor Network (WSN) such as memory, battery lifetime, and size are considered during the design and implementation of our solutions.

Resumen aprobado por: **Dr. Juan Ivan Nieto Hipólito**
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MAESTRÍA Y DOCTORADO EN CIENCIAS E INGENIERÍA

Implementation of Cognitive Radio for Wireless Sensor Networks in Congested IoT Environment

TESIS

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CONTENTS

List of Figures **3**

List of Tables **4**
1 Abstract ... 6

1 Generic Introduction **8**
1 Introduction ... 8
1.1 Background ... 10
1.2 Justification ... 10
1.3 Problem Statement ... 11
1.4 Research Questions ... 12
1.5 Objective of the Thesis ... 12
1.6 Significance of the research ... 13
1.7 Scope and limitation of the thesis ... 13
1.8 Research Methodology ... 13
1.9 Conclusion of the Chapter ... 15

2 Major Existing Classification Matrices and Future Directions for Internet of Things **16**
1 Introduction ... 16
2 Existing Classification Methods ... 16
2.1 Comparison Among the Major Existing IOT Classifications ... 19
3 Future Directions for Designing IoT Classification Factors ... 20
3.1 Security ... 21
3.2 Safety ... 21
3.3 Reliability ... 21
3.4 Timing ... 21
3.5 Social infects ... 21
3.6 Legal issues ... 21
3.7 Heterogeneity and dynamic ... 21
3.8 Multidisciplinary ... 21
3.9 Number of sensors connected ... 21
3.10 Common design constraints ... 21
3.11 Market ... 21
4 Lesson learned form this work ... 22

3 Solutions for Sensing and Primary user interference in cognitive radio implementation of WSN **23**
1 Introduction ... 23
2 Related work ... 24
3 System model ... 25
4 Sensing during inactive period of communication ... 25
5 Application-base PU identification ... 27
6 Channel selection ... 28
7 Channel notification ... 28
8 Coexistence with other technologies ... 30
9 Analysis result ... 30
9.1 PUI comparison ... 30

9.2 PU traffic tracked ... 30
10 Recommendations for future work ... 32

4 Experimental Analysis to Determine the Average Minimum Time Limit for Wireless Sensor Communications 33
1 Introduction ... 33
2 Related works ... 33
3 General scenarios ... 34
3.1 S_{delay}, Service Delay Derivation ... 35
3.2 Q_{delay}, Queuing Delay Derivation ... 36
3.3 D_{MAC}, MAC delay ... 37
4 Cogitative algorithm ... 38
5 Simulation based analysis ... 38
6 Conclusion ... 40

5 Summary of The Thesis and Lessons Learned 42

6 Sample Codes 43

LIST OF FIGURES

1.1 Cognitive radio implementation 9
1.2 Methodology of the research 14

3.1 General Scenario 26
3.2 The modified superframe structure 26
3.3 application besed PU demonstration model 27
3.4 Flowchart for energy scan during inactive portion of communication 29
3.5 Notification message demonstration 30
3.6 Primary User Interferences 31
3.7 Primary user traffics tracked 31

4.1 General scenario 34
4.2 Unlicensed user data transmission on a single channel 35
4.3 Queue delay 36
4.4 The proposed Markov chain for queue state transition. 37
4.5 Uncommon delays registered during the experiment. 39
4.6 Screen-copy of part of simulation environment in omnet++ 40
4.7 Queue and Service delay recorded. 41
4.8 MAC and ACK delay recorded. 41

LIST OF TABLES

1.1 WSN and CR-WSN 12

2.1 Different classification matrices used in current IoT world 20

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3. Cognition-based delay analysis to determine the average min time limit for wireless sensor communications.
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1. ABSTRACT

Nowadays, billions of smart objects are immersed in the communication world; sensing, interacting, and cooperating with each other to enable efficient services. That’s why this work was divided in to three major IoT network related Cognitive Radio(CR). First, when we think about IoT, "classification" is a major challenge particularly if our technology is international level applicable. So, this limitation needs clear and deep analysis of the existing classification matrices and propose some future directions. That is why we decided to start our study by understanding the existing IoT classifications.

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All techniques described in this work are implemented and resulted in a significant reduction of the target problems estimated around 10-30% reduction in average. Main limitations of Wireless Sensor Network (WSN) such as memory, battery lifetime, and size are considered during the design and implementation of our solutions.

Keywords: Cognitive radio, delay, cogitative, interference, primary user, secondary user

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1. GENERIC INTRODUCTION

1. INTRODUCTION

The Internet of Things (IoT) has already been playing a big role in facilitating every aspect of our day to day activity by eliminating the need for face-to-face interaction for basic services, and it opened up the opportunity to different challenges across the globe [1] - [10]. However, due to the increasing IoT data packet congestion problem in the wireless sensor communication network, there is an increasing risk for any data not to be processed on time or the possibility of data getting lost in before it get in to the network.

To understand the problem better, we divided our sturdy in 3 major parts: First, in chapter 2 we analyzed what and how the current IoT world is classified. Our vision and perspective of the development of IoT were published in the paper "Major Existing Classification Matrices and Future Directions for Internet of Things". Second, after analyzing the major classification matrices, in chapter 3 we described the development of our own algorithm to solve the congestion problem, which is dividing users as a primary and secondary depending the level of ownership. The development and results of this chapter were published in a paper called "SenPUI: Solutions for Sensing and Primary User Interference in Cognitive Radio Implementation of a Wireless Sensor Network". Third, in chapter 4 we studied how long it will take for a single packet to reach its destination in congested WSN environment. As a result of this study the paper with title "Cognition-Based Delay Analysis to Determine the Average Minimum Time Limit for Wireless Sensor Communications", was published.

Our very first work, Major Existing Classification Matrices and Future Directions for Internet of Things is helped us to understand the major technologies and the challenges in current wireless sensor based IoT world. The major reason for us to study this as a topic is that classical classification matrices are not sufficient to solve the complex IoT classification issue, and need to be revised to address the complex requirements imposed by IoT. This problem, classification matrix, led us to analyze how the current IoT can be classified and improved. If someone develops a new IoT technology then how he/she can classify, what are the existing classification matrix and how they are effective.

Outcomes from our first study lead us to start new research about how we can implement cognitive radio in wireless sensor network. Our hypothesis was that by implementing solutions for sensing and PU(primary user) traffic identification in WSN (Wireless Sensor Network) it is likely to achieve QoS (Quality of Service), long lifetime of the sensor, possible to search channel holes and allocate them in real time. In this study, we try to answer two major issues: (I) when to perform channel sensing to identify the free channel and (II) how to select a sensor as primary or secondary user depending on the type of packet exchanged (application packet-based classification).

Unlike previous works, our third work focuses on analyzing the AMTL (Average Minimum Time Limit) for applications, which gives a baseline for any-one interested in working with cognitive WSNs. The number of MNs (Mobile Nodes) and their AMTL of channel usage are the two principal parameters considered during result analysis with other factors explained in previous works.

For understanding the importance of Cognitive Radio implementation in WSN we started by analyzing world classification method of IoT. Which helped us understand how to use cognitive radio advantages in different IoT categories. Combining decisions from our very first study with our second study; which helped us understand how much average minimum time needed for single WSN data packet to reach its destination, we designed and developed SenPUI, shows how to implement cognitive radio advantages in WSN IoT world.

In this thesis, we analyze and propose a solution about how to use cogitative radio in WSN, as it is showed in figure 1.1. In our study we implemented “the data transfer from all sensor nodes” to represent a practical implication. We also considered the efficiency of the congested IoT network. It is known, to maximize energy in IoT, we must minimize the average packet transmission delay [8]. To minimize this delay, we observed the current queuing system [9]. After we understood the queuing system constraints, we determined how to best target primary packets at the IoT sensor level. The physicality of our testing sets our study apart from other cognitive radio simulations. We pieced together IoT weaknesses and developed a way to implement cognitive radio within the IoT network.

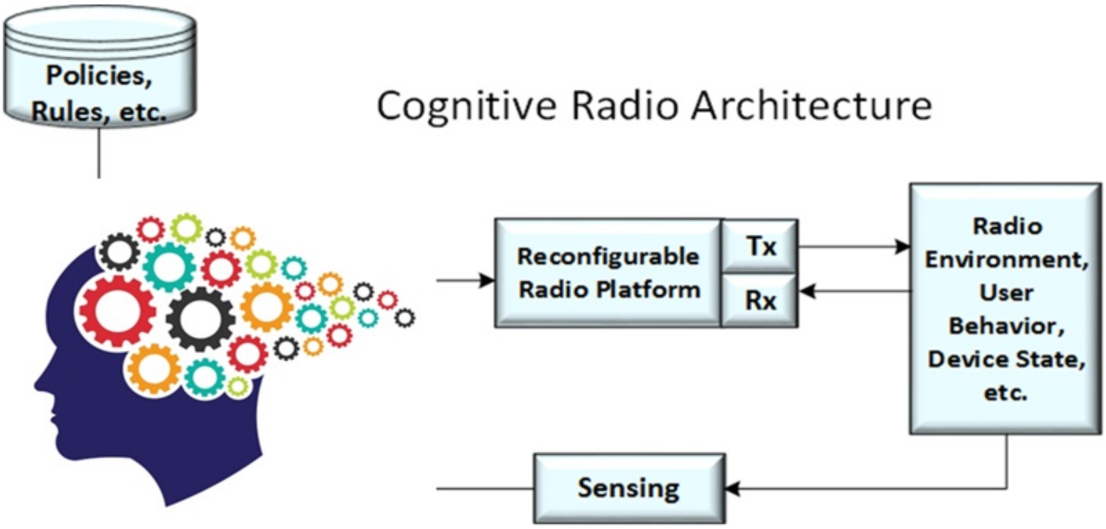

Figure 1.1: Cognitive radio implementation

1.1. Background

Data communication networks are a vital component of any modern society. They are used extensively in numerous applications, including financial transactions, social interactions, education, national security, and commerce. With the rapid evolution of microelectronics, wireless transceivers are becoming more versatile, powerful, and portable. This has enabled the development of software-defined radio (SDR) technology, where the radio transceivers perform the baseband processing entirely in software: modulation/demodulation, error correction coding, and compression.

Joseph Mitola III invented software-defined radio(SDR). Since its introduction in 1993, SDR has been defined as a radio platform of which the functionality is at least partially controlled or implemented in software. In mid-1990s military radio systems were invented by U.S. military's in which software controlled most of the signal processing digitally, enabling one set of hardware to work on many different frequencies and communication protocols. But, in late 1990s SDR started to spread from the military domain to the commercial sector. By 2005 the first SDR product for commercial is available from Airspan which is IEEE 802.16 base station dependent.

The reconfigurability offered by SDR technology enables radios to switch functions and operations. However, an SDR can do this only on demand; it is not capable of reconfiguring itself into the most effective form without its user even knowing it. In Mitola's dissertation and a number of publications, he envisioned such a self-reconfiguring radio and dubbed the term cognitive radio for it, 1999. The latest development of CR technology in the field of WSN is the Chi-Ming Wong and Wen-Pin Hsu simulation of CR implementation for WSN, 2014[1][2].

Today, however, CR has become an all-encompassing term for a wide variety of technologies that enable radios to achieve various levels of self-configuration, and with an emphasis on different functionalities, ranging from ubiquitous wireless access, to automated radio resource optimization, to dynamic spectrum access for a future device-centric interference management, to the vision of an ideal CR. Haykin, for example, defines CR as a radio capable of being aware of its surroundings, learning, and adaptively changing its operating parameters in real time with the objective of providing reliable anytime, anywhere, and spectrally efficient communication [11].

1.2. Justification

Recently, cognitive techniques have been used in wireless networks to circumvent the limitations imposed by conventional WSNs, moreover Cognitive Radio (CR) is a candidate for the next generation of wireless communications system. The cognitive technique is the process of knowing through perception, planning, reasoning, acting, and continuously updating and upgrading with a history of learning. If cognitive radio can be integrated with wireless sensors, it can overcome the many challenges in current WSNs. CR has the ability to know the unutilized spectrum in a license and unlicensed spectrum band, and utilize the unused spectrum opportunistically. The incumbents or primary users (PU) have the right to use the spectrum anytime, whereas secondary users (SU) can utilize the spectrum only when the PU is not using it.

To generalize:

• The amount of available useable spectrum bands cannot be increased but they can be used more efficiently. (electromagnetic spectrum is a precious gift of nature).

• ISM bands are overcrowded limiting the development of new technologies [13]. On the other hand, many licensed spectrum bands are either underutilized or unutilized [14].

• Using CR-WSN increase capability of packet loss reduction, power waste reduction, high degree of buffer management, has better communication quality, and utilizes the spectrum resource efficiently.

• If we think about applying CR in WSN the first problem come in our mind is how to estimate PU data, for example in e-health applications.

Taking advantage of the current liberalization in the spectrum utilization rule and technical advancement in sensor technology, wireless sensors with CR can mitigate the current issue of spectrum inefficiency and increase the network efficiency in a range of terms.

Application area and main challenges we focus on are:

1, Our research work focuses on solving CNR problems in WSN specifically in e-Health.

2, With main target of sensing and wireless communication for assisted living facilities to improve lifestyle and to improve health care.

3, Currently this area is facing problems like real-time sensing, data association, identification of

primary user, understanding its surrounding, dynamicit etc.
4, The other problem e-health face now a days is when can perform spectrum sensing during communication.

1.3. Problem Statement

A cognitive radio wireless sensor network is one of the candidate areas where cognitive techniques can be used for opportunistic spectrum access. Research in this area is still in its infancy, but it is progressing rapidly. The main type of communication used by WSNs for data gathering is convergecast where data travels from many nodes (e.g. sensor nodes) to a single node called sink or base station (BS). With a single radio and a single channel, WSNs cannot provide reliable and timely communication in case of high data rate requirements because of radio collisions and limited bandwidth. Therefore, designing multichannel based communication protocols is essential for improving the network throughput and providing quality communication services. Current WSNs operate in the ISM band, which is shared by many other successful communication technologies. Research has shown that this coexistence in the ISM band can degrade the performance of the WSNs. The wide deployments, large transmit power, and large coverage range of IEEE 802.11 devices and other proprietary devices can degrade the performance of WSNs significantly when operating in overlapping frequency bands. WSN devices are not only a victim but are also an interferer sometimes [2]. The coexistence interference can be avoided by the intelligent use of three types of diversity, namely frequency, time and space. Coexistence issues in unlicensed bands have been the subject of extensive research. Some solutions are also suggested in references [3–5].

Researchers and industry are working to improve the performance of WSNs in terms of cost, energy consumption, data rate, robustness, networks throughput, QoS and security. Considerable hardware and software enhancement has been implemented in recent years to enhance the network performance. A range of logical techniques have been employed to achieve the required network performance, such as power aware MAC, cross-layer design technique, efficient sensing technique, and significant enhancement in hardware design, etc., but these techniques have their own limitations.

Recently, cognitive techniques have been used in wireless networks to circumvent the limitations imposed by conventional WSNs. Cognitive radio (CR) is a candidate for the next generation of wireless communications system. The cognitive technique is the process of knowing through perception, planning, reasoning, acting, and continuously updating and upgrading with a history of learning. If cognitive radio can be integrated with wireless sensors, it can overcome the many challenges in current WSNs. CR has the ability to know the unutilized spectrum in a license and unlicensed spectrum band, and utilize the unused spectrum opportunistically. The incumbents or primary users (PU) have the right to use the spectrum anytime, whereas secondary users (SU) can utilize the spectrum only when the PU is not using it.

