Wireless Body Area Networks: Efficient Coexistence by Interference Management and Avoidance

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Except where otherwise indicated, this thesis is my own original work.

Samaneh Movassaghi

May 25, 2020

To my beloved parents, *Ahmad* and *Soheila*,
my lovely brother *Ali* and my gorgeous sisters.

– May 25, 2020

Acknowledgments

I would like to express sincere gratitude to Dr. David Smith, my primary supervisor, who helped immensely and guided me with his knowledge and experience throughout the critical point of my research phase to completion. I am also grateful for his continuous patience, support and advice during my studies.

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Abstract

Recent advancements in wireless communications, microelectromechanical systems (MEMS) and integrated circuits have enabled the development of low-power, intelligent, miniaturized sensors that can be placed strategically in, on, or around, the human body. The integration of these sensors in the form of a network is called wireless body area networks (WBANs). One key application of WBANs is in health monitoring to transport mission-critical and delay-sensitive data. Thus, a reliable WBAN needs to be highly immune to interference. Based on the IEEE 802.15.6 standard devised for WBANs, nodes in a single WBAN can avoid interference by using techniques such as time division multiple access (TDMA). In fact, the social nature of these networks and their high mobility highlights the importance of efficient communication between multiple WBANs that coexist with one another. Due to their mobility, it is generally not feasible to allocate a global coordinator. Moreover, with an increase in the number of WBANs that can coexist within close proximity of one another, communications can be severely degraded if interference avoidance is not taken into consideration.

Thus, the primary goal of this dissertation is to devise new intelligent radio spectrum allocation strategies not only to avoid interference, but also to make best-use of the limited available spectrum for reliable communication in large-scale deployments. First, we introduce an adaptive and partially orthogonal scheme called Smart Spectrum Allocation (SCA), which allows synchronous and parallel transmissions between nodes in coexisting WBANs. This allows the practical coexistence of these networks with far less communication delay, higher throughput and less interference. A node's traffic priority, packet length, received signal strength along with nnthe density of sensors within a WBAN are further incorporated in the SCA protocol to comply with real-world variations in terms of data type and message length. We later deploy an energy harvesting module for sensor radios in these networks and use the radio interference as a source of energy. Further, in order to better optimize

resource allocation, a hybrid scheme incorporating graph-coloring with pair-wise clustering of coexisting WBANs is proposed.

Next, in order to incorporate variations in channel assignment, based on body-dynamics mobility within each individual WBAN and amongst multiple WBANs, a prediction algorithm is proposed to feed in these dynamics and accordingly update resource allocation. This proposal maximises the resource usage and transmission rate as well as offering a convenient trade-off between spectral reuse, transmission range and outage probability. Simulations and detailed analysis verify that the proposed approach is robust to variations in channel conditions, increase in sensor node-density within each WBAN, and an increase in the number of coexisting WBANs.

Finally, we propose a self-organization scheme for the coexistence of multiple WBANs, which is biologically inspired from synchronization of fireflies in nature. This approach achieves distributed management of the available spectrum amongst coexisting WBANs, and avoids the need for global management. It allows coexisting WBANs to use delayed information from previous transmissions to adjust a collision-free TDMA schedule, avoiding interference across WBANs, for future transmissions. Simulation results show that our protocol achieves rapid convergence to an updated spectrum allocation with higher packet delivery ratio, despite very-limited shared information from coexisting networks, implying that overhead is significantly reduced on WBANs with constrained resources.

Honors and Awards

- Awarded as ICT Student of the year at the Australian Computer Society (ACS) Digital Disruptor Awards *November 2017*
- Awarded Google PhD Fellowship in Networking in recognition of outstanding research in Computer Science *June 2017*
- Nominated as Postgraduate of the year at iAwards Australia *Apr 2017*
- Represented as Top Six Post Graduates Australia-wide on GradAustralia *Feb 2017*
- Awarded best poster presentation at 17th Australian Communications Theory Workshop (AusCTW) held in the Australian National University amongst 42 poster presentations on the project entitled: "Enabling the Practical Deployment of Wearables".

  Jan 2017

- Awarded 2nd Prize in Unearthed Hackathon (Melbourne, Australia), in a team named after “Solution42" where we placed sensors on robotic devices in order to monitor key indicators (such as sound, temperature, and pressure) of processing plants.

  Nov 2015

- Winner of Spirit of Healthhack Award (Sydney, Australia) as a member of a team of seven working a project named “SenseS", which looks at stress detection and management using wearable devices. (http://healthhack.com.au/)

  Oct 2015

- Winner of IEEE Technology of the Future (iToF15) Competition and Exhibition mongst coursework/research students of the Faculty of Engineering from ALL

universities in NSW: Category “Networking, Cloud Computing & Security" for project entitled “Self-Charging, Self-Organizing, Self-less Wearables"

Oct 2015

- Awarded as one of the top Seven Research Scientists Australia-wide known as CSIRO’s Seven. (http://www.csiro.au/seven) *Sept 2015*

- Awarded NASSCOM Australia awards in Technical Business Innovation (one recipient per year) for project entitled “Battery-less, Self-Organizing, Interference-free Wearable Networks". *Sep 2015*

- Nominated as ICT researcher of the year by the CEO of the Australian Computer Society (ACS) for the ACS Digital Disruptors Awards. *Aug 2015*

- Elected as one the representatives of ANU across all faculties at the Global Young Scientist Summit (GYSS) (five recipients per year).

July 2015

- Nominated as Student of the year at the Australian National University (ANU).

Jun 2015

- Awarded the Best Innovation Prize at the FEIT Showcase amongst all researchers in Faculty of Engineering and IT of the University of Technology, Sydney (UTS). *Aug 2014*

- Awarded First Place in the John Holland Tower Building Competition at University of Technology, Sydney (UTS).

Aug 2013

- Awarded Teaching Fellowship, University of Technology, Sydney (UTS). *Mar 2012*

- Awarded Teaching Fellowship for Spring Semester, University of Technology, Sydney (UTS). *July 2012*

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Chapter 1

Introduction

1.1 Research Motivation

A key solution to more affordable and proactive health care systems is through wearable monitoring systems capable of early detection of abnormal conditions resulting in major improvements in ones quality of life. In this case, monitoring vital signals such as heart rate allows patients to engage in their normal activities instead of staying at home or close to a specialized medical service. This can only be achieved through a network consisting of intelligent, low-power, micro and nano-technology sensors and actuators, which can be placed on the body, or implanted in the human body (or even in the blood stream), providing timely data. Such networks are commonly referred to as Wireless Body Area Networks. However, formidable technical and social challenges must be dealt with to allow for their practical adoption. These challenges offer various system design and implementation opportunities with the major objectives of minimum delay, maximum throughput, maximum network lifetime and reducing unnecessary communication related energy consumption (e.g. control frame overhead, idle listening and frame collisions).

Nodes in wireless body area networks (WBANs) have a heterogeneous structure in terms of the computing power and available energy to nodes, such as sensors and the hub. This should be considered in interference mitigation to avoid node depletion and minimize interference. Since WBANs have significantly limited resources, their operations should be extremely energy efficient to extend the battery-lifetime as much as possible. Generally a person is associated with a single WBAN, and as a simpler implementation each WBAN is coordinated by the central hub, i.e., gateway

in a one-hop star topology. As well as an individual WBAN's operation being important itself, Body-to-Body Network (BBN) communications have recently attracted interest, e.g., Cotton and Scanlon [2009]; Alam and Hamida [2015a]; Meharouech et al. [2014]; Elias et al. [2015]; Ben Arbia et al. [2015]; Bhandari and Moh [2015]. In most configurations, BBNs consist of several WBANs that each consist of several wearable sensor nodes operating with coordinator mobile radio terminals. However, the practical deployment of BBNs has not progressed due to a number of challenges, specifically with regards to radio interference mitigation amongst coexisting WBANs.

Co-channel interference mitigation in WBANs is quite challenging due to the large density, high mobility and the uncoordinated nature of WBANs. The mobility of WBANs makes interference more challenging as WBANs can move into each others range and result in a large density of people with their WBANs needing to coexist with each other Zhang et al. [2010]; Hayajneh et al. [2014]. Coexistence has also been shown to be more severely affected at higher data rates Yang and Sayrafian-Pour [2011]. Additionally in most applications WBANs are rational and self-interested so that they do not cooperate with each other to make power decisions and each WBAN may independently chooses its transmission power based on its belief of other WBANs' choices Kazemi et al. [2010]. On the other hand, the most valuable resource of a WBAN is energy, which can be easily wasted by inter-network interference reducing the SINR value and leading to throughput degradation. Furthermore, in order to maintain the minimum acceptable link quality, the transmit power should be limited to minimize the interference level and save battery life Yang and Sayrafian-Pour [2011]. Therefore, interference mitigation schemes aim to decrease the average transmit power using link adaptation mechanisms whilst maintaining link quality at the cost of lower data rate or throughput Yang and Sayrafian-Pour [2011]. This can be even more challenging in the case of WBANs as frequent battery replacement or recharging is not feasible Kazemi et al. [2011b]. Thus, the scarce constraint of energy in WBANs requires simple, robust, intelligent and light solutions for these networks to cope with the small processing power and small memory of their devices.

Even though interference mitigation in wireless networks has been extensively studied over the years, WBANs introduce new challenges, which have not yet been

addressed: The entire WBAN network is in motion due to postural body movements, so the base-stations are mobile which makes coordination amongst WBANs impossible. A WBAN mainly has more frequent topology changes and a higher mobile speed compared to static and low mobility scenarios in Wireless Sensor Networks (WSNs). In fact, the challenges of radio interference mitigation that are specific to WBANs are as follows: 1) Interference on a single node depends on the independent decisions made by multiple coordinators; 2) The system architecture is decentralized as no central entity can provide global control in terms of interference on nodes of different WBANs; 3) Due to the increase in the number of nodes in a WBAN a solution based on a centralized agent will not be scalable; 4) Individual decisions of each WBAN coordinator have to be self-adaptive based on the decisions of the other coordinators and the surrounding environment. 5) Coexisting WBANs use several transmission technologies that share the same unlicensed band (ISM band) which leads to a dramatic increase on the level of interference of coexisting WBANs as well as their network performance. For instance, IEEE 802.15.1 (Bluetooth), IEEE 802.15.4 (Zigbee) and IEEE 802.11 (WiFi) use the same 2.4 GHz ISM band.

1.2 Thesis Statement

This thesis will investigate interference avoidance and self-organization for efficient coexistence of WBANs.

The focus of this thesis is on narrowband communications around the 2.4 GHz carrier frequency. In this context, this thesis aims to answer the following questions:

1. Can the spatial reuse or spectral efficiency of coexisting WBANs increase by allowing simultaneous transmissions when possible?

2. Will graph coloring be able to assist with WBAN coexistence management?

3. Is it possible to jointly harvest energy and avoid interference at the same time while managing coexistence amongst WBANs?

4. How can the unknown dynamics relative to postural body movements and the movement of WBANs with respect to one another be predicted?

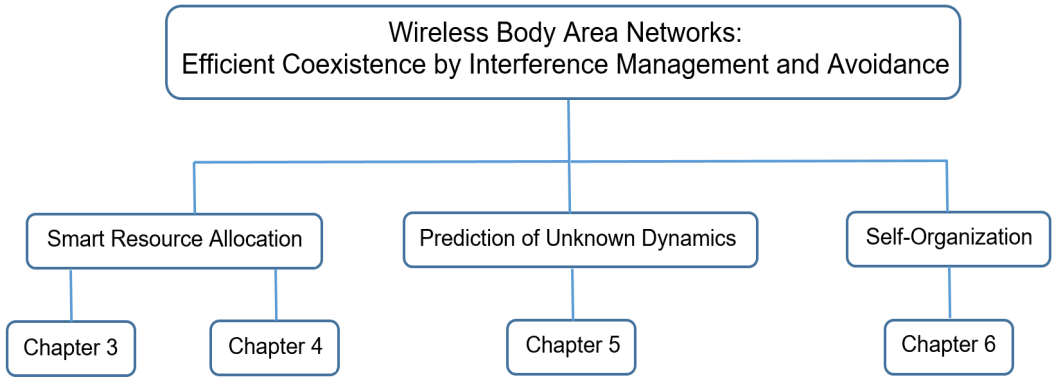


Figure 1.1: Thesis flowchart

5. Can a simple, lightweight self-organization approach be proposed to manage the coexistence of WBANs without the need for a global coordinator?

6. Is it possible to simultaneously apply self-organization and interference mitigation for efficient coexistence of multiple WBANs?

1.3 Thesis Outline

Fig.1.1 presents the outline of this thesis. The work presented in this dissertation is focused on the design of co-channel interference mitigation schemes for coexisting IEEE 802.15.6-based WBANs, more specifically around three main contributions: (i). spectrum allocation for interference mitigation; (ii) prediction of unknown dynamics, and (iii) self-organization for coexistence management. In Chapter 3, node-level spectrum allocation amongst coexisting WBANs is described. Chapter 4 incorporates changes in packet length, type of data, traffic as well as using graph coloring and energy harvesting for extended network lifetime. Prediction of the unknown dynamics relative to postural body movements and the movement of coexisting WBANs with respect to one another is discussed in Chapter 5. A simple light-weight biologically inspired self-organization scheme for efficient coexistence of WBANs without the need for a global entity is proposed in Chapter 6, along with its incorporation into the smart spectrum allocation scheme proposed earlier in Chapter 3.

A summary of the contributions of each chapter are presented below:

Chapter 2: Literature Review

An overview of the wireless body area network technology and its network architecture, followed by discussing the critical factors influencing protocol design in the medium access control/ physical (MAC/PHY) layers of the WBAN protocol stack as well as guidelines provided in the IEEE 802.15.6 standard devised for WBANs are described. The state-of-the-art protocols for the coexistence of WBANs are also explored with an objective to point out a number of open research issues. Finally, a comprehensive review and classification on existing proposals for interference mitigation in WBANs is provided.

Chapter 3: Smart Spectrum Allocation

In Chapter 3, a node-level interference mitigation scheme is proposed to maximize the spatial reuse. More specifically, nodes from different WBANs with lower interference levels are allowed to transmit on the same channel while high interference nodes transmit orthogonally. Simulation results show that the proposed scheme can achieve a spatial reuse of 20 times higher than the fully orthogonal scheme whilst maintaining a low interference level. The proposed scheme is further analysed and a closed form expression is derived for the average spatial reuse. Accordingly, the outage probability is formulated which is defined as the probability that the interference level in a specific time interval is higher than a predefined threshold. Then, a probabilistic approach is proposed to reduce the outage probability at the cost of a very small reduction in spatial reuse. To the authors' best knowledge, such an approach for internetwork interference mitigation in WBANs has not been investigated yet. More specifically, existing internetwork proposals for WBANs, consider each WBAN network as a whole, allowing orthogonal transmission between coexisting WBANs with different approaches. Whilst we are the first to propose an interference mitigation scheme at the node-level which can substantially increase the reuse as well as reduce the delay that is quite beneficial, specifically to medical data with low delay requirements of $125ms$ Sta.

The main contributions of Chapter 3 are as follows:

- A node-level dynamic spectrum allocation algorithm is proposed to reduce the

interference caused by simultaneous transmission of sensors from coexisting WBANs.

- This proposal reduces the number of orthogonal channels allocated to sensors of interfering WBANs, which substantially increases the spatial reuse and significantly reduces the latency with generally improved throughput of the entire network.
- An opportunistic internetwork interference mitigation is formulated as an optimization problem with analytical calculations that define the optimum allocation of transmission time to each sensor amongst collocated WBANs.
- A lightweight solution is proposed that complies with the scarcity of resources in terms of channel availability by increasing the spatial reuse and reducing the overall network transmission delay.

The results of this chapter have appeared in the following publications: (Movassaghi et al. [2014c]; Movassaghi [2018])

C11. **Smart Spectrum Allocation for Interference Mitigation in Wireless Body Area Networks**
Movassaghi, S., Abolhasan, M., Smith, D, B., *Proceedings of the IEEE International Conference on Communications(ICC), pp.5688-5693, July 2014, Sydney, Australia*.

J9. **Opportunistic Spectrum Allocation for Interference Mitigation in Coexisting Wireless Body Area Networks**
Movassaghi, S., Smith, D.B, Abolhasan, M. *Transactions on Sensor Networks (TOSN), pp.1-14, vol 14, Mar 2018*

Chapter 4: Adaptive Inter-network Interference Mitigation Amongst Co-existing WBANs with Energy Harvesting and Graph Coloring

This chapter extends the proposal in Chapter 3 to consider the traffic priority and packet length of a node as well as the number of nodes in each WBAN and their SINR in the transmission of a node. Simulation results and theoretical analysis show that the proposed approach can significantly increase the spatial reuse. The proposed

method significantly degrades the interference level and adds no complexity to the sensors as only the coordinators are required to negotiate for channel assignment.

Also, a joint node-level interference mitigation and energy harvesting scheme is considered to achieve optimum spatial reuse as well as significantly increasing the network lifetime. More specifically, nodes from different WBANs with lower interference levels are allowed to transmit on the same channel while high interference nodes transmit orthogonally. At the same time, the remaining sensor nodes harvest the wireless broadcast energy from the transmission of other sensor nodes. The proposed approach reveals an interesting phenomenon due to both capturing the interference signal to be used as a source of energy, and mitigating the interference at the same time. We refer to the smart spectrum allocation scheme and show that the higher the spatial reuse, the higher the average amount of energy harvested at the expense of higher outage probability. We further propose a probabilistic approach to reduce the outage probability at the cost of a very small reduction in spatial reuse and harvested energy. To the best of our knowledge, there is no prior work on joint energy harvesting and interference mitigation for WBANs.

A combination of graph coloring and cooperative scheduling at node-level for interference mitigation amongst coexisting WBANs is further considered. In fact, cooperative scheduling is deployed amongst each pair of WBANs that form a cluster and later consider graph coloring amongst the pair-wise clusters that have been formed. Nodes from different WBANs with lower interference levels are allowed to transmit on the same channel, whilst allocating orthogonal channels for high interference nodes. Theoretical analysis shows that the proposed scheme can achieve a much higher spatial reuse than either cooperative scheduling or graph coloring alone. The proposed method maintains a low interference level and adds no complexity to the sensors as only the coordinators are required to negotiate channel assignment.

The main contributions of Chapter 4 are as follows:

- Traffic priority, packet length, SINR and number of nodes in a WBAN is considered in the transmission of a node.

- The interference signal that falls into the network is proposed to be used as a

source of energy for future transmissions.

- A scheme is devised to jointly harvest energy from the interference signals and avoid interference at the same time.
- A hybrid of graph coloring and cooperative scheduling is proposed to increase spatial reuse.

The results of this chapter have appeared in the following publications: (Movassaghi et al. [2014d,e,b])

C14. **AIM: Adaptive Internetwork Interference Mitigation Amongst Co-existing Wireless Body Area Networks**
Movassaghi, S., Abolhasan, M., Smith, D, B., Jamalipour, A. *Proceedings of the IEEE Global Communications Conference (GC), pp.2460-2465, December 2014, Texas, Austin, United States*.

C13. **Joint Energy Harvesting and Interference Mitigation Amongst Coexisting Wireless Body Area Networks**
Movassaghi, S., Abolhasan, M., Smith, D, B., Jamalipour, A. *Invited Paper for ACM International Conference on Body Area Networks (BodyNets), pp.240-246, September 2014, London, Great Britain*.

C12. **Cooperative Scheduling with Graph Coloring for Interference Mitigation in Wireless Body Area Networks**
Movassaghi, S., Abolhasan, M., Smith, D, B., *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), pp.1691-1696, April 2014, Istanbul, Turkey*.

Chapter 5: Exploiting Unknown Dynamics Amongst Coexisting WBANs

The aim of this chapter is to leverage the social nature of WBANs to assist BBN communication to achieve enhanced performance, and give significant context in terms of an up-to-date review of relevant literature. More specifically, to maximize performance whilst minimizing the overall power consumption with simple and low-computational models that minimize energy drainage. The effect of channel assign-

ment with dynamics relative to postural body movements and the social interaction of WBANs with respect to one another is taken into consideration.

The main contributions of Chapter 5 are as follows:

- The impact of intra-WBAN and inter-WBAN mobility on communication amongst multiple coexisting WBANs is investigated;
- A viable solution for interference mitigation for mobile coexisting WBANs that functions with limited resources is provided.
- A prediction algorithm based on dynamics of movement of nodes within a WBAN which incorporates the movements of WBANs with respect to one another as well as postural body movements is proposed.

The results of this chapter have appeared in the following publications: (Movassaghi et al. [2016, 2015a])

J8. **Enabling Interference-Aware and Energy-Efficient Coexistence of Multiple Wireless Body Area Networks with Unknown Dynamics**
Movassaghi, S., Majidi, A.,Jamalipour, A., Smith,D., Abolhasan, M., *Invited paper in IEEE Access Journal, 2935 - 2951, vol 4, June 2016*

C16. **Exploiting Unknown Dynamics in Communications Amongst Coexisting Wireless Body Area Networks**
Movassaghi, S., Majidloo, A, M., Smith, D, B., Abolhasan, M., Jamalipour, A. *Proceedings of the IEEE Global Communications Conference (GC), pp.1-6, December 2015, San Diego, USA*.

Chapter 6: Biologically inspired self-organization and node-level interference mitigation amongst multiple coexisting WBANs

In this chapter, a biologically inspired algorithm for achieving global coordination is proposed. In other words, a self-organization algorithm amongst multiple coexisting WBANs with a single-hop star topology based on the theory of pulse-couple oscillators. Given a set of coexisting WBANs that generate events periodically with a fixed period, coexisting WBANs converge to a state where all are evenly allocated

a portion of the spectrum for their transmissions. The proposed algorithm is decentralized, simple and requires a little amount of fixed memory per coordinator node despite the network size. The simplicity of the proposed approach and its operation based on the minimum amount of information exchange make it robust to different scales of deployment and also allow its adaptability to variations. The proposed protocol is also robust to variations of coordinators leaving or joining the network as it self-adjusts to provide fairness amongst the transmissions of coexisting coordinators. Simulation and numerical results confirm that the proposed scheme rapidly achieves stability. To the authors' best knowledge, this is the first time a self-organization approach is proposed amongst coexisting WBANs.

The main contributions of Chapter 6 are as follows:

- A simple, light weight approach is proposed for self-organization of multiple coexisting WBANs biologically inspired from the synchronicity of fireflies in nature.
- Simple and lightweights solutions have been proposed that comply with the scarcity of resources in terms of channel availability by increasing the spatial reuse and reducing the overall network transmission delay.

The results of this chapter have appeared in the following publications: (Movassaghi et al. [2017, 2015b])

C17. **Biologically Inspired Self-Organization for Node-Level Interference Mitigation of Multiple Coexisting Wireless Body Area Networks**
Movassaghi, S., Smith, D.B, and Abolhasan, M. *Proceedings of the 13th IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), pp.1-6, 26-30 June, 2017, Valencia, Spain* .

C15. **Self-Organization Amongst Multiple Co-existing Wireless Body Area Networks**
Movassaghi, S., Majidloo, A, M., Smith, D, B., Abolhasan, M., Jamalipour, A. *Proceedings of the IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), pp 1323-1327, September, 2015, Hong Kong*.

Chapter 7 provides a summary of the results of this thesis, and discusses future work.

1.4 Notation and Terminology

Table 1.1: Notation and Terminology

Notation	Description
N_c	Number of coexisting WBANs
N_s	Number of sensors in each WBAN
T_d	Superframe Length
$R_0(t)$	Reuse factor
$D(t)$	Distance in meters between coordinators of coexisting WBANs
γ_{th}	Threshold SINR
γ_0	Reference SINR
P_r	Received power in dB
P_t	Transmit power in dB
(i,j)	Sensor j from $WBAN_i$
$SINR_{i,j}$	SINR of node j in the vicinity of $WBAN_i$
r	Radius of Sensing Range
R	Radius of Communication Range
$P_{0,dB}(d,t)$	Path loss at distance d
$P_{I,i}$	Interference Power from sensor node i
m	Number of nodes that coexist in the interference region of the WBAN of interest
α	Angle between the direction of movement of a WBAN vs the horizontal access
τ	Time at which interference between coexisting WBANs initiates
τ'	Duration for which coexisting WBANs will interfere on one another
$\vec{RP}$	Location of coordinator node of each WBAN
MN	Sensor nodes of each WBAN
$\vec{GM}$	Vector of group movement of the coordinator of each WBAN with its sensors
$\vec{RM}$	Vector of movement of sensor nodes in each WBAN towards their coordinator
Rx_{sens}	Received sensitivity
M	Number of coexisting WBANs
N	Number of sensors in a WBAN
R	Coverage radius of each WBAN
B_k	kth WBAN
T	Superframe Length
s_k^i	sensor i in B_k
s_{-k}^i	sensor i in B_{-k}
RSS	Intra-WBAN Received Signal Strength
JRIS	Inter-WBAN Joint Received Signal Strength
γ_k^i	RSS from s_k^i to its coordinator
γ_{th}	Threshold RSS
η_{-k}^i	JRIS from s_{-k}^i to its coordinator
P_k	Priority level of B_k accumulated from its sensors
$p(s_k^j)$	Priority level of sensor j in B_k

Chapter 2

Literature Review

World population growth is facing three major challenges Milenkovic et al. [2006]; Otto et al. [2005]: a demographic peak of baby boomers, an increase in life expectancy leading to an aging population and a rise in health care costs. In Australia, life expectancy has increased significantly from 70.8 years in 1960 to 81.7 years in 2010 and in the United States from 69.8 years in 1960 to 78.2 years in 2010, an average increase of 13.5%[1]. Given the U.S. age pyramid[2] shown in Fig. 2.1, the number of adults ranging from 60 to 80 years old in 2050 is expected to be double that of the year 2000 (from 33 million to 81 million people)[3]. It is expected that this increase will overload health care systems, significantly affecting the quality of life. Further, current trends in total health care expenditure are expected to reach 20% of the USA Gross Domestic Product (GDP) in 2022, which is a big threat to the US economy. Moreover, just considering the US, the overall health care expenditures in the U.S. has significantly increased from 250 billion in 1980 to 1.85 trillion in 2004, even though 45 million Americans were uninsured[4]. These statistics, which are generally reflected globally across developed countries, necessitate a dramatic shift in current health care systems towards more affordable and scalable solutions.

It is also very important to consider that millions of people die from cancer, cardiovascular disease, Parkinson's, asthma, obesity, diabetes and many more chronic diseases every year. The common problem with all current fatal diseases is that many people experience the symptoms and are diagnosed when it is too late. Re-

[1] http://www.worldlifeexpectancy.com/history-of-life-expectancy
[2] http://thesocietypages.org/socimages/2010/03/08/the-graying-of-america
[3] http://thesocietypages.org/socimages/2010/03/08/the-graying-of-america
[4] http://healthcare-economist.com/2006/01/30/trends-in-health-care-spending

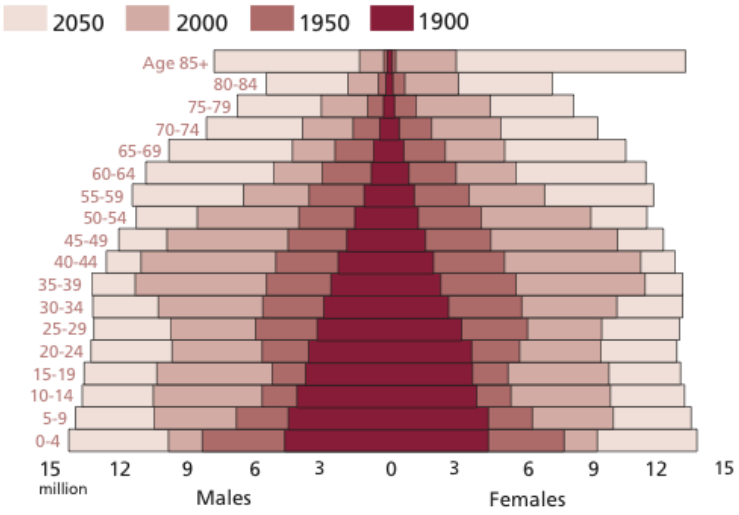


Figure 2.1: U.S. Age Pyramid

search has shown that most diseases can be prevented if they are detected in their early stages. Therefore, future health care systems should provide proactive wellness management and concentrate on early detection and prevention of diseases. One key solution to more affordable and proactive health care systems is through wearable monitoring systems capable of early detection of abnormal conditions resulting in major improvements in the quality of life. In this case, even monitoring vital signals such as the heart rate allows patients to engage in their normal activities instead of staying at home or close to a specialized medical service. This can only be achieved through a network consisting of intelligent, low-power, micro and nano-technology sensors and actuators, which can be placed on the body, or implanted in the human body (or even in the blood stream), providing timely data. Such networks are commonly referred to as wireless body area networks (WBANs). In addition to saving lives, prevalent use of WBANs will reduce health care costs by removing the need for costly in-hospital monitoring of patients.

A typical WBAN consists of a number of miniature, lightweight, micro and nano technology sensors that each collect one or more physical or physiological parameters from the body. A range of sensors used in these networks are as follows: electrocardiogram (ECG); electroencephalograph (EEG); Electromyography (EMG); tri-axial direction and movement acceleration; blood pressure; temperature; perspi-

ration; and pulse rate. The IEEE 802.15.6 working group has considered WBANs to operate in either a one-hop or two-hop star topology with the node in the center of the star being placed on a location like the waist Tachtatzis et al. [2010]; Shah and Yarvis [2006]. Two feasible types Sukor et al. [2008] of data transmission exist in the one-hop star topology: *transmission from the device to the coordinator* and *transmission from the coordinator to the device*.

The communication methods that exist in the star topology are *beacon mode* and *non-beacon mode*. In the *beacon mode*, the network coordinator, which is the node in the center of the star topology controls the communication. It transmits periodic beacons to define the beginning and the end of a superframe to enable network association control and device synchronisation. The duty cycle of the system, which is the length of the beacon period, can be specified by the user and is based on the particular WBAN's standard Sukor et al. [2008]; IEE [2006]. In the *non-beacon mode*, a node in the network is capable of sending data to the coordinator and can use Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) when required. The nodes need to power up and poll the coordinator to receive data. However, the coordinator cannot communicate with the nodes at all times as the nodes must wait till they are invited to participate in a communication Sukor et al. [2008].

Since both one-hop and two-hop star topologies exist in WBANs, there needs to be careful consideration of whether to choose a one-hop or a two-hop topology. When all nodes in the network are directly connected to the sink, the network is considered to have a one-hop star topology. In a WBAN, the coordinator is known as the sink node to which all nodes talk. However, in a multi-hop architecture nodes are connected to access points via other nodes. Literature has shown multi-hop transmission has a higher delay and lower transmission power compared to the one-hop star topology. The multi-hop configuration involves overheads along with its network operation; as increasing the number of hops could lead to a high complexity. As per the latest version of the IEEE standard proposed for WBANs in February 2012 Sta, only two hops are supported in IEEE WBAN standards compliant communication. Proprietary systems could use more than two hops, but then inter-operability would be a problem, as they would not be standard-compliant.

Table 2.1: Applications of WBANs

WBAN Applications	Medical	Wearable WBAN	Assessing Soldier Fatigue and Battle Readiness
			Aiding Professional and Amature Sport Training
			Sleep Staging
			Asthma
			Wearable Health Monitoring
		Implant WBAN	Cardiovascular Diseases
			Cancer Detection
		Remote Control of Medical Devices	Ambient Assisted Living (AAL)
			Patient Monitoring
			Tele-medicine Systems
	Non-Medical		Real Time Streaming
			Entertainment Applications
			Emergency (non-medical)

In terms of applications, WBANs span a wide area such as military, ubiquitous health care, sport, entertainment and many other areas. IEEE 802.15.6 categorizes WBAN applications into medical and non-medical (Consumer Electronics) as can be seen in Table 2.1. The main characteristic in all WBAN applications is improving the user's quality of life Latré et al. [2011]. However, the technological requirements of WBANs are application-specific.

2.1 Communication Architecture of WBANs

A clear description of the communication architecture is essential for the design of any communication protocol. In this section, the communication tiers of WBANs and all possible scenarios are presented. The communication tiers of WBANs as shown in Fig.2.2 can be classified as follows:

- *Tier-1: Intra-WBAN communication:* This tier depicts the interaction of nodes within a WBAN network and their respective transmission ranges (2 meters) in, on and around the human body. Sensory devices within each WBAN forward their data to a Personal Server (PS), also referred to as the coordinator/hub, located in tier-1. The processed data is then transmitted to an access point in Tier-2.

- *Tier-2: Inter-WBAN communication:* This communication tier is formed between the personal server/hub/coordinator and one or more Access points (AP). The access points can be either part of the infrastructure or be strategically placed

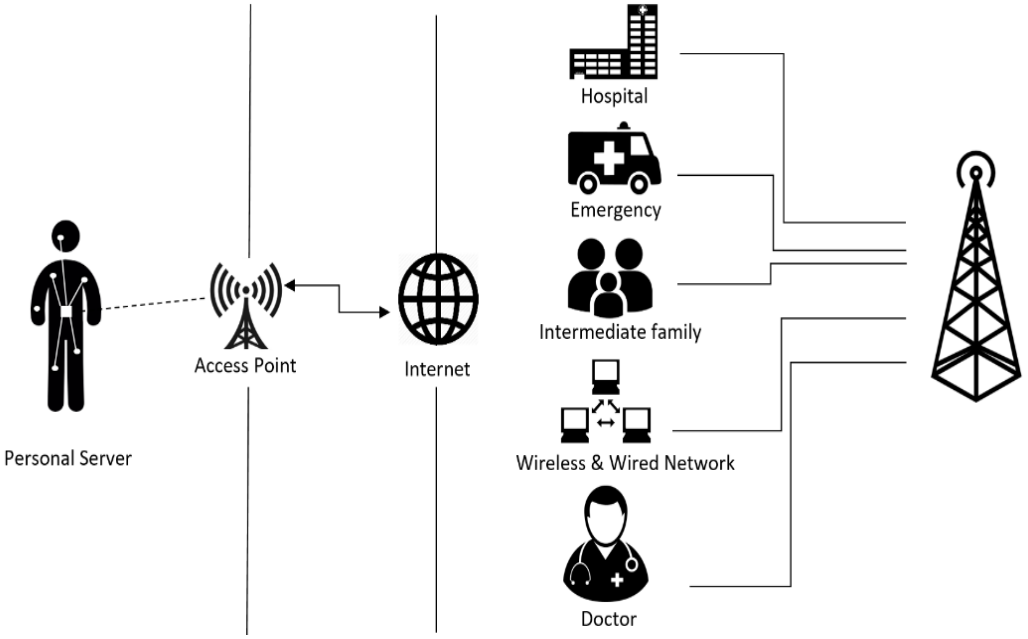


Figure 2.2: Communication Tiers in a WBAN

in a dynamic environment to handle emergency situations. This tier aims to interconnect WBANs with other networks like cellular and the Internet. The inter-WBAN communication tier is later divided into two subcategories: *infrastructure based architecture* and *ad-hoc based architecture*. This architecture allows for the dynamic deployment of WBANs in a limited area while providing centralized management and security control. The *ad-hoc based architecture* consists of multiple APs which form a mesh architecture that enables their fast and flexible deployment and expansion and supports patient mobility and provides larger coverage areas. This feature extends the coverage area compared to the infrastructure-based deployment from 2 meters to 100 meters which are suitable for both short and long term setups.