CR-WSNs normally involve a large number of spatially distributed energy-constrained, self-configuring, self-aware WS nodes with cognitive capabilities. They require cognition capacity for a high degree of cooperation and adaptation to perform the desired coordinated tasks. They have not only to transfer data packets, but also to protect incumbent license users. More explicitly, this is a system that employs most of the capabilities required for a CR system, as defined by International Telecommunication Union (ITU) [12] and also for WSNs. According to Akan et al. [7], a CR-WSN is defined as a distributed network of wireless cognitive radio wireless sensor (CRWS) nodes, which sense an event signal and collaboratively communicate their readings dynamically over the available spectrum bands in a multi-hop manner, ultimately to satisfy the application-specific requirements. Some recent papers in this paradigm, such as references [6–11], proposed wireless sensor equipped with cognitive radio as one of the promising candidates for improving the efficiency of WSNs. Table 3.1 lists the capabilities a wireless sensor with a CR needs to have.

Finally, CR-WSN is a new paradigm in a WS network arena that utilizes the spectrum resource efficiently for bursty traffic. The system has the capability of packet loss reduction, power waste reduction, high degree of buffer management, and has better communication quality.

Factor	WSN	CR-WSN
Wireless medium	ISM bands	Licensed or ISM band (control channel)
Hardware constraints	Small, low processing capacity Intelligent, cogn	Intelligent, small, moderate processing capacity
Availability	Readily available	under conceptual phase
Bandwidth deficient	Sometimes	yes
Standards	ZigBee, IEEE 802.15.4, ISA100, IEEE 1451	Not yet defined
Suitable for	Where ISM band is not crowded	Where ISM band is overcrowded
Whitespace utilization concern	No	Yes
Multichannel	Possible	Required
Researches	there is always room for improvement, most of the areas are explored and now research focus on QoS , reliability, performance enhancement trust and security	Almost all areas are still to explore Currently focus Game theoretic approaches Predictions for the PUs arrival Energy efficient routing Development of middleware architectures Distributed aggregation applications Design of cross-layer algorithms

Table 1.1: WSN and CR-WSN

1.4. Research Questions

1. When to do channel sensing in WSN without disturbing ongoing communication?
2. How to implement First Detected Idle Channel first (FDIC) to find idle channel?
3. How to select available licensed channel, which are received as input from algorithm FDIC?
4. Where and how to do reconfiguration of communication parameters for sensing surrounding environment?
5. How to develop simplest mechanism to notify selected channel?
6. How to estimate primary user (PU) traffic parameters?

1.5. Objective of the Thesis

General Objective

Implementing cognitive radio in IEEE 802.15.4 standard called, IEEE 802.15.4 based UABC-CRSN framework, which can perform spectrum sensing in the inactive portion of communication.

Specific Objectives

1. To analyze current state of IoT classification matrix and develop future direction.
2. To implement First detected idle channel first (FDIC) algorithm.
3. To develop and implement an algorithm to aid in selecting available licensed channel.
4. Consider a beacon-enabled CRSN with star topology.
5. Performing spectrum sensing by the PAN coordinator.
6. Compare and evaluate our work with existing mechanisms.
7. To analyze the average minim time it will take a single packet to reach its destination.
8. To develop an algorithm to assign a channel for PU in a congested environment.

1.6. Significance of the research

WSN with CR has the following significance in generally:-

1. Spectrum sensing (channel sensing): The amount of available usable spectrum bands cannot be increased but they can be used more efficiently (electromagnetic spectrum is a precious gift of Nature).
2. Channel sharing: ISM bands are overcrowded limiting the development of new technologies. On the other hand, many licensed spectrum bands are either underutilized or unutilized [14].
3. Prediction and Fairness: If we think about applying CR in WSN the first problem come in our mind is how to estimate PU data in e-health applications.
4. Reconfiguration capability.
5. Environmental sensing: Using CR-WSN increase capability of packet loss reduction, power waste reduction, high degree of buffer management, has better communication quality, and utilizes the spectrum resource efficiently.

1.7. Scope and limitation of the thesis

The scope of this work is analysing and implementing cognitive radio for WSN to improve resource usage in these small devices, IoT. Even if we covered a broad research idea for for years everything has its limitation, ours is limited to implementing the proposed solution to specific vender, Freescale devices. We have not tested our solution on other products but the possibility of it working is high because all of have same base standard IEEE802.15.4.

1.8. Research Methodology

Our thesis methodology depicted in figure 1.2 requires understanding the current situation of CR-WSN, we get from analyzing existing works on the bases of their results and mechanize of solving the current problem. More by doing related work study it helps to understand every aspect in the area.
We hope to shed light on the following questions and points throughout this thesis:
1. How to solve the current channel usage problem in WSNs?
1.1 how to implement cognitive radio technology in WSN? here what we are doing is designing simple and effective mechanism which is different from existing once to do so existing literature review must be done.
1.2 How to design an algorithm that solve the specified problem?
After reading and analysis most known works in the area especially looking deep in to their algorithms parameters we developed our own which have effective in the way:
1.2.1 how to select channel for every end device during communication?
The idea behind this algorithm is updating list of channels every step when data packet is received. In other word this is a part where we will handle channel sensing, and way of getting overall data about ongoing communication for future determination.
1.2.2 Design an algorithm to select shortest idle channel. This is the main algorithm which make decision for channel selection part of the application depending on the above (1.2.1) input.
2. Choosing communication mode, beacon or non-beacon, based on the algorithms.In the solution proposed the overall activity is done form coordinator side, so it is beacon-enabled IEEE802.15.4 implemented.
3. Preforming channel sensing using coordinator. Coordinator is selected because of the limitations that end devices have like:battery life, memory, energy consumption and mobility.
4. Reconfiguration of communication parameters without affecting the ongoing communication. This is needed because to update end device depending on the surrounding environment which done by:
4.1 Identifying major parameters for reconfiguration
4.2 Mechanism, how to reconfigure selected communication parameters?
5. To what extent we can edit and re-build a communication superframe structure which is defined in original standard, IEEE802.15.4. Here the objective is understanding how much

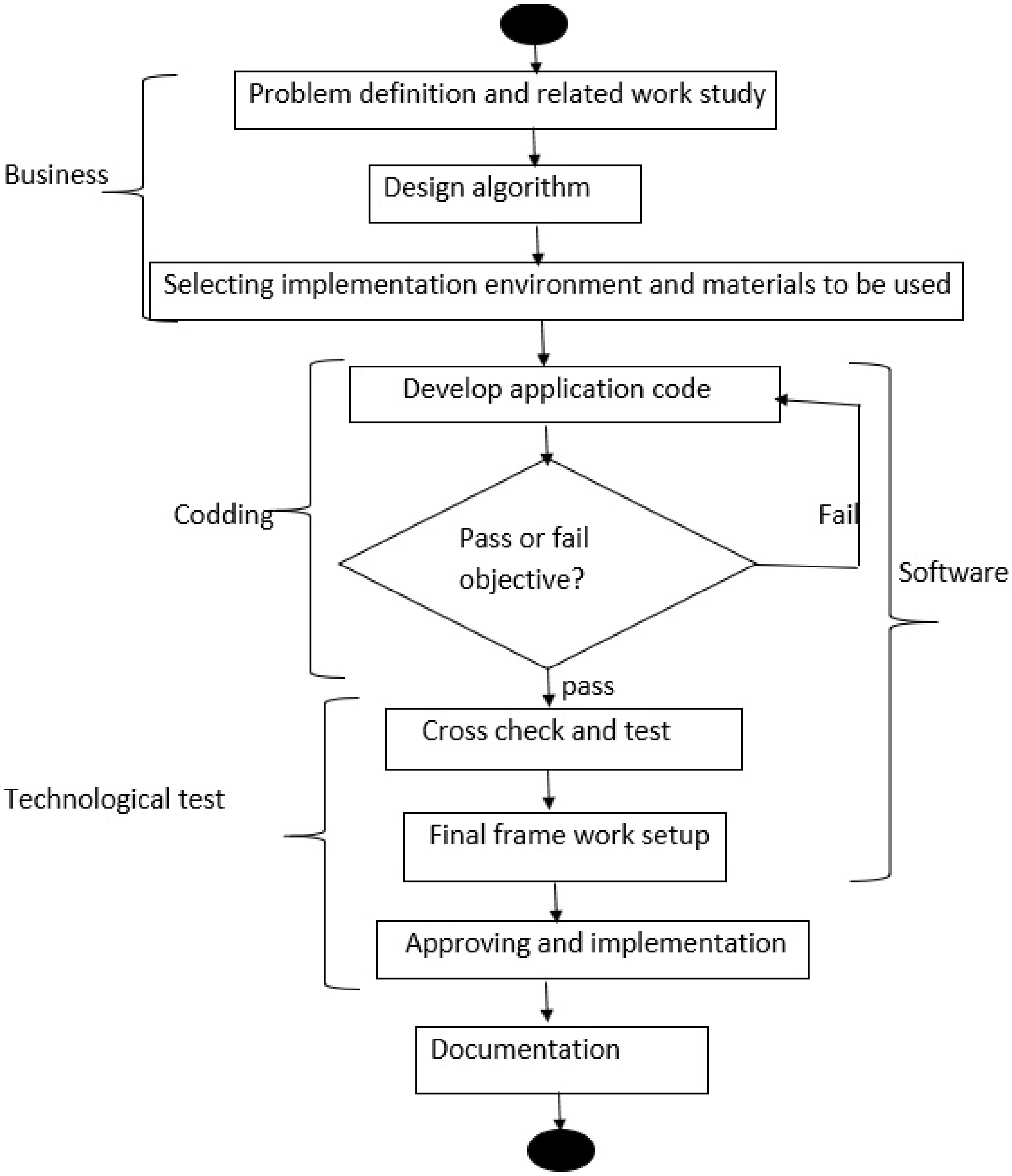

Figure 1.2: Methodology of the research

space we have given form standard to manage commands between devices.
5.1 How to use the reserved bit part of superframe structure and how much bit can we save in this specific part?
5.2 Sending the edited superframe as a command which include the future communication channel with its coordinator and receiving, extracting and applying from end device side.
6. Testing results, analyzing outputs and working on some futures for enhancement of the application. At this step our plane is to test the application in real environment WSN applications in different area (medicine, traffic light, car automation, home applications) with different parameters and work on comments, or some enhancements.
7. Finally, prefer the approved application in framework format and submit, so that everyone can use it as any framework available now a day.

1.9. Conclusion of the Chapter

In this chapter we discuses and showed how much it is important to design, develop, and impalement CN based radio for IoT network. As mentioned above this new technology, IoT suffer a lot of interference problem because of bad resource management problem. So our proposal is CR implementation in IoT.

2. MAJOR EXISTING CLASSIFICATION MATRICES AND FUTURE DIRECTIONS FOR INTERNET OF THINGS

1. INTRODUCTION

This is the introduction part of our work where we tried to explain about why we are interested in IoT, where cognitive radio technique is one part of it. So by starting understanding from the higher general technical level to deep specific level will help us in identifying and drafting our objectives. This chapter surveys IoT classification matrix and classification related issues now a days IoT faced.

Classification method is a formula, logical description generalizing characteristics of objects of related area. Now a day's billions of smart objects are immersed in the environment, sensing, interacting, and cooperating with each other to enable efficient services. When we think about IoT, classification is a major challenge particularly if our technology is international level applicable. So, this limitation need clear and deep analysis of the existing classification matrices and giving some future directions depending on the different researches in the area. In this part of our research we surveys the current state-of-art in the classification of IoT.

It has been estimated that the Internet of Things (IoT) will contain 26 billion devices by 2020 (according to Gartner, Inc.). As a result, recent problems and challenges arise spanning classification of this newly fast developing technology. The major reason is that classic classification matrices are not sufficient to solve this unprecedented issue, and need to be revised to address the complex requirements imposed by IoT. This problem, classification matrix, led us to analyses how the current IoT can be classified. If someone develop a new IoT technology then how he/she can classify, what are the existing classification matrix and how much they are effective.

The reason why we interested to do this analysis is as we believe solving classification problem will result in big solution for problems IoT technology's suffering now a day; like, problems in terms of resource capabilities, lifespan and communication technologies, new standard design if needed in the future and security.

We address the following main points:

1, Discusses various classification matrices which are in use now a day.
2, Explains state-of-art of classification techniques which are very important in internet of things world.
3, Discuses the major currently used IoT classification matrices.
4, Major problems in IoT world because of classification reasons.
5, Finally, we end by suggesting our understandings for future IoT classification matrix.

2. EXISTING CLASSIFICATION METHODS

For doing this research we searched in different publications and ended up with limited number of literatures about IoT classification [1], [2], [3], [4], [5], which is indeed still in its inception phase. This is very important because understanding the existing classification method result in understanding the problems with the existing once and give directions how to solve. This section deals with higher level classification matrices only.

Different scientific community have different view on classification of IoT generally. But as our study indicate that there are two major IoT classification ways are used today's world. Namely, the classic (based on history of IoT) and systematically analyzed and studded (factor dependent classification). In a classic or traditional classification method, it is a classification depending specifically on single factor like real-life application, standard used, application environment, way of data communication, level of smartness, specific devices with whom it communicates, or depending on the end users. In other word, it is a type of IoT classification just only considering single and simple factor. However, the systematically studied and analyzed one is a classification method by which the developer of IoT will analyses from different perspectives before classifying his/her product. Which means classification in which not depending on single specific factor. But, most of the difficulty's facing this classification method are: (1) until today there is no specifically documented material so that every developer can refer before classifying its product. (2) even the existing once are designed by specific organization(industries) to meet only their requirements which is very difficult to use as worldwide. It is known that there are several classification methods, but here only two of the above are considered.

A. Classical or Traditional Way

A type of classification depends on the historical definition of internet of things and limited specifically on single matrix. Which, the concept of a network of internet of things is considered as smart devices early in 1980's. The developers named IoT as "smart" to indicate operation of the technology without human intervention "Smart": Smartphones Smart cars. Smart homes. Smart cities. A smart world. These notions have been exposed for many years. So commonly used classification under this category are:
1, Smart city: if the IoT technology is used for city modernization.
2, Smart farm: IoT technologies for farming.
3, Smart health-care: IoT technologies in health area.
4, Smart transport: IoT technologies in transport.
5, Smart service: protocols or new techniques which advance use of IoT.
6, Smart object: any device from any classifications described above.
We all agree that using such naming is not the problem. The problem arises when we think about what are the specific classification matrices, in this case just only application area. And more now a day's millions of new IoT technology immersing the market and this kind of classification not support from different angle.

B. Factor Dependent Classification

A IoT classification method where experts in the area follow some specific matrices to classify their technology. These specific matrices are designed for specific organization or deigned for international use by international industries in the area. The widespread problem that most of this classification method sparring is highly depending on the classic classification method and every organization have its own matrices. There are different views on the Internet of Things paradigm coming from various scientific communities.
Below we try to analysis Common ones:

i. SO (Smart Object) Classification Model

Which is also known as IoT management architectures, it is a type of classification of IoT depending on specific matrix called smartness. Here classification is only depending on the traditional way of classification which accept the logic IoT is synonym to smart object. Under this classification there are dozens of different classification methods used.