- *Tier-3: Beyond-WBAN communication:* This tier is mainly used in metropolitan areas. It can bridge the gap between Tier-2 and this tier, from the Internet to the medical server. The design of this tier is application-specific. For instance, in the case of a medical environment, a database that consists of the medical

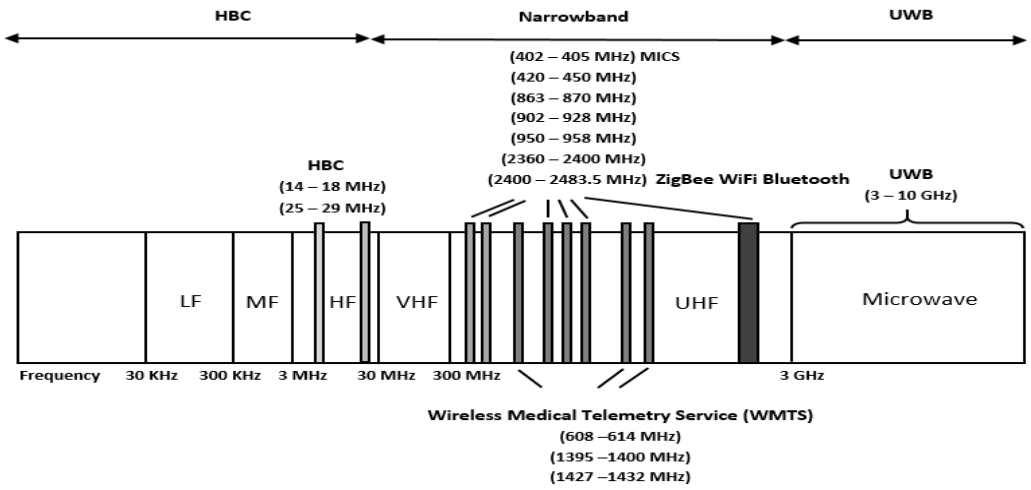


Figure 2.3: WBAN Frequency Bands

history of its users is essential. This allows the patients or doctors to notify an emergency status to the Internet through a Short Message Service (SMS). Moreover, this tier allows the restoration of all necessary information of a patient for its treatment.

2.2 Guidelines from the WBAN Standard

To allow efficient coexistence in WBANs certain requirements and characteristics need to be considered to comply with that advised in the IEEE 802.15.6 standard which is described as follows:

- The physical layer should be capable of supporting up to 10 randomly distributed collocated WBANs in a $6m^3$ cube where each WBAN has to be capable of supporting up to 256 nodes.
- Devices used in WBANs should be capable of transmitting at 0.1 mW (-10 dBm) with the maximum radiated transmission power being less than 1 mW (0 dBm) to comply with the Specific Absorption Rate (SAR) of the Federal Communications Commission's 1.6 W/Kg in 1g of body tissue.
- A 256 octet payload should have a Packet Error Rate (PER) of less than 10% for

about 95% of the best-performing links.

- Power saving mechanisms should be deployed to allow for efficient communication of coexisting WBANs in energy constrained environments.
- WBAN applications should support jitter, latency and reliability. Acceptable latency is less than 125 ms in medical applications and less than 250 ms in non-medical applications where jitter should be less than 50 ms.
- WBAN links should support data rates of the order of 10 Kb/s to 10 Mb/s.
- Adding or removing nodes from the network should not take more than 3 seconds.
- Nodes should maintain reliable communication with variations in postural body movements. Therefore, shadowing, fading and unstable channel conditions must not effect their communication.
- WBANs should deploy QoS management features to be self-healing and secure along with considering priority services.
- In-body and on-body WBANs should be capable of coexisting within each others range.
- WBANs should be able to operate in a heterogeneous environment with different types of networks.

2.3 Coexistence and Interference for WBANs

To understand the issues with the practical deployment of these networks the term *interference* needs to be explicitly defined. *Interference* evolves with the coexistence of multiple wireless networks or sensors, whilst *coexistence* refers to the overlap of ranges between wireless networks. Fig. 2.4 illustrates the different types of radio interference around WBANs. As demonstrated, the signal link is between two devices on a single WBAN (on-body) while the interference link is mainly from a device on another individual (off-body) Zhang et al. [2010]; Yuce and Khan [2011].

Therefore, WBAN interference can be categorized into three types: *Intra-WBAN interference* which occurs amongst sensor nodes within the same WBAN; *inter-WBAN interference* which occurs amongst WBANs working at the same frequency band; and *inter-domain interference* or *cross-interference* which occurs between a WBAN and other wireless networks (e.g., Bluetooth, Zigbee, or WiFi). Since nodes within a single WBAN can avoid interference using multiple access techniques like time division, interference is not troublesome for *intra-WBAN*communication. However, when the transmission ranges of coexisting WBANs overlap ,i.e. when the coordinator of the WBAN of interest is affected by radio interference from a sensor of another WBAN in its vicinity, they will be prone to interference from one another (*inter-WBAN* interference) (Fig.2.4), which can be either *dynamic* (due to mobility) or *static* (non-mobile network nodes) Deylami and Jovanov [2014].

When movement is the main source of channel dynamics as the two objects are not synchronised, signal and interference links are uncorrelated and statistically independent over a large time period. The coexistence problem can be further classified as *homogeneous* and *heterogeneous*. Homogeneous refers to the coexistence of multiple transceivers of the same type, which can be addressed by distributed or centralized methods. Whilst heterogeneous refers to interference between different types of wireless technologies. For distributed methods, coexistence can be detected and managed using collaborative or non-collaborative approaches. In most proposals for interference avoidance amongst coexisting WBANs, the coordinator of each WBAN takes charge as the coexistence manager and exchanges requests and responses for collaboration to find the optimum arrangement of the superframe. However, the complexity relative to synchronization and energy drainage from frequent message exchanges are the major drawbacks Deylami and Jovanov [2014].

Finally, postural body movements make interference more challenging as nodes randomly move in to and out of each other's range. The IEEE 802.15.6 standard for WBANs has defined three levels of mobility as follows (examples provided in Table.2.2)

- *(i) Static (S)*: This state represents constant interference from other WBANs for

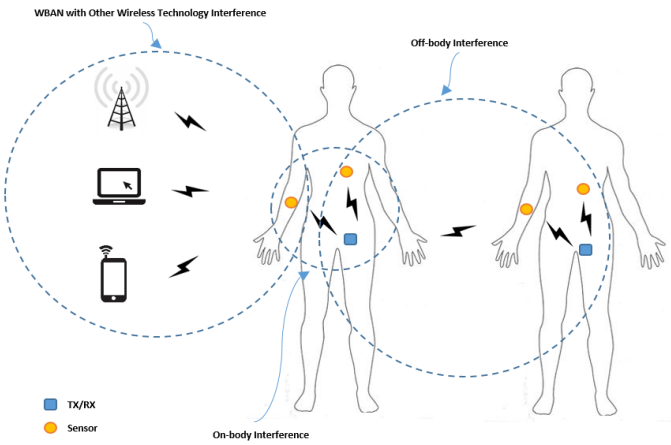


Figure 2.4: Types of Interference for WBANs as in Movassaghi et al. [2014a]

Table 2.2: Supported Mobility Levels in WBANs as per IEEE 802.15.6

Static	A single BAN in a residential environment or a hospital with a single patient node and a fixed bedside hub
Semi-Dynamic	Slowly moving ambulatory patients in an elder care facility requiring infrequent and/or event-based low-rate data transfers
Dynamic	Fast moving ambulatory patients in a hospital with a large number of BANS collecting continuous data traffic from many sensor nodes
None	No Interference

a time duration with no mobility.

- *(ii) Semi-dynamic (SD)*: This state shows there is constant interference from other WBANs for a certain time duration with slow mobility.

- *(iii) Dynamic (D)*: This state demonstrates temporary interference from other WBANs with fast mobility.

- *(iv) None (N):* This state indicates that there is no interference.

Another important factor that affects interference is the frequency of operation. Frequency bands used by WBANs in IEEE 802.15.6 are shown in Fig.2.3. Lower frequencies have less shadowing and attenuation from the body whilst ultra-wideband frequencies offer higher throughput and data rates. As the 2.4 GHz industrial, scientific and medical (ISM) frequency bands are used by multiple wireless technologies,

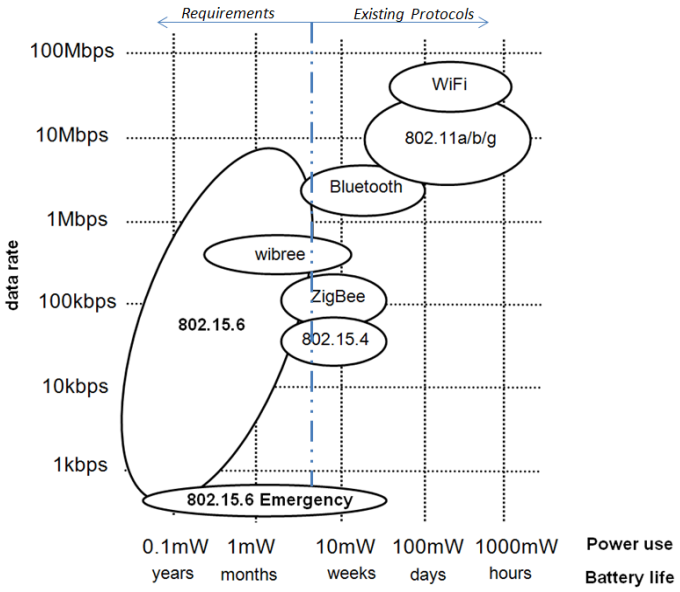


Figure 2.5: Power Requirements and Data Rates in WBANs as in Movassaghi et al. [2014a]

there maybe multiple sources of interference for a wireless transceiver at the same time.

These networks have a wide range of applications from healthcare, sports training and entertainment.

WBANs have stringent power constraints. A comparison of the data rates and power requirements of WBANs with other wireless technologies is shown in Fig. 2.5. As can be seen, some technologies do not meet the power requirement of less 10mw in WBANs. Thus, WBANs need more power efficiency compared to the other networks. The data rates of sensors used in WBANs can range from 1 Kbit/s to 10 Mbit/s Marinkovic et al. [2009]. More specifically, the data rate of in-body nodes vary from few Kbps in a pacemaker to quite a few Mbps in a capsule endoscope. Currently, most devices use Bluetooth (802.15.4) or Zigbee (802.15.1) as their monitoring station where neither of them meet the power requirements of WBANs.

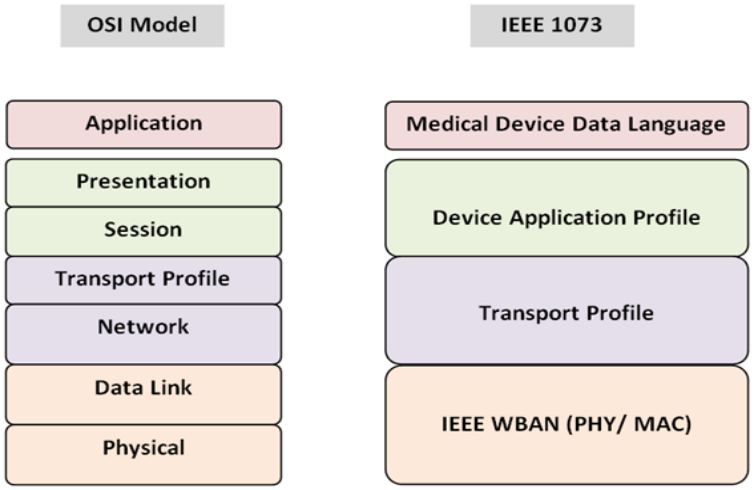


Figure 2.6: Communication Layers in a WBAN

2.4 Physical and Medium Access Control Layer

2.4.1 Physical Layer

The IEEE 802.15.6 standard specifically devised for WBANs defines the Physical (PHY) and Medium Access (MAC) layer protocols for these networks. Compared to other standards such as IEEE 802.11 Crow et al. [1997] and IEEE 802.15.1 (Bluetooth) iee [2005], IEEE 802.15.6 offers low-power, low complexity, low data rates with accompanying reliability to suit the stringent aforementioned requirements of these networks. Table 2.6 offers a brief comparison of the different technologies that use the same frequency bands as WBANs and their variations in terms of frequency, data rates, range, mode of operation and power consumption. The WBAN-specific PHY layer has certain limits defined by standards and regulations which need to be considered in the design of a protocol for these networks. This section looks into those limits to provide the readers with a general overview of these requirements.

The transmit power of a certain node/hub should be set based on the frequency of operation and duty cycle. In a low power low duty cycle (LP/LDC) mode on a center frequency of 403.65 MHz a transmitter should be able to transmit up to -40 dBm effective isotropic radiated power (EIRP). While, a transmitter in the non-LP/LDC mode in the 402 MHz to 405 MHz frequency band, should be capable of transmitting

Table 2.3: Comparison Between Methods of Interference Mitigation

Interference Mitigation Method	Reliability	Mobility	Centralised/distributed	Power Consumption	Efficiency	Complexity
MAC-related Method	No	Yes	Distributed	Medium	High	High
Power Control Method	No	Yes	Distributed	Low	High	Medium
Cognitive Method	Yes	Yes	Distributed	High	Medium	High
UltraWideband Method	Yes	Yes	Distributed	High	Medium	Medium
Hardware Design Method	Yes	No	Distributed	Low	High	High

with at most -16 dBm EIRP. A transmitter should be able to transmit with at least -10dBm EIRP in all other frequency bands. Nodes should aim to transmit with lower power when possible to mitigate interference to other nodes, other coexisting networks as well as for human safety considerations. Therefore, the maximum transmit power should be limited by local regulatory bodies (0 dBm). The transmit power-on ramp for 10% to 90% of maximum power should be less than 5 symbols and the transmit power-down ramp for 90% to 10% maximum power should be less than 5 symbols.

IEEE 802.15.6 defines a ratio for the total power of the adjacent channel to the total power in the wanted channel referred to as the adjacent channel power ratio (ACPR). This ratio is measured at an output transmit power equal to the maximum possible power output of the device. For a packet error rate (PER) of less than or equal to 10% with a PSDU of 255 octets with additive white Gaussian noise (AWGN), shall comply within certain receiver sensitivities ranges. The minimum input levels are measured at the antenna connector, where a noise figure of 13 dB, which may include losses due to external components, and an implementation loss of 6 dB have been assumed. The adjacent channel rejection (ACR) is defined to be the ratio of power of the interfering signal in the adjacent channel to the power of the unwanted signal, with the desired signal strength being set to 3dB above the rate-dependent sensitivity and the power of the interfering signal being raised up to 10% PER is reached with a PSDU length of 255 octets. The interfering signal of the adjacent channel should be compliant with WBAN PHY with the same information data rate, unsynchronized with the signal in the channel of interest and generated with a suitable test source. Also, the compliant device has to conform to the ACR boundaries devised in the standard. Another value defined in the standard is the receiver energy detection (ED) value is the estimated value of the signal strength within the same bandwidth of the channel and can be used by upper layers for multiple tasks including the channel selection scheme and does not require identifying or decoding the signal to do so. The threshold value for ED in the frequency band of 402 MHz to 405 MHz with a minimum value of zero shall denote for its received power being less than that defined in the ETSI standard. The minimum ED value of zero in other frequency bands should indicate a received

power of less than either 10dB above the receiver sensitivity for the lowest data rate in a given band or the one advised as per local regulatory requirements (applicable standards) whichever has a lower value. Also, the range of the received power should be above 40dB to cover the ED values with an accuracy of 6dB. The ED measurement time in the frequency band of 402 MHz to 405 MHz should comply with that advised in the ETSI standard and for other frequencies it should be either pEDtime or that advised by local regulatory requirement (applicable standards), whichever is longer in duration.

The PHY layer should enable the receiver with the capability to perform CCA using of the three methods below:

- CCA Mode 1: Energy above threshold. CCA shall report a busy medium upon detecting any energy above the ED threshold.
- CCA Mode 2: Carrier sense only. CCA shall report a busy medium only upon the detection of a signal compliant with this standard with the same modulation and characteristics of the PHY that is currently in use by the device. This signal may be above or below the ED threshold. The CCA detection time shall be equal to pCCATime.
- c) CCA Mode 3: Carrier sense with energy above a threshold.

CCA shall report a busy medium using a logical combination of the following:

- 1) Detection of a signal with the modulation and characteristics of the PHY that is currently in use by the device, and
- 2) Energy above the ED threshold, where the logical operator may be AND or OR.

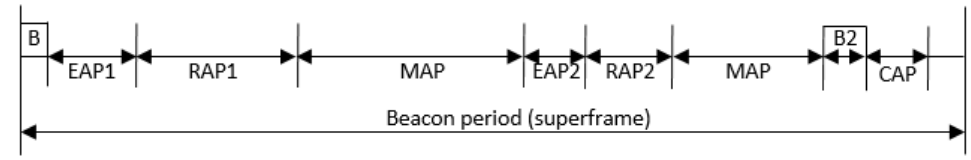
The CCA parameters are subject to the following criteria:

- The ED threshold shall correspond to a received signal power
- The CCA detection time shall be equal to pCCATime. Any CCA and LBT procedures required by local regulatory requirements shall also be supported.

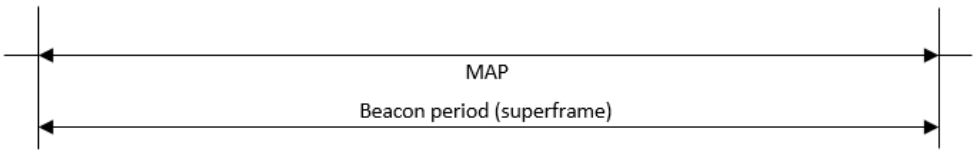
2.4.2 MAC layer

The IEEE 802.15.6 working group depicts a MAC layer on top of the PHY layer to control channel access. The hub divides the entire channel (or time axis) into a series of superframes for time referenced resource allocations. The hub also bounds the superframes by choosing beacon periods of equal length. The hub can shift the offsets of the beacon periods. Beacons are usually sent in each beacon period unless prohibited by regulations in inactive superframes or the MICS band.

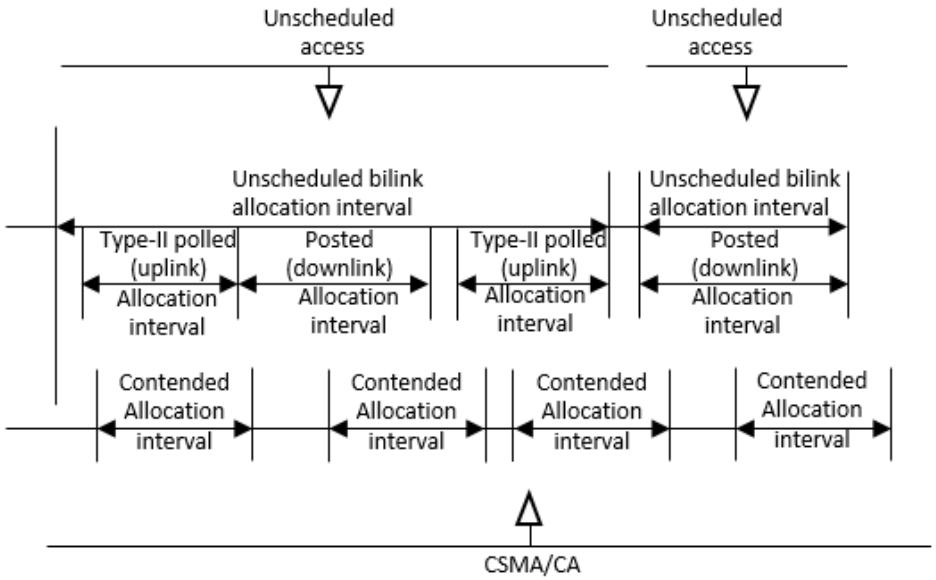
In a wireless body area network, the hub can choose from one of the three access modes based on its time referenced allocation requirements: beacon mode with beacon periods (superframes), non-beacon mode with superframes and non-beacon mode without superframes. In beacon mode with beacon periods (superframes), the hub can maintain inactive superframes after each active superframe if no allocation intervals are scheduled in the inactive superframes. Therefore, the hub shall not transmit any beacon or provide any access phases in an inactive superframe. The hub organizes applicable access phases in active superframes. After the beacon (B) is sent by the hub, the exclusive access phase 1 (EAP1), random access phase (RAP1), managed access phase (MAP), exclusive access phase 2 (EAP2), random access phase 2 (RAP2), another managed access phases (MAP) and contention access phase (CAP) are placed in the order shown in Fig.2.7(a). The hub can set any access phase to zero length, and if the CAP is of non-zero length, the hub shall transmit a preceding B2 frame. A node can acquire and initiate frame transmissions in contended allocations in EAP1, RAP1, EAP2, RAP2, and CAP in the active superframes using CSMA/CA or slotted Aloha-based random access. In MAP, the hub can arrange scheduled uplink, downlink and bilink allocation intervals, provide unscheduled bilink allocation intervals and improvise immediate polled or posted allocation intervals. In the non-beacon mode with superframes, a hub only has managed access phase (MAP) in each superframe (Fig.2.7(b)). In non-beacon mode without superframes , the hub provides unscheduled bilink allocation intervals where the node obtains a contended allocation interval by employing the CSMA/CA based random access method (Fig.2.7(c)).



(a)



(b)



(c)

Figure 2.7: IEEE 802.15.6 Superframe Access Modes: (a) Non-beacon mode Without Superframes (b) Non-beacon Mode with Superframes (c) Beacon Mode with Beacon Periods

2.4.3 Contention access

In EAP1, RAP1, EAP2, RAP2, and CAP, allocations can only be contended allocations, which are not reoccurring time intervals, and the random access methods can be either carrier sense multiple access with collision avoidance (CSMA/CA) or the slotted Aloha access. A hub or a node can only acquire contended allocations in EAP1 and EAP2 if it needs to send data type frames of highest User Priority (Emergency or medical implant event report= Priority 7) (Fig. 2.4). The standard supports prioritized access, by predefining contention window (CW) bonds for CSMA/CA and contention probability (CP) thresholds for slotted Aloha access. In CSMA/CA, the transmitter senses the channel before sending any packets. Nodes that have at least one frame of user priority UP or higher to send, chose a random integer between $[1, CW]$ as the back-off counter where CW is set between CW_{min} and CW_{max} according to respective situations. The back-off counter is paused if it senses the channel is busy. Upon unlocking its back-off counter, the node shall decrement its back-off counter by one for each idle CSMA slot. If the back-off counter reaches zero in the current CSMA slot, the node obtains the contended allocation and starts transmitting at the end of current CSMA slot. In slotted Aloha, the node sets its contention probability, CP, between CP_{min} and CP_{max} according to user priority, UP, and its assignment history. If the newly drawn random value from the interval $[0, 1]$ is smaller than CP, the node obtains a contended allocation restricted to this slot using the current Aloha slot.

2.5 Improvised access and scheduled access

In beacon or non-beacon mode with superframes, a hub may employ improvised access to send polls and posts to a node without advance notice or at previously announced times, thus granting polled or posted allocations in any access mode 2.8. A polled or posted allocation is started by a poll and bounded by an explicit or implicit time interval that does not reoccur subsequently without the hub invoking another instance of improvised access. The polled allocation can be categorized into two types: immediate poll allocation and future poll allocation. Upon receiving the

Table 2.4: Data Traffic Prioritization in IEEE 802.15.6: Contention Window (CW) for CSMA/CA and Contention Probability (CP) thresholds for slotted Aloha access

Priority	User priority	Traffic designation	Frame type	CSMA/CA		Slotted Aloha access	
				CWmin	CWmax	CPmin	CPmax
Lowest	0	Background(BK)	Data	16	64	1/8	1/16
	1	Best effort(BE)	Data	16	32	1/8	3/32
	2	Excellent effort(EF)	Data	8	32	1/4	3/32
	3	Video(VI)	Data	8	16	1/4	1/8
	4	Voice(VO)	Data	4	16	3/8	1/8
	5	Medical data or network control	Data or management	4	8	3/8	3/16
	6	High-priority medical data or network control	Dataor management	2	8	1/2	3/16
Highest	7	Emergency or medical implant event report	Data	1	4	1	1/4

polled allocation destined to a certain node, the node could initiate another frame transaction immediately or in the future.

The nodes can also request a transaction by sending management or data type frames in the uplink allocation interval to ask for the hub to improvise a future post allocation to the node, thus enabling it to initiate a transaction. Upon receiving the posted allocation from the hub, nodes shall initiate another frame transmission. A node and a hub may employ scheduled access to obtain scheduled uplink allocations and scheduled downlink allocations, and may employ scheduled-polling access to obtain scheduled bilink allocations and polled and posted allocations therein. Scheduled uplink allocations, scheduled downlink allocations, and scheduled bilink allocations, which are collectively referred to as scheduled allocations, may be 1-periodic or m-periodic allocations, except that a node shall not have both 1-periodic and m-periodic allocations in the same WBAN.

2.6 WBAN Creation, Discovery and Connection

Before a network is designed, deployed and operated, a number of factors need to be taken into account. At first, the hub is in charge of initiating the communication between itself and its nodes. So it should choose an operating channel based on

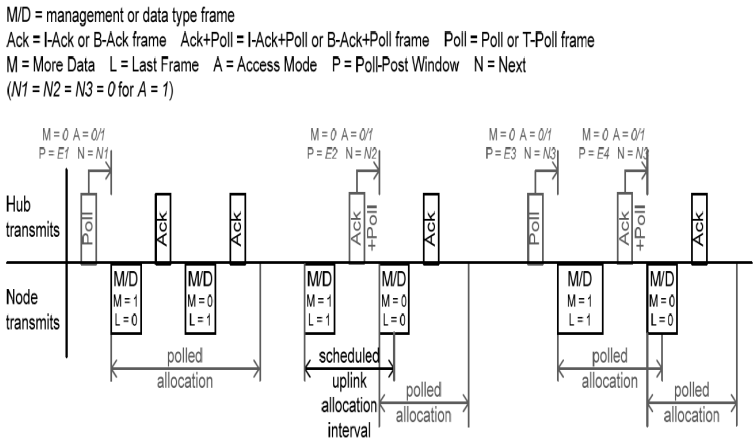


Figure 2.8: poll allocation

channel conditions, policy regulations, coexistence considerations and application requirements. Also, an appropriate choice of an access mode should be made from one of the three access modes: *beacon mode*, *non-beacon mode with superframe*, and *non-beacon mode without superframe*. After the choice of the access mode, the hub sends poll frames to unconnected nodes; then nodes may send a management type frame to request connection to the hub with contention probability. After the hub assigns a node ID to an unconnected node through a managed type frame, it provides polled allocations to this particular node to enable connection or reconnection with it.

For a node to be connected to the coordinator, it should send a connection request frame to the hub and the hub should respond with a connection assignment frame to the node. The unconnected node firstly sends a management type frame to the hub in an unconnected polled allocation with a contention probability (CP) of $P = (\frac{1}{2})$. If the node does not receive an expected acknowledgment, it may retry it in another unconnected polled allocation with a CP of $P = max\left(\frac{1}{8}, (\frac{1}{2})/\lceil\frac{(R+1)}{2}\rceil\right)$, where R counts the retries of the frame, i.e., R equals 1 for the first retry of the frame, 2 for the second retry, and so on. After the hub assigns an ID to an unconnected node through a management type frame sent to the node; it should provide polled allocations specifically addressed (unicast) to this node to facilitate the transmission by the unconnected node. The unconnected node should stay in the active state until it does not need polled or posted allocations (allocations that are not known in

advance).

2.7 IEEE 802.15.6 Coexistence Mechanisms

The IEEE 802.15.6 standard for WBANs has devised the following three techniques to be used from the coordinator of a WBAN for interference mitigation relative to the coexistence of a number of WBANs: Beacon Shifting, Channel Hopping, and Active Superframe Interleaving.

2.7.1 Beacon shifting

Each hub introduces a beacon shifting sequence in its beacons at different time offsets relative to the start of the beacon. In order to avoid scheduled allocation conflicts and repeated beacon collisions between adjacent and overlapping WBANs operating in the same channel, a hub should choose a beacon shifting sequence that is not in use with its neighbor hubs. The beacon transmit time shifts around the allocation slots in a beacon period. The access phases-EAP1, RAP1, EAP2, RAP2 and CAP are numbered allocation slots and shift around with the beacon in the beacon period. The RAP1 and RAP2 of the current beacon refer to EAP1, RAP1, EAP2 and RAP2 in the next beacon period. The choice of the beacon shifting sequence and the access phase in the beacon shift should not split any of the aforementioned access phases into two separate parts. Scheduled allocation slot can be referred to as numbered allocation slots which can shift around with the beacon transmit time in the beacon period. The aggregate length of a beacon should remain the same even though it can be split into two portions due to shifting around the beacon period.

2.7.2 Channel hopping

Channel hopping can be only deployed by a hub only if it has a narrow band (NB) PHY and does not comply with the Medical Implant Communication Services (MICS) band or a frequency modulation ultra-wideband (FM-UWB) PHY. During which a coordinator can periodically change its operating channel in the operating frequency by including the channel hopping state and the next channel hop in its

beacons or in the connection assignment frames of the superframe parameters and it should choose a channel hopping sequence that is not being used by its neighbors. A coordinator should remain in its current channel for a fixed number of superframes before channel hopping and it should initiate shifting to the new channel for a certain duration of time prior to the start of the beacon period.

To communicate with a hub, a node shall hop to the same channel as the hub. If the hub does not enable channel hopping, as indicated by an exclusion of the Channel Hopping State and next channel hop fields from its last transmitted beacon or/and Connection Assignment frames, the node should find the hub's operating channel according to the channel order list provided by the hub, if any.

2.7.3 Active superframe interleaving

A WBAN can share its current operating channel with other WBANs with or without interleaving their active superframes at any time. A coordinator that operates in the non-beacon mode with superframes and supports active superframe interleaving should send a beacon frame in every active superframe. A WBAN can send Command-Active Superframe Interleaving Request frame to the WBAN of interest regardless of whether or not the beacon period length and the inactive duration are suitable for interleaving. Upon receiving the beacon or B2 frame of the WBAN of interest, the superframe interleaving field of the MAC header will be set to one to show that it supports active superframe interleaving. To specify the acceptance or rejection of the request, the coordinator of the WBAN of interest should send a Command-active superframe interleaving response after it acknowledges the receipt of the frame. If it decides to accept the request, it continues with its current superframe length and inactive duration to enable active superframe interleaving. Otherwise it will fix the superframe length and inactive duration to allow for the offered active superframe interleaving before sending the response.

The coordinator of the WBAN of interest should accept the request if it is capable of continuing with its current beacon period (superframe) length and inactive duration to enable the requested superframe interleaving, unless its inactive duration

has been mostly taken by another coordinator also for active superframe interleaving. The coordinator of the WBAN of interest should also accept the request from the other WBAN, if its own coordinator has a lower WBAN priority than the other WBAN. If the coordinator of the WBAN of interest rejects the request, it may continue with its current beacon period (superframe) length and inactive duration, even if it offers an alternative beacon period (superframe) and inactive duration values in its response for active superframe interleaving between the two WBANs. If coordinator of $WBAN_1$ accepts $WBAN_2$'s request, coordinator of $WBAN_2$ should set up or/and adjust its beacon period (superframe) boundary and inactive duration to attain active superframe interleaving as it has requested, once the coordinator of $WBAN_1$ makes its own adjustment if required. If the coordinator of $WBAN_1$ rejects the request from the coordinator of $WBAN_2$, the coordinator of $WBAN_2$ may send another request for active superframe interleaving based on the alternative offer in $WBAN_1$'s response, or may start or continue with $WBAN_2$'s operation in the same channel without active superframe interleaving. The coordinator of $WBAN_2$ might send another Command, Active Superframe Interleaving Request frame, to the coordinator of the $WBAN_2$ even if it has previously sent such a frame containing the same or different requested field values. If the new request is accepted, it should supersede the previous request. However, if the new request is rejected, the last accepted request, if any, should remain valid.

If the coordinator of $WBAN_2$ previously sent a request for active superframe interleaving to the coordinator of $WBAN_1$ and the request was accepted by the coordinator of $WBAN_1$, the coordinator of $WBAN_2$ should send another request to the coordinator of $WBAN_1$ when the coordinator of $WBAN_2$ needs fewer or no active superframes. The coordinator of $WBAN_1$ may send a Command-Active Superframe Interleaving Request frame to the coordinator of $WBAN_2$ for active superframe interleaving any time as well, following the procedure specified above with the coordinator of $WBAN_1$ and coordinator of $WBAN_2$ to swap around their roles.

In order to send a Command-Active Superframe Interleaving Request or a Command-Active Superframe Interleaving Response frame, the sender should send the frame in the same way that it would if it were an unconnected node of the WBAN

that is receiving it, for both medium access and MAC header settings. The setting and transmission of I-Ack frames for acknowledging receipt of the two aforementioned frames should be similar to acknowledging the receipt of any other frame.

2.8 Existing Proposals for Interference Mitigation in WBANs

2.8.1 MAC-Related Proposals

The scarce limitation of resources for nodes in WBANs is highlighted even more when numerous WBANs coexist in each other's vicinity. Data exchange between the gateway and each sensor node is accomplished via a round-robin approach or TDMA, which cancels out interference amongst nodes in a single network. The Medium Access Control (MAC) layer designed for these networks aims to allocate and control access to the medium resources to organize their transmissions. Scheduling in time/frequency domain allocates a specific interval for each transmission to avoid inter-WBAN interference. However, the dense distribution of WBANs implies more frequent exchange of messages amongst them. Most MAC proposals include the exchange of messages or even cooperation among nearby WBANs. Though such communication benefits inter-WBAN scheduling, it would lead to further resource usage from typically scarce channel resources. In the following, we introduce MAC proposals for interference mitigation amongst co-located WBANs.

Alam and Hamida [2015b] have implemented the IEEE 802.15.6 MAC using CSMA/CA, TDMA, slotted aloha, scheduled access as well as polling and posting mechanisms. However, CDMA is not considered as a promising scheduling technique to mitigate interference between WBANs Deylami and Jovanov [2012], since interference in CDMA-based WBAN systems could be mitigated using multiuser receivers, either with a decorrelator or a minimum mean square error (MMSW) receiver Ghanem and Hall [2009]. The MAC layer can operate in three different access modes. In beacon mode with a superframe boundary, the higher priority and emergency data transfer can be executed in the exclusive access phase (EAP) including both EAP1 and EAP2. Two random access phases (RAP1 and RAP2) can be consid-

Table 2.5: Recommended Coexistence Mechanisms

Coexistence Mechanism	10 to 50 MHz HBC/EFC	402 to 405 MHz band	868 MHz band	902 to 928 MHz band	2.4 GHz ISM band	3.1 to 4.8 GHz and 6 to 10.6 GHz UWB band
Beacon Shifting	N/A	N/A given LBT restrictions	SD, D	SD, D	SD, D	D
Channel Hopping	N/A	D	SD, D	SD, D	SD, D	S,SD, D for FM-UWB
Active Superframe Interleaving	S	None	S	S	S	S
B2-aided Time Sharing	S	None	S	S	S	S

ered for regular non-emergency traffic. Both EAP and RAP can only use CSMA/CA or slotted aloha channel access schemes. Further, managed access phase (MAP) can be scheduled both in the beacon-enabled and non-beacon modes.

2.8.1.1 Adaptive CSMA/CA

Huang and Quek [2015a] proposed an adaptive CSMA/CA (A-CSMA/CA) MAC protocol where polling is combined with carrier sensing to avoid inter-WBAN interference. Before each polling, a coordinator will choose a random backoff counter based on its contention window size to reduce the collision probability of the polling message from multiple WBANs. The coordinator then performs clear channel assessment (CCA) for a backoff time slot to ensure that no other WBAN has ongoing transmissions. If the coordinator detects a transmission during its backoff period, it will freeze the backoff counter; otherwise, the backoff timer is decreased by 1 for each time slot. Once the backoff counter reaches zero, the coordinator will send its polling message/beacon to its sensor nodes. The rest of the frame which consists of all scheduled intra-WBAN transmissions will follow the beacon. If a collision is detected, the coordinator will double its contention window in order to reduce collision probability for next transmission, otherwise the contention window will be reduced by half.

2.8.1.2 Coloring-Based Inter-WBAN Scheduling

Another approach to enhance spatial reuse involves graph theory. This implies assigning a color which represents a distinct resource unit (time-slot, frequency-band, or code-sequence) such that concurrent transmissions of coexisting WBANs receive distinct colors Cheng and Huang [2013]. However, such methods assume the system is fully synchronous since all coexisting WBANs initiate their coloring algorithm at the same time, execute each step of the algorithm and broadcast their information simultaneously, which could be challenging in a dynamic topology. A faster and more efficient coloring based method is presented in Lee et al. [2015] where each WBAN calculates its own priority based on the traffic priority levels introduced in the WBAN

standard. If two adjacent WBANs choose the same color at the same time, the one with higher priority wins the color while the lower prioritized one enters the next round to content for next color from color sequence which is scheduled based on the initial color and available colors. However, this approach has significantly increased the time needed to color every WBAN. Therefore, distributed coloring algorithms were introduced in Huang and Quek [2015b] which allows the coordinators to make local and conflict-free coloring assignments without prior knowledge of the interference information of their nodes which allows multiple nodes to be colored within one round, leading to a large increase in efficiency. But, due to environmental dynamics with regards to the mobility of WBANs, channel conditions and interference patterns change rapidly over time which make coloring algorithms hard to implement.

2.8.1.3 Clique-Based WBAN Scheduling (CBWS)

An important characteristic of sensors nodes in a WBAN is the existence of a distinct active mode and sleep mode for communication when connected to a hub. The clique-based WBAN scheduling approach proposed in Xie et al. [2014] uses this characteristic to allocate resources to its sensor nodes such that co-located nodes transmit in the sleep period of an interfering node. The dispatch center adopted in this scheme manages joining, leaving and functional control of the coexisting WBANs. Closely located WBANs form a clique, and are assigned to different virtual groups for time-slot resource allocation. Finally, the dispatch center uses random coloring to allocate time slots to all nodes in the clique. Thus, interference between WBANs can be avoided by mapping different colors (time slots) to adjacent groups. Result-wise, the throughput of this scheme is greater than Random Incomplete Coloring (RIC), as CBWS considers multiple adjacent WBANs as a clique, and later assigns nodes in each clique into different virtual groups which will be allocated distinct time slots to avoid interference. However, this scheme requires a central dispatch manager which is not feasible due to varied dynamics regarding inter-WBAN and intra-WBAN mobility.

2.8.1.4 Dynamic Coexistence management (DCM)

Deylami and Jovanov [2014] look into an interesting perspective of reducing interference relative to beacon collision and data collision by beacon replacement and channel switching, respectively. As CCA is not used for beacon transmissions within the IEEE 802.15.4 standard used in this paper, beacons can easily collide with transmissions of coexisting WBANs. The hub detects a beacon loss when no data frames are received during that period. When the beacon is lost, the hub will monitor the current channel for a whole beacon length to find the longest gap between the active intervals of coexisting WBANs. After which, the hub will reschedule the transmission of its next beacon to the beginning of the gap. Even though the gap might not be long enough for a whole active period, a successful beacon transmission could reestablish the connection with nodes and possibly inform them about a channel switch later on. If the hub detects data loss, it scans a candidate channel either during a full beacon interval or an inactive period in search for a possible channel switch. If a full beacon interval scan is performed, complete information of preexisting WBANs of the candidate channel and the available gap is acquired, but the transmissions for one superframe is given up. By contrast, the advantage of the inactivate period scan is the possibility of finding a candidate channel gap without missing a beacon, but the complete information is not available. The coordinator will continue monitoring other channels if the search is not successful after scanning. If the search is successful, the coordinator will inform nodes to switch to other channels.

2.8.1.5 Interference-Aware Channel Switching

The use of frequency adaptation, also referred to as channel switching in WBANs has proven to provide substantial advantages in terms of success rate which is a prime performance measure for health-related applications, but the energy consumed to listen and switch to other channels may pose further problems Yazdi et al. [2014]. In Mahapatro et al. [2012], a framework is proposed for inter-WBAN interference consisting of a set of network nodes, and the interface connecting them. The framework records the duration in which a node receives/transmits by sending a signal to

confirm its ending and notifies the algorithm when a node is in one of the following states: transmitting, receiving or idle. The framework introduces the Interference-aware Channel Switching (InterACS) algorithm. The coordinator node periodically monitors the Signal-to-noise ratio of the received signal and switches to a different channel when it finds the SIR to be below a threshold. If the SIR falls within the predefined low, moderate and high range, the coordinator switches to the next 2-hop channel, next 3-hop channel and next 4-hop channel, respectively.

2.8.1.6 QoS based scheduling

The diversity in QoS requirements for different WBAN applications has been looked into in Jamthe et al. [2014] where the authors propose a priority preemptive scheduling algorithm based on the PNP-MAC protocol and traffic classification parameters that comply with the IEEE 802.15.6 standard. The proposed scheme allows the coordinators of coexisting WBANs to communicate with each other before data transmission to avoid inter-WBAN interference. Each WBAN begins its superframe by broadcasting its WBAN identification number and timer information in the first beacon period to nodes in its communication range. Thus, nodes will realize who their coordinator is and send time-slot requests in the contention free period (CFP). The coordinator sorts the traffic based on priority levels predefined in the WBAN standard, and assigns slots in the CFP in descending order of priorities. The scheduling information is broadcasted before the next beacon period; therefore, coordinators in each other's communication range can listen to this schedule. If there is an overlap, the slots to be assigned in the area of overlap are compared for their priority levels, the lower priorities are preempted and transmission slots are allocated to higher priority traffic. Preempted transmissions can be resumed later or can be deferred until the next superframe.

In the proposed scheme, the beginning of the CFP is always assigned to higher priority traffic descending towards lower priority traffic until the end of the CFP. This implies that data from the same level of traffic are more likely to compete with each other and be preempted, while the optimum scenario is to secure the transmissions of

high priority traffic while sacrificing some of the low priority ones. The scheme also requires stringent synchronization between coordinators which is almost impossible due to the mobile nature of WBANs. Additionally, the proposed scheme in Jamthe et al. [2014] has not considered the hidden terminal scenario where two coordinators are out of range, but their nodes are still capable of interfering with one another.

2.8.1.7 Coexistence Detection and Prediction

The scheme proposed in Han et al. [2014a] quantitatively defines the coexistence state to be static, semi-dynamic or dynamic based on the time duration within which they are experiencing interference, T_{SINR}. The proposed approach is based on a machine learning algorithm referred to as the Naive-Bayesian classifier that detects the coexistence state in a multiple-WBAN environment using three measured values: packet receive ratio (PRR), Interference time (T_{SINR}) and previous-state to the naive-Bayesian classifier. The output is one of the four states defined in Table 2.2.

$$C_{map} = argmaxP(Cj)Sum(wi|Cj) \tag{2.1}$$

where C_j indicates the posterior's class space and w_i is the featured variable. The value of prior probability of $P(w_i|C_j)$ can be obtained based on how often each class appears in the training dataset. Once all calculations are carried out, the maximum a posterior (MAP) hypothesis selects the class for which the computation is maximized.

Initially, the labeled training data is obtained from a set of experiments used in a variety of WBAN environments (e.g. no interference being represented as the *none* state, fixed interfering nodes being represented as the *static* state and interfering nodes moving at 0.5m/s or 1.5m/s being referred to as the semi-dynamic state or dynamic state, respectively using Zigbee X II modules. Experimental values in terms of packet receive ratio, T_{SINR} and previous-state are also categorized into discrete values producing a total of 28 combinations of conditions to be their current states. Then, the naive-Bayesian classifier accepts the measured values of PRR, T_{SINR} and previous state as the featured variables and computes the probability of each state

based on the training data. Finally in Han et al. [2014a], a state is chosen to have the highest likelihood for the current state based on the results obtained.

2.8.2 Power Control

Transmission power is of utmost importance for resource management and interference mitigation in wireless networks. At the same time, internetwork interference is known to be one of the major causes of energy wastage amongst coexisting WBANs since interference leads to a severe drop in the SINR leading to degraded throughput. Therefore, one approach to reduce interference while considering the scarce limitation of resources in these networks is adjusting the transmission power of each WBAN either cooperatively or non-cooperatively. However, a number of conflicting requirements also need to be taken into account in terms of connectivity, size, operating time, precision and reliability Spanakis et al. [2014].

Two categories of power management exist in WBANs: macroscopic power management and microscopic power management. In macroscopic power management, a node may hibernate being in the inactive state across multiple beacon periods (superframes). However, in microscopic power management, it may sleep and be inactive over some time intervals in its wakeup beacon periods (superframes). In macroscopic power management, a node shall set the requested wakeup period field to 1 if it wishes to stay in the active state in every beacon period (superframe), otherwise it should set the field to an integer m higher than 1 to notify the hub that it only wishes to be active every m beacon periods (superframes) and indicates its next intended wakeup beacon period in the requested wakeup phase field. The hub should honor the requested wakeup period and requested wakeup phase whenever possible, but may set the field in the assigned wakeup period and assigned wakeup Phase to a different value by responding to the connection assignment frame according to operating conditions. After the response, the hub may only grant m-periodic allocations to the node according to its assigned wakeup period field, with the allocation intervals being in the node's wakeup beacon periods (superframes). In microscopic power management, a node could be in an inactive state during beacon transmission

time if it does not need to receive a beacon or be inactive in exclusive access phase 1 (EAP1), random access phase 1 (RAP1), exclusive access phase 2 (EAP2), or random access phase 2 (RAP2) if it does not need to transmit a frame in the corresponding phase. In a MAP, a node may be in an inactive state outside its scheduled allocation interval and polled or posted intervals, or even during its intervals if the remaining interval is relinquished by itself or reclaimed by its hub.

2.8.2.1 Power Control Game

The power control games introduced in Kazemi et al. [2010]; Zou et al. [2014]; Qiu et al. [2016] models each user as a rational player, where each user competes for access to resources by adjusting their transmission power to maximize their utility function such as throughput in a distributed fashion. Since players make their decision non-cooperatively, the Nash Equilibrium point may not be optimal since their can be conflicts of interest when each user seeks to raise their own throughput regardless of others. In cases where the payoff function is relative to the throughput and transmission power, higher power consumption would penalize the utility. This pricing mechanism provides a more powerful tool to achieve an overall socially desirable result. In Fang et al. [2010a], the cost function is further revised to use additional parameters that adjust to the strategy more dynamically. The typical pricing functions researchers use are mainly linear functions of power, while the proposed pricing function is more general and can penalize high power users more severely compared to when a linear cost is used. Even though the innovative proposal made by these researchers is inevitable, this approach has the potential to abandon nodes with low battery and severe path loss.

2.8.2.2 Power Control with Reinforcement Learning

An important aspect to consider for the design of a WBAN-specific protocol is to consider dynamic variations of WBANs. Reinforcement learning is a branch of machine learning and is concerned with nodes learning to act such that their infinite cumulative reward or cumulative reward over an episode of time considering throughput

is maximized Kazemi et al. [2011c]. The learning approach considers each WBAN as an agent which is able to make the best decision by adjusting their transmission power to adapt to dynamic variations and obtain the best SINR. The RL problem thinks which state is most favorable based on the potential rewards of being in that state.

In power control case, that is determining the SINR, transmit power, interference power in the best state of the WBAN, and that will lead to the best SINR rewards in the future. And consequently, the best action in any state is to lead to the most favorable state. The action value, in another word, is the immediate reward of taking the action plus the value of potential states multiplied by a discount factor.

$$r_{t,(i)} = W_c \frac{c_{t,(i)}}{C_{(i)}^{max}} - W_p \frac{P_{t,(i)}}{P_(i)^{max}} - 1 \tag{2.2}$$

in Kazemi et al. [2012b] , or

$$r_{t,(i)} = W_c \frac{c_{t,(i)}}{C_{(i)}^{max}} - W_p \frac{P_{t,(i)}}{P_(i)^{max}} \tag{2.3}$$

in Kazemi et al. [2011c]

The goal of reinforcement learning is to find the best policy of reactions to a set of different states by evaluating the distribution probability that leads to next state and its expected rewards. Since the reward function is concave with respect to the transmit power, there exists a unique NE in the game. Thus, the goal is to learn to reach the NE to maintain a balance amongst collocated WBANs. The effect of variations in the reward function, discount factor, learning rate and eligibility tracer parameters are analyzed in Kazemi et al. [2012a]. The proposed power control scheme will be able to adapt to dynamic variations of the environment and provides a distributed approach that does not require any negotiation or cooperation between networks. But such an approach leads to huge computing complexity for the nodes.

2.8.2.3 Genetic-Fuzzy Power Controller

The Fuzzy Power Controller (FPC) adjusts its transmission power at the next time slot $(P_{t+\epsilon})$ based on its current interference power P_I, $SINR$ and transmission power, $P_{t(t)}$ such that it maximizes network capacity and minimizes power consumption Kazemi et al. [2011a]. Both P_I and $SINR$ are measured at a digital receiver within the same WBAN and fed back via an error-free channel. Inside the Fuzzy Power Controller, Genetic Algorithm (GA) is applied to learn and provide an optimal function for the controller to match the input with the output. GA is a stochastic search algorithm based on Darwin's theory of evolution, where an objective function referred to as the fitness function is optimized. GA take potential solutions to the problem as input and through selection, recombination, mutation and evaluation evolved into better generations of solutions until a criterion is fulfilled, such as finding an appropriate solution function. The GA tries to find the solution that maximizes a given fitness function. In fact, the optimization problem that the GA aims to solve is finding a fuzzy controller which maximizes link capacity using as little power for transmission as possible within the shortest convergence time.

fitness function:

$$\pi = \alpha C - \beta P - \gamma N \tag{2.4}$$

where C is link capacity, P is the normalized transmission power and N is the normalized number of iterations for FPC to converge to a steady state output.

In comparison with the PCG (Power control game) and ADP, the proposed FPC has shown to provide a substantial power savings as well as quick convergence time independent of the number of nodes in the system, whilst sacrificing only a small amount of capacity. Additionally, fuzzy power controllers do not rely on any negotiation between nodes in WBANs which is very important in high interference scenarios where negotiations may make poor conditions worse.

In Chen et al. [2013] a user-oriented power allocation algorithm is introduced which minimizes the transmission power of the sensory nodes whilst guaranteeing the QoS (Quality of Service) at the same time. A genetic algorithm is applied to solve

the optimization problem, where optimal power allocation strategy is found through evaluation, gene selection, and the crossover/mutation process.

2.8.2.4 Power Control Game Using Social Networks

In Zhang et al. [2013], network topology detection and power control game are used for interference mitigation in a cyber-physical WBAN system. Dense deployment of WBANs makes coexisting WBANS more likely to interfere with one another's transmissions as they will using similar frequency bands. This will severely degrade the system performance leading to throughput degradation, more packet loss and earlier depletion of the available power. Thus, the authors obtain the distance between coexisting WBANs by detecting their social interaction using Bluetooth and acoustic wave technology. A four-state dynamic social interaction prediction algorithm is designed to distinguish between the following four states: strong interaction, weak interaction, strong non-interaction, and weak non-interaction. In addition, the channel gain is calculated as a function of the distance between the transmitter and receiver, then the SINR at each node is calculated using the channel gain.

Later, in power control games transmission links between the transmitters and the corresponding receivers are defined as the actual players. At each communication link, the price is calculated as a function of weighted SINR, and weighted transmission power. In the power control game, each WBAN estimates the distance between itself and others to predict the level of social interaction amongst them, and uses it to update the transmission power and price values accordingly.

2.8.3 Cooperative

2.8.3.1 Two-Hop Cooperate

Two hop cooperative communication has shown to provide major benefits to WBANs in both ultrawideband and narrow-band communications. WBANs of vicinity communicate with each other, and a decode-and-forward protocol with two duo-hop links, two relays and selection combining at the hub is experimented. In the scheme, WBAN hub is used as relays, which decode and forward all received signals to the

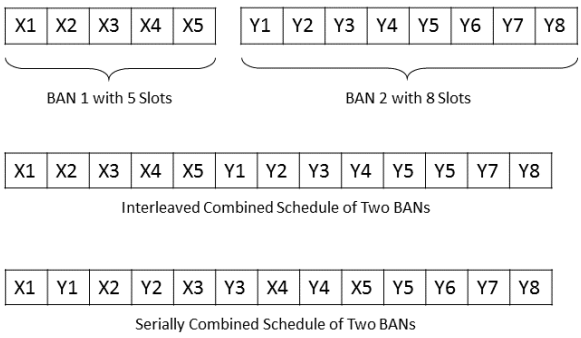


Figure 2.9: Types of Schedule Emerging: Serially or Interleaving Mahapatro et al. [2012]

destination. Three branch coherent selection combining (SC) is adopted where the best branch is chosen according to the average SINR for the whole packet. 12dB improvement in Signal-to-interference plus noise ratio is shown, but since the proposed approach uses TDMA between coexisting WBANs there is a huge delay between the transmission of nodes of a single WBAN in the coexistence of densely deployed WBANs.

2.8.3.2 WBAN Equipped patient

Mahapatro et al. [2012] proposed a solution which allows coexisting WBANs to cooperate with one another to agree to a common TDMA schedule. The coordinator node periodically monitors the SIR level and calculates the probability of interfering with another WBAN when its SIR drops below the threshold value. The WBAN with higher level interference (or victimization probability) begins to exchange its schedule with other interfering WBANs. The two or more interfering WBANs combine their MAC transmission schedule into a common schedule. The schedule can either be emerged either serially or interleaved (as shown in Fig.2.9), thus no more transmissions overlap. Since some nodes have to wait for a relatively longer time compared to other WBANs with more nodes and/or larger data traffic, in order to allocate a fair waiting time to all participating WBANs, they are allowed to repeat their transmission in a common schedule duration which combines the coexisting WBANs schedule together so that no transmissions can overlap.

2.8.4 Cognitive

Cognitive radio is a technology that provides solutions for interference and frequency scarcity. It allows the unlicensed user (or secondary user (SU)) to opportunistically access underutilized licensed spectrum whenever the licensed users (primary users (PUs)) are idle. It allows automatic change of transmission or reception parameters according to the entire wireless environment to use frequency resources effectively and alleviate frequency interference. Cognitive radio has numerous advantages such as channel sensing, resource allocation, spectrum mobility and spectrum sharing. *Spectrum sensing* refers to the ability to estimate channel state information and analyze the radio environment. *Resource allocation* implies opportunistic assignment of available channels to secondary users (SUs) based on their Quality of Service requirement. *Spectrum mobility* allows SUs to hand-off their assigned channel when a PU is detected and to further access a vacant channel to re-establish their communication. Spectrum access can help avoid conflicts between primary and secondary users to avoid harmful interference. Januszkiewicz [2014] presented simplified human body models which can be used in the measurements of cognitive radio channel parameters. Cognitive radio can be further implemented in WBANs to reduce interference by adjusting the transmission parameters of the secondary users, as well as improving the QoS of wireless communications between devices by defining the priority levels of each one in the MAC layer Bhandari and Moh [2015].

2.8.4.1 Hybrid Cognitive Validation Platform

In Han et al. [2012], the authors have developed a Hybrid Cognitive Validation Platform for WBANs, which is based on programmable system-on-chip (SoC) processors and provides a simulation environment close to the real-world scenario, in order to deploy and analyze Cognitive Radio Algorithm. The algorithm treats interfering nodes as rude spectrum users who simply try to access spectrum resource when they need to send packets, and do not care whether WBAN nodes are using the channel or not. While WBAN nodes access spectrum in a polite manner. The coordinator firstly sense the spectrum, makes estimation by cognitive radio algorithm and acquires an

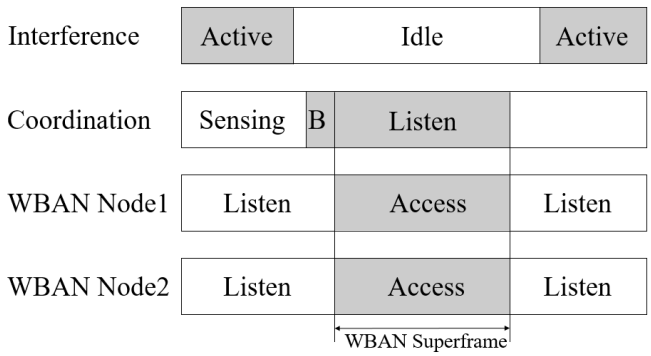


Figure 2.10: Adaptive CR MAC Diagram in Han et al. [2012]

optimized accessing time which will keep potential collision rate under a certain threshold. When the channel becomes idle, coordinator broadcast a beacon containing boundary information about the superframe setting according to the previous optimized access time. The nodes receive the beacon and access the channel during each superframe. But there lies the possibility that interfering nodes suddenly start transmitting and interrupt the WBAN superframe. To mitigate the impact of such cases, each WBAN nodes will sense the spectrum for a small period of time before transmission during superframes, to ensure interference nodes are in the idle state at the time WBAN nodes starting to transmit. With this protection action, even if interference traffic start transmission suddenly, it will cause collision no more than one packet length in this scheme in Han et al. [2012].

2.8.4.2 Fast Dynamic Cognitive Radio Algorithm

In Shen et al. [2013], a Dynamic Cognitive Radio Algorithm (FDCR) is applied on a WBAN validation platform called the Adaptive Cognitive Enhanced Platform (ACEP), to guarantee the harmony of coexistence of WBANs with other wireless systems (e.g. WiFi network) all working on the same spectrum. Compared to the fixed time algorithm, FDRC can dynamically adjust the channel sensing time and channel accessing time based on channel occupancy conditions.

FDRC can be divided into two phases: Channel sensing phase and channel access phase. In the channel sensing phase, the coordinator measures the Received Signal Strength Indicator (RSSI) as an energy detection mechanism to indicate spectrum

status whether idle or busy. If the RSSI value is lower than the threshold gamma value, the channel can be seen as idle, otherwise the spectrum is considered busy as it is occupied for another user's communication. If the channel status is idle, the coordinator broadcasts beacons to WBAN nodes with information of access time; the system enters the access phase. Both sensing time and access time are updated based on the packet collision rate of the last access phases. Lower collision rate corresponds to lower sensing time to leave WBAN nodes more time to transmit packets, while higher collision rate will give longer sensing time to detect more reliable channel status. Also, the higher collision rate will reduce the channel access time which can help enhance transmission reliability. With WiFi deployed as interference in the same spectrum, the dynamically adjusted sensing time and accessing time enhances ACEP's performance effectively with reduced packet drop rate and improved channel utilization in Shen et al. [2013].

2.8.4.3 Cognitive-Receiver Initiated CyclEd Receiver (C-RICER)

The Cognitive-Receiver Initiated CyclEd Receiver (C-RICER) proposed in Nhan et al. [2014] contains 3 major features: channel sensing, power adaptation and channel adaptation. According to the level of interference detected by the coordinator, the WBAN can adaptively switch to the lowest interference channel to prevent any potential harmful interference. But, in some cases, interference appears and disappears suddenly for short periods of time, which makes the WBAN switch its channel too often that leads to draining lots of energy for channel switching. Thus, the C-RICER protocol uses power adaptation (by dynamically assigning transmitting power) before channel adaption is considered.

More specifically, in the channel sensing phase, the coordinator - as the only receiver of WBAN (despite sending control frames) - periodically measures the Received Signal Strength (as interference) when it is not communicating with its nodes. It only senses interference of the current channel in use instead of the whole frequency band to reduce the sensing energy cost. In the power adaptation phase, the transceiver node is proposed to have 2 specific transmission powers, P_1 and P_2. If

the interference level is less than $threshold_1$, the node transmits with P_1 power. If the interference level is greater than $threshold_1$ but not exceeding $threshold_2$, the transmission power will be increased to P_2 to see changes in the interference. If the RSSI value drops beneath the $threshold_1$, the network will go back to use P_1, otherwise, the coordinator scans for new lowest interference channel available and switches to that channel with transmission power of P_1. This avoids using the high transmission power P_2 for a long time. When the RSSI value of the current channel is directly larger than $threshold_2$, the coordinator also switches to the new channel. The proposed protocol combines power control and channel switching to maintain lower energy per packet. Also, C-RICER can keep its packet delay metric steady at a small value with the increase in interference in Nhan et al. [2014]. However, when interference is much lower than the threshold, periodic scanning for the interference level occurs which leads to large power consumption.

2.8.4.4 Medical applications

In hospitals, intra-WBAN communications such as hub-to-patient monitor links are at the high risk of potentially interfering with other critical medical devices in their vicinity. In Chávez-Santiago and Balasingham [2011], the system is designed to avoid electromagnetic interference (EMI) to electronic medical devices, which are considered as primary users. The proposed system deploys the detect-and-avoid technique, which is based on the multiband orthogonal frequency multiplexing (MB-OFDM) transmission mode. The IFFT/FFT engine in OFDM transceivers can be used as a spectrum analyzer with a frequency resolution of 4.125MHz Batra et al. [2006], thus the available spectrum can be opportunistically detected for use. Spectrum shaping and zeroing multiple subcarriers that overlap with the primary user (other medical devices), can be used to mitigate electromagnetic interference. But, the complexity of such a hub is relatively high (as the hub is used as the CR-Controller); hence, inter-WBAN communication has to be simple and energy efficient to compensate for the high power consumption on the hub. Dong et al. [2011] proposed a CR-based ad-hoc network for WBANs, allowing the coordinator of the WBAN of interest to manage

coexisting wireless networks to efficiently allocate the spectrum resources with interference avoidance. The coordinator of the WBAN of interest estimates the physical locations of medical devices based on a function of the received signal strength, time and angle of arrival of the signal and adjusts its channel frequency and transmitting power accordingly. Also, information theory can be used to compress correlated information such as the patient's systolic and diastolic pressures; thus reducing the amount of transmission data as well as the probability of interference Syed and Yau [2013].

2.8.5 Ultra Wideband

UWB may be a preferred means of communication amongst nodes and hubs due to its low power pulses and high data rate. However, since other wireless networks like Wifi use the same spectrum as UWB, narrowband interference will degrade the UWB signals Chiani and Giorgetti [2009]. Various methods have been proposed to overcome this issue such as eigen value decomposition Luo et al. [2004], and multiple antenna selection diversity Bae et al. [2011]. But their system complexity, makes them unfeasible for use in WBANs. When Wireless Body Area Networks utilize the IEEE defined 3.1 to 10.6 GHz UWB band, they are easily affected by narrowband interference from existing wireless networks. Single hermite pulse has shown to cancel single narrowband interference Rout and Das [2014a], the characteristics of hermite pulse are further investigated in Rout and Das [2014b] and a hybrid pulse that has multiple notches is designed in exact same frequencies where interference is present. Such a pulse is called the hybrid hermite pulse, and is designed by using shifted and modulated hermite pulses. The proposed pulse shape does not require complex operations for generation and modulation. It also maintains its unaltered spectral characteristics under fading and distortion in the UWB WBAN channel. This means the modulated hybrid pulse can be efficiently radiated with lower power leading to better energy savings.

2.8.6 Hardware Design

Interference mitigation can also be dealt with through the use of physical components such as multiple antennas at the transmitter or receiver to provide diversity gain, strengthen the desired signal, detect interference and suppress it. Antennas that operate in the ISM band are very important for WBAN communications, specifically relative to limits due to transceiver specifications in terms of transmitted power EIRP ($<$ -16 dBm) and SAR ($<$ 1.6 W/Kg) as well as the surrounding environment (the lossy medium of the human body) that affect the complexity of antenna design Astrin et al. [2012]. Also, to comply with health regulations as well being user-friendly, the body-worn antennas need to be compact, light-weight, flexible and with reduced radiation on the body.

2.8.7 Signal processing

An ultra-low power Wake-Up Receiver (WUR) is implemented in Marinkovic and Popovici [2011] for WBANs to achieve low power consumption and avoid interference from wireless devices such as GSM phones. The wake-up receiver uses a simple command to identify and only wakes up the sensor being addressed. This allows other parts of the nodes other than the WUR receiver to remain asleep until awaking to exchange information, which leads to energy savings for on-body devices. Gaussian frequency shift keying (GFSK) is used for data transmission, and Gaussian on-off keying (OOK) is used for wake-up transmissions modulated by the pulse width in WUR. The proposed WUR filters interference by using a preamble detector and a narrowband Surface Acoustic Wave (SAW) filter.

2.8.7.1 Interference Cancellation With Interrupted Transmission (ICIT) Scheme

In Khan et al. [2010], two receiving antennas are mounted on each node to provide diversity gain. If the amplitude and phase of the interference signal are known, the two branch signals can be combined with weights that set them equal in amplitude and out of phase. Thus, this mechanism requires knowledge of the amplitude and phase of the interfering signals for which the corresponding transmitter is turned off

temporarily at regular intervals allowing the receiver to only measure the interference signals and store them. The estimated value of the interference signal is then used to calculate the weight factor, W, of each receiver until the desired signal is interrupted and turned off again. However, the computing complexity is large as well as using two antennas which make the node bigger in size and less comfortable for practical use.

2.8.7.2 Dual-Band Circular Antenna Equipped with AMC

In Di et al. [2014], a miniascape-like dual-band monopole antenna integrated above a circular-shaped Artificial Magnetic Conductor (AMC) is introduced. Fig.2.11 illustrates the ring-shaped printed monopole antenna on above with orange and 3×3 circular shaped AMC with blue. The monopole antenna has the omni-directional radiation patterns just as dipoles. The current resonate in monopole antenna has two different physical lengths so that it could work on both ISM bands of 2.4 GHz and 5.8 GHz. But when the antenna is in direct contact with the human body, the strong backwards scattering wave will be harmful to human's health. Therefore, an AMC array which acts as an in-phase reflector is placed underneath the antenna, resonating at the same operating frequency as the antenna. This reduces backwards scattering towards the skin and increases forward radiation making it harmless to one's body. The low-profile, flexibility, and low backward scattering of this design make it suitable for use in medical monitoring applications of WBANs. The band of 2.4-GHz (2.4-2.48 GHz) and 5.8-GHz (5.725-5.85 GHz) is satisfied with the design, and the front-to-back ratio is about 10 dB.

2.8.8 WBAN interfering with other communication technologies

The presence of other wireless communication technologies such as WIFI which uses the same unlicensed ISM band as WBANs can severely affect intra-WBAN transmissions. Hence, proposed protocols need to consider these interfering scenarios to avoid them in advance to allow for their practical deployment.

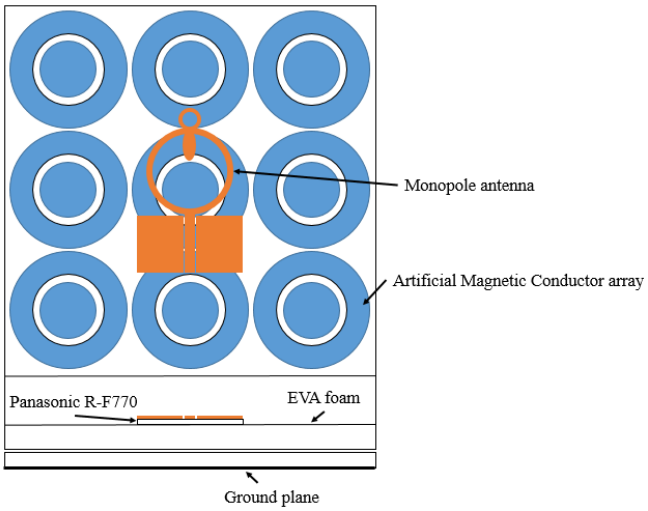


Figure 2.11: Structure of dual-band

2.8.8.1 Adaptive load control

ZigBee is one of the widely used wireless technologies for WBANs and is targeted at a low data rate and long battery life. However, ZigBee has a severe interference problem with WiFi networks as most ZigBee channels overlap with WiFi channels. In order to solve the problem, in Kim et al. [2016] an algorithm is proposed that controls the load in WiFi networks to guarantee the delay requirements of essential signals from ZigBee sensors. The aim of the adaptive load control algorithm is to guarantee that the delay between a ZigBee sensor and a coordinator in a WBAN is no longer than the maximally tolerable delay time. The algorithm initially classifies the traffic into two classes: real-time (RT) traffic such as PPLive, and non-real-time (NRT) traffic such as BitTorrent. The ZigBee coordinator determines its maximally tolerable delay and detects its PER of packets sent from the sensors to the coordinator, and then it computes the maximum allowable WiFi channel utilization with the parameter above and observes the current channel utilization and received signal strength from each WiFi node. If the channel utilization exceeds the maximum allowable utilization, the coordinator sends the list of WiFi nodes in descending order of received signal strength to the Access Point (AP). The AP controls the WiFi nodes of non-real-time traffic until channel utilization drops below the maximum allowable utilization.

Modes of inter-network interaction in beacon-enabled IEEE 802.15. 4 networks- The

Table 2.6: Comparison Between Methods of Interference Mitigation

Interference Mitigation Method	Reliability	Mobility	Centralised/distributed	Power Consumption	Efficiency	Cmplexity
MAC-related Method	No	Yes	Distributed	Medium	High	High
Power Control Method	No	Yes	Distributed	Low	High	Medium
Cognitive Method	Yes	Yes	Distributed	High	Medium	High
UltraWideband Method	Yes	Yes	Distributed	High	Medium	Medium
Hardware Design Method	Yes	No	Distributed	Low	High	High

factors that exacerbate the impact of inter-network interference are introduced in Feeney et al. [2015]. One of which is the challenges of highly optimized, low duty cycle transmission schemes in recovering from disruptions caused by co-located networks, because the protocol is very sensitive to loosing any of the tightly scheduled beacon frames. Another challenge is relative to the repetitive occurrence of interference due to bursty patterns of disruptions which can emerge as the networks active periods synchronize and de-synchronize with each other again and again.

Reliability in co-located 802.15. 4 personal area networks- Feeney and Fodor [2016] experimented on the interference amongst co-existing beacon-enabled 802.15.4 WPANs. The results show reliability to be severely compromised, experiencing periods of severe disruption lasting for many minutes, even when the channel is only lightly loaded. Since the disruption can not be eliminated by increasing the battery or memory resources, as the main cause of disruption is the lack of coordination amongst coexisting networks.

Coexistence of IEEE Std 802.15.6TM-2012 UWB-PHY with other UWB Systems- The situation where 802.15.6 standard defined UWB-PHY WBANS coexist with other UWB systems is explored in Hernandez and Miura [2012]. Several IEEE standard UWB systems operate in the same UWB bands as the WBAN which are as follows: IEEE 802.15.4a-2007 (pico-nets) and 802.15.4f-2012 (RFID). Hence, exploring the issue of co-existence and its impact on performance due to operating in the same band is important to further guarantee the quality of service of medical applications. Results show that a WBAN with 802.15.6 UWB devices in default mode can tolerate up to 10 FM-UWB interference devices in the same frequency band during the contention period.

Coexistence Issues for Wireless Body Area Networks at 2.45 GHz- In Martelli and Verdone [2012] WBANs operating at the 2.45 GHz frequency with other wireless networks (IEEE 802.11 Wi-Fi and IEEE 802.15.4 Zigbee) working at the same frequency is studied. Results show that the packet loss rate (PLR) is the most affected performance metric which also suggests performing appropriate periodic channel selection methods to avoid interference in dynamic deployments.

Electromagnetic field radiation on health- The electromagnetic field radiation gener-

ated during transmission from an on-body antenna can negatively influence one's health. The Specific absorption rate (SAR) is a measure of the amount of radio frequency energy absorbed by the human tissue. Current interference mitigation schemes do not significantly consider SAR level, but Wu and Lin [2015] use a particle swarm optimization algorithm to discover the optimal position of on-body relay nodes to have the lowest SAR for two-hop transmissions. The use of relays for two-hop transmissions has the potential to positively affect the coexistence of multiple WBANs by reducing the transmitting power of each node with the help of relays.