Some authors call SO as police aware, activity aware, process aware object [6]. They used list of design dimensions where every SO type is characterized among them: 1) ability to understand events from sounding (environmental or human event) which is called Awareness. 2) considering the programming model of SO called representation. 3) way of communication with its users called interaction. Major limitation with this classification is it not operational, only design dimension based. Creator and purpose based classification of SO's [3]. Creator: an individual creates SOs for personal use(self-made). Industrial company: creates SOs for business (ready-made). However, still considering two dimensions (creator and purpose) but IoT classification needs more factors than used here. In [4] Smart Object Description (SODD) and Profile Description Document(PDD) it is another two-dimension (matrix) classification method. Under SODD meta data of SO like list of name, vendor, and profiles. On the other side, PDD is profile specifier (detector or actuator). Limited to only management and implementation which is specifically FedNet middleware an example. Metadata model [7], [5] use as a factor type, service, device, and location. Which are generic for division and used only for SmartSearch, discovery and dynamic as their main limitation. SO is cyberpysical object (sensing, processing, storing, and network capability) [8]. SO is still in its inception phase.

ii. From Today's Intranet of Things to A Future Internet of Things [15]

The authors classified from wireless- and mobility-related view. IoT is technology where integrate and worldwide connect smart city, smart grid, building automation system body sensors. With this classification the facts like social, political, and technological impacts are not considered.

iii. Consumer Internet of Things [10]

It is a type of classification for Consumer Internet of Things only. With the option of constructor should chose the users advantage, what most wanted to adopt a category that relates. We think the categories are solid. Also mixing the genus of his classifications. We do like the identification of power source and connectivity styles/patterns the thing is there is no classification matrix of devices and device types. For example, wearable are really a subcategory of "portables or mobilables", some devices will be "static" some will be read only – some will have visual / audio sensors and output.

iv. The Center Electric Story [11]

Classification based on ecosystem (Internet of Things Tectonics). IoT as ecosystem of connected and non-connected devices. Enterprise and consumer application, industrial automation, entire stack. infrastructure ecosystem (routing/ processing, connectivity, power, storage, security) and hardware ecosystem (design, manufacturing, component hardware, supply-chain, protocol).

v. Right Message and Data Sharing Standard for IoT [12]

Classification factor based on devices used, amount of data, and level of safety the technology applications use. Divided in to two 1) consumer, CIoT: group of consumer oriented applications where data volumes are low. All devices, in communication, are represented as smart. 2) Industrial IoT: group of industrial oriented applications where data amount is bigger. Devices like machines operating in industry, energy medical or transport technology's.

vi. Internet of Things – Challenges and Opportunities beyond the hype

Classification based on ecosystem of internet of things (IP based ecosystem). The author of [13] divided as 1) Internet of Peoples: involves billions of smart objects which communicate directly over internet, without human intervention. And 2) internet of things with or without IP address, where devices like standardized RFID, active RID, real time location system, mush sensor network, communicate with the Internet.

vii. Creating a Taxonomy for The Internet of Things

Classification based on how implemented by human. Author[3] proposed taxonomy with the human at center of all.
1) Embeddable: things in the user.
2) Wearables: things on user.
3) Holdables: things near user.
4) Surroundables: things around user.

viii. Power Source for Internet-of-Things [14]

Classification factor based on technology applications. Type of classification based on available technology's and standards.

Communication: (infrared, Bluetooth, radio frequency identification, ZigBee, high speed LAN). Identification: (biometry and object tracking) Location tracking (advancement in RFID and GPS). Sensor (control of temperature, MEMS, motion sensor and image sensor). Devices: (RFID tagging, mobile phone and embedded portable electronic devices).

To generalize, as mentioned by many studies when we come to types or classification matrices of IoT everyone has mixed feelings, which by itself make difficult the way how to classify and name the term "Internet of Things". Some of the developers describe the term "everything and nothing" [10] because of no defined criteria used for classifying. Even if we had many types of IoT just using classic way of classification the problem is most of classifications are mixed and repeated.

2.1. Comparison Among the Major Existing IOT Classifications

Below in table-I, we have a comparison between some major IoT classification methods and matrices used for classification now a day. Most companies and organizations have their own classification methods which resulted in current IoT classification problems what we faced, like, no common standard to classify newly developing IoT technology's, every developing company have its own matrices even if the technology is designed for different organizations which don't have same classification matrix as a developer had.

Table 2.1: Different classification matrices used in current IoT world

IoT Classifications	Matrices Used	Types Included
A Review of Smart Cities Based on the Internet of Things Concept [2]	Application, interlinks between objects Considered only for Smart Cities	Home: health, entrteyment, security. Transport: parking, traffic, emergency service, highways. Society: surveillance, environment, social network. National: utilities, military, smart grids
JAPAN PATENT OFFICE [15]	technique of creating new values and services through utilization of information.	ZIT (IPC,FI and CPC system is not enough)
SO [3]	classification according to the concepts of creator and purpose (creator and purpose)	self-made: personal purpose.ready-made: industrial company
Smart objects as building block for IoT [16]	Awareness, Representation Interaction	Activity aware, police aware, process aware objects
Design and implementation of framework for building distributed smart objects system [4]	Operation based classification	SODD : smart object description document , profile description document (PDD)
User Innovation for the Internet of Things [17]	User innovation and market based innovation (user centered ecosystem)	User-led and market based innovation
Internet of Things Tectonics [11]	Infrastructure ecosystem hardware side (collection of connected devices)	Enterprise and consumer application, industrial automation, entire stack of infrastructure beneath those devices
Corsaro sort IoT [12]	Any application (collect-store-analyses-share)	Consumer (CIoT) and Industrial (IIoT)
Web [10]	Based on user advantage	Wearables, Media, Home automation, Smart appliances.
Internet of things ecosystem [13]	With or without IP address internet of people.	Internet of people and internet of things with IP based or not
Classification based on human [18]	Functionality of the technology, industrial or consumer dependent	Embeddable, Wearables, Moldable, Surmountable

Now a day the common way of classifying depends on the way group of products that compete, cooperate, share technology, partner, shared distribution or manufacturing expertise. Some other groups believe strongly naming should replicate type of connectivity rather than describing the things which are in it. We agree with both ideas but the thing is beside the above factors we should consider more and more than making common ground for international use. As we shown in our study, now a day's classification of IoT technology is based on factors of specific organization or technology developer. Which, resulted a problem like, same product in various categories, no international level classification method where every developing company can depend on, resulted in difficulty of technology chose from user side, difficult for companies, newly entering in to the business of future IoT technology development.

3. FUTURE DIRECTIONS FOR DESIGNING IOT CLASSIFICATION FACTORS

As we believe that system's complexity doesn't matter in IoT. The important aspect that identifies an object is its capability to connect to the network and exchange information without any defect. But the reality now a day is far different. As described in our study the solution is beside the above factors we should think about:

3.1. Security

Global connectedness is a key reason for security threats. It is known that in IoT world everything connected affect everything. In fact highly secure islands of very sensitive information are typically not connected at all to IoT world[19].

3.2. Safety

Error in information processing part of the system can spread in to physical parts and dangerous to people or for environment.

3.3. Reliability

Some of the the technology will not consider this factor but it is very important, providing service at run time. The reasons may be design error, hardware or environmental error.

3.4. Timing

All about linking physical system. The amount of available energy, external devices communication load must be considered. bsubsection Energy efficiency Classifying technologies which generate energy by themselves to other types of technologies which does not have the ability should be different.

3.5. Social infects

The overall impact on human society is largely unknown. It must be considered.

3.6. Legal issues

Different components with different legal entity, then who owns the communication as well who will take the risk when there is damage.

3.7. Heterogeneity and dynamic

Components designed for different communication protocol by different companies.

3.8. Multidisciplinary

Some issues need knowledge from different disciplines, now a day's communication engineering is linked to computer and electrical engineering.

3.9. Number of sensors connected

Number of communicating devices/sensors in the technology also affect many things so it must be considered.

3.10. Common design constraints

Devices transmit mass amount of data frequently, device size constrained, transmit data over long distance, device operate for a day, weeks, months without stopping, consumer trust.

3.11. Market

How an open market place for IoT might be realized that enables people with minimum technical skills to create, distribute, and monetarize. Or how can we give ordinary persons a voice? How can we insure that IoT allows for user-led innovation?

4. LESSON LEARNED FORM THIS WORK

It is known that internet of things is a big idea full of complex technologies. That's why we need a common ground to classify these complex technologies to do so every company working in the area must come up with common ground used for classification. Some of open issues are:

• Many products play role in multiple categories. For a given technology it is important to ask a user what am I buying this instead of? What does it sit next to on the shelf? Most of us being very market focused.

• IoT technologies have lack of the environment that Clear Strategy in Becoming Smarter. One key obstacle is citizens themselves, who don't see the value in them.

• Clarifying IoT and M2M: M2M is often used as a synonym for IoT, particularly in the IIoT world. But while similar, there are differences in which rungs of the IoT ecosystem ladder they occupy.

• Find a way of describing things in such a way that developers don't have to know about the details or underlying communication patterns. developers looking to answer [20]: How do I publish a Thing? How do I access a Thing? What is the lifecycle of a Thing? How do I add a new property to a Thing?

• It seems like there are as many standardizations and bodies focusing on IoT protocols as there are IoT protocols. But, we should come together and to have a common worldwide standard.

• Get a look at the science behind wireless IoT communication and the benefits and constraints of using wireless communication in IoT technologies.

3. SOLUTIONS FOR SENSING AND PRIMARY USER INTERFERENCE IN COGNITIVE RADIO IMPLEMENTATION OF WSN

1. INTRODUCTION

After introduction of cognitive radio technology in communication, the hot research topics are: sensing, Primary User Interferences, spectrum management, security, spectrum sharing, and environmental sensing. Among the listed once sensing and Primary User Interferences (PUI) are the bold once. It is clear that the base query for CR (cognitive radio) is to find a means where which channel in what specific time is available, sensing. In other word real time sensing and usage of channel is still challenging problem in WSN communications.

The idea behind CR technology in a WSN is granting these small devices to make a decision defending in which they operate in a specific time and place to achieve end-to-end goals. The general goal of applying CR to WSN is to improve their performance by efficient use of available bandwidth and reduce interference (collisions). Even more, CR could facilitate a better way to provide Quality of Service (QoS) to WSNs applications and longtime battery.

With the unique characteristics and emerging challenges of real-time use of sensors in Cogitative Radio Wireless Sensor Network, CRWSN is far beyond the scope of CR itself, i.e., yet not designed with the consideration of real-time communication with respect to Non-Orthogonal Multiple Access (NOMA) which is growing as spectrally effective various access technique for the CR mobile networks, where increased users served at the same time-frequency but with different power levels [21]. Wireless communications usually consist of non redundant data; for example, carried information is highly compressed. Therefore, providing end-to-end congestion control acquires significance to satisfy real-time communication and high data rate delay sensitive applications QoS requirements in CRWSN. CR should be aware of the amount of sensory data being communicated and know when and where to forward it. Here we indicate the real-time relationship between knowing free channels and using them. Also, a high level of knowledge about the type of environment they operate helps us to identify Primary Users (PU) using a packet type exchanged.

Most recently, NOMA has been proposed in numerous systems of cognitive radio implementation, that is, amplify-and-forward scheme for spectrum sharing in cognitive radio channels [22], convolutive superposition for multi carrier cognitive radio systems [23], power allocation for interference alignment [24], Cooperative Non-Orthogonal Multiple Access in Cognitive Radio [25], and Advances and Future Challenges in Non-Orthogonal Multiple Access [26].

Amplify-and-forward (AF) relaying scheme allows the SU (Secondary User) to amplify a signal of PU by some scaling factor and let the channel used be either active or inactive [21–23]. Hence SU is active in all the channels allocated for the PUs; then power consumption and related factors are significantly problematic. As well, even it is in a fraction of time, there is a delay for PU data while amplified by SU. Three-level power allocation is performed to maximize the throughput of SU’s [24]. Such an algorithm can recommend if the PUs and SU’s exact power consumption is known and measured depending on the surrounding conditions not only by considering the internal power level of communicating device. In contrast, our proposal named "SenPUI" does not require an internal power level (PL); preferably it depends on the condition of the overall network operating environment. In [25], cooperative NOMA has been applied to underlay CR network and its performance based on the probabilities derived of the proposed cooperative scheme over non cooperative scheme under CRNOMA system. So far, the simulation result indicates in this work that cooperative NOMA is more efficient over the noncooperative implementation of cognitive radio.The fundamental effectiveness of any NOMA scheme is studied by analyzing its result in improving power/energy efficiency, complexity in professional implementation, interference, and power domain multiplexing [26]. So, that is why in our work sensing the available channels energy detection is employed by WSN coordinator during the inactive period of communication as described in [27]. The beacon-enabled IEEE 802.15.4, a superframe which consists of an active portion and an inactive part, starts at the beginning of a beacon frame and ends at the beginning of the next beacon frame. WSN PAN coordinator will scan licensed frequency spectra during the inactive time to find the free licensed channel for sensor nodes to be used in next super frame. WSN PAN coordinator scan allowed channels during the idle period to determine the available permitted channel for sensor nodes used in next super frame. Once a cognitive radio knows the type of information exchanged between users, it is easy to propose users as primary and secondary based on the type of data transferred. So, in SenPUI, a device is PU when it is planning to send data which is so essential.

The aim of this work is to show solutions for two major obstacles that CR-WSN facing, sensing and Primary User Inferences (PUI). To be clear we try to answer two major questions in this work which are: 1) When to do channel sensing for hole detection, inactive period of communication as a solution and 2) How to assign a sensor as primary or secondary user depending on the type of packet to be exchanged, application packet-based classification. Because the traffic in WSN is very dependent on the application scenario, only those selected during initial set up as a primer user data traffics application are considered as PU. So, it is very important that during initialization of the network to identify which application traffics are very important even if it is known that every data in communication is important but hoping that we have some priority level of our communicating application data.

2. RELATED WORK

Up to date, data traffic in many WSN based communications is dynamic because of the traffic modeling used and specific application designed for. So, during the implementation of cognition, two main issues are challenging: one is PU packet identification and the other is channel sensing and real-time usage of sensed results. To solve both mentioned problems, an increasing number of algorithms based on the Wireless Sensor Network cognitive radio have been proposed. In Evangelia Matskani et al.'s work [28] with the title "The Mutual Benefits of Primary-Secondary User Cooperation in Wireless Cognitive Networks by Increasing the Probability of Successful Packet Transmission for the PU," the SU essentially increases the service rate of the PU queue. However, such strategies work under the constraint that the interfering effect of the SU transmitters on the PU receivers must be known. In F. Verdeet al.'swork [29],the overlay based approaches for CRWSN allow the SUs to transmit through standard orthogonal methods. Later, such an approach is difficult to implement, due to the energy- and hardware-constraint nodes, for obtaining accurate and timely knowledge about the spectrum holes. But an overlap of SU transmissions with the PU signals in the frequency, time, and space domains relieves the burden of spectrum sensing. In IEEE Computer Society's work [30], the standard provides an option to use super frame structure in beacon-oriented communication and the super frame has the inactive part where it enters idle mode. So it is possible to use this time for energy detection and next communication channel notification. Leslie Choong [31] proposes several different approaches used for non-burst traffic communications for prediction of PU packet arrival in WSN communication. But nowadays it is known that sensors are everywhere, and traffic is highly burst. Liu, W. Gabran, P.Pawelczak, and D. Cabric [32] present a mathematical analysis of the accuracy of estimating PU's mean duty cycle, as well as the mean off- and on-times, but the method considers the PU characteristics and sensing problem is not considered. To generalize this part almost similar methods are implemented in all references [33–40]. Nowadays, millions of sensors are entering the market and the world of sensor communication is getting more attention with its problems as explained in our previous work in Kedir et al. [41]. So, our recommendation is designing PU based on the application packet communicated. The advantage of using such way is that it is easy to implement in a real environment. This technique is used only if the very significant applications packet in the network is known and primarily set during initialization.

Regarding our contribution, unlike previous works, SenPUI focuses on developing a technique that can solve the two main problems of CRWSN together, sensing and PUI. In other words, this part describes how to use an inactive time sensing strategy that has dynamic time length depending on the traffic of the network and addresses the compromises that exist between primary and secondary users. Since PU classification is based on the application packet to be sent, a MN can be PU when it plans to send PU application packet and the same MN classified as SU when it transmits SU packet in a same operating area. Therefore, we propose a strategy called SePUI to solve two key issues for the application of CRWSN to maximize communication throughput and minimize interference:(I) sensing strategy during the inactive period of communication and (II) application-based PU-interference avoidance.

3. SYSTEM MODEL

Design considerations are formulated to bring and implement the most common manners of WSN application design assumptions in practice. Crucial considerations throughout the entire implementation process are: beacon-enabled CRWSN selected where whole licensed channels are assumed to have same channel gain, sensing and identification of PU data is done by PAN coordinator, to have effective outcome we considered a beacon-enabled network of one PAN coordinator and N-number of sensor nodes (star topology), we expect that battery and other factors are fully functioning, and selection as-well-as notification of selected channels for next communication is the PANs function. The only function of mobile nodes is change its communication parameter, CurrentChannel parameter, based on the notification it received from a PAN during successful packet reception and set-up a flag for notifying a coordinator weather the data to be sent is PUs application data or not. Finally, every time when a PAN receives a packet it will do sensing and notify the sender end device that which channel to be used in next communication.

Basic general scenario case is shown in the figure 3.1 below, Consider one coordinator and N-end devices. Hence end devices can be primary user or secondary user, only depend on initial application set-up specified. Because identifying PUs is depend on the specific application take place at specific time, so this character makes end devices to act dynamically based on the type of application and data they are going to exchange. In turn will have great advantage for PU data traffic identification and make PAN coordinator alarmed when the packet reaches it. Also it is important to understand that when end device sends its PU application packet must add a flag which indicate either packet is primary user data or not, that makes easy for PAN to give priority.

4. SENSING DURING INACTIVE PERIOD OF COMMUNICATION

Sensing strategy over multiple channels for SUs is an important issue that needs to be addressed in this new technology, CR-WSN. Considering the problem from perspective of throughput, delay, energy consumption, and other factors decision are made either secondary user (unlicensed user) can access the channel or not. If not considered in such manner perhaps different users assigned same channel at the same time and led to packet loss and inefficient communication environment.

In a beacon-enabled communication, the two major communication periods are active and inactive [22]. Nothing to do with active portion which is for information transfer meanwhile inactive portion is a time where the device enters to a low-power (sleep) mode. Which gives us an opportunity to use this free period. During inactive portion of communication some special type of sensing, energy detection and notification is proposed in ours case. The active period is most of the time equal to superframe duration and the whole active and inactive period is equivalent to beacon order so to get the duration of inactive Period simply subtracting superframe duration from beacon order.

As seen below in the fig 3.2 from the standard [22] active and inactive portion of communication can be calculated:

$$SD = aBaseSuperframeDuration \quad * \quad 2^{SO}$$

$$BI = aBaseSuperframeDuration \quad * \quad 2^{BO}$$

Where SD superframe duration, SO represents superframe order, BI denotes beacon

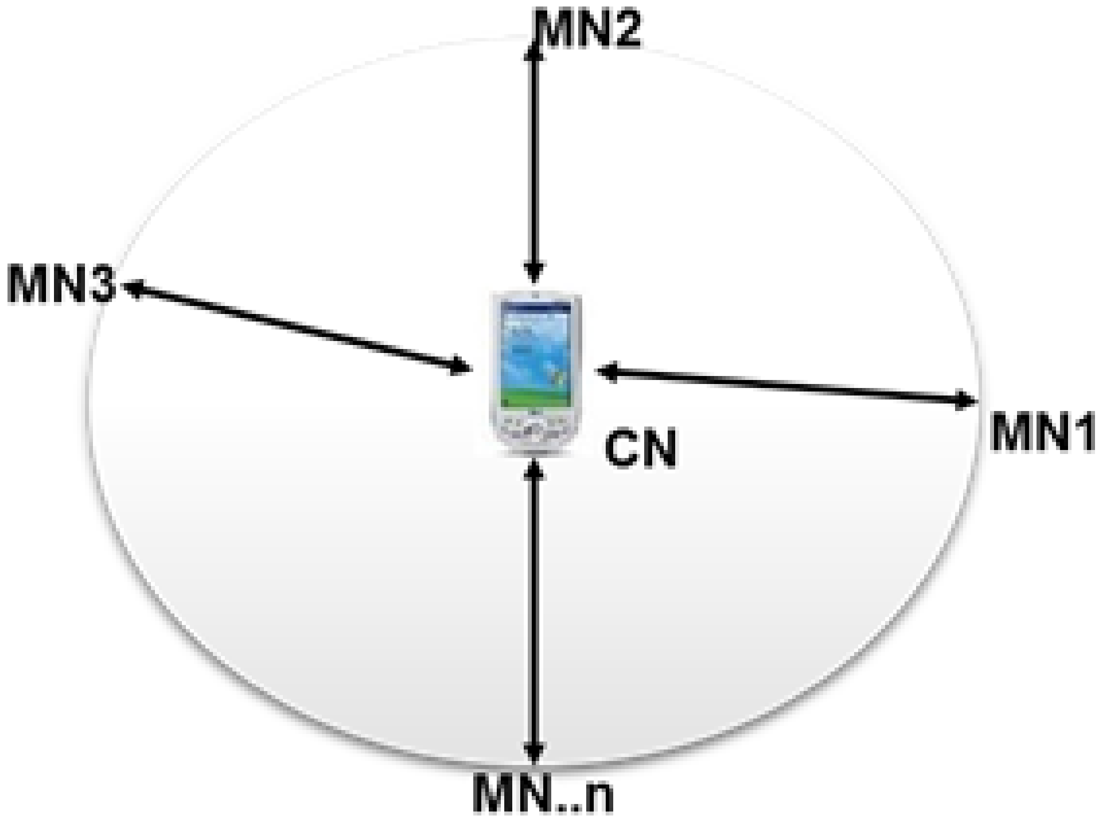

Figure 3.1: General Scenario

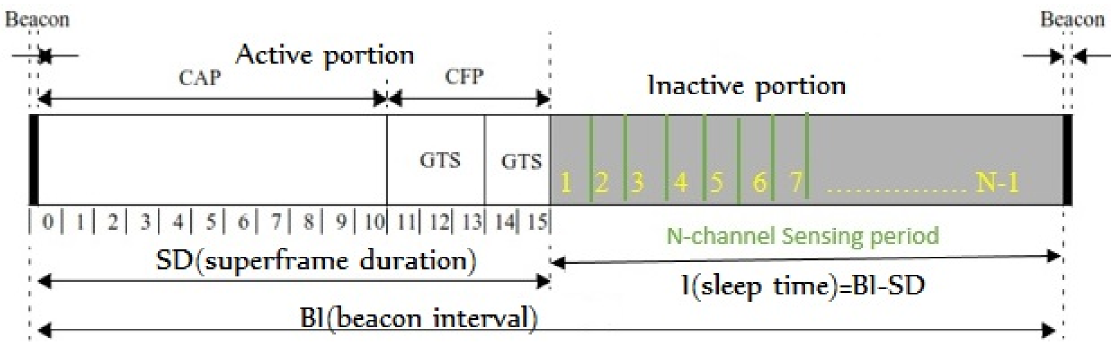

Figure 3.2: The modified superframe structure

interval, BO is beacon order.
So inactive portion(I) is :

$$I = BI - SD \quad \approx$$
$$aB.Supfra.Duration * 2^{BO} - aB.Supfra.Duration * 2^{SO}$$
$$= aBaseSuperframeDuration \quad * \quad (2^{BO} - 2^{SO})$$

As seen in the fig 3.2 inactive portion is divided N-1 number of time slots. Where all time slot intervals divided equaly so every sensing time slot is represented by general formula :

$$Ts = \frac{aBaseSuperframeDuration \quad * \quad (2^{BO} - 2^{SO})}{(N-1)}$$

where Ts is time slot.

5. APPLICATION-BASE PU IDENTIFICATION

Primary user interferences minimization is huge concern during implementation of CR. Expected to result in no or minimum interferences with primary user (PU), and yet it is a challenging problem. Not knowing when PUs claim for the channel is major challenge. Most designs consider secondary users explore spectrum holes which are licensed to PU in either temporal or frequently in a Dynamic Spectrum Access(DSA) network. So, that means SU must sense channel then find to communicate. Well this is recommended when SU have long opportunity to use vacant channel if not results in low throughput. In WSN applications, now a day's sensors are multi-functional, one sensor for many applications. In such conditions classifying users as PUs and SUs is not depend on the sensor rather it must depend on the application embedded in the sensor. Sensors in the same network, either licensed or not, running applications which used to communicate data's that are very sensitive and less sensitive. In such scenario our PUs is sensor which try to send information which is very sensitive.

Finally considering all factors, we agreed that the application taking place at that specific moment is defining factor for a device to call it PU or not. Application based PU identification needs information about what kind of applications have higher priority in the operating network. So, applications with higher priority must be set during initialization. As an example, let us consider some sensors designed for medical information monitoring service; ECG, temperature, location. . . etc. all applications embedded in all sensors. Assuming that during initial set up ECG data is selected as highest priority. So, a device is considered as PU when it tries to send ECG data to a PAN coordinator and same device treated as SU when it sends temperature data. For identification purpose sender must find some way like attaching flag with the outgoing message.

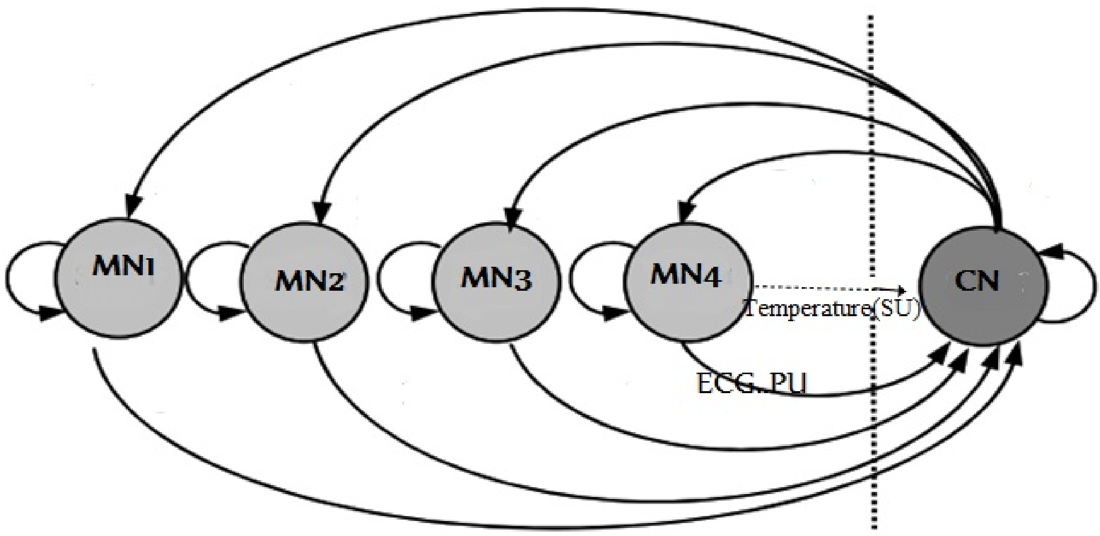

Figure 3.3: application besed PU demonstration model

Considering a PAN coordinator with four end devices as shown above in figure 3.3. PU's activity and channel use are assumed independent as many literatures consider [25] and transmission is done in time slot manner. For MN4 in the figure 3.3 above assuming that the network is designed to collect health information (ECG, temperature. . . etc) and during initial set-up ECG application given with higher priority (PU application). If MN4 claiming for channel, for transmitting ECG data, and one of the others claiming the same channel at the same time for temperature data transmission then channel is granted for MN4 and seen as PU. But, what if the same device is requesting for sending temperature information then it is considered as SU and channel is allocated if and only if no other device is requesting the channel for ECG data transfer at that specific time.

After successful transmission every end device receive notification from a CN. This notification data includes information about the next channel to be used in the next communication between specific device and CN. While receiving the notification data end device will modify automatically its communication parameter accordingly.

6. CHANNEL SELECTION

While finishing sensing time the last time slot is reserved free for notification and time for something else if the application has to go under short period process, if not, it is possible to use the whole N time slots for sensing. Afterward we have results, so the next step is to decide on the results like: 1, did we have results from energy scan? 2, the current channel is idle or busy for next communication? 3, if it is busy which channel is the best choice for the next communication with this specific device? It is recommended to use the same channel for next communication if it the channel is idle or if it is with lowest energy level from the list. On the other hand, a channel with shortest idle time is also recommended because the shorter idle time means the longer availability of the channel. Over all process is explained in detail in figure 3.4.

$$where:- \qquad TNs = totalnumberoftime - slots$$
$$Inat\_period = inactiveperiod$$
$$Ts = singletimeslot$$
$$Prev\_Ch = previouschannel$$

Among many program parts below we have algorithm for checking scan results.

Algorithm for updating channel list

$$check(int \quad x)$$
$$for(i = 0; i < n(ED); i++)$$
$$if(x == ED[i])$$
$$breack$$
$$end \quad if$$
$$end \quad for$$
$$ED[n(ED)] = x$$

Where ED denotes overall energy scan results stored, collected during inactive period of communication.

Decisions based on the results; if the current channel is idle we don't need to change to other channel it is recommended to continue the communication through same channel. In case if the current channel is assigned and had energy level of maximum then we need to select a channel with less load from the scan result from the list. Regarding the selection method it depends on the requirements of the operating network, our recommendation is to select a channel with shortest idle channel from the list because as described above if the shorter idle time means longer availability of a channel.

7. CHANNEL NOTIFICATION

After each successful reception of packets from a device it is the PAN coordinators responsibility to notify communicating device about the next channel to be used. Notification message includes the channel which is used in the next communication. This message is generated and sent at the last time slot of inactive portion of communication.