2.8.9 Mobility for WBANs

The IEEE 802.15.6 standard for WBANs does not provide explicit support for mobility and can perform poorly in mobility scenarios as demonstrated in Miluzzo et al. [2008]; Stevanovic and Vlajic [2008]; Cuomo et al. [2009]. The accuracy of simulations for WBANs is dramatically effected from the mobility model being used. However, the proposed mobility models for ad hoc and sensor networks cannot be deployed in WBANs to their differences in movement patterns. Nodes in WBANs have group mobility which implies nodes move within a group and have a particular relationship on the movement of others in their group. In fact, the sensor nodes used in WBANs move relative to the coordinator node of that WBAN which is used as their reference point. Since the coordinator of WBANs is mostly placed in the chest area, the relative position of the sensor nodes in its network can be predicted in correlation with it. For instance, in the case of a person walking with the coordinator placed on his chest and sensory devices placed on his/her arms, nodes on the legs and arms move forward and backward repeatedly; thus, their location can be predicted. Since the trunk is less mobile, nodes placed on it will show lower variation with respect to the coordinator. However, in the lying position the next location of the nodes in hard to be predicted accurately. But, an area in which the node is most likely to appear in can be defined. Accordingly, the movement of nodes in different postures can be predicted with details provided in Sandhu et al. [2015]. Similarly, we can visualize the movement of nodes placed on human body in different postures.

In Nabi et al. [2011], a configurable mobility model referred to as MoBAN is proposed for evaluating intra-WBAN and inter-WBAN communication. The proposed model considers variations in posture as well as mobility of sensory devices in each posture. Therefore, different postures have been specified for which specification parameters can clarify which posture belongs to which category of mobility. Then the local mobility of nodes within each posture are defined. Then, Markov chain models are used to find the transition probability from one posture to another. However, the nodes within each sensor are fixed and the authors do not consider variations once a node joins or leaves a WBAN. The Random Contention-based Resource Allocation (RACOON) medium access control protocol proposed in Cheng et al. [2011] supports quality of service (QoS) for multi-user mobile WBANs. It considers inter-WBAN interference and inter-WBAN priorities with which impose excessive energy-wastage and inter-network collisions. A probing interference detection is used for detection of interference through which data collision is avoided by calculating distance from the interference edge. Further, the user priority and bandwidth requirement are also considered in resource allocation for them. However, the authors have not considered the mobility models of sensors in each WBAN and the movement of WBANs towards one another and rather used a more general and iterative approach to encounter intra and inter WBAN mobility.

Chen et al. [2014] have proposed an enhanced group mobility model to reduce the number of control messages used in the group-based proxy mobile IPv6 (PMIPv6) domain, since (PMIPv6) has poor performance in coexistence scenarios of WBANs. Specifically, the new format of control message proposed carries many identifiers in one message to reduce the handoff delay and decrease the number of control messages and signalling cost. A new group based hand-off scheme is also proposed that consists of three phases of registration, uplink handoff and downlink handoff. Each WBANs actively scans its surrounding by sensing a beacon request to its nearby WBANs. The WBAN in its coexistence that receives the beacon, decides if it is within the same mobile access gateway or if it has moved to a new one. A learning-based prediction algorithm is proposed in Han et al. [2014b] to predict coexistence in a multiple-WBAN environment. The proposed approach uses the SINR, packet

reception ratio (PRR) and previous-state via the naive-Bayesian classifier to predict the performance of multi-WBAN scenario and measure the quality of communication. Therefore, the authors quantitatively defines the coexistence states using the duration of interference and SINR value being above or below a certain threshold. Movement of WBANs leads to substantial variations on the SIR. Hanlen et al. [2010] develop a lognormal statistical model that matches distance to signal power from their time-base measurements.

In Sandhu et al. [2015], a mobility model is presented for the group based movement of nodes deployed on a human body as a WBAN. Different postures are encountered such as sitting, laying, walking, etc. The movement pattern of these postures and their pattern is analysed. The transition probabilities for moving from one posture to another are calculated. The mechanism for mobility detection is accomplished through two different phases: posture selection phase and node's movement phase. The posture is selected from sitting, standing, lying, walking and running with the probability of its change being detected from real human traces. Then, in the second phase nodes move based on the selected posture. Braem and Blondia [2011] analysed the performance of the Loose association Implicit reservation Protocols for Mobile WBANs (LIMB) and found the topology to be quite dominating in their performance. In fact, the energy consumption and channel utilization of the Reduced Function Devices (RFD) has shown to be independent on the number of RFDs given a specific number of Fully Functional Devices (FFD). However, random scenarios and the effect of backbone protocols have not been investigated.

In Denis et al. [2014], radio-location experiments for mobility detection and indoor navigation applications of WBANs have been accounted for. Behavioural analysis of time stamped radio-location with respect to Human captured body mobility is proposed. In fact, RSSI measurements are used for preliminary learning and subsequent decision based on Bayesian tools and machine learning, where high deviation links account for mobile sequences. Additionally, mobility detection rates are reinforced with joint Bayesian decisions. Also, the distinction between different arm postures can be made based on absolute deviation levels. However, posture detection based on on-body links and contextual body shadowing mitigation for RSSI ranging

and navigation over off-body links needs to be further investigated.

2.9 Conclusion

To better motivate our research on effective interference management and avoidance schemes for the efficient coexistence of multiple WBANs, we firstly reviewed important background literature underlining the importance of WBANs, along with their communications architecture and guidelines for implementation from IEEE 802.15.6. Together with these, the importance of this work was then highlighted with extensive literature relevant to coexistence and radio interference mitigation, particularly at the MAC and physical layers. Thus, existing interference management schemes for WBANs have been investigated, providing a review and insights on state-of-the-art coexistence mechanisms. However, there are several shortcomings, as pointed to in this chapter, in previous work on interference management and avoidance for WBANs, motivating the innovative contributions for their coexistence to be given in the following chapters.

Chapter 3

Smart and Probabilistic Spectrum Allocation

3.1 Introduction

Wireless Body Area Networks (WBANs) are a vital enabling technology for developing new generations of medical applications, such as remote health monitoring. Hence, it is expected that WBANs will often transport mission-critical and delay sensitive data, so communications reliability is paramount. A key aspect of building a reliable WBAN is to ensure that they are highly immune to radio interference. To achieve this, new and intelligent wireless spectrum allocation strategies are required not only to avoid interference, but also to make the best-use of limited available spectrum.

As elucidated earlier in this thesis, interference avoidance schemes in WBANs can achieve a higher signal-to-interference+noise-ratio (SINR) level compared to interference reduction schemes, but their throughput is usually lower . Moreover, in terms of computational complexity, interference avoidance techniques require less complex receivers but extra cooperation between coordinators is inevitable. In interference reduction schemes, the receiver has a more complex decoder because it needs to decode several messages with differing SINR, data rate and received-signal strength; but as there is not cooperation between WBAN coordinators lower transmission overhead can be achieved by these approaches. However, the main drawback of existing proposals for inter-network interference mitigation amongst coexisting WBANs is that they typically consider each WBAN as a whole which is practically inefficient due to

typical requirements of high spectral efficiency and low delay of these networks.

Thus, this chapter presents a new spectrum allocation scheme referred to as Smart Channel Assignment (SCA), which maximizes the resource usage and transmission rate by deploying a partially-orthogonal channel assignment scheme between coexisting WBANs, as well as offering a convenient trade-off between spectral reuse efficiency, transmission rate and outage. More specifically, we allow nodes from different WBANs with lower interference levels to transmit on the same channel while high interference nodes transmit orthogonally. Simulation results show that the proposed scheme can achieve a much higher spatial reuse than the fully orthogonal scheme whilst maintaining a low interference level. We further analyse the proposed scheme and derive a closed form expression for the average spatial reuse. Accordingly, the outage probability is defined according to the probability that the interference level in a specific time interval is higher than a predefined threshold. We then propose a probabilistic approach to reduce this outage probability at the cost of a very small reduction in spatial reuse. Detailed analytical studies verify that the proposed SCA strategy is also robust to variations in channel conditions, increase in sensor node-density within each WBAN and an increase in number of coexisting WBANs.

The following summarises the key contributions of this chapter:

- A dynamic resource allocation scheme is designed to avoid interference among coexisting Wireless Body Area Networks (WBAN) which has many, essentially different characteristics to existing proposals. Mathematical analysis is also provided on the proposed scheme to validate its efficiency for increasing spectral efficiency and avoiding interference.

- In the proposed scheme, each WBAN generates a table consisting of interfering nodes from coexisting WBANs in its vicinity. This allows for efficient interpretation of Interference Region (IR) between each pair of WBANs. The nodes in the IR are later allocated orthogonal sub-channels while other nodes can transmit simultaneously.

- A precise trade-off is further demonstrated between the minimum interference level and spatial reuse. Simulation results show that the proposed scheme has

far better spectral efficiency compared to the conventional orthogonal schemes, whilst maintaining an acceptable interference level.

- To further reduce the interference level, the smart spectrum allocation scheme is enhanced by incorporating propose a probabilistic approach in the second half of the chapter (Section 3.6). Later it is analytically shown that the outage probability can be effectively reduced at the cost of a slight change in the spatial reuse factor.

To the authors' best knowledge, such an approach for internetwork interference mitigation in WBANs has not been investigated yet. To highlight the differences, existing internetwork proposals for WBANs, consider each WBAN network as a whole, allowing orthogonal transmission between coexisting WBANs with different approaches. Whilst we are the first to propose an interference mitigation scheme at the node-level which can substantially increase the reuse as well as reduce the delay that is quite beneficial, specifically to medical data with low delay requirements of 125ms Sta. In this chapter, we also provide in-depth analytical study and demonstrate the benefits of using a probabilistic approach, optimization of its relative parameters and validating its performance in terms of outage probability, delay and reuse.

The rest of this chapter is organized as follows. In Section 3.2 the system model is presented. The proposed smart spectrum allocation scheme is described in Section 3.3 along with analysis and simulation results. The opportunistic spectrum allocation scheme which is an extension to the SCA scheme is presented in Section 3.4 along with simulation results and analysis. Finally, Section 3.5 concludes the chapter.

3.2 System Model

We consider a one-hop star topology, where N_s sensor nodes aim to transmit their data to a common destination, known as the coordinator of each WBAN. The coordinator is the master-node in the one-hop star topology which has added functionality, more battery power and therefore takes charge of calculations for channel assignment on behalf of the WBAN of interest to avoid energy drainage on the nodes. The

architecture deployed in this chapter is depicted in Fig. 3.1(a) where all sensor nodes are placed on the human body. The nodes in each WBAN are coordinated by the coordinator using a Time Division Multiple Access Scheme (TDMA). For simplicity, we model each WBAN by a circle of radius r, where the coordinator is located at the centre while sensor nodes are uniformly located at random within the circle. We consider N_c coexisting WBANs that use the same technology for communication with their sensor nodes (inter-WBAN communication) and creating a backhaul infrastructure for inter-WBAN communication. The nodes in each WBAN are coordinated by a hub (coordinator) using time-division-multiple-access (TDMA). Synchronization amongst WBANs is achieved by the beacon of the coordinating WBAN. Information regarding the value of N_c and N_s is contained in the common beacon. It is important to note that this approach is different to a global TDMA scheme, which requires a central base station for channel assignment whilst the proposed scheme considers dynamic allocation of the spectrum without the need for a global coordinator. This feature is better appreciated in dynamic cases when WBANs are moving into and out of each others range.

We then define the intra-WBAN and inter-WBAN channel models. The channel between the sensors and the coordinator in each WBAN (intra-WBAN) is modeled with gamma fading. The channel between the sensors and coordinators of different WBANs (inter-WBAN) is modeled by Rayleigh fading. For the small scale fading model between two pair of WBANs, we use the Jakes model with $f_D = 2Hz$ as its Doppler spread, where the Doppler fading parameter is $\frac{f_D}{f_s} = 0.01$ and the sampling rate at the receiver is $f_s = 200Hz$. Rayleigh fading uses fading coefficients of $CN(0,1)$ which are distributed around the shadowing path-loss which interprets as shadowed path loss being the mean power of the fading coefficients. We apply the the Free Space Path Loss (FSPL) model shown in (3.1) to obtain the mean path loss without shadowing between two WBANs by considering the distance between them. This model uses the path loss exponent of $n = 2$ and is proportional to the distance

between the WBANs.

$$FSPL = (\frac{4\pi df}{c})^2 \tag{3.1}$$

where f is the frequency of the transmitted signal in Hz ($f = 2.4\ GHz$), d is the distance between WBANs in meters, c is the free-space speed of electromagnetic wave propagation $(3.0 \times 10^8 m/s)$.

We then obtain the mean path loss without shadowing amongst two WBANs from the Free Space Path Loss (FSPL) model to be as follows:

$$P_{dB}(d) = P_{0,dB} + 10nlog(d/d_0) \tag{3.2}$$

where $P_{0,dB}$ is the path loss at reference distance d_0 (d_0 is considered to be 10cm), n is the path loss exponent considered as 2 in free space and is stated to vary in different body locations based on investigated measurements.

However, there will not always exist a line of sight path amongst the WBAN of interest and the interfering WBAN in cases where people are in random motion towards each other. Therefore, non-line-of-sight transmission or obstructed line-of-sight will exist in these scenarios which is interpreted as the *shadowing effect* and is applied as an offset to the FSPL. Based on the observations in Smith et al. [2008], the median channel gain in on-body channels at 2.4 GHz is -71 dB; which is due to postural body movements and significant shadowing. Accordingly, we increase the path loss related to shadowing in varied amount from 0 dB (No shadowing) to 20 (partial shadowing) and then 40 dB (full shadowing).

The entire channel in a WBAN is divided into superframe structures, where each superframe contains network beacons that are of the same size in every network. The coordinator of a WBAN is in charge of selecting the boundaries of a beacon period where a beacon frame is transmitted at the beacon period of every superframe. The IEEE 802.15.6 superframe structure consists of the following: Exclusive Access Phase (EAP1, EAP2), Random Access Phase (RAP1, RAP2), Type I/II phase, Exclusive Access and a Contention Access Phase (CAP). CAP initiates after GTS requests and

topology management and is controlled by the CSMA-CA algorithm. CFP initiates at the end of the CAP and consists of a number of Guaranteed Time Slots (GTS) which can be assigned by the coordinator to the sensors based on TDMA Wang et al. [2013]. Also, collision never occurs between one WBAN's data frame and another WBAN's control frame. Whilst, interference can occur between different WBAN's data frames in the CFP Grassi et al. [2012].

We consider all WBANs use of the same technology, protocol and similar superframe structures, where inter-WBAN superframe synchronization is achieved before transmission. However, this it is not limited to the use of a particular technology alone Movassaghi et al. [2012]. The different characteristics and operational environments of WBAN applications require an appropriate selection of the wireless technology being used. We have compared the convenience of different technologies suitable for WBANs in Movassaghi et al. [2012]. The specific features of each wireless technology is described along with their major advantages, drawbacks and most appropriate application in WBANs. Comparison of the described technologies are provided from different aspects of frequency range, data rate, coverage area, modulation technique and network topology. Through this thesis, we clarify that the most convenient technology for use in WBANs is Zigbee (IEEE 802.15.4) and later IEEE 802.15.6. Hence, it is not practical to use other technologies such as Bluetooth and WiFi for practical deployment of WBAN. Additionally, since the majority of WBAN implementations use ZigBee (IEEE 802.15.4) and IEEE 802.15.6 (since Feb 2012); thus, radios used in WBANs are based on the IEEE 802.15.4 chipset and researchers have adapted the MAC protocols of these technologies to be more suitable for these networks Latré et al. [2011]. Hence, the use of other wireless technologies such as Bluetooth or WiFi would not be as energy-efficient or comply with the standard requirements of these networks. We consider all WBANs use of the same technology, protocol and similar superframe structures, where inter-WBAN superframe synchronization is achieved before transmission. However, this it is not limited to the use of a particular technology alone Movassaghi et al. [2012].

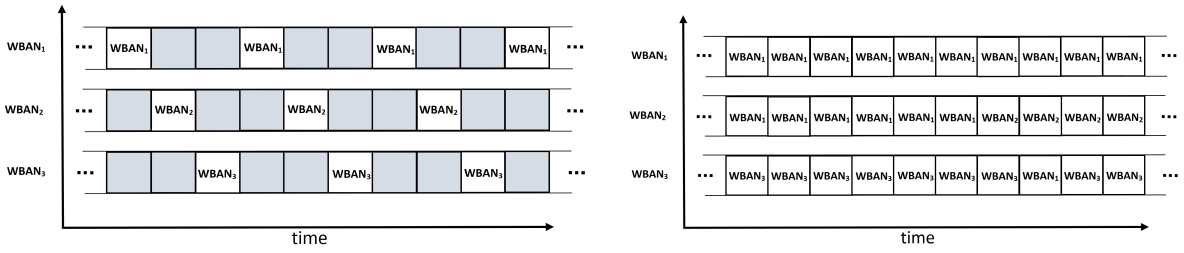


Figure 3.1: Channel Assignment between three coexisting WBANs: (a) Existing Schemes (b) Proposed SCA Scheme

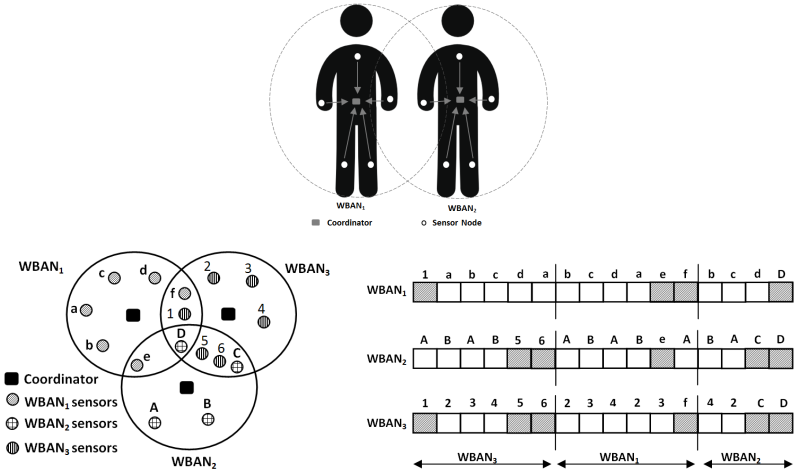


Figure 3.2: Inter-WBAN Channel Assignment for coexisting WBANs: (a) Topological distribution (b) Sensors within coexisting WBANs (c) Proposed SCA Scheme

3.3 Smart Spectrum Allocation

Existing proposals for interference mitigation consider limited or distributed coordination for inter-WBAN channel assignment amongst the coexisting WBANs, which is mainly on the network-level, to orthogonally allocate the channel amongst coexisting WBANs as shown in Fig.3.1.(a). which shows channel allocation for three coexisting WBANs in existing schemes. In many coexistence deployments, sensing data can be shared amongst trusted parties without any privacy concerns Z.Ren [2016]. Existing privacy research can also be integrated in the proposed solution. If we consider the number of coexisting WBANs to be N_c and the length of the superframe to be T_d, then each sensor chooses the start time of every superframe following a uniform distribution over $[0, (N_c - 1)]$ and therefore, randomly with respect to the existing

WBANs. When $N_c = 1$, the WBAN of interest is isolated. In the case where no coordination exists amongst $WBAN_1$, $WBAN_2$ and $WBAN_3$ ($N_c = 3$), all WBANs choose the time following a uniform random distribution over $[0, (N_c - 1)T_d]$, as shown in Fig.3.1(b).

In the case of N_c coexisting WBANs, each consisting of N_s sensor nodes, the delay for orthogonal channel allocation to each of the sensors also referred to as the *Idle period* can be calculated as follows:

$$Idle\ Period = (N_c N_s - 1)\frac{T_d}{N_c N_s} \tag{3.3}$$

Using the proposed opportunistic spectrum allocation, the practical coexistence of WBANs will be accomplished much faster, and the delay in being allocated communication channels will be much smaller, and is calculated as follows:

$$Idle\ Period = \left(\frac{N_s}{N_c N_s - s_i}\right) T_d \tag{3.4}$$

where s_i is the number of nodes that exist in the inter-WBAN interference set of the pair wise coexisting WBANs. We consider that each WBAN allows adaptive allocation of the spectrum which is relative to the number of nodes in that WBAN and the SINR of the nodes in the vicinity of the WBAN of interest. More specifically, if the SINR level of a sensor node of the WBAN of interest is higher than a threshold, that node will need to transmit orthogonally and will be allocated a portion of the channel such that no other sensor node from its coexisting WBANs in its coverage can simultaneously transmit with it. Otherwise, it can be allocated a one portion of the channel that allows simultaneous transmission with other sensor nodes of coexisting WBANs as well. The channel is interference dominated, but the noise is non-negligible, therefore, we consider the use of the SINR value [1].

The concept of using graph coloring for scheduling is not new to wireless networks and was previously looked into in GSM networks where an interference graph

[1] There is a tradeoff between the amount of energy spent at the initial stage for calculations regarding the allocated time slot versus the overall energy consumption and delay. A small amount of energy consumption at the initial stage leads to less chance of interference, far less internetwork delay, higher spatial reuse and throughput which translates into overall energy savings.

represents interfering signals between antennas for a pair of transmitting frequencies, used for frequency assignment in GSM networks Eisenblätter et al. [2001]; Aardal et al. [2007]. In a broader context the proposed approach can be deemed as a graph coloring approach. Thus, we can represent the network as an undirected graph where the vertices represent nodes in the WBAN of interest, and the edges represent interferences so that no other node utilizes the channel assigned to nodes which exist in the interference graph of coexisting WBANs. Thus far our approach can be deemed as a graph coloring approach. However, we later consider channel assignment to be done very simply and without the need to comply with an objective which is mainly the case for most graph coloring approaches. Since the main objective here is to reduce the computations and keep the algorithm as simple as possible such that no channels are assigned to adjacent nodes in each other's coexistence.

The proposed algorithm has a common feature with slotted aloha in the sense that when a node has a packet to send it waits to the start of the next slot to send it. However, slotted ALOHA allows for simultaneous transmission of nodes even though they might be existing in the interference set of one another. This leads to added delay and will not comply with the stringent requirements of WBANs specifically in terms of delay. Whilst the proposed opportunistic approach presented in this chapter, goes one step further and finds nodes that exist in the interference set of one another and only allow for simultaneous transmission of nodes that do not exist in each other's interference set. Thus, the proposed approach avoids interference and retransmission therefore saving energy and increasing the network lifetime. In other words, this approach incorporates the slotted aloha strategy with the added information relative to their interference list to avoid collisions such that simultaneous transmissions are allowed when nodes do not exist in the coexistence of one another. In fact, this approach incorporates scheduled access within each WBAN (intra-WBAN). Thus a more relevant comparison would be against scheduled access which is also supported by the IEEE 802.15.6 standard which is similar to the inter-WBAN orthogonal approach to which we have compared with this proposal. However the CSMA/CD approach is not supported as per the IEEE 802.15.6 MAC standard and therefore cannot be compared against.

The proposed Smart Channel Assignment (SCA) is accomplished through four stages described as follows:

- *Step I: Orthogonal Transmission:* Coordinators of coexisting WBANs negotiate to assign orthogonal channel for each WBAN. Therefore, the shared channel has to be divided evenly into N_c time-slots where each of these time-slots are further divided into N_s for each sensor node to be allocated a specific time slot. Thus, each node goes into idle mode for $(N_c \times N_s - 1)$ time slots. We assume that the l^{th} sensor of $WBAN_i$ transmits at time slot $T_{i,l}$. After that, each sensor node transmits to its coordinator in its allocated time slot while other coordinators try to calculate the interference level of that sensor (from the received power). Let $\gamma_{i,j,l}$ denote the received power from the l^{th} sensor of $WBAN_j$ at $WBAN_i$.

- *Step II: Interference Set Formation:* After the first round of orthogonal transmission, each coordinator creates a table consisting of the received power from each sensor of all WBANs. Each coordinator then finds the minimum received power from its sensors and compares it to the received power from sensors of other WBANs. Let us consider that the minimum receive power of the sensors in $WBAN_i$ at its coordinator is $\gamma_{min,i}$, then $\gamma_{min,i} = \min\{\gamma_{i,i,l}\}$. If the receive power of a sensor from other WBANs is larger that $\gamma_{min,i} - \gamma_{Th}$, that sensor is added to the Inter-Interference list, otherwise it considered as a low interference node. We show the interference list of $WBAN_i$ by $\mathcal{I}_i$, where $\mathcal{I}_i = \{(j,l)|\gamma_{i,j,l} > \gamma_{min,i} - \gamma_{Th}\}$. If the received power of a sensor from other WBANs is larger than the acceptable threshold, that sensor is added to the Inter-Interference list.

- *Step III: Information Exchange:* In this stage each coordinator broadcasts its interference list. Therefore, each coordinator is able to verify which of its sensors severely interfere on other WBANs. Also, each coordinator can verify which sensors of other WBANs have severe interference on itself. Each coordinator then creates a set, namely an interference set, which consists of all sensors that have an interference level above the acceptable interference threshold. More specifically, the interference set of $WBAN_i$ is $\mathcal{S}_i = I_i \cup \{(i,l)|(i,l) \in \mathcal{I}_j,\ j \neq i\}$.

- *Step IV: Smart Channel Assignment:* Channel assignment is updated at this stage. Specifically, in $WBAN_i$, node (j,l) in the interference set is assigned with the same time slot as before, i.e., $T_{j,l}$. Also, node (i,l) in the interference set is assigned with the time slot $T_{i,l}$. We assume the number of nodes in $\mathcal{S}_i$ is s_i, then s_i out of $N_c N_s$ time slots are assigned for nodes in the interference set. The remaining $N_c N_s - s_i$ time slots are allocated equally to nodes of $WBAN_i$ which are not in the interference set. This way each node will have twice more the spatial reuse of the orthogonal inter-WBAN TDMA scheme.

An example of the proposed interference mitigation scheme for three coexisting WBANs with a number of sensory devices deployed on each WBAN with a configuration provided in Fig. 3.2.(a) and Fig. 3.2.(b) is shown in Fig. 3.2.(c). The intersection of coverage radiuses between coexisting WBANs represents their interference region. Thus, the interference region of each WBAN is formed with a tuple where the first component is the ID of the WBAN which is interfering with the WBAN of interest and the second component is the ID of the sensor node of that WBAN which is interfering with our WBAN of interest. Next, WBANs will broadcast their inter-network interference sets as follows: $\mathcal{S}_1 = \{(1,e),(1,f),(2,D),(3,1)\}$, $\mathcal{S}_2 = \{(1,e),(2,D),(2,C),(3,5),(3,6)\}$, and $\mathcal{S}_3 = \{(1,f),(2,C),(2,D),(3,1),(3,5),(3,6)\}$. Then, each WBAN allocates an orthogonal channel to sensors within itself that coexist in another WBANs interference set and allows the remaining sensors to simultaneously occupy the rest of the channels. For instance, Fig. 3.2.(c) shows the channel allocation for three coexisting WBANs when $WBAN_3$ is transmitting first. Since $WBAN_1$,$WBAN_2$ and $WBAN_3$ contain 6, 4 and 6 sensors, respectively, the whole channel will be divided into 16 time slots. If we consider $WBAN_3$ to transmit first, since sensor with $ID = 1$ of $WBAN_3$ exists in the interference region of sensors of $WBAN_1$, an orthogonal channel will be allocated to it and no other sensor from $WBAN_1$ can transmit simultaneously along with it. Also, sensors with $ID = 5$ and $ID = 6$ exist in the interference region of $WBAN_2$, therefore, no sensors from $WBAN_2$ can transmit simultaneously with $WBAN_3$ during the transmission of these two sen-

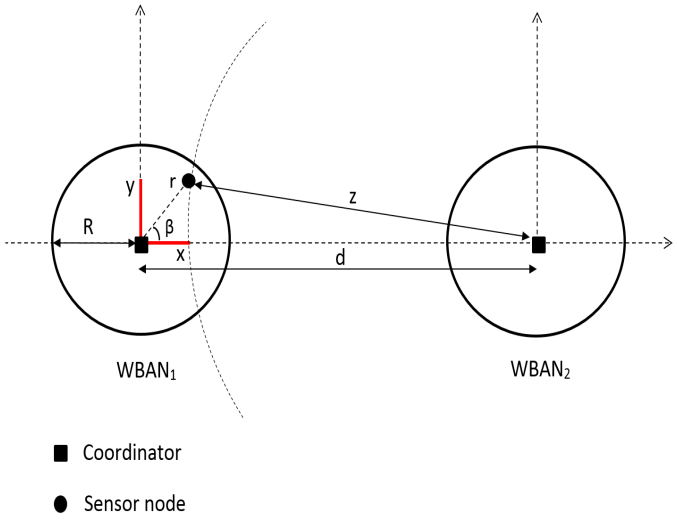


Figure 3.3: Inter-WBAN Distance Model

sors and an orthogonal channel should be assigned to them to avoid interference amongst them. Also, if any sensors from coexisting WBANs exist in the interference list of $WBAN_3$, an orthogonal channel needs to be allocated for their transmission. Since, sensor with $ID = f$ from $WBAN_1$ and sensors with $ID = C$ and $ID = D$ from $WBAN_2$ exist in the interference region of $WBAN_3$, orthogonal channels will be assigned to them. Finally, the remaining sensors of $WBAN_3$ will transmit simultaneously with sensors of coexisting WBANs until the remaining channels are fully occupied. The same procedure is accomplished simultaneously for $WBAN_2$ and $WBAN_1$. This approach increases the spatial reuse as well as lowering the delay as opposed to fully orthogonal channel assignment which is done in existing schemes since interference is only looked at from the network level and not the node-level. The pseudo code for the proposed SCA algorithm is shown in Algorithm 1.

3.3.1 Analysis

In this section we calculate the average reuse factor for $WBAN_0$; a result that can be applied to all other WBANs due to symmetry.

Let z denote the distance between a sensor node of a WBAN to a coordinator of another WBAN which is located in the distance d (Fig. 3.3), where $x = r\cos\beta$ and

Algorithm 1: Smart Channel Assignment (SCA)

Step 1. Orthogonal Transmission;
for $i = 1$ *to* N_c **do**
  for $j = 1$ *to* N_s **do**
    Sensor (i, j) is transmitting;
    $WBAN_\ell$ estimates the received signal power, $\gamma_{i,j}$, from sensor (i, j)
  end
end

Step 2: Determine the inter-interference set;
for $i = 1$ *to* N_c **do**
  $\gamma_{min,i} = \min\{\gamma_{i,j}\}$
end
for $\ell = 1$ *to* N_c, $\ell \neq i$ **do**
  for $j_2 = 1$ *to* N_s **do**
    if $\gamma_{\ell,j_2} > \gamma_{min,i} - \gamma_{Th}$ **then**
      Add (ℓ, j_2) to set $\mathcal{I}_i$
    end
  end
end

Step 3: Broadcast;
for $i = 1$ *to* N_c **do**
  Broadcast $\mathcal{I}_i$
end

Step 4: Determine the interference set;
for $i = 1$ *to* N_c **do**
  $\mathcal{S}_i = \mathcal{I}_i \cup \{(i, j) | (i, j) \in \mathcal{I}_\ell, \ell \neq i\}$
end

Step 5: Channel assignment;
for $i = 1$ *to* N_c **do**
  Leave the time slots for nodes in $\mathcal{S}_i$ unchanged
  Equally assign the remaining channels to nodes that do not belong to $\mathcal{S}_i$.
end

$y = r\sin\beta$. Thus, z can be calculated as follows:

$$z = \sqrt{(d - r\cos\beta)^2 + r^2\sin^2\beta = d^2 - 2dr\cos\beta + r^2} \tag{3.5}$$

where β is a uniform random variable over $[0, 2\pi]$ and the probability distribution function of r is $f(r) = \frac{2r}{R^2}$. We consider $R = 1$ throughout this thesis. Accordingly, the cumulative density distribution (CDF) for z, which is a random variable, for $d - R \leq z_0 \leq d + R$ can be calculated as follows:

$$P_z(z) = \begin{cases} 1 & \text{for } \; z_0 \geq d + R \\ 0 & \text{for } \; z_0 \leq d - R \end{cases} \tag{3.6}$$

Accordingly, the PDF of z for a fixed d, referred to as $f_z(z)$ can be calculated be as follows:

$$\begin{cases} \left(\frac{2z}{\pi R^2}\right) \arccos\left(\frac{d^2+z^2-R^2}{2dz}\right) & \text{for } d - R \leq z_0 \leq d + R \\ 0 & \text{Otherwise} \end{cases} \tag{3.7}$$

According to the path loss model, the received power from a sensor node in WBAN_i at WBAN_0 is as follows:

$$P_{r,dB} = P_{t,dB} - 10\log(\frac{4\pi d_i f}{c})^2 + 10\log({h_i}^2) - X_{i,dB}, \tag{3.8}$$

where $P_{t,dB}$ is the transmit power, h_i is the rayleigh fading coefficient between WBAN_i and WBAN_0, d_i is the distance between the sensor of WBAN_i to WBAN_0 and $X_{i,dB}$ is the shadowing offset that for simplicity we consider to be constant for the whole network. We can easily rewrite (3.8) as follows:

$$P_{r,dB} = A_{dB} + 20\log(\frac{h_i}{d_i}), \tag{3.9}$$

where $A_{dB} = P_{t,dB} - 20\log(\frac{4\pi f}{c})^2 - X_{dB}$ is a constant value.

Let P_I denote the probability that the received power is above the threshold value γ_{th}, thus we have:

$$P_{I,i} = P(P_{r,dB} > \gamma_{th}) = P(A_{dB} + 20log(\frac{h_i}{d_i} > \gamma_{th}) = P(\frac{h_i}{d_i} > 10^{\frac{\gamma_{th}-A_{dB}}{20}}). \tag{3.10}$$

Since, h_i and d_i are independent random variables and h follows Rayleigh distribution with parameter $\frac{\sqrt{2}}{2}$, we have:

$$P_{I,i} = \int_0^\infty P(h_i > d_i \times 10^{\frac{\gamma_{th}-A_{dB}}{20}} | d_i = s) P_d(s) ds, \tag{3.11}$$

3.3.1.1 Average Reuse Factor

Let $p_{m,i}$ denote the probability that m number of nodes exist in the interference region of WBAN_1, then we have:

$$p_{m,i} = \binom{N_s}{m} P_{I,i}^m (1 - P_{I,i})^{N_s - m}, \tag{3.12}$$

Thus, the number of nodes of each WBAN that are in the interference region is a binomial distributed random variable with parameters N_s and P_I. Therefore, the mean value and variance of m can be calculated as follows:

$$m_m = \text{E}[m] = N_s P_I, \tag{3.13}$$

$$\sigma_m^2 = \text{E}[(m - m_m)^2] = N_s P_I (1 - P_I). \tag{3.14}$$

The following lemma then gives the average reuse factor for WBAN_0.