The next step is to select not busy channel from the list of results collected during energy scan, the one which not makes interference with PU. And notifying the current communicating device about which channel to be used for next communication. There is list of mechanizes; 1, periodically broadcasting method, as the communication is beacon enabled and 2, sending back a message for specific device about changes by customizing superframe specification filed. Many experts in the area agree that the second technique, customizing superframe specification filed and sending back notification message, is recommended [21]. We also agree with this recommendation. because in compered to others the time it takes to process is short and easy

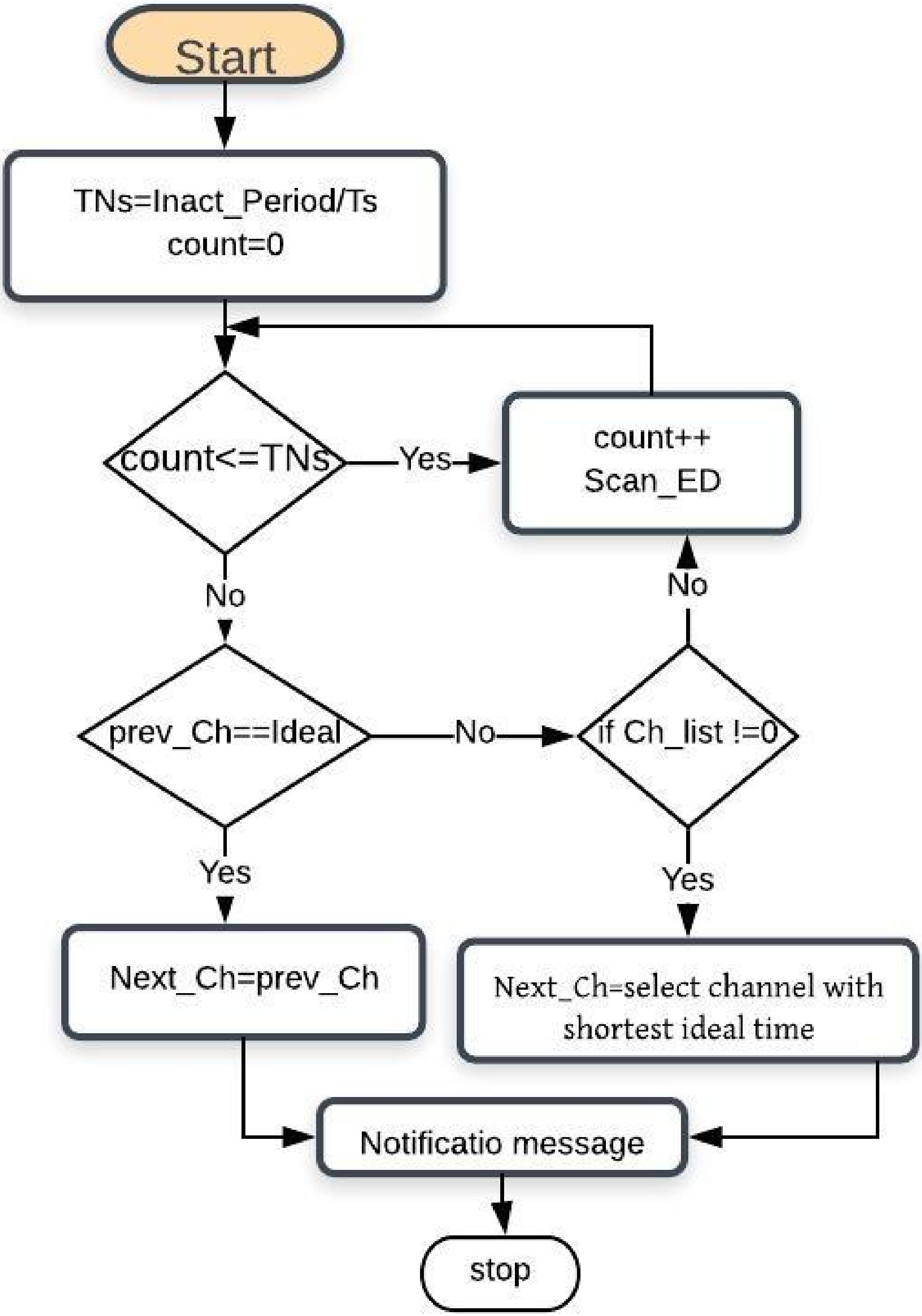

Figure 3.4: Flowchart for energy scan during inactive portion of communication

for channel management. Also have less chance of unsuccess for various reasons.

In this work we have a simple and easy notification technique described as follow: - From the standard [63] superframe structure includes some reserved fields for such usage. Reserved bit 13^{th} is used for notification of channel changes. Notification bit, bit 13^{th}, is used to store a channel to be used for next communication that is selected by its PAN coordinator. Up on Receiving the notification message the responsibility of end device (communicating device) is extracting the information and reconfiguring its communication parameter for CurrentChannel. By doing so, the device adapts changes in its surroundings. The message notification structure packet is showed in figure 3.5.

Bits: 0–3	4–7	8–11	12	13	14	15
Beacon Order	Superframe Order	Final CAP Slot	Battery Life Extension (BLE)	Reserved Notification bit	PAN Coordinator	Association Permit

Figure 3.5: Notification message demonstration

8. COEXISTENCE WITH OTHER TECHNOLOGIES

CR-WSN are widely deployed and used very intensively now a day because of the characters they have, low transmission power, easy to localize because of their size. Many researches are done on the coexistence of this technology with other, the best recommendation is that it should be considered with what technologies used. Since, every technology had its own standard. So, how much these standards integrate with IEEE802.15.4 will define integrity efficiency.

9. ANALYSIS RESULT

Points to be considered during result collection; efficiency depend on the running application, and the operating environment. First, below we list out how to analysis the overall network throughput in such environment but take in consideration that these are not the only ways rather the common once.

Analyzing Primary User Interference (PUI): calculating the probability of interference between PU Vs SU in heterogenous PU traffic with your proposed algorithm. In other words, analyzing network with PU which character with different ON/OFF time traffic. Result comparison can be done by comparing with original standard, IEEE802.15.4, and others work in developer’s application area. Real-time channel information: analysis consider how much time difference between channel scan time and channel use time. It is clear, the less difference in these two values the more recommended. The objective of this analyses is to bring the difference between scan and usage time to zero. Dynamic adaptability of end devices with changes from coordinator side: since sensing is done from CN (coordinator) it is important how to notify changes to communicating end device and when to notify. This analysis is measured depending on how long the process take without interfering on going communication.

Real-time implementation conducted for result verification of our approaches. We have a single hope beacon-enabled PAN coordinator with 5 inactive period (I) of interval. Our algorithm shown in figure 3.4 is applied. Four channels are selected for analysis, 11,12,13,14. Number of PU and SU vary from one to-to ten all of them communicating with full data rate of 250 kbps in available licensed channel with its coordinator. The Packet arrival rate is random in between 0.4 to 1.5 seconds and results collected using software called termite.

9.1. PUI comparison

PUI is an important criterion for CRWSN implementation. Opportunity for use of secondary users by not interfering PU is a major aim of CRWSN. In figure 3.6 it is clearly seen that in both, our work and the standard, results decrease when number of PU increases. Results are calculated based on the average of 20 consecutive different values recorded in different test environment.

9.2. PU traffic tracked

In figure 3.7 we have average of 20 repeated PU packet traffic tracked in different time for same applications, health area applications. By implementing our technique, the results are changed to more throughput. Further, as observed for PU data identification the average packet identified

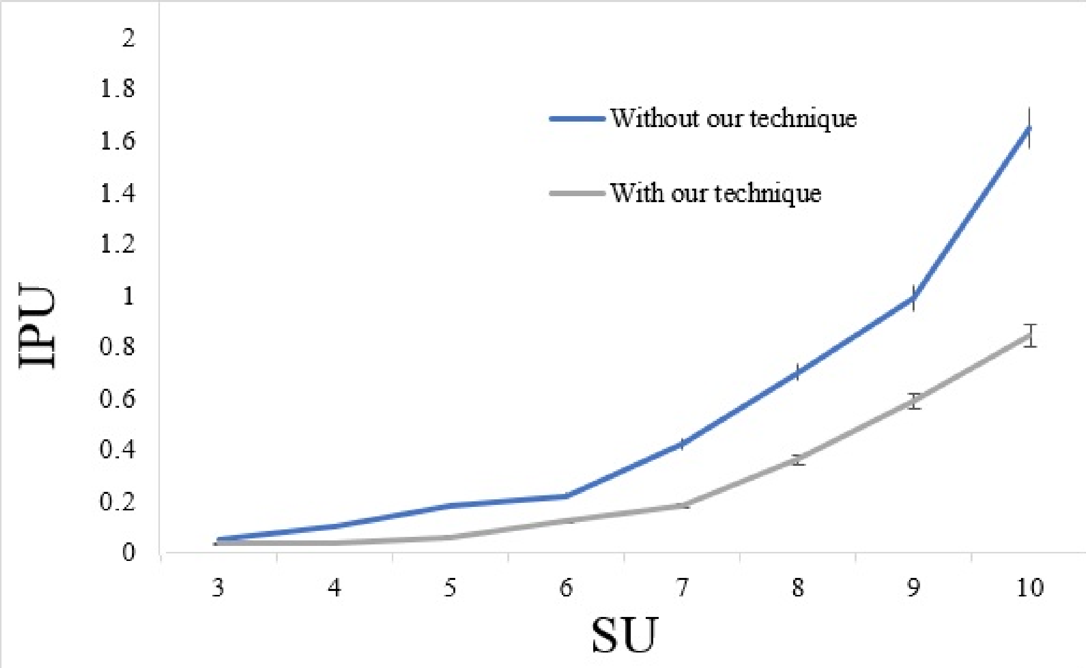

Figure 3.6: Primary User Interferences

increases to a moderate value. one to seven SU are used during result collection and the average of all is represented in the graph below.

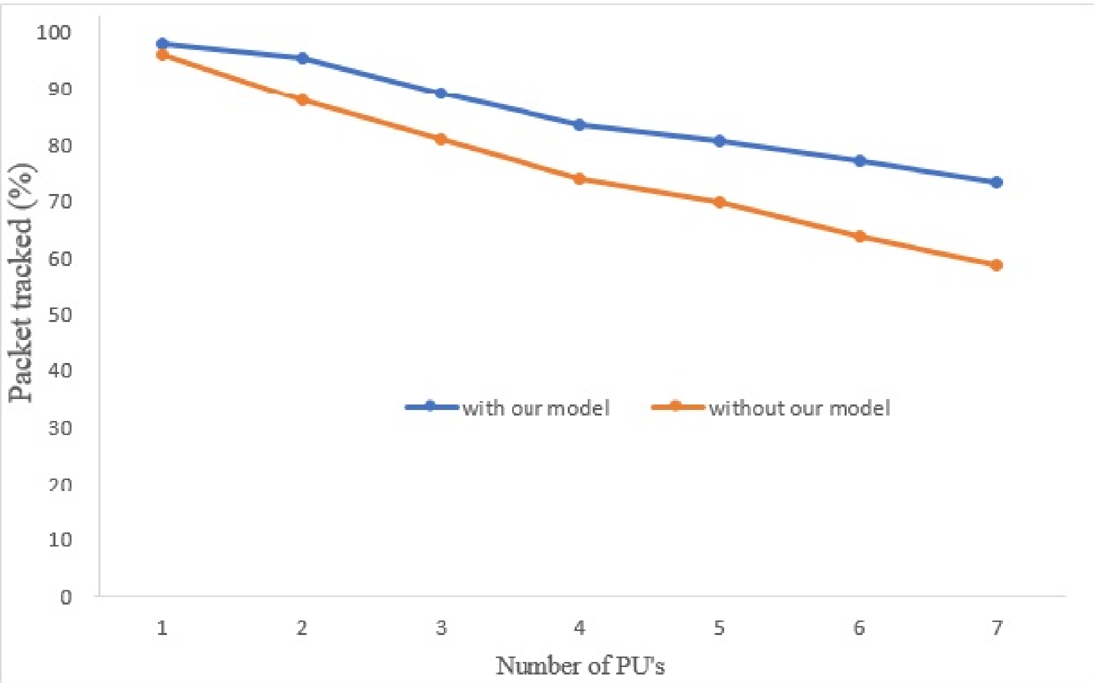

Figure 3.7: Primary user traffics tracked

What we noticed is that results change with type of application, load of packets, operating environment, number of PU and SU and internal device factors. So, reader must remember that these results may varies for different applications in different area. It is known that analyzing in real world is somewhat different compered to doing in simulation.

To summarize, sharing channel for SU is very important now a day, many new technologies emerging, and we have limited number of free channels. Assuring the quality of PU in a communication is also crucial point. Various communication conditions need to be addressed when designing cognitive WSN, from implementation environment to the type of application (priority for applications, frequency of applications claiming for channel).

In this work, we present a solution for two major problems in cognitive radio implementation of WSN, sensing and PUI (Primary user interferences). Our major focus is on sensing channels, using results in real time and avoiding interference to PU. This work allows readers to: 1, when to do channel sensing during communication without interrupting on going communication. 2, how to use scan results. 3, mechanism to notify changes for communicating device. 4, application-based PU identification. Dividing inactive period of communication in to N time slots and using for N or N-1 channel scans. After completion of energy scan results are checked and the shortest idle channel is assigned for next communication. 13^{th} bit of superframe structure is used for notification of changes. The responsibility of communicating end-device is reconfiguring its CurrentChannel parameter during reception of notification message.
As seen in result part the method grants efficient communication outcome with minimized PUI, which is major goal of this work.

10. RECOMMENDATIONS FOR FUTURE WORK

While a number of investigations have been published in the area, still many research issues remain to be addressed specially in cogitative implementation of WSN. Among the areas to be explored in the future; PU identification, energy efficient spectrum sensing, spectrum management, spectrum handoff, channel allocation, channel access, and topology generation. The other big deal is that now a days most of result collections are almost simulation based nothing bad with that but the problem is when we try to implement in real environment every thing will change and it is very important to consider.

4. EXPERIMENTAL ANALYSIS TO DETERMINE THE AVERAGE MINIMUM TIME LIMIT FOR WIRELESS SENSOR COMMUNICATIONS

1. INTRODUCTION

Although, WSNs are successful in providing excellent services using a limited resource and gathering information with smaller devices. These networks are very vulnerable for collisions, delay, and packet loss that is if used without considering the AMTL (Average Minimum Time Limit). The major problem lays in having information not only about the broadcast latency of MNs but also understanding the average minimum channel access time interval of end devices communicating in the network. AMTL information regarding the end devices is an essential parameter in determining the QoS of a network and spectrum sharing mechanisms to be used [42]. If we need an efficiently working WSN environment, the baseline is simple that having full information about the number of end devices communicating a WSN coordinator and the average minimum time interval in which these end devices send data to their central coordinator.

Enormous WSN techniques explained on how to increase the number of communicating MNs by sharing spectrum, time, and power [43-46]. But, in none of the listed references that AMTL is under consideration. Even though those are the principal factors for most of current cognitive WSN based algorithms, it is good practice to consider the AMTL of data reception during any WSN algorithm design.

One of the common problems that we noticed is that most of the researchers not consider how many nodes supported at a specific average time interval during the design of the cogitative radio-related mechanism. Conventionally techniques like congestion, cognitive radio, and hand-off are used to solve QoS of WSN by minimizing the end-to-end delay. However, if implemented without considering AMTL, all listed solutions may not solve the problem. Because, how much MNs supported in a given average time is a baseline for those techniques. As we are living the age of IoT, dealing with sharing resources [46-47], we need to know how much we have, how much we left, and when to use different mechanisms in advancing network output. As mentioned by reference [48], most real-environment experimental results show that delay in IoT devices varies depending on various circumstances. So, it is essential to evaluate the AMTL for cognitive WSN communication.