Lemma 1. *Let R_0 denote the average reuse factor for $WBAN_0$ and $P_{I,i}$ is the probability that a sensor node of $WBAN_i$ exist in the interference region of $WBAN_0$. Then R_0 can be calculated as follows:*

$$R_0 = N_c - \sum_{i=1}^{N_c - 1} P_{I,i} \tag{3.15}$$

Proof. Since $P_{I,i}$ is the probability that a sensor node of WBAN_i exist in the interference region of WBAN_0, then on average $N_s P_{I,i}$ sensors of WBAN_i exist in the

interference region of WBAN$_0$, for $i = 1, 2, ..., N$. Due to the symmetry, $N_s P_{I,i}$ sensors of WBAN$_0$ exist in the interference region of WBAN$_i$. The total number of available channels is $N_c N_s$, which among them $2\sum_{i=1}^{N-1} N_s P_{I,i}$ channels will be allocated orthogonally. The remaining channels will be uniformly assigned to the sensor nodes of WBAN$_0$. The number of the sensor nodes of WBAN$_0$, which are in the interference region is $\sum_{i=1}^{N-1} N_s P_{I,i}$, and so the average reuse factor can be calculated as follows:

$$R_0 \quad = \quad \left(\frac{1}{N_s} (\sum_{i=1}^{N-1} N_s P_{I,i}) \times 1 \; + \; \frac{(NN_s - 2\sum_{i=1}^{N-1} N_s P_{I,i})}{N_s - \sum_{i=1}^{N-1} N_s P_{I,i}} \; \times \; (N_s - \sum_{i=1}^{N-1} N_s P_{I,i}) \right).$$

This completes the proof. □

3.3.1.2 Outage Probability

Let $P_{out,i}$ denote the probability that the total interference at time instant i is larger than γ_{th} at $WBAN_0$. Then it can be calculated as follows:

$$P_{out,0} = p(\sum_{j=1}^{N-1} \gamma_j > \gamma_{th}). \tag{3.16}$$

Here, we propose a probabilistic approach to effectively reduce the outage probability and then we analytically prove that the proposed probabilistic approach scheme achieves a lower outage probability. As stated before, WBAN$_0$ put a sensor node in the interference region, if the received SNR from that sensor is higher than a threshold. Let γ_j denote the received SNR from a sensor node in WBAN$_j$ at WBAN$_0$. It is clear that if $\gamma_j > \gamma_{th}$, then that sensor nodes will be assigned an orthogonal channel. Otherwise, if $\gamma_j < \gamma_{th}$, we propose to assign an orthogonal channel for that sensor with a certain probability which is proportional to $\frac{\gamma_j}{\gamma_{th}}$. The average interference level at time instant i by using the proposed probabilistic approach can then be calculated as follows:

$$\gamma_i = \sum_{j=1}^{N-1} \gamma_j (1 - \frac{\gamma_j}{\gamma_{th}}), \tag{3.17}$$

which arise from the fact that by using the probabilistic approach, a sensor is assigned with an orthogonal channel with probability $\frac{\gamma_j}{\gamma_{th}}$. The following lemma gives the outage probability for the proposed probabilistic approach.

Lemma 2. *Let $P_{out}^{(prob.)}$ denote the outage probability for the proposed probabilistic approach, and P_{out} is the outage probability for the original scheme. Then, $P_{out}^{(prob.)} < P_{out}$. Moreover, if R_0 and $R_0^{(prob.)}$ are the average reuse factor for the proposed scheme with and without probabilistic channel assignment, respectively, then $R_0^{(prob.)} < R_0$.*

Proof. According to the definition of the outage probability, we have:

$$P_{out}^{(prob.)} = p\left(\sum_{i=1}^{N-1}\gamma_i(1-\frac{\gamma_i}{\gamma_{th}}) > \gamma_{th}\right) = p\left(\sum_{i=1}^{N-1}\gamma_i > \gamma_{th} + \sum_{i=1}^{N-1}\frac{\gamma_i^2}{\gamma_{th}}\right) < \quad p(\sum_{j=1}^{N-1}\gamma_j > \gamma_{th}) = P_{out},$$

where the last step arises from the fact that the cumulative probability distribution function is an increasing function of its argument.

Let $P_{I,i}^{(prob.)}$ denote the probability that a sensor node of WBAN_i is in the interference region of WBAN_0 after deploying the probabilistic approach. Then we have

$$P_{I,i}^{(prob.)} = P(\gamma_i > \gamma_{th}) + P(\gamma_i < \gamma_{th})\frac{\gamma_i}{\gamma_{th}},$$

which is clearly larger than $P_i = P(\gamma_i > \gamma_{th})$. According to lemma 1, the average reuse factor can be calculated as follows:

$$R_0^{(prob.)} = N - \sum_{i=1}^{N-1} P_{I,i}^{(prob.)} = N - \sum_{i=1}^{N-1} P_I - \sum_{i=1}^{N-1} p(\gamma_i < \gamma_{th})\text{E}(\frac{\gamma_i}{\gamma_{th}}) < \quad N - \sum_{i=1}^{N-1} P_I = R_0.$$

This completes the proof. □

3.3.2 Simulation Results

We have considered 19 WBANs where WBAN_0 is located in the middle. We consider different WBAN densities of low, middle, high and extremely high by considering N_s to be 12, 25, 50 and 100, respectively. We also consider that all sensor nodes excluding the coordinator in a WBAN have similar transmit power (P_t). The average spatial reuse versus the threshold interference for all WBANs with variations in the

shadowing offset from no shadowing to partial shadowing and full shadowing is shown in Fig.3.4. As can be seen in this figure, a higher spatial reuse is obtained for interference thresholds lower than -50 dB which is quite efficient in the case of WBANs. The amount of spatial reuse in these scenarios are approximately 4 times the coloring-based approach [5] and 20 times the conventional orthogonal approach. This figure also contains information regarding variations in the density of nodes within each WBAN from 12 to 25, 50 and 100; where the higher the number of nodes the more the interference and the lower the spatial reuse.

Fig. 3.6 compares the average reuse factor for the probabilistic approach and that for the original scheme. As can be clearly seen in this figure, the probabilistic approach achieves a lower reuse factor for all interference thresholds. Also, Fig.3.7 shows the minimum SINR level for both schemes which clearly shows that the probabilistic approach provides a higher minimum SINR level as it decreases the reuse factor by putting more sensors in the interference region of each WBAN. We have also evaluated the minimum SINR value of $WBAN_0$ versus the interference threshold for no shadowing to partial shadowing and full shadowing in Fig.3.5; where a higher SINR which corresponds to a lower outage probability is obtained when the threshold interference is increased. In fact, there is a trade-off between the level of SINR and the value of spatial reuse. Higher spatial reuse can only be achieved when lower SINR can be handled. In other words, when the interference threshold decreases, more sensor nodes are included in the interference set of each WBAN, leading to a lower spatial reuse and a higher SINR value. In addition, as can be seen in Fig.3.4, the average reuse factor for each WBAN when $N = 2$ and the shadowing offset is 20 dB. It is important to note that due to symmetry the average reuse factor for both WBANs are the same. As can be clearly seen in this figure the proposed scheme achieves the optimal reuse factor (which is 2) when the distance between two WBANs is larger than 7 m when $\gamma_{th} = -70$ dB. Also when γ_{th} increases, which means that the coordinator can tolerate a higher amount of interference, the optimal reuse factor is achieved in lower distances, i.e. < 3 m and < 2 m when $\gamma_{th} = -60$ dB and $\gamma_{th} = -50$ dB, respectively. Also it can be seen in this figure that when the interference threshold reaches zero, the proposed scheme will approach the fully

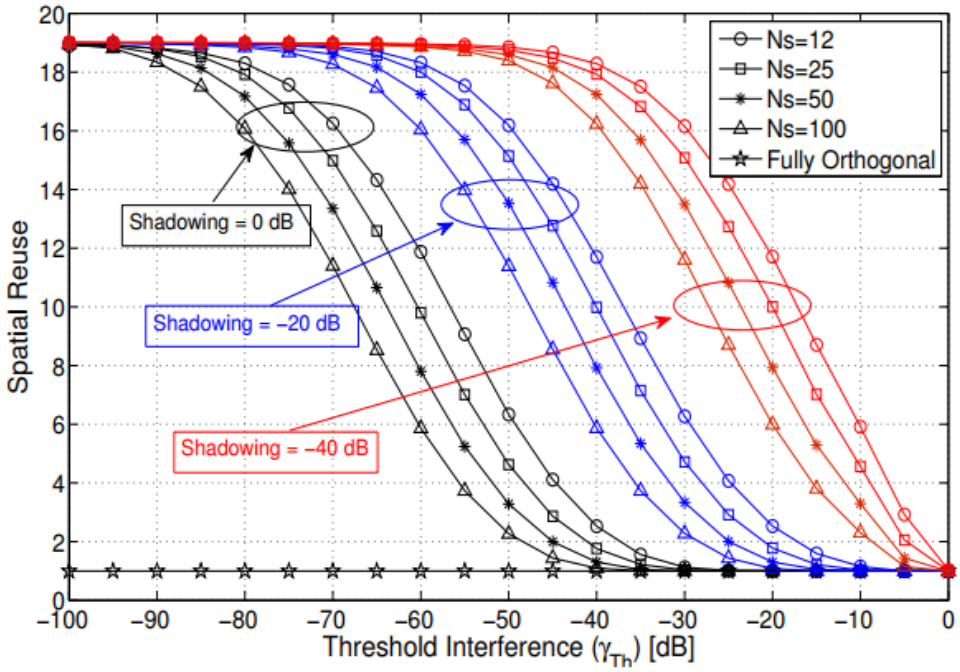


Figure 3.4: Average value of the spatial reuse for all WBANs versus the interference threshold value when the Shadowing offset is 0 dB

orthogonal scheme in terms of spatial reuse. Accordingly, the highest SINR will be achieved due to the fact that all sensors transmit orthogonally. It is important to note that the interference threshold can be adaptively selected according to the minimum interference level. This means that a lower interference threshold is selected when the minimum interference level is relatively low. Otherwise higher values should be selected for the interference threshold. Also, the proposed scheme adds no complexity to the sensor nodes as all the calculations are carried out by the coordinators.

3.4 Probabilistic Spectrum Allocation

This part of the chapter enhances on the smart spectrum allocation scheme proposed earlier in Section 3.3. Here we assign an orthogonal channel to nodes that do not exist in the interference set of collocated WBANs with a probability of $\frac{\gamma_j}{\lambda\gamma_{th}}$, where γ_{th} refers to the SINR value and λ represents the interference probability. We have shown the interference probability to decrease with increasing the value of λ. We later had an optimization approach to find the optimum value of λ for which the node that

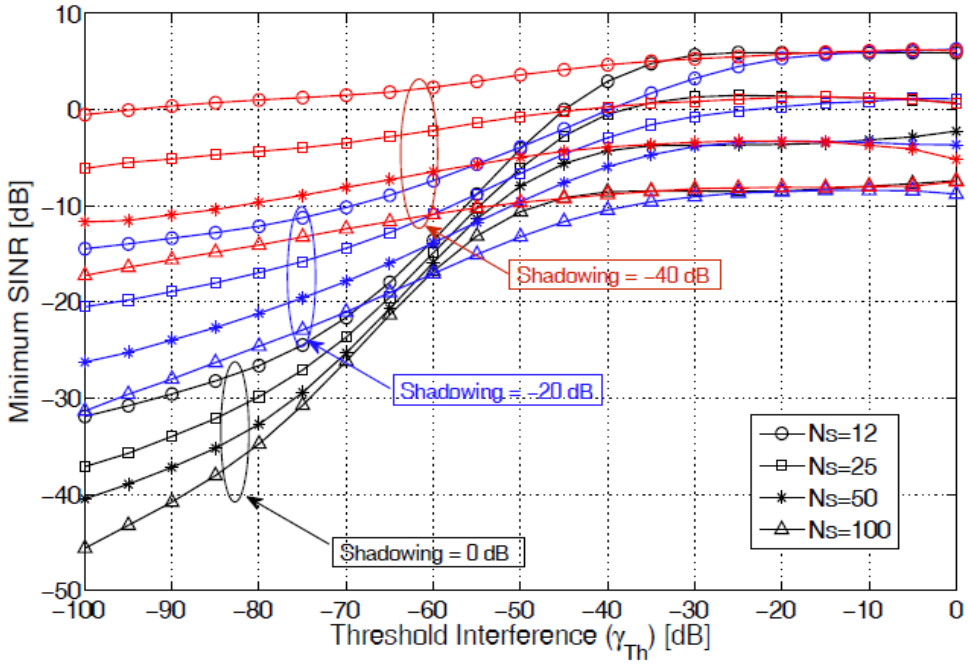


Figure 3.5: Minimum value of SINR for WBAN0 versus the interference threshold value for different shadowing offsets and number of nodes.

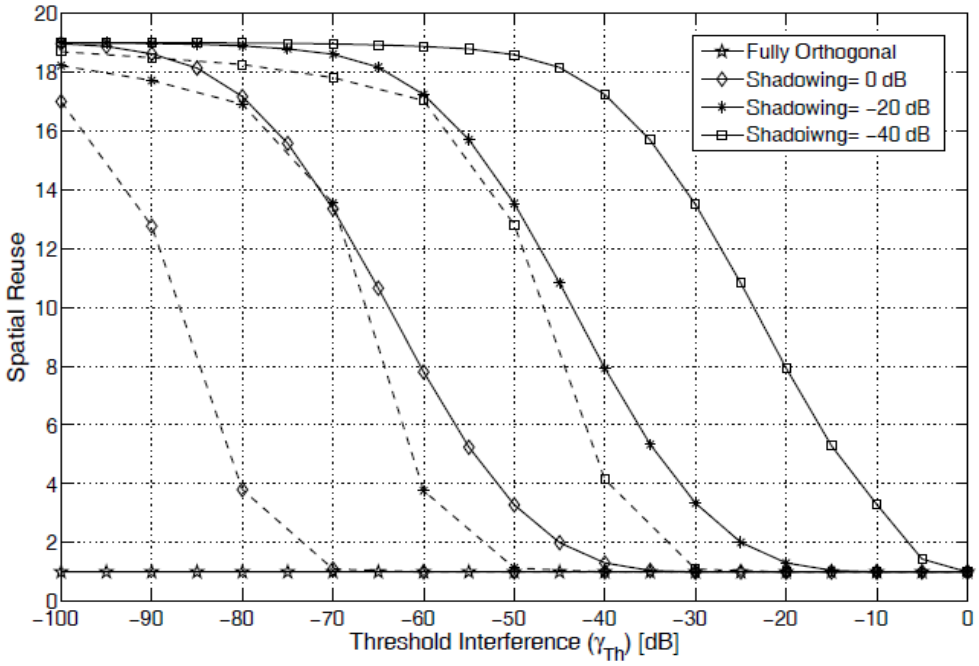


Figure 3.6: Average reuse factor versus the interference threshold. Solid lines show the original approach and dashed lines show the probabilistic approach.

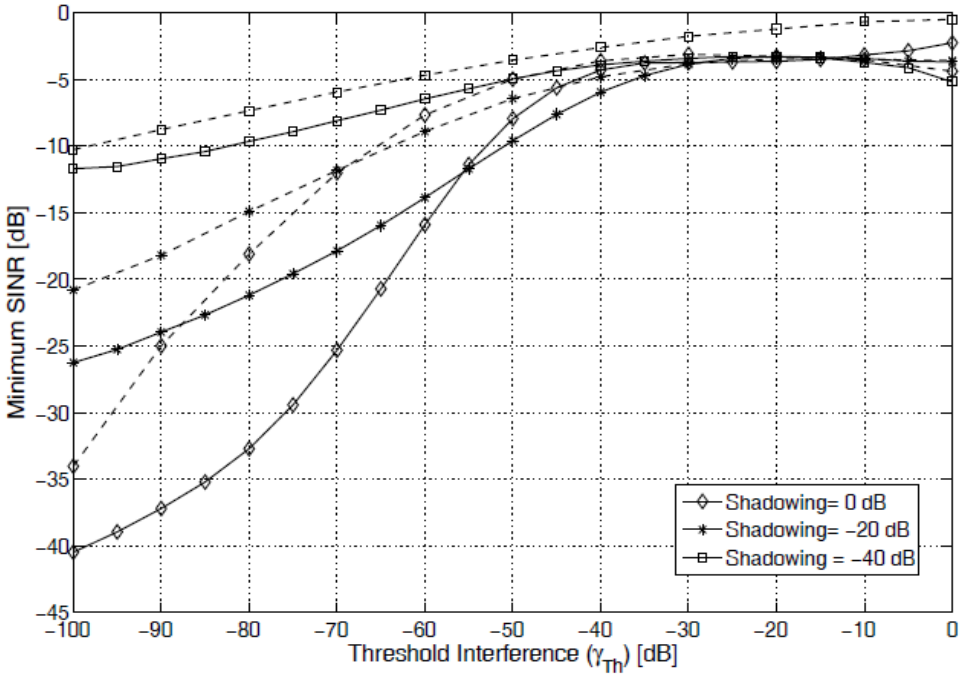


Figure 3.7: Minimum SINR value versus the interference threshold. Solid lines show the original approach and dashed lines show the probabilistic approach.

exists in the interference set would be allocated an interference probability where the optimum value of λ was found to be 1.7. We have also gone a step further and evaluated the efficiency of the proposed probabilistic approach in terms of outage probability, delay and spatial reuse. Additionally we provide further analysis to the chapter to evaluate its functionality.

Additionally, in order to effectively reduce the outage probability we introduce a new term namely, interference probability factor λ. We define outage probability to be the probability that the SINR is below the threshold value. As per the proposed SCA algorithm, a WBAN places a node in the interWBAN interference set if the received interference power, γ_j, from that sensor node is higher than the threshold interference power, γ_{th}. If $\gamma_j > \gamma_{th}$ that sensor is allocated an orthogonal channel with a probability of 1. Otherwise, if $\gamma_j < \gamma_{th}$, we propose to assign the sensor an orthogonal channel with an interference probability of $\frac{\gamma_j}{\lambda\gamma_{th}}$ where λ here introduces the probability of interference.

The probability that the received power from a sensor of another WBAN is higher

than the threshold value, γ_{th}, can be calculated as follows:

$$P\left(P_{r,dB} \geq \gamma_{th}\right) = P(P_{t,dB} - 10\log\left(\frac{4\pi f d_i}{c}\right)^{n} - X_{dB} + 10\log({h_i}^2) > \gamma_{th}) \\ = P\left({h_i}^2 \geq \left(\frac{\gamma_{th} {d_i}^{n} X}{P_t}\right)\left(\frac{4\pi f}{c}\right)^{n}\right) \tag{3.18}$$

Since, h_i and d_i are independent random variables where h_i follows a rayleigh distribution, then ${h_i}^2$ follows an exponential distribution with parameter 0. Thus, we have the following:

$$P\left(P_{r,dB} > \gamma_{th}\right) = \int_{d-R}^{d+R} \frac{2z}{\pi R^2} \arccos\left(\frac{d^2 + z^2 - R^2}{2dz}\right) \times \exp\left(-\left(\frac{\gamma_{th} X}{P_t}\right)\left(\frac{4\pi f}{c}\right) z^n\right) dz \tag{3.19}$$

We then define the reference received power γ_0 as the average received power at the edge of each WBAN from its coordinator given by:

$$P_r = P_t \left(\frac{4\pi f}{c}\right)^{-n} \equiv \gamma_0 \tag{3.20}$$

Thus, we have the following:

$$q_I = P\left(P_{r,dB} > \gamma_{th}\right) = \int_{d-1}^{d+1} \frac{2z}{\pi} \arccos\left(\frac{d^2 + z^2 - 1}{2dz}\right) \\ \times \exp\left(-\left(\frac{\gamma_{th} X}{\gamma_0}\right) z^n\right) dz \tag{3.21}$$

In this section we calculate the interference probability as a function of distance for each WBAN. We then calculate the average reuse factor as a function of the interference probability. This result is applicable to all WBANs due to symmetry. The interference probability for the probabilistic approach referred to as q_I can be calculated as follows:

$$q_I = \int_{d-1}^{d+1} \left(1 - \left(\frac{\gamma_j}{\lambda\gamma_{th}}\right)\right) \frac{2z}{\pi} \times \arccos\left(\frac{d^2+z^2-1}{2dz}\right) \times \exp\left(-\left(\frac{\gamma_{th}X}{P_t}\right) \times \left(\frac{4\pi f}{c}\right)^n z^n\right) dz \tag{3.22}$$

$$+ \int_{d-1}^{d+1} \left(\frac{\gamma_j}{\lambda\gamma_{th}}\right) \frac{2z}{\pi} \arccos\left(\frac{d^2+z^2-1}{2dz}\right) dz$$

The probability that a node exists in the interference region at time instant i by using the proposed probabilistic approach, referred to as $q_{I_{Prob}}$ can then be calculated as follows:

$$\begin{aligned} q_{I_{Prob}} &= P\left(P_{r,dB} > \gamma_{th}\right) \times 1 + P\left(P_{r,dB} < \gamma_{th}\right) \times [1 - (\frac{\gamma_j}{\lambda\gamma_{th}})] \\ &= P\left(P_{r,dB} > \gamma_{th}\right) [1 - (\frac{\gamma_j}{\lambda\gamma_{th}})] + (\frac{\gamma_j}{\lambda\gamma_{th}}) \end{aligned} \tag{3.23}$$

where $P_{t,dB}$ is the transmit power, h_i is the rayleigh fading coefficient between WBAN$_i$ and WBAN$_0$, d_i is the distance between the sensor of WBAN$_i$ to the coordinator of WBAN$_0$, n is the path loss exponent and $X_{i,dB}$ is the shadowing offset that we consider to be constant for the whole network.

It is important to note that the proposed scheme can be used in conjunction with other WBANs that are hidden terminals such as multihop communication and transmit power control. The proposed approach is robust to mobility variations of WBANs moving into and out of each others range due to the generally slow movement of WBANs and the relatively large coherence time for any WBAN, which is up-to-1 second for everyday use of WBANs Smith and Hanlen [2015]. Our assumptions are made under a quasi-static environment since our proposal can execute within the 100–400 ms length of a frame, during which the channel is considered to be stable. Also due to the variations in distance induced by inter-WBAN mobility Katayama et al. [2009], we have evaluated the interference probability for different inter-WBAN distances in Fig. 4 to investigate the influence of distance on channel conditions. Another advantage of this approach is its capability to operate in the low to medium

SINR range, which implies sensor circuit power consumption is reduced leading to energy savings.

3.4.1 Optimization of the Interference Probability Factor

Fig. 3.8 shows changes in the q_I value versus the inter-WBAN distance ($\frac{d}{R}$) for two coexisting WBANs for different values of ($\frac{\gamma_{th}}{P_t}$) being 0.01, 0.1 and 1, respectively. As can be seen in this figure, the higher the inter-WBAN distance, the lower the probability of interference. Also, the higher the value of $\frac{\gamma_{th}}{P_t}$, the lower the interference. This is because with increasing the distance the interference signal will be much weaker and therefore the probability of interference will be much lower. Additionally, with decreasing the ratio of $\frac{\gamma_{th}}{P_t}$, we are increasing the term $\exp(\frac{\gamma_{th}}{P_t})$ which increases the overall interference probability. It is important to note that the value for γ_{th} was found through an iterative approach of evaluating the output metrics based on the predefined values for transmit power, channel gain and received power to find the most optimum value and later using this local optima to optimize the interference probability factor.

The following lemma calculates the reuse factor for $WBAN_0$.

Lemma 3. *Let R_0 denote the average reuse factor for $WBAN_0$ and $q_{I,i}$ as the probability that a sensor node of $WBAN_i$ exists in the interference region of $WBAN_0$. Then R_0 can be calculated as follows:*

$$
\begin{aligned}
R_0 &= N_c - \sum_{j=1}^{N_c-1} q_{I,j} \qquad (3.24)\\
&= N_c - \sum_{j=1}^{N_c-1} \left(q(P_{r,dB} > \gamma_{th}) \left[1 - \left(\frac{\gamma_j}{\lambda \gamma_{th}} \right) \right] \; q(P_{r,dB} < \gamma_{th}) \left(\frac{\gamma_j}{\lambda \gamma_{th}} \right) \right) \\
&= N_c - \sum_{j=1}^{N_c-1} \left(\int_{d-1}^{d+1} \left(1 - \left(\frac{\gamma_j}{\lambda \gamma_{th}} \right) \right) \frac{2z}{\pi} \times \arccos \left(\frac{d^2 + z^2 - 1}{2dz} \right) \right. \\
&\left. \times \exp \left(- \left(\frac{\gamma_{th} X}{P_t} \right) \left(\frac{4\pi f}{c} \right)^n z^n \right) dz + \int_{d-1}^{d+1} \left(\frac{\gamma_j}{\lambda \gamma_{th}} \right) \frac{2z}{\pi} \arccos \left(\frac{d^2 + z^2 - 1}{2dz} \right) dz \right)
\end{aligned}
$$

We can then calculate the Signal to Interference Plus Noise Ratio (SINR) as fol-

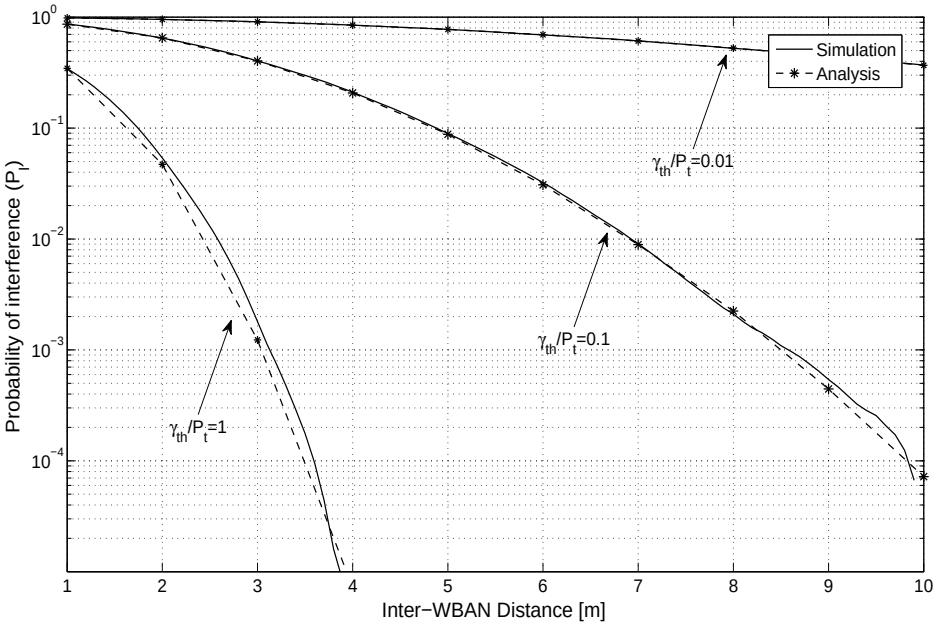


Figure 3.8: Interference Probability versus the Inter-WBAN distance for different values of $(\frac{\gamma_{th}}{P_t})$ when $\lambda \to 0$

lows:

$$SINR = \frac{P_r}{N + I} = \frac{P_r}{N_0 + mP(d)} \tag{3.25}$$

where N_0 is the AWGN noise and the interference is a function of the number of simultaneous transmissions (referred to as m) of sensor nodes of WBANs that coexist with the WBAN of interest, each with a received power that is a function of their distance to the WBAN of interest, namely $P(d)$. We consider the received power of sensor nodes of other WBANs transmitting at the same time from an average distance d to be calculated with $P(d)$ and we can calculate the number of sensors transmitting simultaneously with the WBAN of interest as follows:

$$n = \frac{(N_c - 1)R_0 N_s}{N_c N_s} = (N_c - 1)\frac{R_0}{N_c} \tag{3.26}$$

Thus, the SINR can be calculated as follows:

$$SINR = \frac{P_r}{N_0 + (\frac{N_c-1}{N_c})R_0P(d)} \tag{3.27}$$

By dividing (3.27) by N_0 and, substituting $P(d) = P_r d^{-n}$ and received SNR $\gamma_0 = \frac{P_r}{N_0}$, we have the following:

$$SINR = \frac{\gamma_0}{1 + (\frac{N_c-1}{N_c})\gamma_0 d^{-n} R_0} \tag{3.28}$$

In order to find the optimum λ we have the following:

$$\begin{aligned} \frac{\gamma_0}{1 + (\frac{N_c-1}{N_c})\gamma_0 d^{-n} R_0} &\geq \gamma_{th}, \\ \frac{\gamma_0}{\gamma_{th}} &\geq 1 + (\frac{N_c - 1}{N_c})\gamma_0 d^{-n} R_0, \\ (\frac{\gamma_0}{\gamma_{th}} - 1)(\frac{N_c}{N_c - 1})\frac{d^n}{\gamma_0} &\geq R_0 \end{aligned} \tag{3.29}$$

Since $R_0 = N_c - (N_c - 1)P_I(d)$, we have:

$$(\frac{\gamma_0}{\gamma_{th}} - 1)(\frac{N_0 N_c}{N_c - 1})\frac{d^n}{\gamma_0} \geq N_c - (N_c - 1)P_I(d)(\frac{N_c}{N_c - 1})1 - (\frac{\gamma_0}{\gamma_{th}} - 1) \tag{3.30}$$

And, for different values of $\frac{\gamma_0}{\gamma_{th}}$ we have:

$$\begin{cases} (1 - 0.1d^n)(\frac{10}{9}) \leq P_I(d) & \frac{\gamma_0}{\gamma_{th}} = 10 \;\; and \;\; N_c = 10 \\ (\frac{10}{9}) \leq P_I(d) & \frac{\gamma_0}{\gamma_{th}} = 1 \;\; and \;\; N_c = 10 \\ (1 + d^n)(\frac{10}{9}) \leq P_I(d) & \frac{\gamma_0}{\gamma_{th}} = 0.1 \;\; and \;\; N_c = 10 \end{cases} \tag{3.31}$$

The value of λ is found to tend to infinity for $\frac{\gamma_0}{\gamma_{th}} = 20\ dB$. This implies with increasing λ the interference probability merges to zero and the proposed method will have similar functionality to the probabilistic approach. Whilst in the case that $\frac{\gamma_0}{\gamma_{th}} = 0\ dB$, λ is found to merge to zero which means the probability of other nodes existing in the interference set will become quite high. This implies the proposed

approach will have similar functionality to the orthogonal scheme as the probability that a node exists in the interference set will be maximized. Hence, after exhaustive analysis and evaluating the values obtained from sketching P_I over d we were able to find the optimum value for the interference probability factor, λ, to be 1.7 and we further continue analyzing our proposed approach using this value.

3.4.2 Simulation Results

We have considered 3 coexisting WBANs where $WBAN_0$ is located between the other two WBANs and each WBAN consists of 10 sensor nodes. We also consider that all sensor nodes excluding the coordinator in a WBAN have the same transmit power (P_t). As stated previously, we are considering an open environment for operation, which could either be large indoors or outdoors.

3.4.2.1 Interference Probability

Simultaneous transmissions of coexisting networks leads to the likelihood of interference of transmitting sensors on another WBAN's transmission. In our proposed scheme, we find the nodes that exist in the interference set of each WBAN and assign them orthogonal channels accordingly, where the interference probability is defined as the probability at which a node is placed in the interference set. Fig. 3.9 shows the interference probability versus the inter-WBAN distance for different values of λ when $\frac{\gamma}{\gamma_{th}} = 1$. As can be seen in this figure, the higher the value of λ, the lower the interference probability, which implies there will be fewer nodes in the interference set. As can be seen in this figure, using the probabilistic approach there is the cost of a slightly higher probability of interference.

3.4.2.2 Spatial Reuse

WBANs are required to support up to several Mbps which implies their need for high spectral efficiency. Also, due to the scarce limitation of resources in terms of battery supply, the network is required to deliver the offered traffic to its absolute advantage. Additionally, variations in the distance amongst coexisting networks should not de-

grade the network performance as much. In fact, the spatial reuse is the cumulative distribution function of the SINR up to the threshold value that it is being accounted for. The average spatial reuse versus the threshold interference for three coexisting WBANs with variations in distance in full shadowing of 40 dB and $\gamma_0 = 30dB$ for $\lambda = 1.7$ is shown in Fig. 3.10. As can be seen in this figure, a higher spatial reuse is obtained for interference thresholds greater than -20 dB which is quite significant in networks with stringent resources as in the case of WBANs. In fact, the amount of spatial reuse in the proposed approach is approximately N_c times the reuse of coexisting schemes which use TDMA for inter-WBAN transmissions approach. This figure also contains information regarding variations in the average inter-WBAN distance ranging from d =2 to 5 and 9; where the higher the inter-WBAN distance the lower the probability of existence of nodes in the interference set and the higher the spatial reuse. This figure shows a maximum improvement in spectral efficiency of up to 65% and an average spectral efficiency of 40% compared to existing proposals for inter-WBAN communication that use the orthogonal approach. Additionally, this figure demonstrates variations in coexistence distance of coexisting WBANs due not degrade their network performance as much.

3.4.2.3 Outage Probability

Fig. 3.11 shows the outage probability versus the inter WBAN distance for full shadowing of $40dB$ and $\gamma_0 = 30dB$ for three coexisting WBANs with $\lambda = 1.7$ (obtained from the optimization discussed) for three different average inter-WBAN distances d =2, 5 and 9, respectively. As can be seen in this figure, the outage probability overlaps for different inter-WBAN distances for a wide range of SINRs, which implies variations in distance does not affect the efficiency of our proposed approach since we are achieving the same outage as the distance changes. From Fig. 3.10 and Fig. 3.11 we can realize a trade-off between the outage probability and the spatial reuse. Accordingly, in the proposed approach we are achieving a much higher reuse at the cost of a slight increase in the outage probability. Also, since a 10% outage probability corresponds to a guideline for 10% maximum packet error rates in the

IEEE 802.15.6 BAN standard Smith et al. [2011b] we did not see the need to look into evaluating the throughput.

3.4.2.4 Delay

One of the basic requirements of WBANs is their requirement for low latency, specifically in mission critical applications such as a real life hospital scenario where the speed of communicating a patient's vital information is of utmost importance. Thus, packet delay in a WBAN should be kept at its minimum at all times. The average packet delay encountered in this chapter demonstrates the time required for successful reception of a packet after its initial transmission. Fig. 3.12 depicts significant improvements in delay for all inter-WBAN distances, and the improvements in delay become greater as the inter-WBAN distances increase. Since there are three coexisting WBANs, each consisting of 10 sensors, each sensor has to wait for 29 more transmissions before it can transmit once again in the orthogonal scheme. Whilst, as per our proposed approach, sensors of coexisting WBANs that do not interfere with each other's transmissions can transmit simultaneously, thus; leading to a much lower delay. This is more evident in the case where the distance between the coexisting WBANs increases since that implies a lower possibility for the nodes to interfere with each other and therefore the lower interference.

The main reason that the our work is not comparable to the existing approaches is the fact that this is based on node-level interference mitigation for WBANs which is not the case for other interference mitigation proposals in WBANs, since they mainly consider network-level comparison. In order to demonstrate a general picture regarding its comparison with other existing algorithms we have compared the proposed approach with the orthogonal approach in terms of interference probability, spatial reuse, outage probability and average delay through Fig.3.9 to Fig.3.12. With regards to other probabilistic approaches, our approach considers the unique features in WBANs in terms of available energy and minimum tolerable delay which is not an important factor for proposals in typical ad-hoc networks or sensor networks since they do not have a scarce limitations in such resources. Hence, providing a compar-

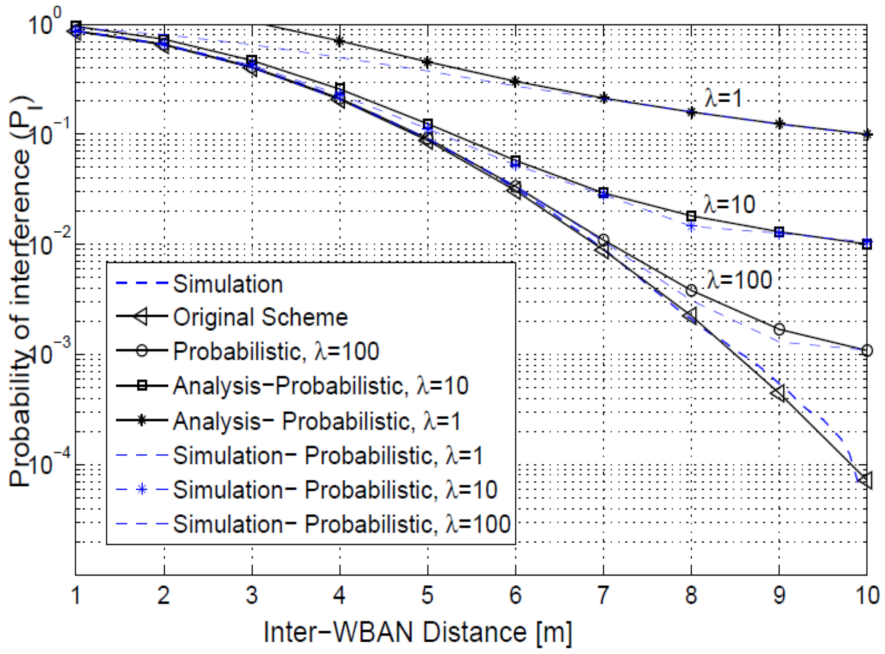


Figure 3.9: Interference Probability versus the Inter-WBAN distance for different values of $(\frac{\gamma}{\gamma_{th}} = 1)$

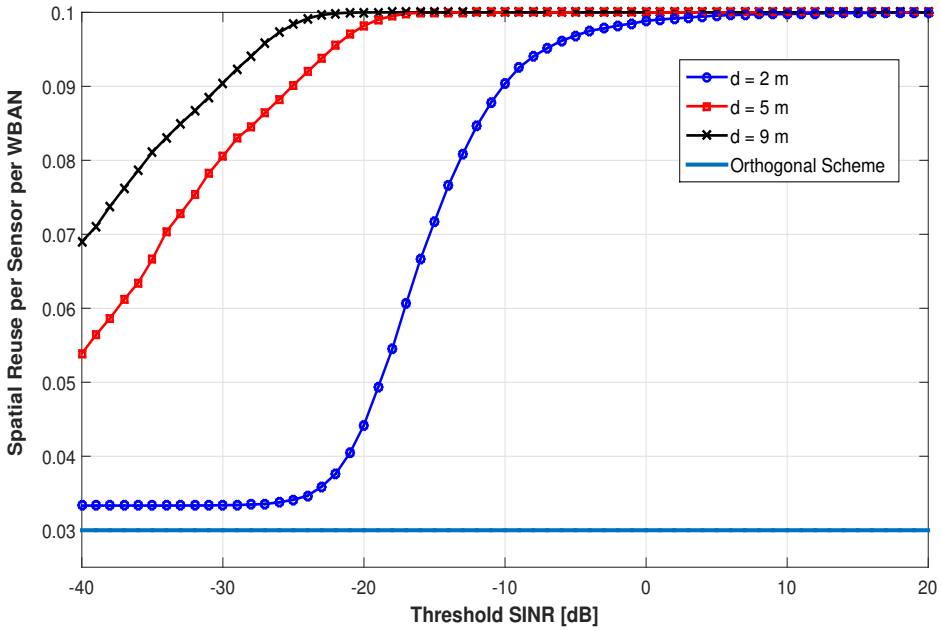


Figure 3.10: Spatial Reuse per sensor per WBAN versus the threshold SINR for d=2, d=5 and d=9 for shadowing 40 dB and $\lambda = 1.7$

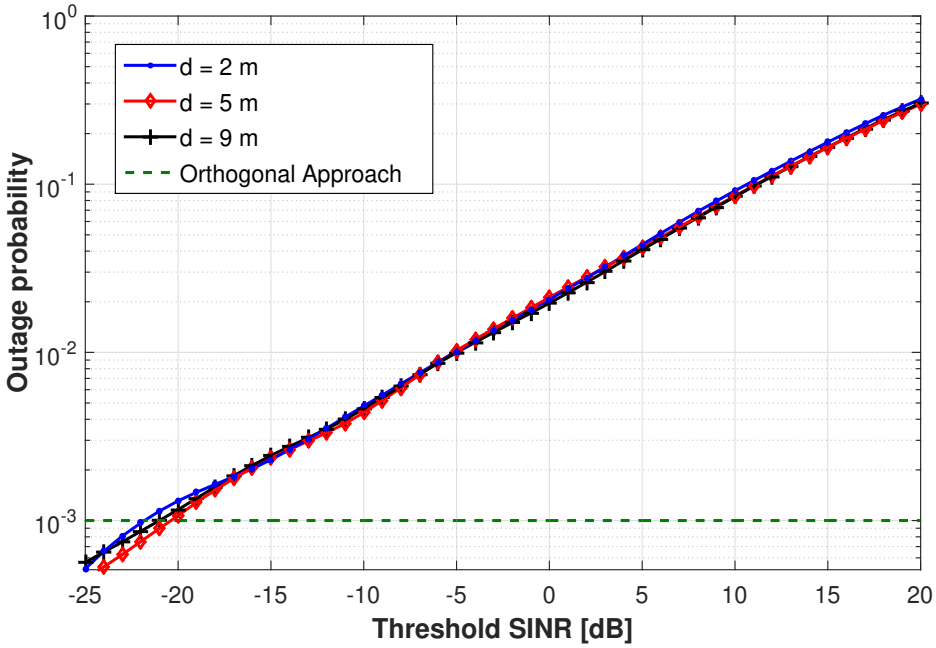


Figure 3.11: Outage Probability versus the threshold SINR for d=2, d=5 and d=9 for shadowing $40dB$ when $\gamma_0 = 30$ dB and $\lambda = 1.7$

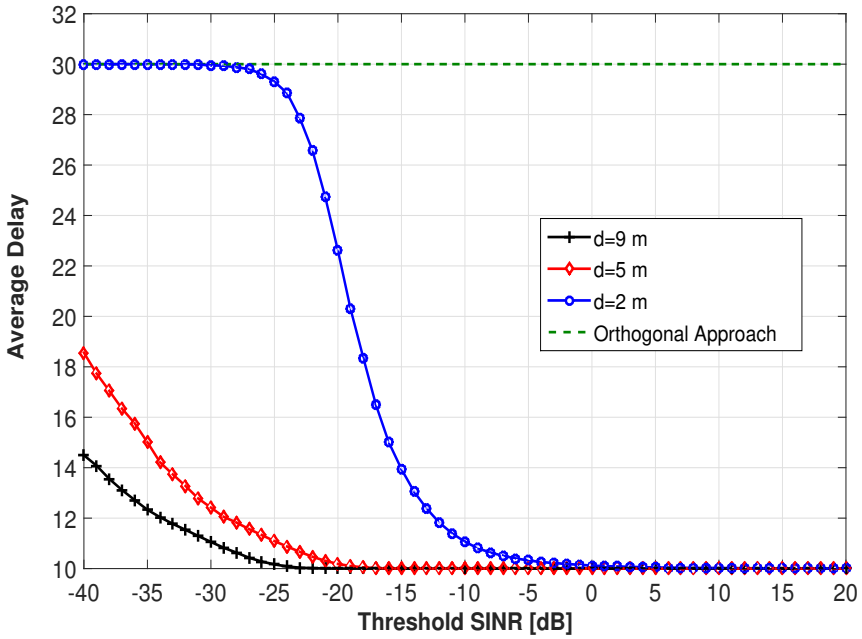


Figure 3.12: Average Delay per versus the threshold SINR for d=2, d=5 and d=9 for shadowing $40dB$ when $\gamma_0 = 30$ dB and $\lambda = 1.7$

ison with them is not feasible either. However, we have compared the performance of our proposal with conventional channel assignment for coexisting WBANs which is based on orthogonal transmission across coexisting networks.

3.5 Conclusion

In this chapter we have proposed an opportunistic and smart spectrum allocation scheme interference mitigation approach, which deals with the issue of coexistence of multiple wireless body area networks. We allow sensor nodes of coexisting WBANs that do not exist in the interference coverage of coexisting WBAN networks to transmit simultaneously, and all other sensor nodes in all WBAN networks to transmit orthogonally. Through exhaustive simulation and analysis, this approach has been shown to significantly enhance the system performance in terms of throughput and delay as well as offering up to N_c times more spectral efficiency compared to existing schemes that consider orthogonal transmission for inter-WBAN communication. This way, the limited resources in WBANs are used much more efficiently, which results in a higher network lifetime and much longer depletion time.

The main tradeoff that motivated us for this research was the capability of achieving a significantly higher rate of communication due to lower delay. This is at a slight cost for higher throughput and reliability requirements in critical health-care at an outage probability of 1%, and also a slight cost at 10% outage probability, which corresponds to a packet error rate of 10%, the maximum PER allowed in the IEEE 802.15.6 guidelines. At the same time the proposed scheme achieves better reuse than existing schemes, as a function of the number of nodes that exist in the interference set, and can reach up to (the number of coexisting WBANs) N_c times- more the available spectrum. In the next chapter, we will expand this to account for variations in traffic priority and packet length, as well as the number of WBAN nodes and received SINR from each nodes transmissions.

Chapter 4

Adaptive Spectrum Allocation with Energy Harvesting and Graph Coloring

4.1 Introduction

An assumption in most proposals for spectrum allocation is that all sensors have the same length and priority, whilst in reality each sensor measures a different signal and therefore has a specified length and priority for transmission. For instance, if that sensor carries more mission-critical data it would require a higher priority for channel assignment. Also, its length may vary depending on the amount of data it requires to transmit at each interval. In Chapter 3, we introduced a dynamic resource allocation scheme specifically designed for WBANs which satisfies the requirements of the IEEE 802.15.6 standard (Section 3.3). In Section 4.2 of this chapter, we extend those contributions to consider the traffic priority and packet length of a node as well as the number of nodes in each WBAN and their SINR in the transmission of a node. Simulation results and theoretical analysis show that our proposed approach can significantly increase the spatial reuse. Our proposed method significantly degrades the interference level and adds no complexity to the sensors as only the coordinators are required to negotiate for channel assignment.

Another important part of this chapter covers the use of energy harvesting for extended battery lifetime for which we use interference signal as a source of energy

for future transmissions. To do so, we deploy an energy harvesting module on each sensor to absorb the interference that falls into the network. This allow simultaneous transmission of power and energy and extends the network lifetime (Section 4.3). Further to simplify the resource allocation, we form clusters amongst pairwise WBANs and use graph coloring for channel assignment. This enhances the spectrum allocation as there on distinct colors are allocated to pair-wise clusters instead of each individual WBAN.

The following summarises the key contributions of this chapter:

- The SCA scheme proposed in Chapter 3 is enhanced to consider a nodes' traffic priority, packet length and density of sensors in each WBAN (Section 4.2). An iterative approach is proposed for channel assignment which considers the aforementioned factors as well as the nodes' existence in the interference region.

- Simultaneous transfer of information and energy is proposed for interference mitigation by using an energy harvesting module devised on each sensor. The proposed approach utilizes the interference signal that falls into the network as a source of energy, which is mainly discarded in conventional schemes (Section 4.3).

- Graph coloring is cooperatively incorporated with the SCA scheme to form clusters amongst pair-wise WBANs to enhance spatial reuse (Section 4.4). More specifically, a color-based approach is used to allocate distinct colors to coexisting pairs of WBANs.

The rest of this chapter is organized as follows. Enhancement on the proposed SCA scheme with considering a nodes' traffic priority, packet length, signal strength and density of sensors is described in Section 4.2 along with evaluation through both simulation and analysis. Incorporating an energy harvesting module on the sensors being used for joint energy harvesting and interference mitigation is described in Section 4.3 followed by simulation and analysis. In Section 4.4, we incorporate graph coloring into the proposed smart spectrum allocation approach to enhance the coex-

istence of pair-wise WBANs along with analytical evaluation and simulation. Finally, Section 4.5 concludes the chapter.

4.2 Adaptive Inter-network Interference Mitigation (AIM)

In our proposed approach, namely adaptive inter-network interference mitigation (AIM), we consider that each WBAN allows adaptive allocation of the spectrum according to the traffic priorities (P_i), the packet length (L_i) of each sensor node, the number of nodes in that WBAN and the SINR of nodes in the vicinity of the WBAN of interest to identify, and the nodes interfering on the transmission of its sensor nodes.

4.2.1 The AIM Protocol

Our proposed approach proceeds with four phases for interference mitigation which are described as follows:

4.2.1.1 Phase 1. Orthogonal Transmission

Let us consider that two WBANs are co-located, where WBAN_1 consists of N_1 sensor nodes and WBAN_2 consists of N_2 sensor nodes. In the first round of transmission, the coordinator of each WBAN negotiates to assign orthogonal channels to each of its sensors. Thus, the shared channel is initially divided into equal portions amongst the two WBANs; each of which are later divided according to the packet lengths of sensors in each WBAN. We consider that the ℓ^{th} sensor of WBAN_i, denoted by (i, ℓ), transmits at time slot $T_{i,\ell}$ for $i \in \{1, 2\}$. Therefore, while each sensor is transmitting its message to its coordinator in its allocated time slot, the coordinator of each of its coexisting WBANs calculates the interference level imposed on them based on the received power from that sensor node, the packet length and its priority level.

4.2.1.2 Phase 2. Interference Set Formation

In the next step, each coordinator finds the minimum received power from its sensors and compares it to the received power from sensors of other WBANs. Let $\gamma_{i,j,\ell}$ denote the received power from the ℓ^{th} sensor of WBAN$_j$ at WBAN$_i$. Let us consider that the minimum received power of sensors in WBAN$_i$ at its coordinator is $\gamma_{min,i}$, then $\gamma_{min,i} = \min\{\gamma_{i,i,\ell}\}$. If the received power of a sensor from the other WBAN is larger than $\gamma_{min,i} - \gamma_{Th}$, that sensor is added to the Inter-Interference list; otherwise, it is considered as a low interference node, where γ_{Th} is a predefined threshold value. We show the interference list of WBAN$_i$ by $\mathcal{I}_i$, where $\mathcal{I}_i = \{(j,\ell)|\gamma_{i,j,\ell} > \gamma_{min,i} - \gamma_{Th}\}$.

4.2.1.3 Phase 3. Exchanging Information

In the next step each coordinator broadcasts its interference list. Therefore, each coordinator is able to verify which of its sensors severely interfere with other WBANs. Also, each coordinator can verify which sensors of other WBANs have severe interference on itself. Each coordinator then creates a set, namely an interference set, consisting of all sensors which have a severe interference level. More specifically, the interference set of WBAN$_i$ is $\mathcal{S}_i = I_i \cup \{(i,\ell)|(i,\ell) \in \mathcal{I}_j,\ j \neq i\}$ [1].

4.2.1.4 Phase 4. Scheduling

Traffic priority is modeled as per IEEE 802.15.6 shown in Table. 4.1 Shin et al. [2012]. After the first round where each WBAN assigns orthogonal portions of the time slot to nodes in its network, we consider the traffic priority, packet length and number of nodes in each WBAN for channel assignment. Given two coexisting WBANs with interference set $\mathcal{S}$, where node $(1,i)$ and node $(2,j)$ are nodes with highest priority in WBAN$_1$ and WBAN$_2$, respectively, which should be now scheduled, we proceed with the following procedure for channel assignment:

Rule 1: Channels are allocated to WBANs in an iterative manner, where a sensor node with the highest priority is selected from each WBAN for channel scheduling at each iteration.

[1] Phase 1 to phase 3 are similar to the SCA algorithm introduced in the previous chapter

Table 4.1: Priority Levels in WBANs as per IEEE 802.15.6

Priority	Traffic Priority	Traffic Designation
Lowest	0	Background (BK)
	1	Best Effort (BE)
	2	Excellent Effort (EE)
	3	Controlled Load (CL)
	4	Video (VI)
	5	Voice (VO)
Highest	6	Medical Data or Network Control

Rule 2: If node $(1,i) \in \mathcal{S}$ no other node can transmit simultaneously with that node's transmission. Therefore, in cases where $(1,i) \in \mathcal{S}$, WBAN_2 remains silent for packet length of node $(1,i)$, referred to as $L_{1,i}$. Then, node $(2,j)$ and node $(1,i+1)$ are selected for channel scheduling in the next iteration.

Rule 3: If either node $(1,i) \in \mathcal{S}$ or node $(2,j) \in \mathcal{S}$, no other node can transmit orthogonally with that node's transmission. Therefore, in cases where $(1,i) \in \mathcal{S}$, WBAN_2 remains silent for packet length of node $(1,i)$, referred to as $L_{1,i}$. In other words, node $(2,j)$ can only send its packet after the transmission of node $(1,i)$ has finished.

Rule 4: If neither node $(1,i)$ nor node $(2,j)$ exist in the interference region, they can both transmit simultaneously. Thus, the minimum channel length that should be allocated for these nodes to transmit simultaneously is $\max\{L_{1,i}, L_{2,j}\}$.

The pseudo code for the proposed scheme is provided in Algorithm .2.

4.2.1.5 Example of the Proposed Protocol

We have demonstrated an example of channel assignment in our proposed method for a typical network shown in Fig.4.1 with two coexisting WBANs known as $WBAN_1$ and $WBAN_2$. Table. 4.2 shows the values of priority and traffic for each node in the network shown in Fig. 4.1. The interference region amongst them is shown as the intersection of the coverage range of the WBANs. The inter-interference set of each WBAN is as follows, $\mathcal{I}_1 = \{(1,2)\}$, and $\mathcal{I}_2 = \{(A,1)\}$. These WBANs broadcast their inter-interference sets, and then create the interference set as follows: $\mathcal{S} = \{(A,1),(1,2)\}$. Then each WBAN will assign orthogonal channels for its sen-

Algorithm 2: Pseudo code for the AIM Protocol

Step 1. Orthogonal Transmission

for $i = 1$ to 2

for $j = 1$ to N_i Sensor node (i, j) is transmitting

WBAN$_i$ estimates the received signal power, $\gamma_{i,j}$, from sensor node (w, j)

Step 2: Determine the inter-interference set

for $i = 1$ to 2 $\gamma_{min,i} = \min\{\gamma_{i,j}\}$

for $\ell = 1$ to i, $\ell \neq i$

for $j_2 = 1$ to N_i

if $\gamma_{\ell,j_2} > \gamma_{min,i} - \gamma_{Th}$ Add (ℓ, j_2) to set $\mathcal{I}_i$

Step 3: Broadcast

for $i = 1$ to 2 Broadcast $\mathcal{I}_i$

Step 4: Determine the interference set

for $i = 1$ to 2 $\mathcal{S} = \mathcal{I}_i \cup \{(i, j) | (i, j) \in \mathcal{I}_\ell, \ell \neq i\}$

Step 5: Channel assignment Choose one node which currently has the highest priority and has not been scheduled yet, from each WBAN. We refer to this node as nodes $(1, j_3)$ and $(1, j_4)$.

if Sensor node $(1, j_3) \in \mathcal{S}$ Allocate orthogonal channel to node $(1, j_3)$.

Choose nodes $(2, j_4)$ and $(1, j_3 + 1)$, and go to Step 5.

if node $(1, j_3) \in \mathcal{S}$ and $(2, j_3) \in \mathcal{S}$ Allocate orthogonal channel to node $(1, j_3)$ and $(2, j_3)$ Choose nodes $(1, j_3 + 1)$ and $(2, j_4 + 1)$, and go to Step 5.

if node $(1, j_3) \notin \mathcal{S}$ and $(2, j_3) \notin \mathcal{S}$ Allocate a channel of length $\max\{L_{1,j_3}, L_{2,j_4}\}$ to node $(1, j_3)$ and $(2, j_3)$, to simultaneously transmit.

Choose nodes $(1, j_3 + 1)$ and $(2, j_4 + 1)$, and go to Step 5.

sors, which are in the interference region of other co-located WBANs and allocates the rest of the time slots to the other sensors based on their priority and traffic. It is important to note that we have made the assumption that all nodes within a WBAN have the same level of priority and in the case that they are in the interference set they are assigned an orthogonal channel to avoid their transmission being interrupted as well as avoiding their transmission interfering with other nodes amongst its coexisting network. This way a higher portion of the time slots are allocated to nodes that contain data of higher priority and more traffic and a lower portion is assigned to nodes with lower priority. This approach avoids idle wastage of the bandwidth compared to the approach proposed in Movassaghi et al. [2014c] as well as a significant increase in the spatial reuse of the overall network. Since there more number of low priority nodes compared to the higher priority nodes, they dominate the traffic. We have not considered the case where the number of high priority nodes dominates the number of low priority nodes, which is something to look into for future work.

For instance, in the case of the network shown in Fig.4.1, the order of assignment for nodes between the two networks is in the order of their priority. As can be seen in Table.4.2, we have the following: $P_B > P_A$ and $P_3 > P_2 > P_1$. Since $node_B$ and $node_3$ do not exist in the IR region, they can be assigned channels simultaneously. Since the $L_3 < L_B$, $WBAN_2$ can assign its remaining channel to its next node in its priority que since it does not belong to IR. Since the $L_B < L_3 + L_2$ and the next node of $WBAN_1$ is in the IR, $WBAN_1$ has to remain silent for till $node_2$ has finalized its transmission. The next highest priority node in $WBAN_1$ is $node_A$ which is in the IR, and is therefore assigned the next channel after the silent period where no other node can transmit. More specifically, $WBAN_2$ remains for the packet length of $node_A$. Then, its $WBAN_2$'s turn for channel assignment, which is given to its next highest priority node, which is $node_1$, during which $WBAN_1$ remains silent. After the first round of transmission, and based on the amount of data being sent in each round of transmission, Table 4.2 gets updated.

Fig. 4.2 shows the first round of channel assignment after orthogonal transmission for the configuration deployed in Fig. 4.1. As can be seen, a higher portion of the channel is assigned to nodes with higher traffic priority. Also, since the length

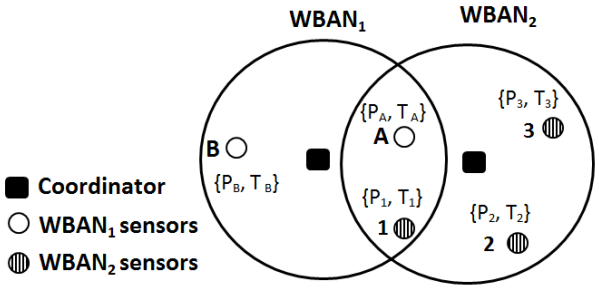


Figure 4.1: System Model of the AIM protocol

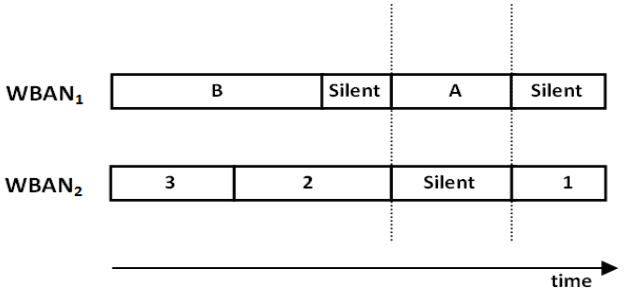


Figure 4.2: Channel Assignment with the AIM Protocol

of channel assignment is based on a nodes' packet length, which is sufficient for transmission of its generated data. Moreover, as clearly seen in Fig. 4.2, nodes in the interference set are not transmitting at the same time, which ensures that the interference level is kept as low as possible.

4.2.2 Analysis

In this section, we calculate the average reuse factor for WBAN_0; a result that can be applied to all other WBANs due to symmetry. Let d_i denote the distance between a sensor node in WBAN_i and the coordinator of WBAN_0 which can be calculated as follows:

$$d_i = \sqrt{(r_i \cos\theta_i - r_0 \cos\theta_0)^2 + (r_i \sin\theta_i - r_0 \sin\theta_0)^2} \tag{4.1}$$

where r and θ are uniform random variables over $[0, r_0]$ and $[0, 2\pi]$, respectively. According to the path loss model calculations in Chapter 3, (Equations 2.6-2.8), since,

Table 4.2: Values of Traffic and Priority for nodes in $WBAN_1$ and $WBAN_2$

$WBAN_1$	L	P
$node_A$	8	5
$node_B$	2	2
$WBAN_2$	T	P
$node_1$	3	1
$node_2$	2	2
$node_3$	5	4

h_i and d_i are independent random variables and h_i follows Rayleigh distribution with parameter $\frac{\sqrt{2}}{2}$, we have:

$$P_{I,i} = \int_0^\infty P\left(h_i > d_i \times 10^{\frac{\gamma_{th}-A_{dB}}{20}} | d_i = s\right) P_d(s) ds, \tag{4.2}$$

where $P\left(h_i > d_i \times 10^{\frac{\gamma_{th}-A_{dB}}{20}} | d_i = s\right) = e^{-B^2}$ and $B \triangleq s \times 10^{\frac{\gamma_{th}-A_{dB}}{20}}$.

We then define two scenarios: With Priority and Without Priority and calculate the average reuse for both scenarios as follows:

4.2.2.1 Analysis of the proposed scheme without considering the priority

In this case, nodes that are in the interference set (IR) are allocated with orthogonal channels. Let $I_{i,j}$ denote an event that the jth node in $WBAN_i$ is inside the IR. Therefore, $I_{i,j}$ can be defined as follows:

$$\begin{cases} 1 & \text{if } S_j^i \text{ in } WBAN_i \in \text{IR} \\ 0 & \text{otherwise} \end{cases} \tag{4.3}$$

It is clear that $(P_{i,j} = 1) = 1 - (P_{i,j} = 0) = P_I$. Since we assume that nodes in the IR are allocated with orthogonal channels, then the total amount of channels, T_1, required to allocate to nodes in IR is given by:

$$T_1 = \sum_{i=1}^{2} \sum_{j=1}^{N_i} L_{i,j} I_{i,j} \tag{4.4}$$

where $L_{i,j}$ is the length of a channel required for transmission of the *jth* node in $WBAN_i$. Moreover, nodes outside IR can simultaneously transmit. More specifically, let T_2 denote the amount of channel required for nodes outside IR to transmit their packets. Then, T_2 is given by:

$$T_2 = max_i\{\sum_{j\notin IR} L_{1,j}, \sum_{j\notin IR} L_{2,j},\} \tag{4.5}$$

which arises from the fact that nodes outside IR can transmit at the same time; thus, the total channel required for both WBANs to allocate to their nodes outside IR is characterized by the maximum length of the sum of packet length of those nodes in each WBAN.

Therefore, the amount of channel required for transmission in the case that the priority is not considered, denoted by T_{WOP} is given by:

$$T_{WOP} = T_1 + T_2 = \sum_{i=1}^{2}\sum_{j=1}^{N_i} I_{i,j}L_{i,j} + max_i\{\sum_{j\notin IR} L_{i,j}\} \tag{4.6}$$

The average amount of required channel in this case can then be calculated as follows:

$$E[T_{WOP}] = \sum_{i=1}^{2}\sum_{j=1} E[I_{i,j}E[L_{i,j}]] + max_i\{\sum_{j\notin IR} E\{L_{i,j}\}\} = \tag{4.7}$$
$$P_I(L_1 + L_2) + (1 - P_I)L_2 = P_I L_1 + L_2$$

where $L_1 \triangleq \sum_{j=1}^{N_1} L_{i,j}$, $L_2 = \sum_{j=1}^{N_2} L_{2,j}$, and without loss of generality we assume that $L_2 \geq L_1$. The average reuse factor, R_{WOP} defined as the ratio of T_{WOP} and the time required for orthogonal transmission can be found as follows:

$$R_{WOP} = \frac{L_1 + L_2}{T_{WOP}} = \frac{L_1 + L_2}{P_I L_1 + L_2}, \tag{4.8}$$

and accordingly the average delay for each packet, d_{WOP} is given by :

$$\bar{d}_{WOP_1} = \frac{P_1 L_1 + L_2 - L_1}{N_1} = \frac{(P_1 - 1)L_1 + L_2}{N_1} \tag{4.9}$$

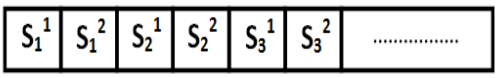


Figure 4.3: Transmission priorities for sensors in $WBAN_1$ and $WBAN_2$, and their priorities amongst one another

$$\bar{d}_{WOP_2} = \frac{P_1 L_2 + L_2 - L_2}{N_2} = \frac{(P_1 L_2)}{N_2} \tag{4.10}$$

4.2.2.2 Analysis of the proposed approach with considering the priority

Let $f(n)$ denote the average channel required for the proposed approach with priority consideration when the total number of nodes is n. Without loss of generality, we assume that the nodes are sorted with respect to their priority, which means that $P_i \geq P_j$, when $i \leq j$. Also, WBANs are transmitting in a sequential manner; i.e. when a node in $WBAN_1$ transmits, another node from $WBAN_2$ transmits in the next step. Fig. 4.3 shows the transmission priorities for both WBANs.

It is clear that when S_1^1 is in IR, then it transmits orthogonally, that the average required channel is given by:

$$T_1 = P_I[L_{1,1} + f(N_1 + N_2 - 1)] \tag{4.11}$$

However, if S_1^1 is not in IR, the average required channel depends on whether S_1^2 is in IR or not. In this case, the average required channel is given by:

$$\begin{aligned} T_2 = (1 - P_I)P_I[L_{1,1} + L_{2,1} + f(N_1 + N_2 - 2)] \\ +(1 - P_I)^2 \ell_2 + f(N_1 + N_2 - 2) \end{aligned} \tag{4.12}$$

which arises from the fact that when S_1^2 is in IR then both S_1^1 and S_1^2 must orthogonally transmit and when S_1^2 is not in IR, then S_1^1 and S_1^2 can transmit simultaneously. Thus, according to the law of total probability, the average required channel is given by:

$$f(n) = T_1 + T_2 \tag{4.13}$$

Let $\ell_1 \triangleq E\{L_{1,j}\}$ and $\ell_2 \triangleq E\{L_{2,j}\}$, then $\overline{T}_{WP}$ can be written as follows:

$$\begin{aligned} f(n) = P_I\ell_1 + (1-P_I)P_I\ell_1 + (1-P_I)P_I\ell_2 + (1-P_I)^2\ell_2 \\ +P_I f(N_1+N_2-1) + [(1-P_I)P_I + (1-P_I^2)]f(N_1+N_2-2) \end{aligned} \tag{4.14}$$

where we assume that $\ell_2 \geq \ell_1$. When $\ell_1 = \ell_2 = \ell$, (4.14) can be further simplified as follows:

$$f(n) = (1 + P_I + P_I^2)\ell + P_I f(n-1) + (1-P_I)f(n-2) \tag{4.15}$$

It is clear that $f(1)= \ell$ and $f(0)=0$; thus, $f(n)$ can be found in a sequential manner. The average reuse factor is then given by:

$$\overline{R}_{WP} = \frac{L_1 + L_2}{f(n)} \tag{4.16}$$

and the average delay is given by:

$$\begin{aligned} \overline{d}_{WP_1} = \frac{f(n) - L_1}{N_1}, \\ \overline{d}_{WP_2} = \frac{f(n) - L_2}{N_2} \end{aligned} \tag{4.17}$$

4.2.3 Simulation Results

Fig. 4.4 shows the average reuse factor for each WBAN when $N_s = 12$. As can be seen in this figure the proposed scheme achieves the optimal reuse factor (which is 2) when P_I=0. Also when P_I increases, which means with the increase in the probability of the node in the interference set, the optimal reuse factor is achieved at a lower factor. It is important to note that the proposed approach without considering the priorities achieves a slightly better reuse factor, as the silent time for this case is smaller than the one with considering priority. Moreover, the orthogonal approach

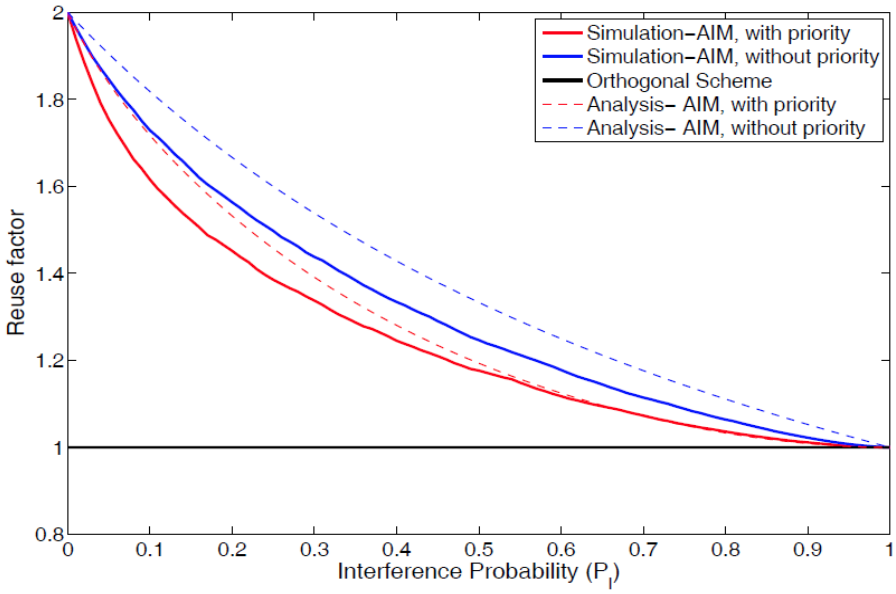


Figure 4.4: Average Reuse Factor versus the interference probability comparing the AIM protocol with and without priority with the orthogonal scheme through both simulation and analysis (The solid and dashed lines represent simulation results and analysis, respectively.)

which allocate orthogonal channels to all sensor nodes has a reuse factor value of 1, which is inefficient in cases that the majority of sensor nodes from each WBAN has negligible interference on the other WBAN.

Fig. 4.5 shows the expected delay for transmission versus the probability of node existing in the interference set of the two coexisting WBANs, referred to as Interference Probability (P_I), when $N_s = 12$. It is important to note that in conventional approaches, nodes in the network transmit orthogonally, which means that the overall channel is divided into orthogonal time slots according to the packet length of sensor nodes, and each sensor can only transmit in one of these time slots and remains silent while other nodes are transmitting. Such an approach leads to a huge delay, which is very inefficient especially in emergency applications of WBANs where mission-critical data needs to be sent. Fig. 4.5 demonstrates that our proposed scheme achieves an optimal spatial reuse, which is increased by the probability that a node exists in the interference set.

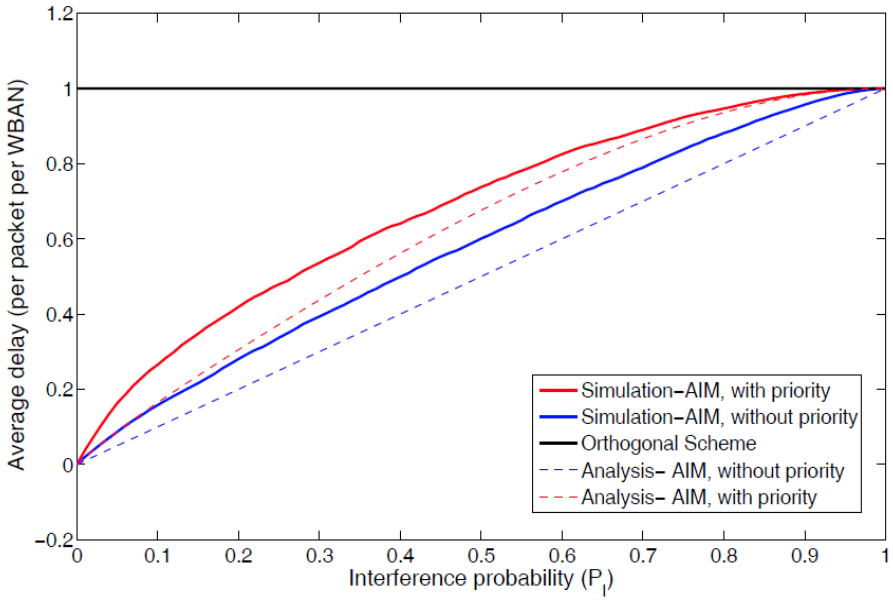


Figure 4.5: Expected Delay for Transmission comparing the AIM protocol with and without priority with the orthogonal scheme through both simulation and analysis f(The solid and dashed lines represent simulation results and analysis, respectively.)

4.2.4 Summary

In this section of the chapter we have extended the proposal in Chapter 3 to consider a node's priority, packet length, number of nodes in each WBAN and its SINR value to allow for adaptive spectrum allocation while dealing with the issue of channel assignment for interference avoidance amongst coexisting WBANs. Analysis has shown that the proposed scheme can achieve a much higher average reuse, as well as maintaining a very low delay with the aim of interference avoidance amongst multiple simultaneous transmissions between co-located WBANs. Simulation results have shown that the minimum delay requirements of mission critical data are met at the same time as well as achieving a significantly higher reuse. This work will be extended to support energy harvesting for extended network lifetime in the following section.