Unlike previous works, this work focuses on analyzing the AMTL for applications, which gives a baseline for anyone interested in working with cognitive WSNs. The number of MNs and their AMTL of channel usage are the two principal parameters considered during result analysis with other factors explained in previous works.

Next, we will go through the related work and general scenario used in sections 2 and 3 respectably. In section 4, an end-to-end delay derivation presented. Under section 5, we will discuss the performance evaluation. Finally, under section 6, we will conclude our analysis.

2. RELATED WORKS

Designing spectrum-time related solutions for cognitive WSNs is challenging since the characteristics of QoS metrics in WSNs are varying for every environment. Due to this nature, probabilistic QoS metrics introduced during the early 2000s, [49-51]. In these studies, the worst-case analyzed, but it is limited for three main reasons in WSNs: i) randomness, ii) low power nature of the communication links, and iii) high variance in their end-to-end delay. These motivate the need for general AMTL analysis rather than probabilistic QoS assurance.

Recently, a large number of works have analyzed the delay distribution of radio transmission errors experienced by wireless channel in Wireless Multimedia Sensor Networks (WMSNs) like: [52] for healthcare, [53] for video surveillance, [54] for real-time target tracking, and [55] for habitat monitoring. However, AMTL needed by wireless channels in cogitative WMSNs makes it hard to achieve these qualities simultaneously. Therefore, it is great to have a good understanding of the factor, AMTL.

A lot of research has been carried out on developing delay calculation methods[56-59]. These works mainly focus on evaluating the general average delay time needed in WSN. On the other hand, some researchers focus on WSN dimensioning by a mathematical tool called network calculus [60], and they care about the worst-case performance of WSN. But in our method, we considered the general condition not only the worst scenario.

3. GENERAL SCENARIOS

Design considerations are formulated to bring and implement the most general manners of WSN application assumptions in practice. The crucial points through-out the entire implementation process are: beacon-enabled WSN where whole licensed channels are assumed to have the same channel gain, data packets are sent from different MNs to a CN, every communication recorded in order to check success, consider N-number of CN, one SN and N-number of MNs in a star topology, 6 consecutive channels are used for result analysis and various time intervals used for result collection.

As seen in figure 4.1, during each step of communication, we record the values for significant delays (Queue, MAC, Service, and ACK delays). Then the total delay is calculated by adding all delay values recorded starting from sending MN to the whole way to destination SN. All participating devices own all types of delays except that the SN node has no queuing delay. The value ACK delay displayed in the result part is the sum of all ACK delays registered from the origin up to the destination and the same wise for the queue, service, and MAC delays.

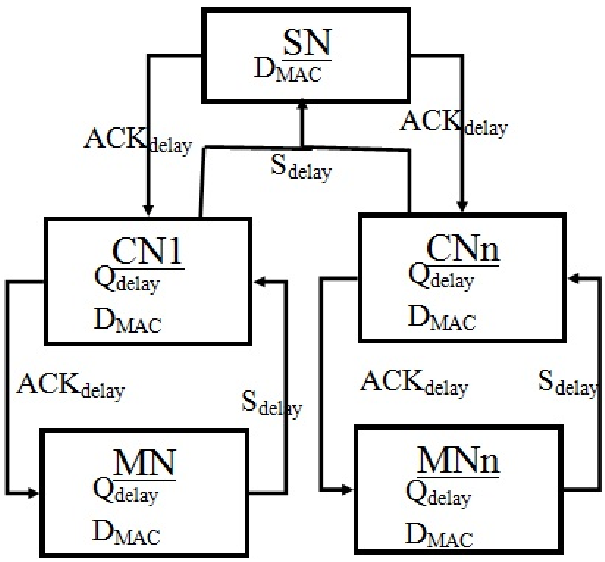

Figure 4.1: General scenario

Because the objective is for cognitive-based delay analysis, energy detection is performed when every packet reception is completed. The cognitive algorithm presented in our previous work [44] is applied. Spectrum sensing, selects the available licensed channel and broadcasts selected channel to all MNs through the periodical beacon frame is the responsibility of CN.
Also, we considered an arbitrary data packet of 16 to 250-bytes from different nodes at a given time interval of Poisson Distribution, α. Every node sends the same data a hundred times (100x) using α interval. With 2-10 number of licensed users are executed for each result collection.
The purpose of this work is to analyze the possible number of MNs supported within a specific time delay limit of α in cogitative radio-based WSN. Finally, we can rationally reconstruct the

approximated execution to determine how network load and delay are adjusted and use the result as a reference. end delay presented.

Calculation of the AMTL value considers four main delays: 1) service delay, 2) queuing delay, 3) MAC delay, and 4) ACK delay. Where α represents the Poisson Distribution based packet generated during experiment reference [61] while S_{delay} , Q_{delay} D_{MAC} and ACK_T, represent four delays, respectively. Only S_{delay}, D_{MAC} and Q_{delay} are explained in the following sections considering that ACK_T is constant so simply adding it to the total time derived.

$$Delay = \alpha\left(ACK_T + D_{MAC} + S_{delay} + Q_{delay}\right). \tag{4.1}$$

Below, we present the details for S_{delay}, D_{MAC} and Q_{delay} delay derivation.

3.1. S_{delay}, Service Delay Derivation

We measured the service delay which is described as the continuation that unlicensed user data packet is successfully transmitted to its sink node. Regarding licensed once they are served as soon as they need without any service delay time [44].

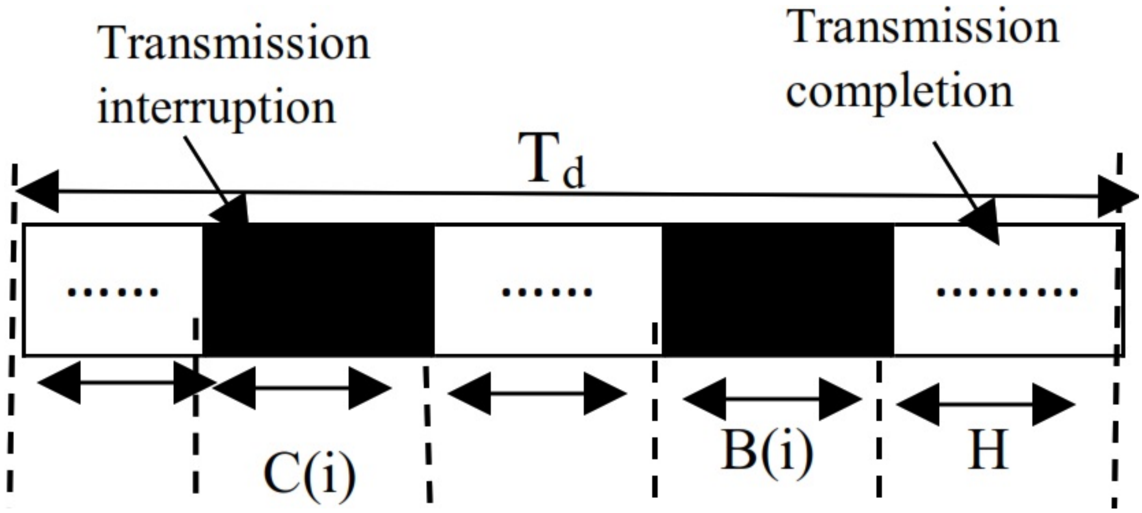

Figure 4.2: Unlicensed user data transmission on a single channel

Figure 4.2 Explains the most common steps that an unlicensed user packet transmission transmitted successfully on channel CH (11, 12, . . . , 26). From the figure C(i) and B(i) denotes the unsuccessful transmission time of a packet due to the collision and the busy period of the channel, respectively. Mostly these kind of delays occurred basically due to primary user activities or channel rendezvous. Finally, we have H at the end represents the time that MN transmits a packet successfully without interruptions. The whole process is represented by T_d, the entire duration that the MN executes a successful transmission of a single packet of an unlicensed user.

$$T_d = \sum_{i=1}^{n}[C(i) + B(i)] + H. \tag{4.2}$$

Moreover, Poisson process with a service rate of λ_p used for the busy period analysis, due to primary user activity. Every packet transmission time which is a reason for busy channel time (licensed user transmission) follows exponential distribution with expectation of H_P as described in reference [62]. The service for such traffic is:

$$\mu_p = \frac{1}{H_p} \tag{4.3}$$

where μ_p represents service rate of priority activities.

The expected value of a busy period, B, on a given communication channel in a specific time interval is given by:

$$E[B] = \frac{1}{\mu_p - \lambda_p}. \tag{4.4}$$

We assumed that: 1) condition for the unlicensed user transmission interruption due to the licensed user activity is that the idle period on the channel is smaller than the unlicensed user packet length. 2) and W is the duration, then we obtain the interruption probabilities between unlicensed user transmissions and licensed user as follows:

$$P(n = N_c|W) = (1 - e^{-\lambda_p})^n e^{-\lambda_p W}, n = 0, 1, 2, ... \tag{4.5}$$

N_c represents the number of collisions. The expected value of T_d is

$$E(T_d|W) = E\left[\sum_{i=1}^{n}[C(i)W + B(i)W] + W\right] E[N_c](E[C|W] + E[B|W] + W) \tag{4.6}$$

where E[B|W] = E[B] = eq.4

$$S_{delay} = E(T_d) = E[E[T_d|W]] \qquad = E[N_c(E[E[H[|W]] + E[B|W]) + E[W] \tag{4.7}$$

then

$$S_{delay} = \left(\frac{1}{\lambda_p} + \frac{1}{\mu_p - \lambda_p}\right) E\left(e^{-\lambda_p H} - 1\right) \tag{4.8}$$

3.2. Q_{delay}, Queuing Delay Derivation

Figure 4.3 shows the general queue state of the source MN and the destination nodes, coordinator (CN) and sink node (SN). More, both the source and destination nodes follow a First In First Out(FIFO) buffer strategy.

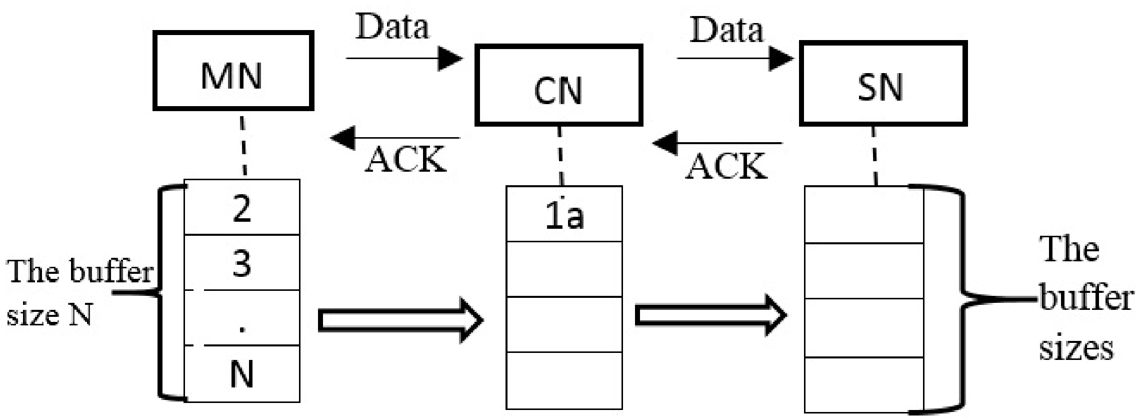

Figure 4.3: Queue delay

N state discrete Markov chain is considered where N$>$3, but first implemented for the signal-hop cognitive radio WSN is introduced. Explained in figure 4.4, where the source and destination is a multiple hop away. The N states defined by two parameters:the number of data packets and number of ACK packets in each node.

Three major scenarios of channel usage between the source and destination node are considered: i) successfully accessed by the source node, P$_{suc}$ is the probability that the source node, MN or CN, sends a data packet to the destination node, SN. ii) the destination node accesses successfully, P$_{ack}$ denotes the probability that the destination node sends an ACK

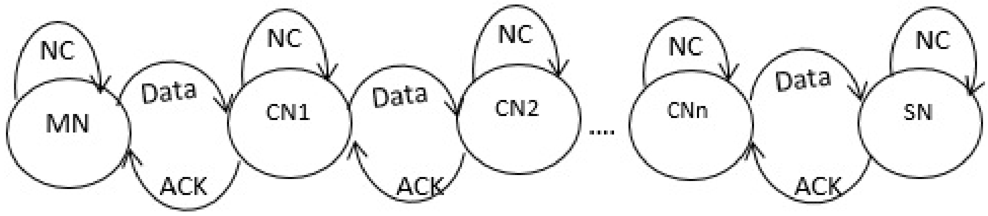

Figure 4.4: The proposed Markov chain for queue state transition.

packet to the source node and iii) we used P_{not} to represent the probability of no data packets is transmitted in the current slot. In addition, the steady state probabilities used for all the states and represented by letter β.
From conservation law, we get

$$\begin{aligned} \beta_{MN} &= P_{notMN}\beta_{MN} + P_{ackCN}\beta_{CN}. \\ \beta_{CN} &= P_{sucMN}\beta_{MN} + P_{notCN}\beta_{CN} + P_{ackSN}\beta_{SN}. \\ &. \\ \beta_{SN} &= P_{sucCN}\beta_{CN} + P_{notSN}\beta_{SN}. \\ \beta_{MN} &+ \beta_{CN} + ... + \beta_{SN} = 1. \end{aligned} \tag{4.9}$$

which take us to queuing delay equation which is represented by:

$$\begin{aligned} D_{queue} = P_{sucMN}L_P + P_{ackMN}L_{ack} + P_{sucCN}2L_P \\ +P_{sucCN}P_{ackMN}L_{ack} + ... \\ +P_{sucSN}3L_P + P_{sucSN}P_{ackMN}L_{ack}. \end{aligned} \tag{4.10}$$

where L_{ack} and L_P represents ACK packet and length of data packet respectively. Finally, we represent D_{queue}(MN), and D_{queue}(CN) as states of delay in our queue.

$$D_{queue}(MN) = P_{sucMN}L_P + P_{sucCN}2L_P + P_{sucCN}P_{sucMN}L_{ack} + P_{sucCN}P_{ackCN}2L_{ack}. \tag{4.11}$$

$$\begin{aligned} D_{queue}(CN) = P_{sucMN}L_P + P_{sucCN}2L_P \\ +P_{sucSN}3L_P + P_{sucSN}P_{ackMN}L_{ack} \\ +P_{sucSN}P_{ackCN}2L_{ack} + P_{sucSN}P_{ackSN}3L_{ack}. \end{aligned} \tag{4.12}$$

The generally queuing delay calculated as:

$$D_{queue} = \sum_{j=1}^{x} \left(\sum_{i=1}^{j+N-1} {P_{suc}}^{i} i L_P + {P_{suc}}^{x+1} \sum_{i=1}^{2j+N-1} {P_{ack}}^{i} i L_{ack} \right). \tag{4.13}$$

3.3. D_{MAC}, MAC delay

Finally, we calculated a delay from the moment that a packet reaches a physical layer to the pass through the end of the MAC layer successfully. Therefore cooperative MAC, the physical layer cooperates to MAC layer, considered which improve the throughput in wireless networks [62]. Where equation 8 of the same reference [62], implemented for four state transition scenario.

$$D_{MAC} = \sum_{i=1}^{nc} T_{ci} + \sum_{i=1}^{n'c} T'_{ci} + \sum_{i=1}^{n's} T_{si} + Idletime \tag{4.14}$$

where nc- number of re-transmissions, n'c- number of collisions, ns- number of successes full transmissions. Finally T_S and T_c represent success full and unsuccessful time respectively.