4.3 Joint Energy Harvesting and Smart Channel Allocation (E-SCA)

With this proposal we still allow nodes from different WBANs with lower interference level to transmit on the same channel while high interference nodes transmit orthogonally. In addition, we deploy an energy harvesting module the remaining sensor nodes harvest the energy they hear from information transfer between the sensor node of interest and its coordinator, which is referred to as interference. In fact, this section investigates simultaneous transfer of information and energy for interference mitigation amongst multiple coexisting Wireless Body Area Networks (WBANs). We propose to utilize interference that falls into the network as a source of energy, which is mainly discarded in conventional interference mitigation schemes. More specifically, in each time slot, a single sensor node is scheduled to receive information whilst the remaining sensor nodes opportunistically harvest the ambient radio frequency energy. We develop a novel opportunistic scheduling scheme, which offers a significantly high network lifetime through a tradeoff between a sensor's spectral efficiency and average amount of energy harvested. Simulation results show that the proposed energy harvesting with smart channel allocation (E-SCA) scheme can achieve optimal spatial reuse and good energy harvesting. We also show that the proposed approach is robust to variations in channel conditions, density of sensor nodes in each WBAN and increase in number of coexisting WBANs.

As the sensor nodes use a portion of the battery energy for each of their transmissions, each sensor node can transmit so long as its energy level does not exceed its minimum critical battery capacity. Accordingly, since the sensor nodes in all WBANs are associated with an energy harvesting model, we propose for each sensor to harvest energy in all of the slots that the sensor is not transmitting. The higher the interfering signal from simultaneous transmissions of a sensor in another WBAN, the higher the amount of harvested energy. Additionally, our proposed scheme adds no complexity to the sensor nodes as all the calculations are carried out by the coordinators.

As the coordinator is not as energy critical as the sensor nodes, our focus in

mainly on the sensor nodes within each WBAN. Each sensor node is associated with a rechargeable battery and an energy harvesting device. We adopt the energy harvesting model described in Movassaghi et al. [2014d], where the amount of harvested energy for a unit-length time slot can be calculated as follows:

$$E_h = \zeta_i P_r, \tag{4.18}$$

where $(0 < \zeta_i < 1)$, $i = 1, ..., K$ is the energy harvesting efficiency at the receiver and P_r is the received power at the sensor. For convenience, we consider $\zeta_1 = ... = \zeta_K = \zeta$ in the sequel of this chapter. More specifically, the average harvested energy at sensor node (j, i) can be calculated as follows:

$$\mathcal{E}_{j,i} = \zeta \sum_{t \notin \mathcal{T}_{j,i}} \sum_{(\ell,m) \in \mathcal{S}_t} \gamma_{j,\ell,m}, \tag{4.19}$$

The achievable transmission rate of the i^{th} sensor node in WBAN_i is then calculated as follows:

$$\mathcal{R}_{j,i} = \frac{1}{N_c N_s} \sum_{t \in \mathcal{T}_{j,i}} \log_2 \left(1 + \frac{\gamma_{j,j,i}}{1 + \sum_{(\ell,m) \in \mathcal{S}_t} \gamma_{j,\ell,m}} \right), \tag{4.20}$$

where $\mathcal{T}_{j,i}$ is the set of time slots which are allocated to sensor node (i, j) and $\mathcal{S}_t$ is the set of sensor nodes that are simultaneously transmitting at time instant t.

4.3.1 The E-SCA Approach

Let $P_{out,i}$ denote the probability that the total interference at time instant i is larger than γ_{th} at $WBAN_0$. Then $P_{out,i}$ can be calculated as follows:

$$P_{out,0} = p \left(\sum_{j=1}^{N-1} \gamma_j > \gamma_{th} \right). \tag{4.21}$$

Here, we propose a probabilistic approach to effectively reduce the outage probability and then we analytically prove that the proposed probabilistic approach achieves a lower outage probability. As stated before, WBAN_0 places a sensor node in the

interference region if the received SNR from that sensor is higher than a threshold. Let γ_j denote the received SNR from a sensor node in WBAN_j at WBAN_0. It is clear that if $\gamma_j > \gamma_{th}$, then those sensor nodes will each be assigned an orthogonal channel. Otherwise, if $\gamma_j < \gamma_{th}$, we propose to assign an orthogonal channel for that sensor with a certain probability which is a function of $\frac{\gamma_j}{\lambda\gamma_{th}}$, where λ is the predefined probability factor. The average interference level at time instant i by using the proposed probabilistic approach can then be calculated as follows:

$$\gamma_i = \sum_{j=1}^{N-1} \gamma_j \left(1 - f(\frac{\gamma_j}{\lambda\gamma_{th}})\right), \tag{4.22}$$

which arises from the fact that by using the probabilistic approach, a sensor is assigned with an orthogonal channel with probability $\frac{\gamma_j}{\gamma_{th}}$.

The achievable transmission rate of each sensor node can then be calculated as follows:

$$\bar{\mathcal{R}} = \frac{R_0}{NcNs} \log_2\left(1 + \gamma_{avg}\right), \tag{4.23}$$

where γ_{avg} is the average SINR of each sensor node. Also, the average harvesting energy can be calculated as follows:

$$\bar{\mathcal{E}} = (NcNs - R_0)\gamma_{avg}. \tag{4.24}$$

4.3.2 Simulation Results

We consider that N_c WBANs are randomly deployed in a $10m \times 10m$ area, where the minimum distance between two coexisting WBANs is considered to be $0.5m$. We model each WBAN with a circle of radius $0.5m$, where N_s sensor nodes are randomly positioned within this circle. We also consider that all sensor nodes excluding the coordinator in a WBAN have similar transmit power (P_t). We consider different WBAN densities of low, middle, high and extremely high by considering N_s to be 12, 25, 50 and 100, respectively. We have also evaluated our proposed scheme for different channel conditions: *No Shadowing* (0 dB), *Partial Shadowing* (20 dB) and *Full*

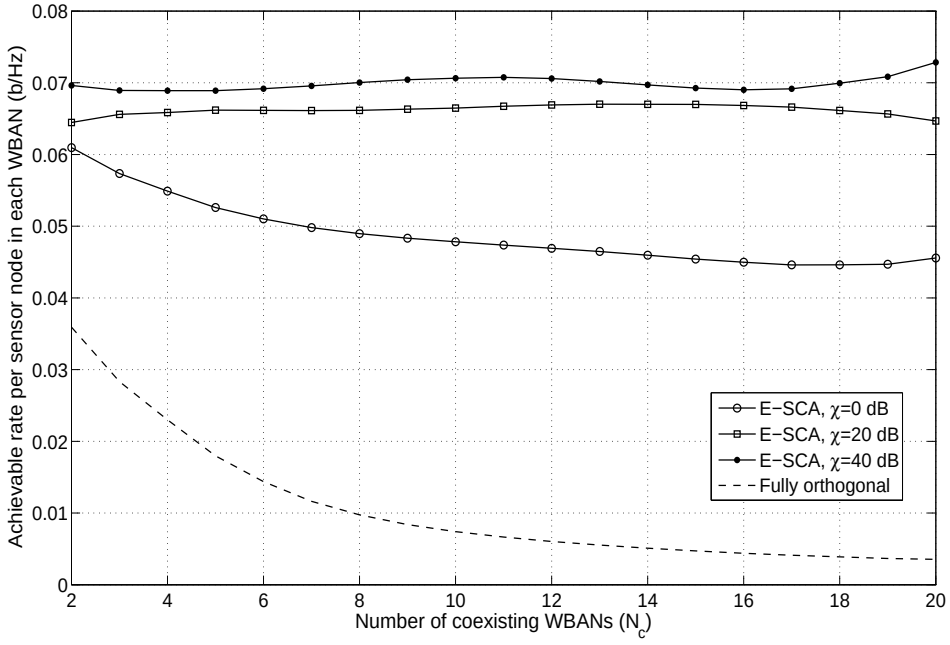


Figure 4.6: Achievable rate versus density of coexisting WBANs for the E-SCA algorithm for *No Shadowing* (0 dB), *Partial Shadowing* (20 dB) and *Full Shadowing* (40 dB) compared to the orthogonal scheme

Shadowing (40 dB).

The achievable rate versus N_c for all WBANs with variations in the shadowing offset from no shadowing to partial shadowing and full shadowing is shown in Fig. 4.6. As can be seen in this figure, a higher rate is obtained for different shadowing offsets compared to the fully orthogonal scheme, where the higher the shadowing offset the better the achievable rate. In fact, the achievable rate in these scenarios is approximately 4 times the conventional orthogonal approach. The higher the number of coexisting WBANs the higher the interference and the lower the achievable rate. We have also evaluated the amount of harvested energy of each sensor node versus variations in the number of coexisting WBANs in Fig. 4.7; where a higher number of coexisting WBANs corresponds to a higher amount of harvested energy obtained when the number of coexisting WBANs is increased.

Fig. 4.8 demonstrates the amount of harvested energy with the probabilistic approach for different probability factors. As can be clearly seen in this figure, the probabilistic approach harvests a higher amount of energy for higher probability fac-

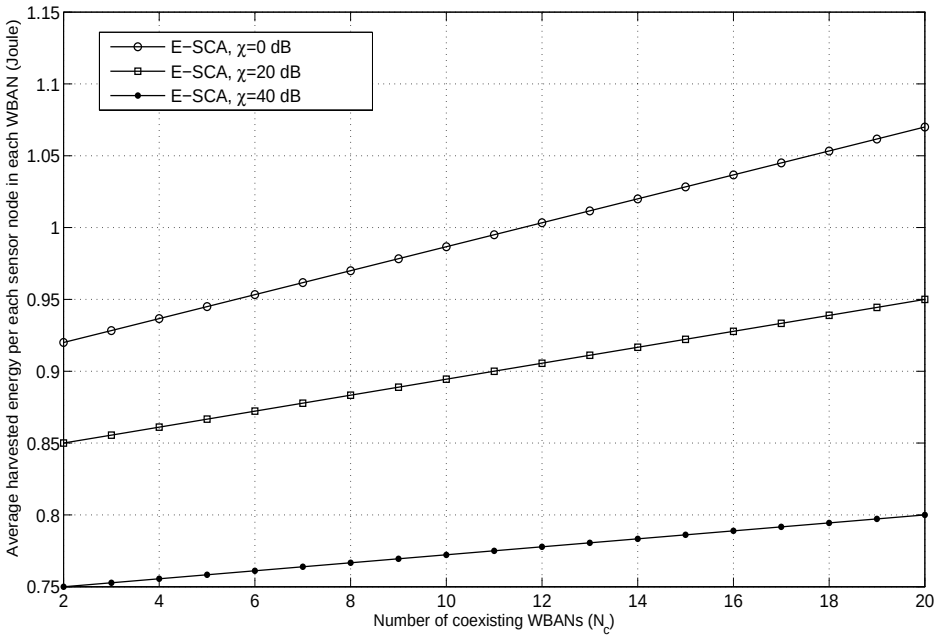


Figure 4.7: Amount of harvested energy in each sensor node versus the number of coexisting WBANs for the E-SCA algorithm for *No Shadowing* (0 dB), *Partial Shadowing* (20 dB) and *Full Shadowing* (40 dB) compared to the orthogonal scheme

tors. In fact, the higher the probability of existence of nodes in the interference set, the more the harvested energy. Also, Fig. 4.8 shows variations in channel condition for the probabilistic approach, where a higher amount of energy is harvested with a lower shadowing offset which is due to the fact that the lower the shadowing offset, the higher the interference from the coexisting neighbors and the higher amount of harvested energy.

In addition, as can be seen in Fig. 4.9, when the probability factor reaches zero, the proposed scheme will achieve its highest achievable rates in terms of spatial reuse. Accordingly, in higher shadowing offsets a better rate will be achieved due to the fact that less interference is imposed. In fact, there is a tradeoff between the amount of harvested energy and the achievable rate which is shown in Fig. 4.10. Accordingly, a higher amount of energy is harvested when the achievable rate is lower. In other words, when more sensor nodes are included in the interference set of each WBAN, interference is much higher which leads to a higher amount of energy to be harvested at the expense of lower achievable rate.

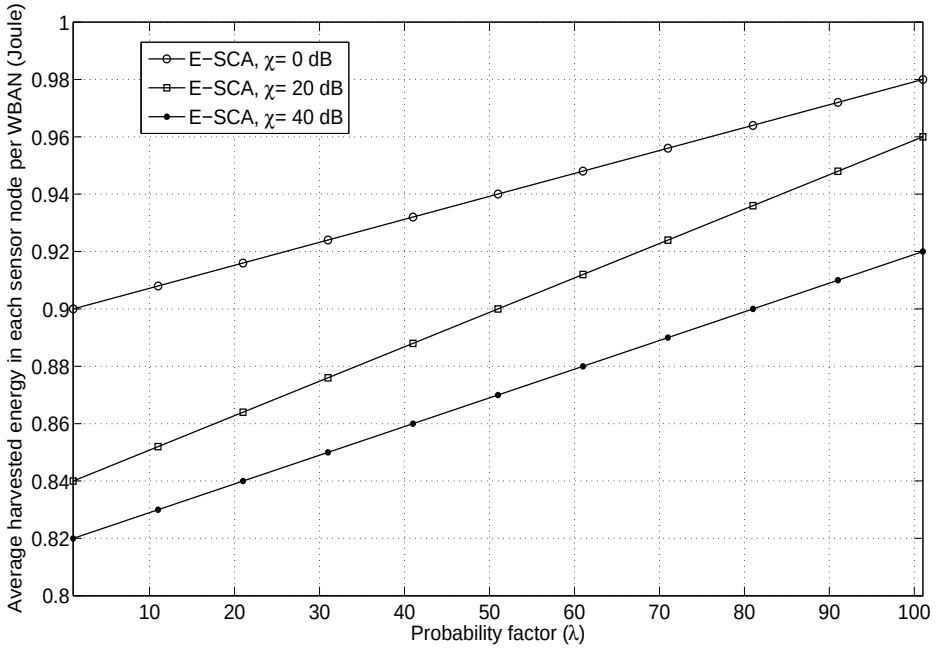


Figure 4.8: Amount of Harvested Energy versus the Probability Factor for the E-SCA algorithm for *No Shadowing* (0 dB), *Partial Shadowing* (20 dB) and *Full Shadowing* (40 dB) compared to the orthogonal scheme

4.3.3 Summary

In this section of the chapter, a novel approach for interference mitigation between coexisting WBANs in proposed that increases the channel reuse as well as increasing the energy level of each sensor node for future transmissions. In fact, the proposed inter-network scheduling scheme controls the tradeoff of spectral efficiency and amount of harvested energy for simultaneous transmissions of multiple coexisting WBANs. A partially orthogonal channel assignment was proposed for nodes amongst coexisting WBANs to mitigate inter-WBAN interference. In our proposed method, nodes that cause interference to other WBANs are allocated orthogonal channels whilst others are allowed to use the whole time slot until all are occupied. Meanwhile, sensor nodes are associated with an energy harvesting model which stores the ambient radio energy it collects from additive simultaneous transmissions of other coexisting WBANs. Our approach aims to Our proposed scheme has been evaluated by simulation showing 20 times higher spatial reuse as well as increasing

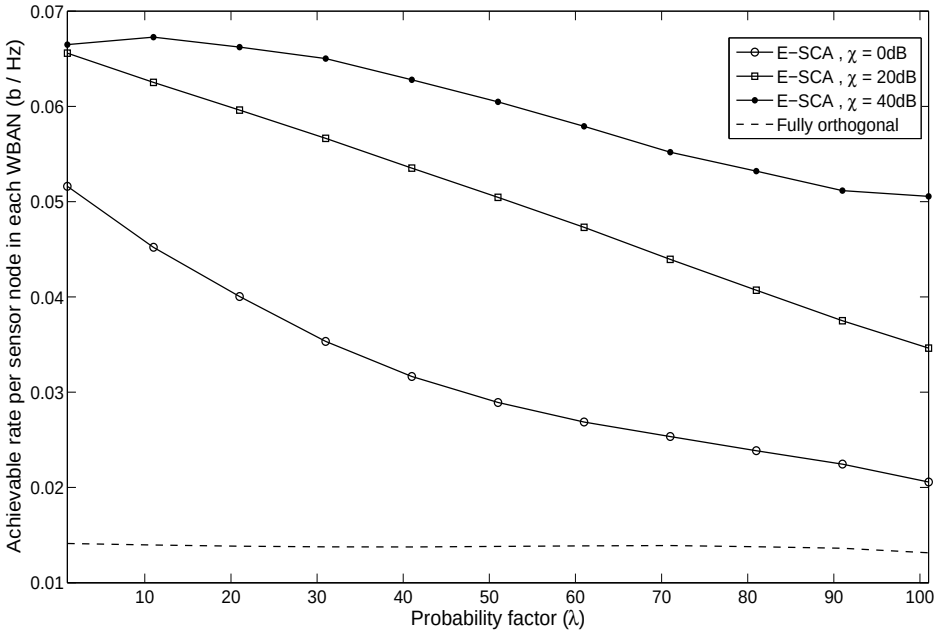


Figure 4.9: Achievable rate versus the probability factor for the E-SCA algorithm for *No Shadowing* (0 dB), *Partial Shadowing* (20 dB) and *Full Shadowing* (40 dB) compared to the orthogonal scheme

its energy levels from harvesting the ambient radio energy related to transmissions from coexisting WBANs. Our results reveal that the higher the number of coexisting WBANs causing interference to the transmission of a sensor node, the higher the amount of harvested energy and the higher the network lifetime. This way, more efficient usage of the limited resources in WBANs is achieved which results in a higher network lifetime and much longer depletion time. In the following section we want to enhance the network throughput of coexisting networks by forming clusters around each pair of WBANs and using graph coloring for channel assignment for their enhanced coexistence.

4.4 Cluster-based Cooperative Scheduling with Graph Coloring

To extend the proposed scheme to the case that there are N coexisting WBANs, we assume that WBANs can form a cluster in pairs, where each cluster consists of

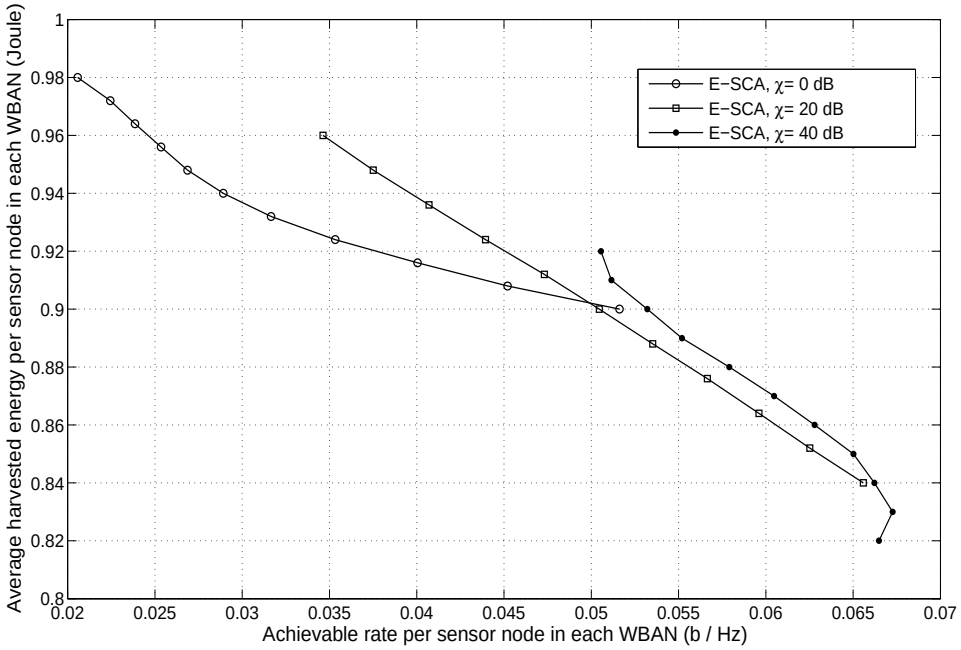


Figure 4.10: Amount of Harvested Energy versus the achievable rate for the E-SCA algorithm for *No Shadowing* (0 dB), *Partial Shadowing* (20 dB) and *Full Shadowing* (40 dB) compared to the orthogonal scheme

only two WBANs. For this aim, initially a cluster is formed around each pair of WBANs, then graph coloring is used to assign resource units (time slots) amongst coexisting clusters. It is important to note that we only consider two WBANs in each cluster as the proposed channel assignment algorithm is optimal for two coexisting WBANs. In fact, with a higher number of WBANs in each cluster, it is highly probable that the interference level at each WBAN is higher than the threshold when two or more WBANs are transmitting at the same time. This significantly decreases the outage probability and transmission efficiency. Thus, we only consider two coexisting WBANs in each cluster throughout the chapter.

4.4.1 Cluster Formation

First, each WBAN broadcasts a HELLO message to its neighboring WBANs. The neighboring WBANs then respond to this message by broadcasting a RESPONSE message, which indicates whether they can pair with that WBAN or not. The WBAN

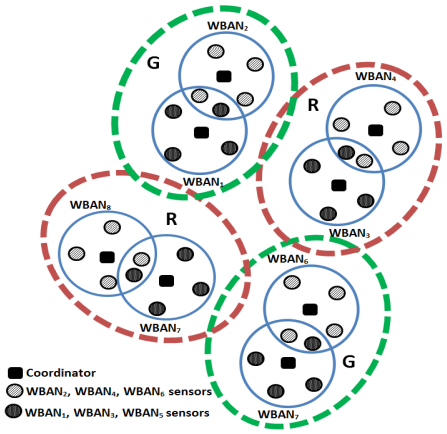


Figure 4.11: Cluster Forming around pair-wise WBANs

then selects one of the neighboring WBANs and sends an acknowledgement to confirm that two WBANs have been paired. This way each WBAN finds a pair with which it forms a cluster. In cases where an odd number of WBANs coexist, the remaining WBAN can be kept single and does not need to form a separate cluster on its own, but will still be allocated a color for resource usage.

4.4.2 Color-based Approach

We can model interference-avoidance via graph coloring where the network topology is modeled with a graph G(V,E). In fact, the wireless nodes are represented by the vertices V of G and radio resource collision between mutually interfering nodes is modeled with a edges E of G. Distinct resource units (time) are represented by the color set C in G. This way a k-coloring vertex maps vertices V(G)$\rightarrow$ C ($|C|$=k) such that distinct colors are assigned to mutually interfering collocated clusters. Color mapping between vertices is accomplished via a bidircetional message exchange between adjacent vertices where the coloring procedure is fully synchronous. The procedure for color assignment to each cluster is shown in Algorithm .3.

Each cluster is labeled with a color from the k-coloring vertex, where $|k|$ is the number of coexisting WBANs which has been defined to be a maximum of 10 by the IEEE 802.15.6 standard. Each color represents a specific channel as in conventional graph coloring and the optimum spatial reuse can be achieved by using the minimum

Algorithm 3: The cluster-based cooperative scheduling with graph coloring algorithm

Given $G = (V, E)$ and $u, v \in V(G)$; $C_u(r)$ is the set of available colors of u in the coloring round r. For each coloring cycle we have the following: Step 1. Color Selection

u selects a color c_u from $C_u(r)$

Step 2. Broadcast of selected color with message

u broadcasts a color message with c_u to its adjacent vertices.

Step 3. Color Assignment

if u receives a color message from $v \in N(u)$ u is colored by c_u if $c_u \neq c_v$

Step 4. Color Assignment Acknowledgement

The selected color is broadcasted if u wins the color.

Step 5. Color removal from available set of colors

The color selected by $N(u)$ is removed from the next coloring round $C_u(r+1)$

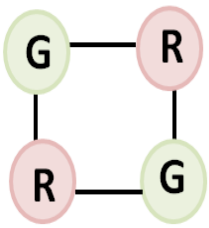


Figure 4.12: Graph Coloring for Clusters: R represents the Red color and G represents the Green color

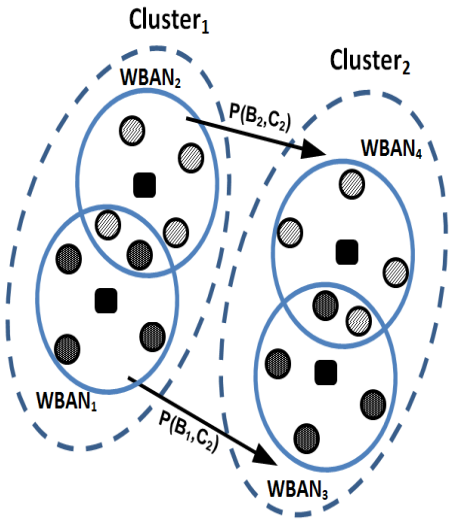


Figure 4.13: Collision Probability of $WBAN_1$ in $Cluster_1$ with $WBAN_2$ in $Cluster_2$

number of colors. In fact, the fewer colors are used the higher the spatial reuse and channel utilization amongst vertices. Once this approach is taken at each pair of WBANs, a cluster is formed as shown in Fig. 4.11. Each pair is considered as a circle in the graph theory, where clusters that coexist in each other interference range are assigned different colors whilst clusters that do not have mutual interference are free to use the same color shown in Fig. 4.13. As can be seen in this figure the colors are assigned such that distinct colors are assigned to adjacent vertices. If a separate color was to be used for each WBAN four colors were required in the graph in Fig. 4.13, whilst considering distinct colors only for interfering WBANs is sufficient. This way the same graph could be colored using two colors which interprets as better channel utilization.

4.4.3 Analysis of the cluster-based SCA scheme

First, we calculate the probability that two clusters are colliding. Let A_{ij} be the event that $WBAN_i$ collides with $WBAN_j$, and $B_{i,C2}$ be the event that $WBAN_i$ collides with C_2. Therefore, the probability that the clusters will be colliding, P_c, can be calculated as follows:

$$P_c = p(B_{1,C2}) + p(B_{2,C2}) - p(B_{1,C2}B_{2,C2}), \tag{4.25}$$

where $p(B_{1,C2})$ is the probability that WBAN_1 collides with C_2 and $p(B_{2,C2})$ is the probability that WBAN_2 collides with C_2. $p(B_{1,C2})$ can then be calculated as follows:

$$\begin{aligned} p(B_{1,C2}) = \;& p(A_{1,3}) + p(A_{1,4}) - p(A_{1,3}A_{1,4}) \\ &= 2P_I - P_I^2, \end{aligned} \tag{4.26}$$

which arises from the fact that two WBANs are colliding with probability P_I, which can be found using (3.10). By replacing (4.26) in (4.25) and due to symmetry, we have:

$$\begin{aligned} P_c &= (2P_I - P_I^2) + (2P_I - P_I^2) - (2P_I - P_I^2)^2 \\ &= 4P_I - 6P_I^2 + 4P_I^3 - P_I^4. \end{aligned} \tag{4.27}$$

Now suppose that m clusters have been colored with S_m colors. Therefore, if a new cluster is added to the network, then the average number of required colors will be S_{m+1}, which can be calculated as follows:

$$S_{m+1} = S_m(1 - P_c^m) + (S_m + 1)P_c^m = S_m + P_c^m \tag{4.28}$$

which arises from the fact that a new cluster will be allocated a new color if it collides with all m clusters, otherwise it will assigned by one of the S_m colors. Since $S_1 = 1$,

we have:

$$S_m = 1 + P_c + P_c^2 + ... + P_c^{m-1} = \frac{1 - P_c^m}{1 - P_c} \tag{4.29}$$

Therefore the average number of allocated colors is $\lceil \frac{1-P_c^m}{1-P_c} \rceil$, where $\lceil x \rceil$ shows the lowest integer, which is larger than or equal to x.

4.4.4 Numerical Results

Let us first investigate the proposed SCA approach for two coexisting WBANs. Fig. 4.14 shows the average reuse factor for each WBAN when the shadowing offset is 0 dB and $N_s = 12$. As can be seen in this figure the proposed scheme achieves the optimal reuse factor (which is 2) when γ_{th}=−70 dB and the distance between two WBANs is larger than 7 m. Also when γ_{th} increases, which means that the coordinator can tolerate a higher amount of interference, the optimal reuse factor is achieved at lower distances, i.e. less than 3 m and less than 2 m when γ_{th}=−60 dB and γ_{th}=−50 dB, respectively.

Fig. 4.15, shows the average reuse factor versus the distance between WBANs when the shadowing offset is 20 dB and $N_s = 12$. In this case, the received signal from each WBAN at other WBANs has more attenuation due to larger shadowing. As a result, each coordinator will experience a lower level of interference, and accordingly a higher spatial reuse will be achieved even at low distances. It is important to note that in conventional approaches, nodes in the network orthogonally transmit, which means that the overall time frame is divided into $2 \times N_s$ equal length time slots, and each sensor transmits in only one of these time slots and remains silent in remaining $2 \times N_s - 1$ time slots. Such an approach leads to a very low spatial reuse, which is exactly 1, independent of the distance between two WBANs. Fig. 4.14 and Fig. 4.15 demonstrate that our proposed scheme achieves a near optimal spatial reuse, which is increased by the distance between two WBANs.

Fig. 4.16 shows the spatial reuse for the proposed cluster-based SCA scheme. As can be seen in this figure, when the average inter-WBAN distance is small, the clustering approach achieves a higher reuse factor compared to the color-based ap-

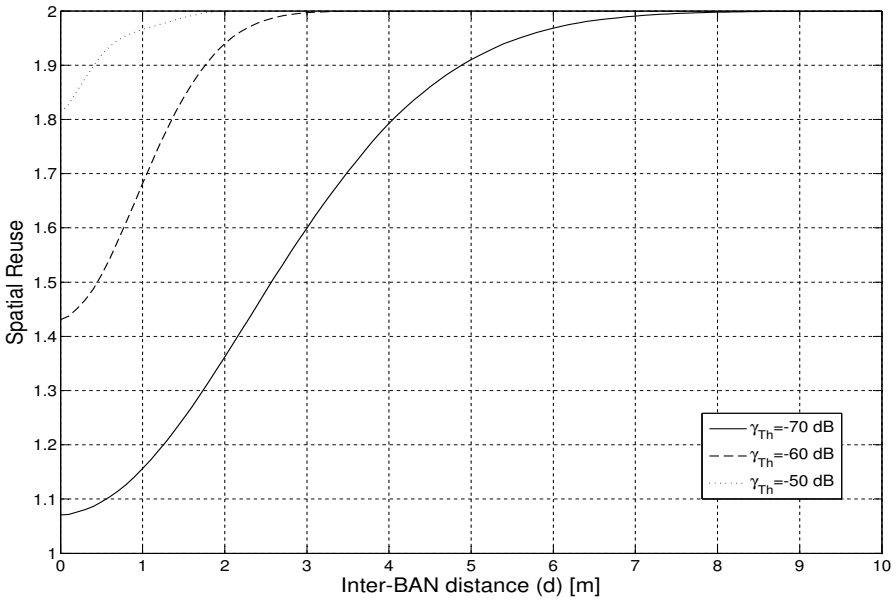


Figure 4.14: Average spatial reuse versus the distance between two WBANs when the shadowing offset is 0 dB for different values of γ_{th}=−50 dB, −60 dB, −70 dB.

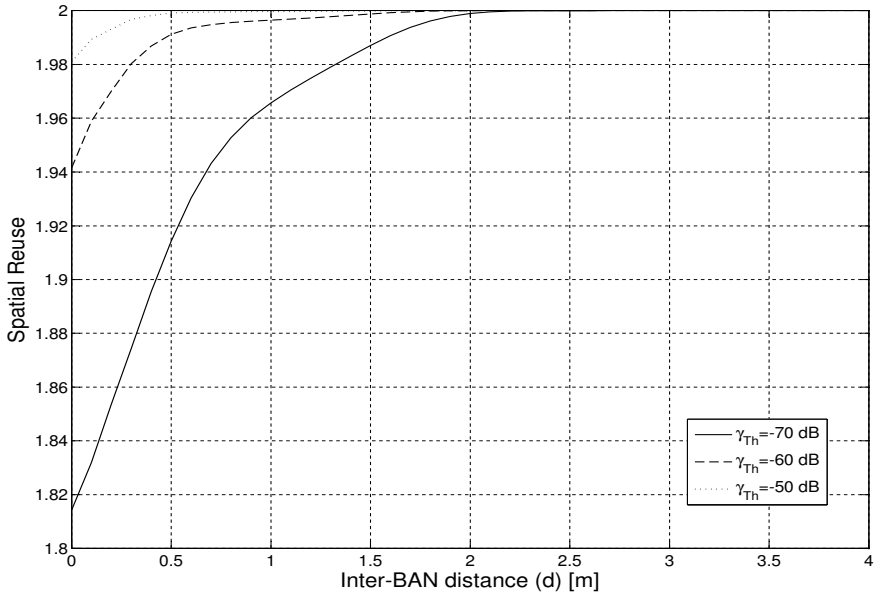


Figure 4.15: Average spatial reuse versus the distance between two WBANs when the shadowing offset is 20 dB for different values of γ_{th}=−50 dB, −60 dB, −70 dB.

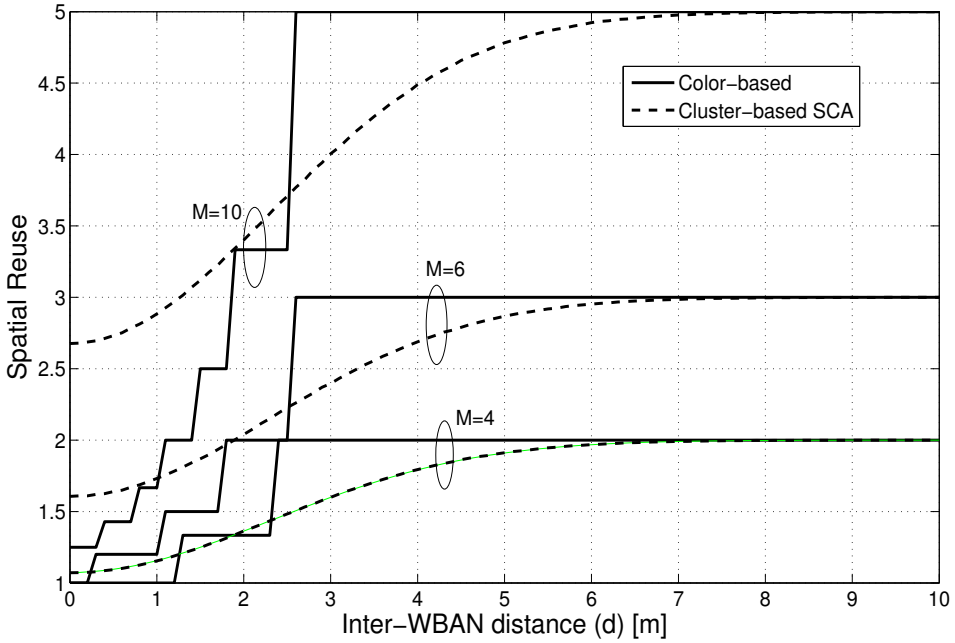


Figure 4.16: Spatial reuse versus the average inter-WBAN distance for different number of coexisting WBANs $M = 4, 6, 10$ comparing the cluster-based SCA with the color-based scheme.

proach. Moreover, with an increase in the number of coexisting WBANs, the proposed cluster-based SCA scheme outperforms the color-based scheme in a larger range of inter-WBAN distances. Note that the color-based approach outperforms the proposed cluster-based SCA scheme when the average inter-WBAN distance is large (> 3 m). This is because in the cluster-based SCA scheme, the probability that two clusters are interfering with each other is larger than the probability that two WBANs are interfering. Thus, the minimum number of colors required for the cluster-based SCA approach is slightly higher than the color-based approach.