Both are multiplied with their corresponding probability, pT

$$T_S = \sum_{i=1}^{4} T_{si}.pT_{si} \quad .... \quad ref.[62] T_C = \sum_{i=1}^{4} T_{Ci}.pT_{Ci} \tag{4.15}$$

4. COGITATIVE ALGORITHM

Besides, hardware and software constraints, an efficient cognitive-channel algorithm must be addressed to achieve adequate network performance in cognitive WSN communication.

Algorithm 1: Cogitative algorithm

Input : Ass_ Req
Output : CH_AssResp

CH_i =11, $table\ of\ scan\ result(TSR)$, $Superframe\ order$, $Beaconorder$;
$Inactive\ period$ = $Beacon\ order$ - $Superframeorder$;
if *Ass_ Req == true* **then**
    $CH\_AssResp$ = $select\ a\ channel\ with\ smallest\ energy\ value\ from\ TSR$;
    $send\ CH\_AssResp\ as\ a\ notification$;
    ;
else
    return;
if *Inactive period == true* **then**
    $do\ energy\ scan$;
    $update\ TSR$;
    return;
else
    return;

In our algorithm, the central coordinator notifies MNs about through which node they can communicate during association. Moreover, the effects of the operating environment are taken well care under our algorithm. The inactive portion of communication is used for sensing, channel energy level detection, updating and results saving in a table, TSR, so that we can use it in the future. The whole process is described in our previous work [44]. Using cognitive channels resulted in effective ATML due to the fact that it effectively manages the communication spectrum.

5. SIMULATION BASED ANALYSIS

To evaluate the performance of the proposed AMTL scheme, we conducted extensive software simulation using OMNET++. The main advantage of performing our proposed scheme using a simulation environment is that it is easy to analyze the type of delays which are challenging to examine in real environment experiments. Some general parameters applied in our simulation are listed below.

Simulation parameters

Number of MNs	20
Number of channels used	6
Transmission range	150M
Length of channel sensing period	1ms
Data rate of the channel	2Mbps
Size of all types of ACK packets	240 bites
Size of data packet	16-250 bytes
Simulation time	5000 s
Number of executions done	3000

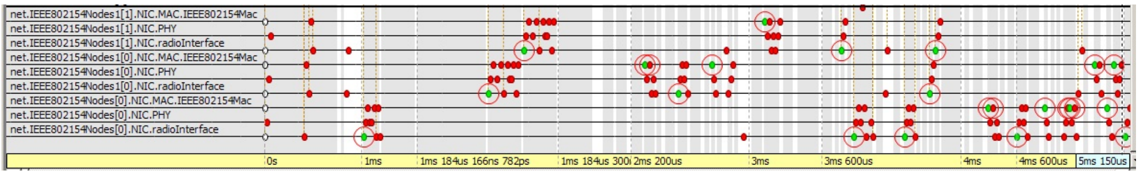

Figure 4.5: Uncommon delays registered during the experiment.

ACK, queue, service, and MAC delays are the main parameters studied. In the 4.5 we try to show what it look likes the ruining test environment.

Also in figure 4.6, we show a screen of the simulation environment.

First, we showed the results traced for the average minimum queue and service delay times. These are the two most significant delays that any WSN communication experiences.

The simulation results in 4.7 shows that the largest average minimum delay value registered is queue delay compered to service delay. Obviously, in a high traffic environment queue delay depends on the service delay. The traffic flows are used to build queuing delay at node 1,2,3,... SN which is of interest in our evaluation.

Our proposed scheme achieves hi5gh accuracy for evaluating AMTL for queuing and service delays in burst network traffic. It’s known that result collection for these parameters in the real-environment experiment are more complicated compared to the simulation environment because of other environmental factors.

Second, we displayed in figure 4.8 the average delay registered for MAC and ACK delays. The results for MAC and ACK delay which is shown in the are same throughout 2000 consecutive evaluation. What we noticed is that all the delay types are interrelated and have direct influence on each other.

Figure 4.5 also shows the unconditional delays registered in three different MNs during simulation analysis, the once in green color. As seen in the figure, it happens in two most common layers, physical and MAC. Notification, channel rendezvous, and inter-layer delay are some of the main reasons for such kind of delays. Even it is an unconditional delay the AMTL takes into account all classes of delays including these once.

Considering the dynamic changes in all types of delays, the proposed scheme consistently performs high measurement accuracy for a different number of MNs.

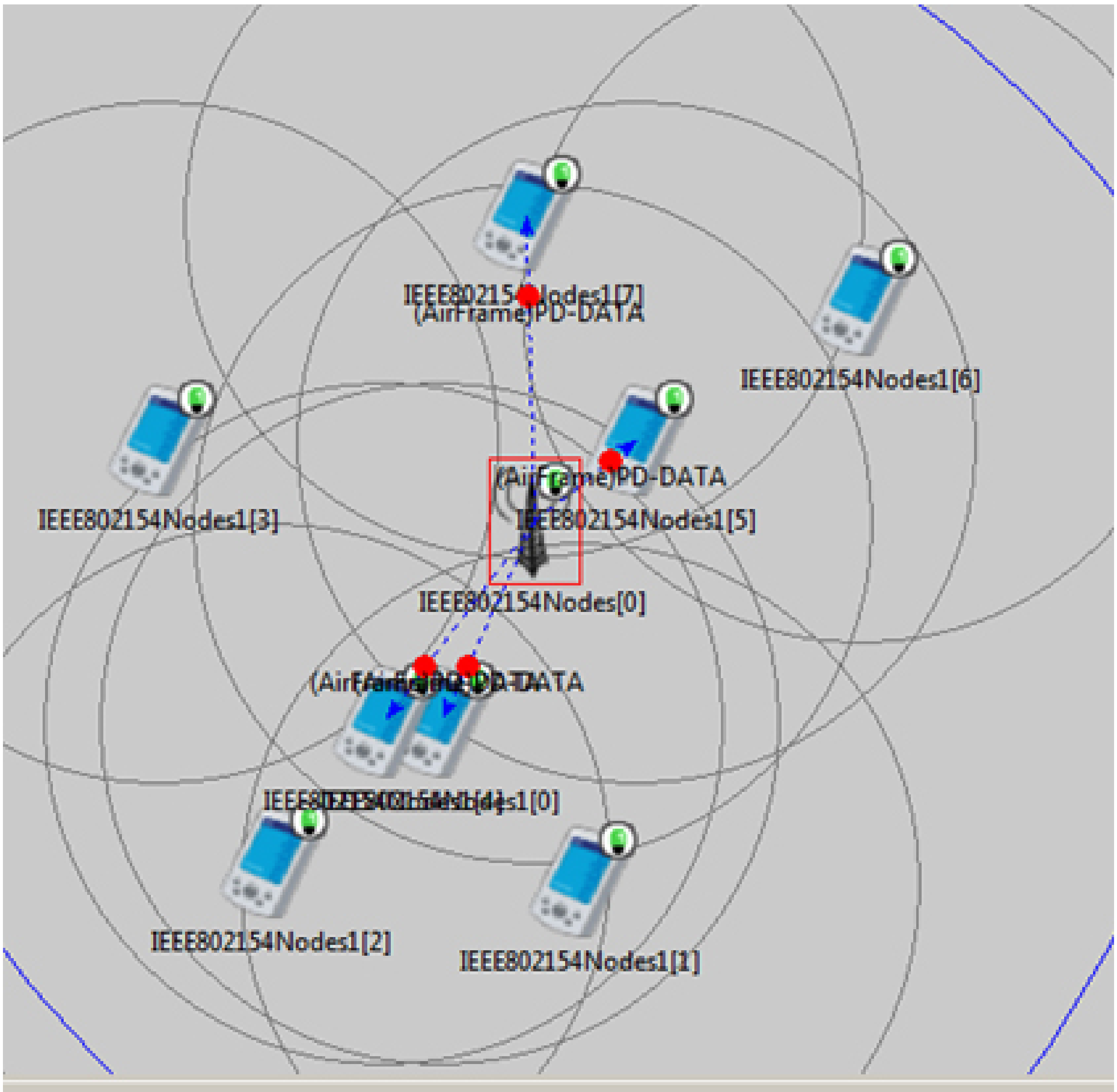

Figure 4.6: Screen-copy of part of simulation environment in omnet++

6. CONCLUSION

These days WSN researches are about spectrum-time-power (cognitive radio) and the number of MNs supported. However, it is essential to know what is the average minimum limit to use the techniques that these technologies offer. If we are below the minimum limit baseline and try to use any methods, improvements can't be expected in our operating environment. So, knowing the AMTL will help anyone interested in designing any WSN applications especially for thous interested in cognitive radio based WSN.

In case the reader is interested to know the total AMTL for his/her environment, the only thing he/she has to do is add up all the delays; queue, service, MAC, and ACK delays, together. Also, the reader should understand that the algorithm used and test circumstances remain the significant impact factors in such experiment, which are not part of the objective of this study.

Regarding the channel congestion for IEEE 802.15.4 standard, it is an open problem for future study.

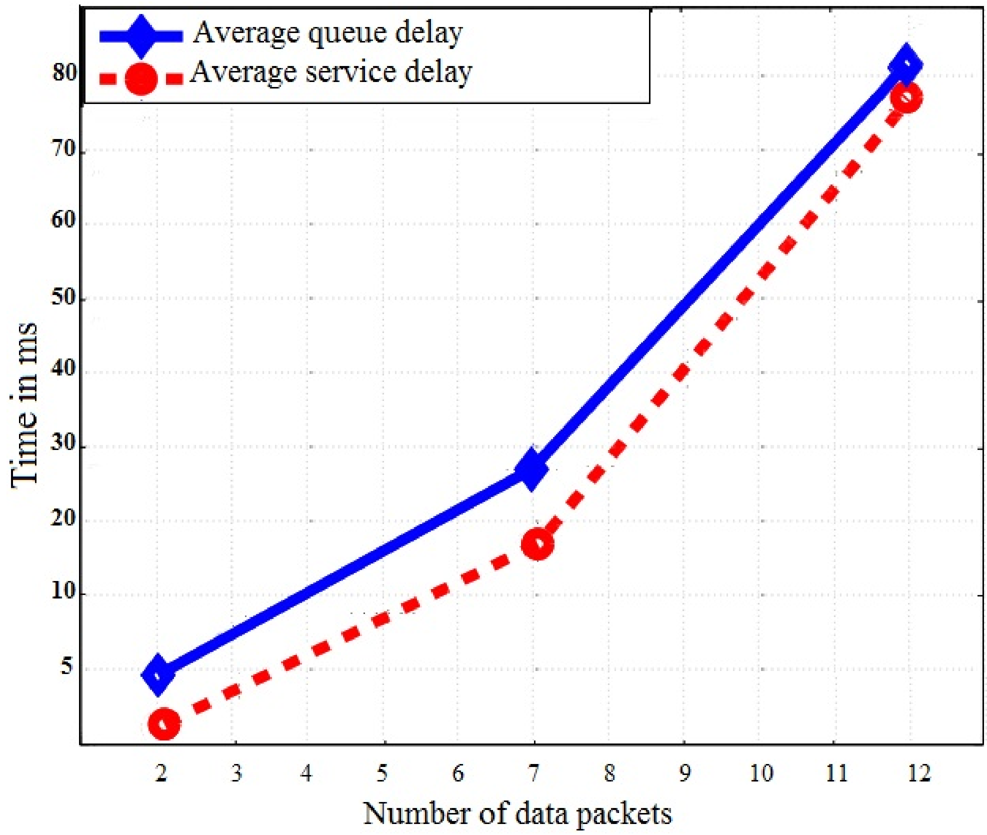

Figure 4.7: Queue and Service delay recorded.

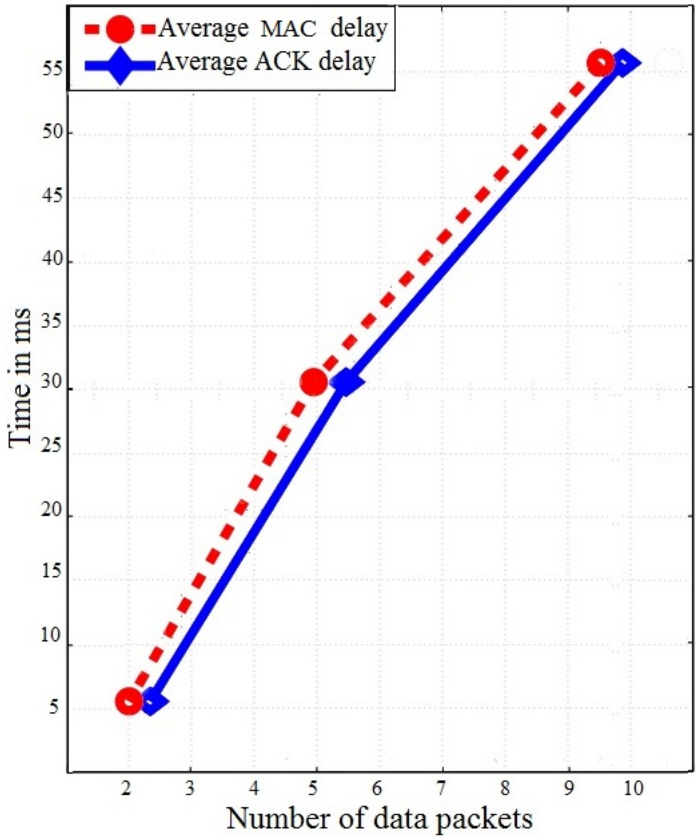

Figure 4.8: MAC and ACK delay recorded.

5. SUMMARY OF THE THESIS AND LESSONS LEARNED

To increase the effective usage of 5G and IoT technologies it is very important to address problems that face these rapidly growing technologies. It is very important to mention the importance of wireless sensor networks in achievements of the mentioned technologies. Almost in all aspects of 5G and IoT the main data source is from wireless sensor network. And implementation of cognitive radio technology in wireless sensor communication is one of the major problems which is being tackled by many researchers these days.

In this thesis we tried to analyze most of the factors which lead us to solving cognitive radio implementation in wireless sensor network. For simplicity we divided the objective of our study in to three sub objectives: 1) current IoT classification matrices and future directions which helped us understanding what look like the current IoT classification, 2) SenPUI(sensing and primary user interference): where we developed an algorithm that can take care of when, how and who can do energy scan to detect non congested channel in an environment where there is a secondary user, and 3) determine the average minimum time delay needed for a single wireless sensor data packet to reach its destination.

As far as our part one study, Major Existing Classification Matrices and Future Directions for Internet of Things, we effectively identified the currant matrices used to classify IoT, the common once are Classical or Traditional Way and Factor Dependent Classification. In this work we also studied future directions to be considered when developing or designing IoT classification factors. And we found that factors like security, safety, reliability, timing, energy efficiency, social infects, heterogeneity and dynamic are some of the base points to be considered for future standardized classification method.

SenPUI: Solutions for Sensing and Primary User Interference in Cognitive Radio Implementation of a Wireless Sensor Network is our second study. Which focus on how to share a channel for SU by assuring the communication of PU. This is implemented from prospective of when and how to do channel sensing while communicating without interrupting ongoing communication. We also developed a mechanism to notify changes for communicating device and application-based PU identification in this work. In SenPUI, some communication parameters, super-frame order, and beacon order are changing dynamically based on the number and payload of a packets to be received, which is managed by applying session during reception of packets.

Once we have information about IoT and cognitive radio implementation for WSN the final step is to see how long it will take for an average IoT packet to reach its destination, studied in our third part named Cognition-Based Delay Analysis to Determine the Average Minimum Time Limit for Wireless Sensor Communications. In this study four main delays used to calculate the end-to-end delay: 1) service delay, 2) queuing delay, 3) MAC delay, and 4) ACK delay. We also knew from our experiment that queuing delay is the most highest delay that WSN can experience most of the time. This work is done to help anyone interested in designing any WSN applications especially for those interested in cognitive radio based WSN.

All mentioned paper parts are published in world ranking journals you can find the links at beginning of this document. Even if the objective of this thesis is only implementing cognitive radio for WSN, we analyzed broader ideas which are related to the main objective. This by itself helped us to learn and analyze our objective from different perspective.

The detail analysis in this thesis will help further research in CN-WSN and channel scanning.

6. SAMPLE CODES

Below we have some of basic functionality cods used for simulating our results which is implemented in OMNET++ simulator:

```
#include "IEEE802154Mac.h"
Define\_Module(IEEE802154Mac);
void IEEE802154Mac::initialize(int stage)
{
    cSimpleModule::initialize(stage);
    if (stage == 0)
    {
        // initialize the debug output bool from NED parameter value
        macDebug = (hasPar("macDebug") ? (par("macDebug").boolValue()) : (false));
        macEV << "Initializing Stage 0 \n";
        // all Confirm Message types which could come in from the lower layer
        mappedMsgTypes["PLME-SET-TRX-STATE.confirm"] = SETTRXSTATE;
        mappedMsgTypes["PLME-GET.confirm"] = GET;
        mappedMsgTypes["PLME-SET.confirm"] = SET;
        mappedMsgTypes["PLME-CCA.confirm"] = CCA;
        mappedMsgTypes["PLME-ED.confirm"] = ED;
        mappedMsgTypes["PD-DATA.confirm"] = CONF;
        // all Request Message types which could come in from the upper Layer
        mappedMlmeRequestTypes["MLME-ASSOCIATE.request"] = MLMEASSOCIATE;
        mappedMlmeRequestTypes["MLME-DISASSOCIATE.request"] = MLMEDISASSOCIATE;
        mappedMlmeRequestTypes["MLME-GET.request"] = MLMEGET;
        mappedMlmeRequestTypes["MLME-GTS.request"] = MLMEGTS;
        mappedMlmeRequestTypes["MLME.RESET.request"] = MLMERESET;
        mappedMlmeRequestTypes["MLME-RX-ENABLE.request"] = MLMERXENABLE;
        mappedMlmeRequestTypes["MLME-SCAN.request"] = MLMESCAN;
        mappedMlmeRequestTypes["MLME-START.request"] = MLMESTART;
        mappedMlmeRequestTypes["MLME-SYNC-LOSS.request"] = MLMESYNC;
        mappedMlmeRequestTypes["MLME-POLL.request"] = MLMEPOLL;
        mappedMlmeRequestTypes["MLME-SET.request"] = MLMESET;
        mappedMlmeRequestTypes["MLME-ASSOCIATE.response"] = MLMEASSOCIATERESP;
        mappedMlmeRequestTypes["MLME-ORPHAN.response"] = MLMEORPHANRESP;
        syncLoss = false;
        scanning = false;
        scanStep = 0;
        mlmeRxEnable = false;
        txBuffer.setName("txBuffer");
        rxBuffer.setName("rxBuffer");
        isCoordinator = false;
        associated = false;
        associationProcessStarted = false;
        Poll = false;
        startNow = par("startWithoutStartReq").boolValue();
        isFFD = par("isFFD").boolValue();
        mpib = MacPIB();
        mpib.setMacSecurityEnabled(par("SecurityEnabled").boolValue());
```

```
mpib.setMacAssociatedPANCoord(false);
mpib.setMacBeaconOrder(15);  // it will change if we receive a Beacon or if we are the PA
mpib.setMacRxOnWhenIdle(true);  // if not, we wont receive any Messages during CFP / CAP
mpib.setMacPromiscuousMode(par("promiscuousMode").boolValue());
// initialize MacDSN (data sequence number) and MacBSN (beacon sequence number) to random
//mpib.setMacDSN(intrand(255));
mpib.setMacBSN(intrand(255));
// XXX instead of randomly selecting a 8-bit MacDSN, we use the index of the node for the
// module path to traverse: net.IEEE802154Nodes[index].NIC.MAC.IEEE802154Mac
unsigned int hostIndex = this->getParentModule()->getParentModule()->getParentModule()->g
ASSERT(hostIndex <= 255);   // msgHandle is 8-bit at the moment, to avoid collisions, we
mpib.setMacDSN(hostIndex);
macEV << "Initialization for MacDSN = " << mpib.getMacDSN() << " and MacBSN = " << mpib.g
//mpib.setMacAckWaitDuration(aUnitBackoffPeriod + aTurnaroundTime + ppib.getSHR() + (6 -
ASSERT(getModuleByPath("^.^.PHY") != NULL);// getModuleByPath returns the PHY module here
mpib.setMacAckWaitDuration(aUnitBackoffPeriod + aTurnaroundTime + (getModuleByPath("^.^.P
// inizialize PHY-related variables from PHY.ned -> FIXME -> PLME-GET msg should be used
phy_channel = getModuleByPath("^.^.PHY")->par("currentChannel").longValue();
ASSERT(phy_channel <= 26);  // check if parameter set in NED file is within boundaries
phy_bitrate = getRate('b');
phy_symbolrate = getRate('s');
trx_state_req = phy_IDLE;
nb = NotificationBoardAccess().get();
nb->subscribe(this, NF_RADIO_CHANNEL_CHANGED);
mlmeReset = false;
counter = 0;
waitGTSConf = false;
myPANiD = 0xffffU;
const char *addressString = par("macAddr");
if (myMacAddr.isUnspecified())
{
    if (!strcmp(addressString, "auto"))
    {
        ASSERT(getModuleByPath("^.^.^.") != NULL);    // getModuleByPath shall return the
        // generate MAC address with node index (e.g., node[3] -> MAC ...:03)
        myMacAddr = MACAddressExt::generateMacAddressWithNodeIndex(getModuleByPath("^.^.^
        macEV << "myMacAddr is unspecified -> assigning generated address = " << myMacAdd
        // change module parameter from "auto" to the generated address
        par("macAddr").setStringValue(myMacAddr.str().c_str());
    }
    else
    {
        myMacAddr.setAddress(addressString);
        macEV << "myMacAddr is unspecified -> assigning user set address (macAddr in omne
    }
}
trxState = false;
headerSize = 0;
// initialize timers
backoffTimer = new cMessage("backoffTimer", MAC_BACKOFF_TIMER);
deferCCATimer = new cMessage("deferCCATimer", MAC_DEFER_CCA_TIMER);
bcnRxTimer = new cMessage("bcnRxTimer", MAC_BCN_RX_TIMER);
bcnTxTimer = new cMessage("bcnTxTimer", MAC_BCN_TX_TIMER);
ackTimeoutTimer = new cMessage("ackTimeoutTimer", MAC_ACK_TIMEOUT_TIMER);
txAckBoundTimer = new cMessage("txAckBoundTimer", MAC_TX_ACK_BOUND_TIMER);
txCmdDataBoundTimer = new cMessage("txCmdDataBoundTimer", MAC_TX_CMD_DATA_BOUND_TIMER);
ifsTimer = new cMessage("ifsTimer", MAC_IFS_TIMER);
txSDTimer = new cMessage("txSDTimer", MAC_TX_SD_TIMER);
```

```
rxSDTimer = new cMessage("rxSDTimer", MAC_RX_SD_TIMER);
finalCAPTimer = new cMessage("finalCAPTimer", MAC_FINAL_CAP_TIMER);
scanTimer = new cMessage("scanDurationTimer", MAC_SCAN_TIMER);
gtsTimer = new cMessage("gtsTimer", MAC_GTS_TIMER);
if (true == startNow)
{
    isCoordinator = par("isPANCoordinator");
    unsigned short tmpBo = par("BeaconOrder");
    mpib.setMacBeaconOrder(tmpBo);
    unsigned short tmpSo = par("SuperframeOrder");
    mpib.setMacSuperframeOrder(tmpSo);
}
ASSERT(getModuleByPath("^.^.^.Network.stdLLC") != NULL);    // getModuleByPath returns th
unsigned short llcTXoption = getModuleByPath("^.^.^.Network.stdLLC")->par("TXoption");
ASSERT(llcTXoption <= 7);  // check if TXoption value is a recognized value
switch (llcTXoption)
{
    case 0: // direct CAP without ACK
    case 1: // direct CAP with ACK
    {
        dataTransMode = DIRECT_TRANS;
        break;
    }
    case 2: // direct GTS without ACK
    case 3: // direct GTS with ACK
    {
        dataTransMode = GTS_TRANS;
        break;
    }
    case 4:  // indirect CAP without ACK
    case 5:  // indirect CAP with ACK
    {
        dataTransMode = INDIRECT_TRANS;
        break;
    }
    case 6:   // indirect GTS without ACK
    case 7:   // indirect GTS with ACK
    {
         error("FIXME check if txOption => 6 and 7 are valid cases at all according to th
    }
    default: {
        error("[IEEE802154MAC]: wrong TXOption set / unknown value set!");
        break;
    }
}
panCoorName = par("panCoordinatorName").stdstringValue();
isRecvGTS = par("isRecvGts");
gtsPayload = par("gtsPayload");
ack4Gts = par("ackForGts");
// for beacon
rxBO = 15;
rxSO = 15;
beaconWaitingTx = false;
bcnLossCounter = 0;
// for timer
inTxSD_txSDTimer = false;
inRxSD_rxSDTimer = false;
index_gtsTimer = 0;
```

```
// for transmission
backoffStatus = 0;
inTransmission = false;
waitBcnCmdAck = false;
waitBcnCmdUpperAck = false;
waitDataAck = false;
waitGTSAck = false;
numBcnCmdRetry = 0;
numBcnCmdUpperRetry = 0;
numDataRetry = 0;
numGTSRetry = 0;
// device capability
capability.alterPANCoor = false;
capability.FFD = true;
//capability.mainsPower     = false;
capability.recvOnWhenIdle = mpib.getMacRxOnWhenIdle();
capability.secuCapable = false;
capability.alloShortAddr = true;
ASSERT(getModuleByPath("^.^.^.") != NULL);    // getModuleByPath returns the host module
capability.hostName = getModuleByPath("^.^.^.")->getFullName();
// GTS variables for PAN coordinator
gtsCount = 0;
for (int i = 0; i < maxGTSAllocations; i++)
{
    gtsList[i].devShortAddr = myMacAddr.getShortAddr();
    gtsList[i].startSlot = 0;
    gtsList[i].length = 0;
    gtsList[i].isRecvGTS = false;
    gtsList[i].isTxPending = false;
    gtsList[i].Type = false;
}
tmp_finalCap = aNumSuperframeSlots - 1;  // 15 if no GTS
indexCurrGts = 99;
// GTS variables for devices
gtsLength = 0;
gtsStartSlot = 0;
gtsTransDuration = 0;
/**
 *  FIXME --> untested
 *  for indirect transmission
 txPaFields.numShortAddr = 0;
 txPaFields.numExtendedAddr  = 0;
 rxPaFields.numShortAddr = 0;
 rxPaFields.numExtendedAddr = 0;
 */
// packet and statistics counter
numUpperPkt = 0;
numUpperPktLost = 0;
numCollisions = 0;
numBitErrors = 0;
numLostBcn = 0;
numTxBcnPkt = 0;
numTxDataSucc = 0;
numTxDataFail = 0;
numTxGTSSucc = 0;
numTxGTSFail = 0;
numTxAckPkt = 0;
numRxBcnPkt = 0;
```

```
        numRxDataPkt = 0;
        numRxGTSPkt = 0;
        numRxAckPkt = 0;
        numTxAckInactive = 0;
    }
    else if (stage == 1)
    {
        macEV << "Initializing Stage 1 \n";
        WATCH(bPeriod);
        WATCH(inTxSD_txSDTimer);
        WATCH(inRxSD_rxSDTimer);
        WATCH(numUpperPkt);
        WATCH(numUpperPktLost);
        WATCH(numCollisions);
        WATCH(numBitErrors);
        WATCH(numLostBcn);
        WATCH(numTxBcnPkt);
        WATCH(numTxDataSucc);
        WATCH(numTxDataFail);
        WATCH(numDataRetry);
        WATCH(numTxGTSSucc);
        WATCH(numTxGTSFail);
        WATCH(numGTSRetry);
        WATCH(numTxAckPkt);
        WATCH(numRxBcnPkt);
        WATCH(numRxDataPkt);
        WATCH(numRxGTSPkt);
        WATCH(numRxAckPkt);
        WATCH(numTxAckInactive);
        WATCH(isCoordinator);
        WATCH(associated);
        WATCH(scanning);
        WATCH(myMacAddr);
        WATCH(phy_bitrate);
        WATCH(phy_channel);
        WATCH(phy_symbolrate);
    }
    else if (stage == 2)
    {
        macEV << "Initializing Stage 2 \n";
        bcnRxTime = 0;
        if (true == startNow)
        {
            macEV << "startNow==true -> Starting up immediately \n";
            // lets start things
            if (true == isCoordinator)
            {
                if (false == isFFD)
                {
                    error("[IEEE802154MAC]: you want to start up a PAN Coordinator who is not an
                }
                mpib.setMacCoordExtendedAddress(myMacAddr);
                mpib.setMacShortAddress(myMacAddr.getShortAddr());  // simply use MAC short addre
                mpib.setMacPANId(myMacAddr.getInt());  // simply use MAC extended address
                mpib.setMacAssociationPermit(true);
                if (mpib.getMacBeaconOrder() < 15)
                {
                    // use superframe -> define slot duration and start beacon timer
```

```
                    txSfSlotDuration = aBaseSlotDuration * (1 << mpib.getMacSuperframeOrder());
                    startBcnTxTimer(true, simTime());  // send out first beacon ASAP
                }
                else if (mpib.getMacBeaconOrder() == 15)
                {
                    // don't use superframe (BO = 15) -> simply turn on receiver
                    genSetTrxState(phy_RX_ON);
                }
                else
                {
                    error("[IEEE802154MAC]: undefined Beacon Order found during startup");
                }
            }  // if == isCoordinator
            else
            {
                mpib.setMacPANId(0xffff);   // set broadcast PAN ID
                genSetTrxState(phy_RX_ON);
            }  // if != isCoordinator
        }
        else
        {
            macEV << "Waiting for MLME-START primitive from upper layer \n";
        }
    }
}
```

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