4.4.5 Summary

In this section, cooperative scheduling and graph coloring have been integrated for interference mitigation amongst coexisting Wireless Body Area Networks. In our proposed method each WBAN forms a pair with one of its collocated neighbors. Nodes from each paired WBAN that exist in the interference region of the other WBAN are allocated orthogonal channels whilst the rest of the nodes do not require

orthogonal assignment. Graph coloring is deployed on the pair-wise combinations where each pair is allocated a color. This interprets as the WBANs bandwidth being divided into portions that exist in each others interference regions. We show that our proposed approach provides twice as much spectral efficiency and throughput compared to the graph coloring approach on its own. We will look into the means of self-organized coexistence of multiple WBANs without the existence of a global coordinator in the following chapter.

4.5 Concluding Remarks

In this chapter we investigated enhancements to our proposal in Chapter 3 to consider variations in packet length, number of nodes in each WBAN and their traffic priority. We further introduced energy harvesting modules for the sensor used in the WBANs to harvest the interference signal that falls into the network as a source of energy for extended network lifetime. To further enhance the resource usage and simplicity of channel assignment, we formed clusters amongst pair-wise WBANs and allocate distinct colors to each cluster. This way the existing resources are shared amongst the paired WBANs improving the overall spatial reuse as well as avoiding interference between coexisting clusters. In the following chapter we will look into incorporating the social nature of these networks and formulating the postural body movements of WBANs as well as their movement in respect to one another.

Chapter 5

Exploiting Unknown Dynamics on the Communication Amongst Coexisting Wireless Body Area Networks

5.1 Introduction

The social nature of WBANs and their high mobility does not enable coexistence of multiple WBANs by control via a global coordinator. When coexisting WBANs use the same channel, transmissions conflict since the active periods overlap Grassi et al. [2012]. Additionally, an increase in the density of coexisting WBANs can often lead to performance degradation. In fact, a specific WBAN can encounter significant inter-WBAN interference even for a small number of closely located WBANs Yang and Sayrafian-Pour [2011]. Furthermore, WBANs can practically either exchange information such as channel gain, interference and current transmission power or collect such information through their own measurements Kazemi et al. [2010]. Thus, the main intention of the coordinators of different WBANs should be to eliminate the interference accumulated at a node in its network, in a distributed fashion and maintain interference under a certain threshold. This distributed coordination has the following advantages: 1) Computational efficiency as parallel processing gain is achieved. 2) Robustness and reliability as the system can tolerate uncertainty. 3) Scalability relative to the number of coordinators and dynamic changes in body

posture. In addition, the unpredictable nature relative to unknown dynamics with respect to postural body movements or the movement of WBANs in relation to each other leads to nodes moving into, or out of, each others range Boulis et al. [2012]. In the case of wireless technologies with higher coverage areas this issue is even further highlighted.

Thus, this chapter presents an adaptive interference mitigation scheme for multiple coexisting wireless body area networks (WBANs) based on social interaction. The proposed scheme considers the mobility of nodes within each WBAN as well as the relative movement of WBANs with respect to each other. With respect to these mobile scenarios: traffic load, signal strength, and the density of sensors in a WBAN are incorporated to optimize transmission time with synchronous and parallel transmissions to significantly reduce radio interference and energy consumption of nodes. This approach leads to better use of the scarce resources in these networks, increased network lifetime, energy savings, higher throughput through higher packet delivery ratio (PDR); and such benefits even with nodes dynamically moving into, and out of, each others interference region. Channel assignment is made more energy-efficient and power consumption is further reduced using transmit power control with simple channel prediction. We conduct extensive simulations for coexistence prediction in different mobility scenarios using the NS-2 simulator to demonstrate the efficiency of the proposed protocol in providing interference-free channel assignments and higher energy savings. Simulation results show that our approach maintains optimum spatial reuse with a range of channel dynamics within, and between, coexisting WBANs.

The following summarises the key contributions of this chapter:

- The influence of intra-WBAN and inter-WBAN mobility on communication amongst multiple coexisting WBANs is investigated;
- A viable solution for interference mitigation is provided for mobile coexisting WBANs that function with limited resources.
- A prediction algorithm based on dynamics of movement of nodes within a WBAN is proposed which incorporates the movements of WBANs with respect to one another as well as postural body movements.

The rest of this chapter is organized as follows. In Section 5.2 the system model is presented. The proposed prediction algorithm for unknown dynamics is described in Section 5.3. The mobility scenarios amongst coexisting WBANs are presented in Section 5.4. Simulation results of the proposed scheme are provided in Section 5.5. Finally, Section 5.6 concludes the chapter.

5.2 System model

We consider a set of coexisting WBANs denoted by $\{w_k|k = 1, ..., M\}$, where M is the number of WBANs and w_k refers to the kth WBAN. Each WBAN is composed of a homogenous set of N sensors denoted by $\{s_k^i|i = 1, ..., N\}$ of equal importance and one coordinator node as the receiver placed in the center. For simplicity, we model each WBAN by two concentric circles, one of radius r known to be its sensing range, and one of radius R, known as its communication range ($R = 2r$). Sensor nodes are uniformly located at random within the circle.

We utilize the Smart Spectrum Allocation Scheme (SCA) proposed in Chapter 3 for channel allocation. After the first round of data transmission, the change in positioning of sensor nodes throughout the network can be realized, through which sensor nodes that are static can be told apart from those that are dynamic. More specifically, the nodes which have moved closer to the r region can be discovered. For instance, if a sensor node is within 190 cm of the R region, there is a huge difference to when it is within 110cm of the R region, which implies it is only 10cm far from the r radius region. This way, sensor nodes which are more likely to join the inter-WBAN interference set can be known beforehand and planning can be done in advance before any interference is acknowledged.

5.3 Proposed Prediction Algorithm for Unknown Dynamism Amongst Coexisting WBANs

Coexisting WBANs initially use the authors Smart Spectrum Allocation technique proposed in Chapter 3. During the first round of orthogonal transmissions each

WBAN also informs coexisting WBANs of its sensors unique identification address, localization information and residual energy. Each WBAN stores the minimum received power of its sensors at the previous time slot and the current time slot. In the case that the received power at the time instant t is similar to time instant $t-1$ and still in the range of above threshold received power or below that, there will not be any changes in channel assignment. Whilst, in the case that the distance of a sensor minus the radius of the sensing range is less than zero, the sensor node has moved into the R region. If the received power of the node at time instant t has increased from its value at time instant $t-1$ that node is moving close to the r region. Therefore, it is added to the interference set and smart channel assignment is updated accordingly. In the case that the received power of a node at time instant t has decreased from its value at time instant $t-1$ that node is moving out to the R region, is removed from the interference set and smart channel assignment is updated accordingly. The pseudo code for the proposed prediction algorithm for capturing unknown dynamics amongst coexisting networks in given in Algorithm. 4.

In the case that there are x nodes in the network, x timeslots are needed in each period to be allocated to the x nodes. The allocations can be made through $x!$ functions shown with f and g for two coexisting WBANs. Let us consider that in a period T, the function f has been used to map the x available timeslots to the x number of nodes as follows:

$$(t_1, t_2, ..., t_x) \xrightarrow{f} (N_1, N_2, ..., N_x) \tag{5.1}$$

The function g has been used in the same period T to map its nodes to the allocated timeslots as follows:

$$(t_1, t_2, ..., t_x) \xrightarrow{g} (N_1, N_2, ..., N_x) \tag{5.2}$$

In the case that the two functions do not overlap we do not have any changes within the network, however, if there is an overlap between two specific nodes for

instance N_2 and N_5, which means the value of the function f is equal in $\{t_2, t_5\}$, this implies we have interference: $f|t_1, t_2 = g$.

The S-MAC (Sensor MAC) protocol proposed in Ye et al. [2002] is implemented because S-MAC reduces energy consumption as well as providing good scalability and collision avoidance. This MAC protocol is quite beneficial for use in WBANs as it aims to eliminate energy consumption from different sources of collision, idle listening, overhearing and control overhead. This feature reduces energy consumption relative to idle listening; however, the delay is slightly increased as the radio needs to wait for the sender to wake up before sending data again. Thus S-MAC reduces energy consumption through a number of advantages. It allows for periodic sleep and listen, which implies reducing the listen time by allowing the node to go into sleep mode. Another advantage of using S-MAC is collision and overhearing avoidance for which it uses the Request To Send (RTS)/ Clear to Send (CTS) mechanism to contend for the medium. The first node to send a RTS packet wins the channel and the receiver which is the coordinator of the WBAN of interest will respond via a CTS message. The overhearing avoidance in S-MAC allows the interfering nodes to go into sleep mode after they hear an RTS or CTS packet and therefore, reduces the energy consumption relative to overhearing packets that are not directed to that node. Additionally, the percentage of delay in the network for a sender to wake up to transmit its' packet is fairly negligible when compared to the amount of energy savings it provides. More specifically, an increase of 80 % energy efficiency is obtained for an increase of less than half a second in the delay. The proposed S-MAC protocol also allows for message passing which means long messages can be fragmented into many small fragments and transmitted in bursts using only one RTS and one CTS packet. The sender waits for a ACK message from the receiver each time a data fragment is transmitted. Failure to receive the ACK will extend the reserved transmission time for another fragment and immediately retransmit its current fragment Polastre et al. [2004].

Table 5.1: Supported Mobility Levels in WBANs as per the IEEE 802.15.6 Sta

Static	A single BAN in a residential environment or a hospital with a single patient node and a fixed bedside hub
Semi-Dynamic	Slowly moving ambulatory patients in an elder care facility requiring infrequent and/or event-based low-rate data transfers
Dynamic	Fast moving ambulatory patients in a hospital with a large number of WBANs collecting continuous data from many sensor

5.4 Mobility Scenarios Amongst Coexisting WBANs

Three levels of mobility in WBANs are as follows (examples provided in Table.5.1)

- *(i) Static(S)*: This state shows that there is constant interference from other WBANs for a time duration with no mobility.
- *(ii) Semidynamic (SD)*: This state shows there is a constant interference from other WBANs for a certain time duration with slow mobility.
- *(iii) Dynamic (D)*: This state demonstrates temporary interference from other WBANs with fast mobility. (iv) None (N) state indicates that there is no interference.

We have first considered the coexisting WBANs to be assigned interference-free channels using the SCA scheme statically. We now consider network dynamics relative to the movement of WBANs towards each other (inter-WBAN mobility) and the movement of sensors within the WBAN (intra-WBAN mobility).

We consider the case of two coexisting WBANs, where both ($WBAN_1$ and $WBAN_2$) are approaching each other with a speed of V_{WBAN1} and V_{WBAN2} with an angle of α (α is the angle between the direction of movement of $WBAN_2$ and the horizontal axis of movement shown in Fig.5.1).

The important aspect to discover is if the two WBANs will interfere with one another's transmission. This selection is based on three factors: α being the angle of the direction of movement between the WBANs; τ' being the duration for which the WBANs remain in each others interference region and $D(t)$ which is the distance

between the coexisting WBANs. Hence, we need to find the time duration for which a sensor of coexisting WBANs will move into the interference range of the WBAN of interest. If this time duration is above the allowed threshold time (t_{TH}) allowed, changes need to be made to avoid interference which leads to throughput loss and energy drainage. The threshold time can be calculated as follows:

$$t_{TH} = \frac{T_d}{R_0(t)} \tag{5.3}$$

where $R_0(t)$ is the reuse factor and $T_{superframe}$ is the duration of each superframe.

As sensor nodes in WBANs have high mobility, their link connectivity and Packet Delivery Ratio (PDR) varies between different postures, the proposed channel allocation scheme should support variations in link quality and network topology.

Due to the social nature of WBANs, they will have interaction that lasts for a certain duration Zhang et al. [2013]. Thus, we need to find the time instant where two WBANs move into each others coexistence and further obtain the duration for which they stay in each others interference region. We consider (a, b) to be the coordinates of the center of $WBAN_1$. Since $\tan(\pi - \alpha) = -tan(\alpha)$, we have the following:

$$y(t) = -\tan(\alpha) \times x(t) + c \tag{5.4}$$

$$m = \frac{-1}{-\tan(\alpha)} = \cot(\alpha) \tag{5.5}$$

$$y(t) - a = \cot(\alpha)(x(t) - b) = \cot(\alpha)x(t) - \cot(\alpha)b + a \tag{5.6}$$

By substituting (5.4) into (5.6) we have the following:

$$-\tan(\alpha) \times x(t) + c = \cot(\alpha)x(t) - \cot(\alpha)b + a \tag{5.7}$$

Since the values of a, b and c are known in advance, we can find the value of $x(t)$ and $y(t)$. We can also calculate $D(t)$ as follows:

$$D(t) = \sqrt{(x(t) - a)^2 + (y(t) - b)^2} \tag{5.8}$$

If $D(t) > 2R$ we do not have intersection of regions between the coexisting WBANs. If $D(t) < 2R$, the coexisting WBAN intersect in their regions where the equation $2R - D(t)$ shows the extent of their intersection. The higher this value, the more the interference. If $D(t) = 0$ their intersection ratio will be 100%. The value of $D(t)$ also shows how far or how close we are to the r region ($D(t) < 2r$ and $D(t) > 2r$). Based on the aforementioned calculations, the WBANs will realize if they would need to make any changes to their assigned allocations.

Thus, the time at which any significant interference between two coexisting WBANs starts is a function of the speed of the co-located WBANs and can be calculated as follows:

$$\begin{aligned} D(t) - 2r &= |V_{WBAN_2} \pm (V_{WBAN_1})| \times \tau \\ \Rightarrow \tau &= \frac{D(t) - 2 \times r}{(V_{WBAN_2} + V_{WBAN_1})} \end{aligned} \tag{5.9}$$

The duration at which there is a likelihood for the coexisting WBANs to interfere with each other, referred to as τ' can be calculated as follows:

$$\begin{aligned} 4r &= (V_{WBAN_2} \pm V_{WBAN_1}) \times \tau' \\ \Rightarrow \tau' &= \frac{4 \times r}{(V_{WBAN_2} + V_{WBAN_1})} \end{aligned} \tag{5.10}$$

where the relative velocity of the coexisting WBANs is accumulated if they are moving towards each other and deducted when the coexisting WBANs are not mov-

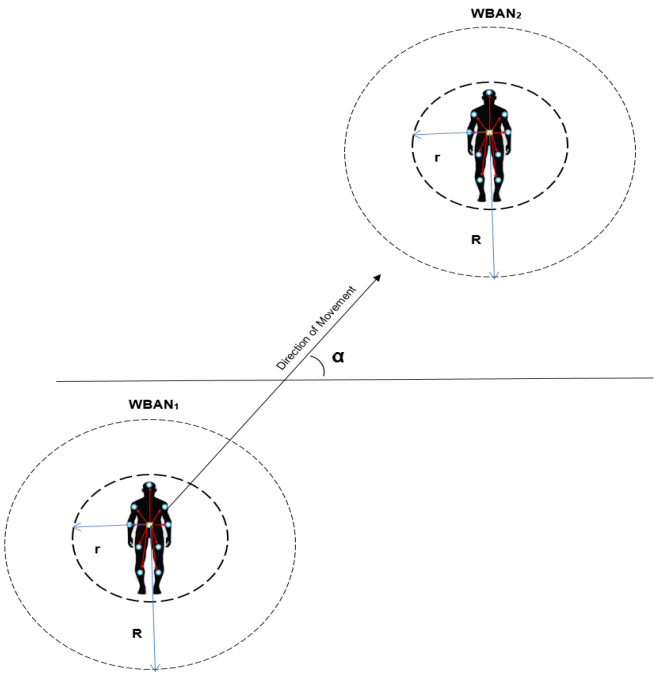


Figure 5.1: Movement of two WBANs with respect to each other

ing towards one another.

In the case where the duration of coexistence of the new WBAN that has moved into the interference region of the WBAN of interest is less than t_{TH}, the amount of interference is negligible and no changes need to be made in the channel assignment as each sensor will be able to successfully transmit its packets. However, in the case that the duration of coexistence exceeds the threshold value, we need to consider to either update the channel assignment or proceed with node-level power control.

5.4.1 Intra and Inter WBAN Mobility Model

We employ the Reference Point Group Mobility (RPGM) model to represent the random motion of a group of WBANs as well as the random motion of each individual WBAN within the group. This model has been shown to provide high Packet Delivery Ratio (PDR), low delay and high throughput amongst other existing group based mobility models Camp et al. [2002]. In this mobility model, the group movements of each WBAN are based upon the route travelled by a group motion vector, $\vec{GM}$ from a logical center for the entire network. The motion of the Mobile Node (MN) within

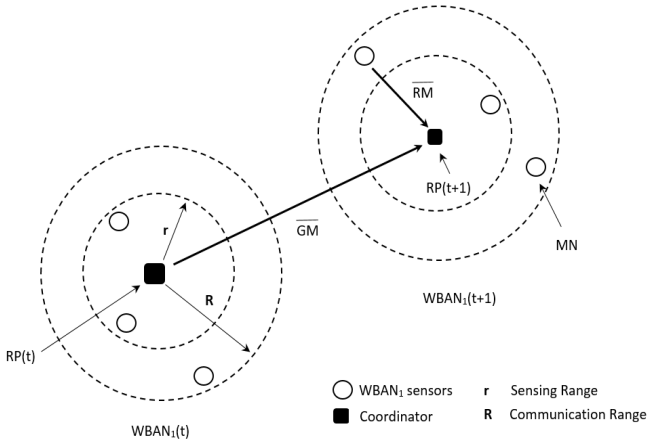


Figure 5.2: Movement of a WBAN with its sensors using the RPGM Model

their group is reliant on the motion of the group center along with their direction and speed. The random movements of each MN from their pre-defined reference point is relative to the group movement. The location of individual reference points from time instant t to $t+1$ is updated based on the group logical center. Then, the random motion of each MN from its reference point is updated via the combination of the updated reference point $RP(t+1)$ with the random motion vector, $\vec{RM}$.

The group motion vector $\vec{GM}$ is used to calculate the new reference point of the WBAN, $RP(t+1)$, at time $t+1$. It is important to note that the $\vec{GM}$ can be predefined or randomly chosen. Fig. 5.2 provides an illustration of a WBAN consisting of a number of sensors at time instance t and $t+1$ using the RPGM model for its movement. The reference point (RP) denotes the coordinator of the WBAN of interest and the MN represents the sensor nodes within each WBAN. The movement of the sensors of each WBAN towards their coordinator is represented via the random motion vector, $\vec{RM}$. Thus, the new position of each MN is further calculated by adding the random motion vector, $\vec{RM}$, with the new reference point, $RP(t+1)$. The length of $\vec{RM}$ is uniformly distributed within a specified radius centered at $RP(t+1)$ and its direction is uniformly distributed between 0 and 2π and with the length of 0 to $\frac{R}{2}$.

We consider the coordinator of the WBAN of interest at time instant t to be the origin with coordinates of $(0,0)$. Thus, the coordinates of the WBAN of interest at time instant $t+1$ using the movement vectors can be calculated as follows:

$$RP(t+1) = RP(t).\vec{GM} \tag{5.11}$$

$$MN(t+1) = MN(t).\vec{RM} \tag{5.12}$$

5.4.2 Power Control

In this section, we propose a power control approach to do the inter-network interference mitigation for WBANs. Because the WBANs are battery-supported, it is critical to reduce the energy consumption of WBAN system, prolong its lifetime and enhance the system's reliability. Therefore, the goal of the power control is to maximize the network utility while minimizing the power consumption.

We propose to reduce the transmission power of the sensor nodes that have just joined the interference region of a coexisting WBAN. Based on a simple comparison between the the received interference power of nodes at different time instances we can realize that the nodes have moved into each other interference range. If the received power from node j of $WBAN_1$ at $WBAN_2$ is above the γ_{th}, it can be predicted that they have moved into each others interference range. For instance, in the case where interference is detected between node i of $WBAN_1$ and node j of $WBAN_2$ at time t and the interference distance is d_0, then at the next time instant the transmission power of the signal of node i needs to be changed by some step which can calculated as follows:

$$P_t(t+1)_{\text{dBm}} = \max\left(\min[P_t(t) - P_r(t) + Rx_{sens} + \text{ offset}, 0\text{dBm}], -30\text{dBm}\right) \tag{5.13}$$

(5.13) is calculated in the dB domain. In fact, (5.13) also describes simple "Sample-and-Hold" channel prediction, where the last estimate of interfering channel gain is used as an approximate estimate of the next channel gain , following from Smith

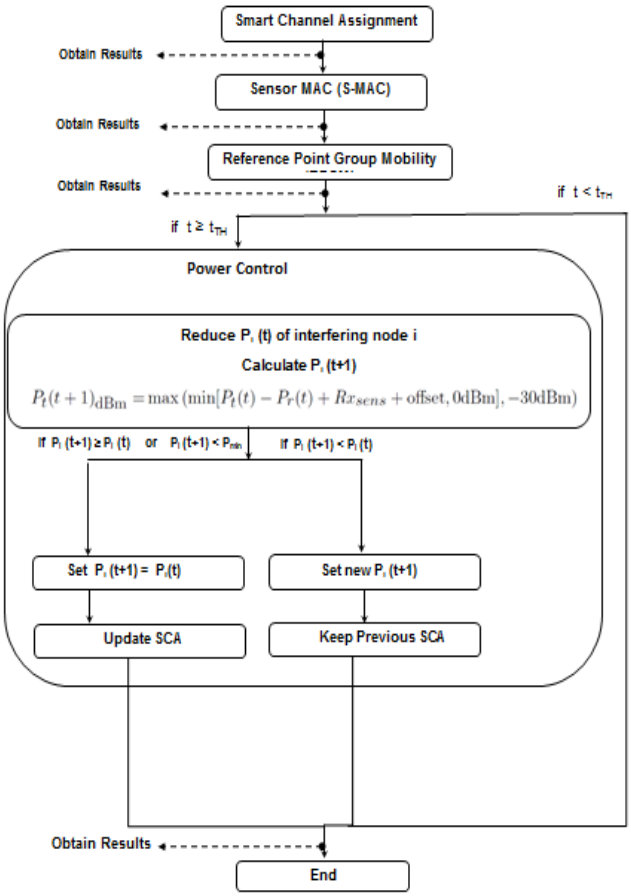


Figure 5.3: Flowchart of Proposed Approach

et al. [2011a] Initially, we consider a constant transmit power of $0dBm$ for all sensor nodes throughout the chapter ($P_t = 0dBm$) and a threshold power of -70 dB with an offset of 15dB and a received sensitivity Rx_{sens} of $-90dBm$. Then this power control is only calculated in the interfering nodes If power of interfering node at time instant $t+1$ is still above the γ_{th}, the channel assignment is updated. If not, transmissions are continued with the new calculated power. The pseudo code for the proposed prediction algorithm for capturing unknown dynamics using the SCA scheme, SMAC and power control is shown in Algorithm.3.2. Also, the flowchart for the step by step procedure and results obtained is shown in Fig. 5.3.

Algorithm 4: Energy-Efficient Channel Assignment for coexisting WBANs with Unknown Dynamics

Initially set $\mathcal{I}_i = \varnothing$ and $\mathcal{S}_i = \varnothing$,

for $t = 0$ to $t_{network\ lifetime}$

Step 1. Orthogonal transmission

for $i = 1$ to N_c

for $j = 1$ to N_s

Sensor (i, j) is transmitting

$WBAN_l$ estimates the received signal power, $\gamma_{i,j}$, from sensor (i, j)

Step 2. Determining the inter-interference set

for $i = 1$ to N_c

$\gamma_{min,i} = \min\{\gamma_{i,j}\}$

for $l = 1$ to (N_c), $l \neq i$

for $j_2 = 1$ to N_s

if $\gamma_{l,j_2}(t) > \gamma_{min,i}(t) - \gamma_{Th}$

Add (l, j_2) to set $\mathcal{I}_i(t)$ for $(D_{l,j_2}(t) - r) \leq 0$

if $\gamma_{l,j_2}(t) > \gamma_{min,i}(t) - \gamma_{Th}$ and $\gamma_{l,j_2}(t-1) \leq \gamma_{l,j_2}(t)$ and $t \geq t_{TH}$

if $\max\left(\min[P_t(t) - P_r(t) + Rx_{sens} + offset, 0dBm], -30dBm\right) \geq SINR_{th}$

Add (l, j_2) to set $\mathcal{I}_i(t)$

else if update SCA channel assignment

else if $\gamma_{l,j_2}(t) > \gamma_{min,i}(t) - \gamma_{Th}$ and $\gamma_{l,j_2}(t-1) \geq \gamma_{l,j_2}(t)$

Remove $(l, j_2)(t)$ from set $\mathcal{I}_i(t)$

Step 3. Broadcast

for $i = 1$ to (N_c)

Broadcast $\mathcal{I}_i(t)$ in R region

Step 4. Determining the interference set

for $i = 1$ to (N_c)

$\mathcal{S}_i = \mathcal{I}_i \cup \{(i, j) | (i, j) \in \mathcal{I}_l, l \neq i\}$

Step 5. Channel assignment

for $i = 1$ to (N_c)

Leave the time slots for nodes in $\mathcal{S}_i(t)$ unchanged

Equally assign the remaining channels to nodes that are not belong to $\mathcal{S}_i(t)$.

$t = t + 1$;

5.5 Simulation Results

Table 5.2: Simulation Parameters

Simulator	NS-2
Active Time of the Network (Sec)	120
Simulation area	20m X 20m
Number of Sensor Nodes per WBAN	9
Number of Coordinators per WBAN	1
Number of WBANs	2
MAC Layer Protocol	IEEE 802.15.4
Queue Size	50
Packet rate	4 packets/sec
Packet Size	512 Bytes
Sensing Range	100 cm
Initial Energy	50 J

In order to evaluate the performance of the proposed prediction algorithm, we have performed simulation of the proposed scheme in NS-2 simulator (version 2.34) ns2 with a one hop star topology for four different cases: SCA only, SCA with S-MAC, SCA with RPGM, SCA with power control. In this section, we compare the performance of the proposed scheme in these four cases in terms of inter-WBAN communication to evaluate the delay, throughput, PDR and energy consumption. The parameters used for these simulations are provided in Table. 5.2.

Fig. 5.4 depicts the average delay of each sensor per WBAN for transmission versus the simulation time for the four considered cases. As can be seen embedding SMAC in the SCA algorithm slightly decreases the delay which is due to the channel being switched off at times where the sensors are not transmitting and then being switched back on when required to transmit that leads to a slight delay for waiting to be switched back on to transmit again. In the case where coexisting WBANs move in the vicinity of one another, new sensors can move into and out of each others range, which implies the need for changes in channel assignment. In such a case, some delay is caused to compute the new channel and upgrade channel assignment to align with the SCA protocol to avoid interference and minimize energy consumption and delay. In the case that power control is also taken into account, delay is further introduced as the sensor's transmission will not be allowed if it exceeds the acceptable threshold

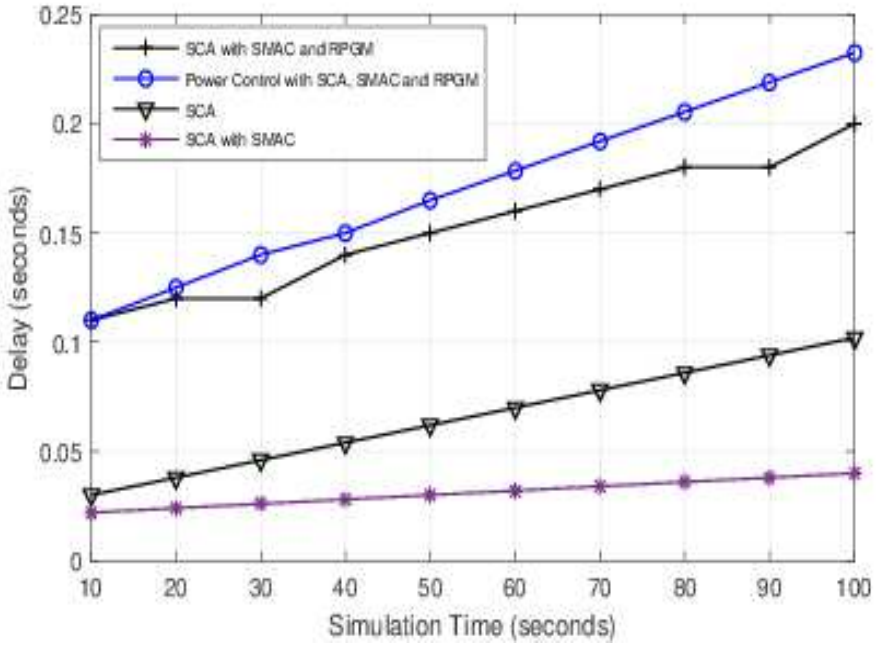


Figure 5.4: Average Delay versus Active Time of the Network

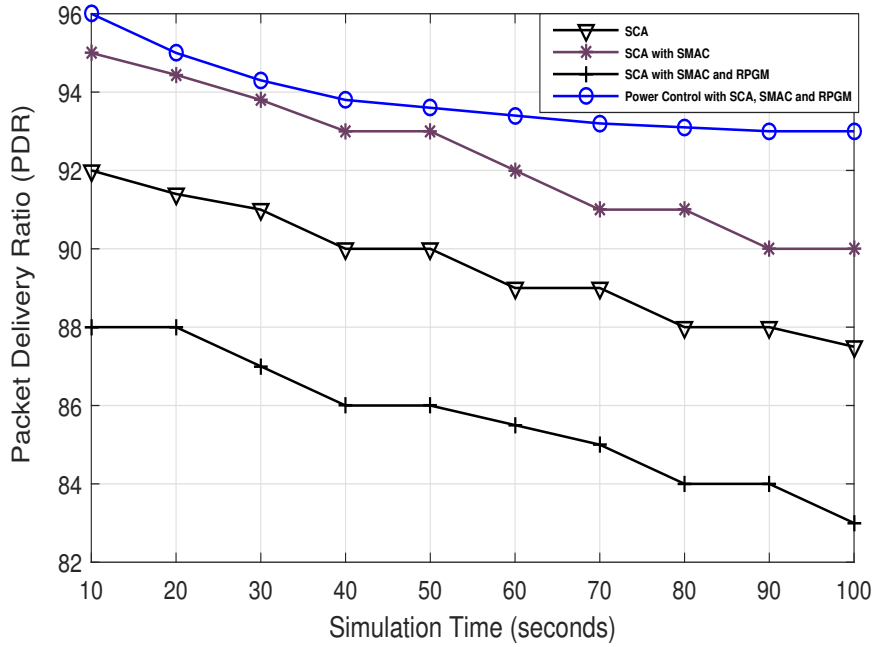


Figure 5.5: Average Packet Delivery Ratio versus Active Time of the Network

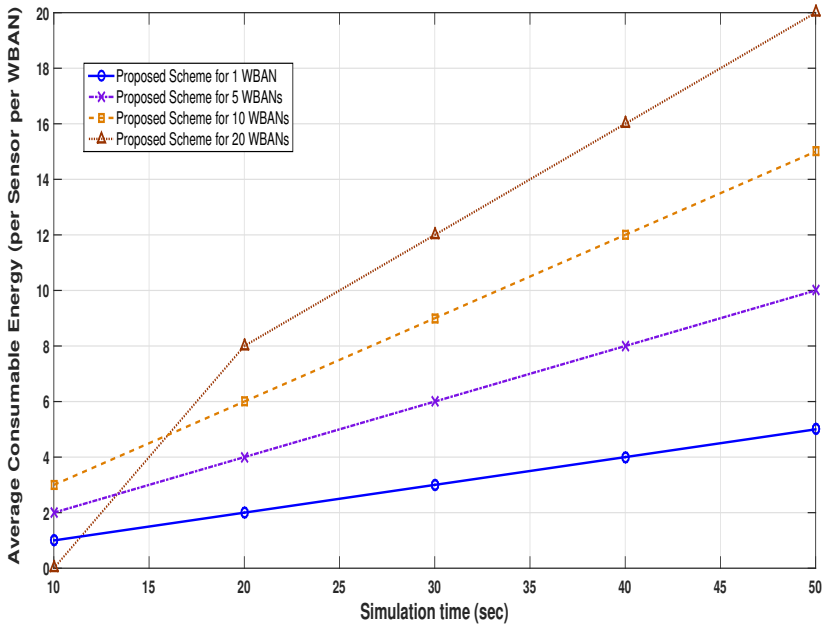


Figure 5.6: Average Consumed Energy versus Active Time of the Network

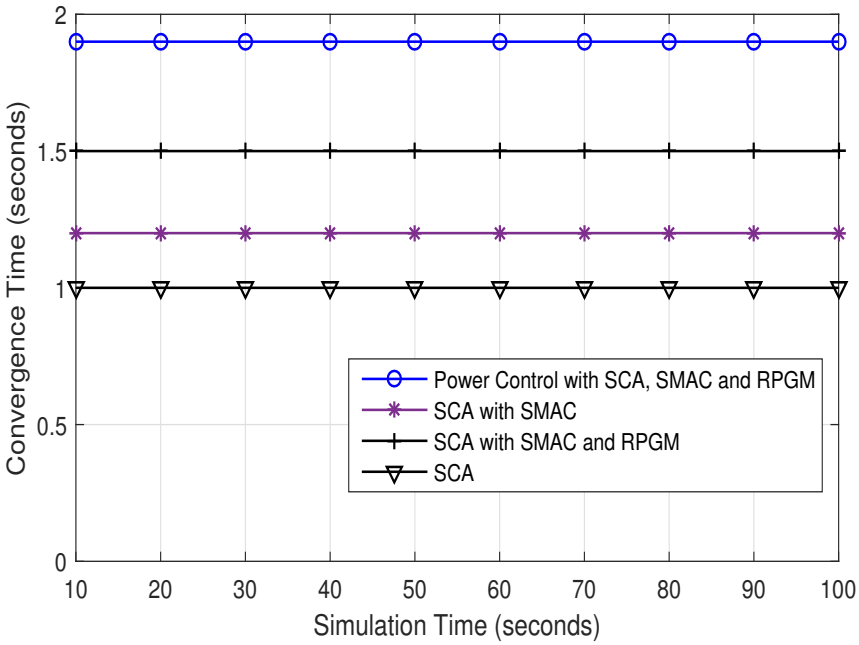


Figure 5.7: Average Convergence Time versus Active Time of the Network

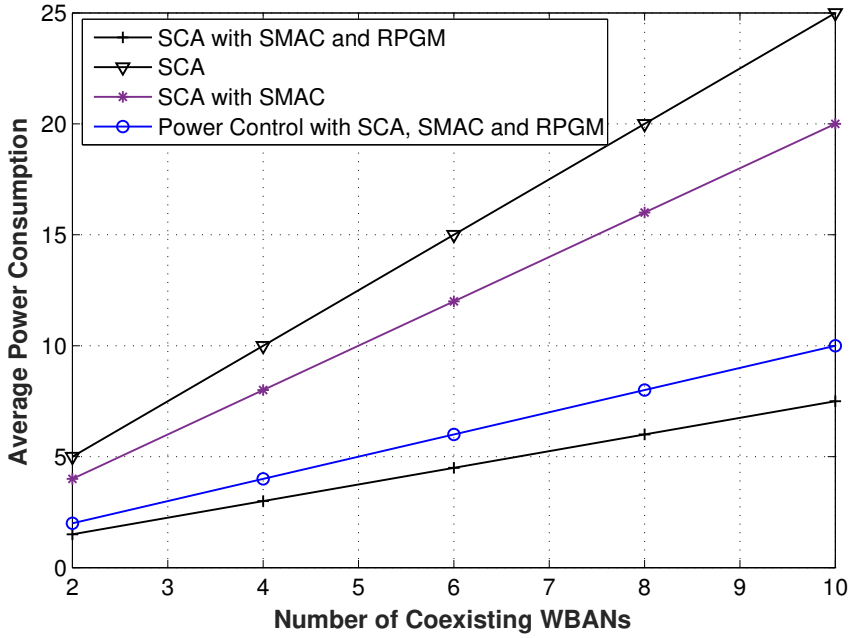


Figure 5.8: Average Power Consumption (dB) versus the Number of Coexisting WBANs

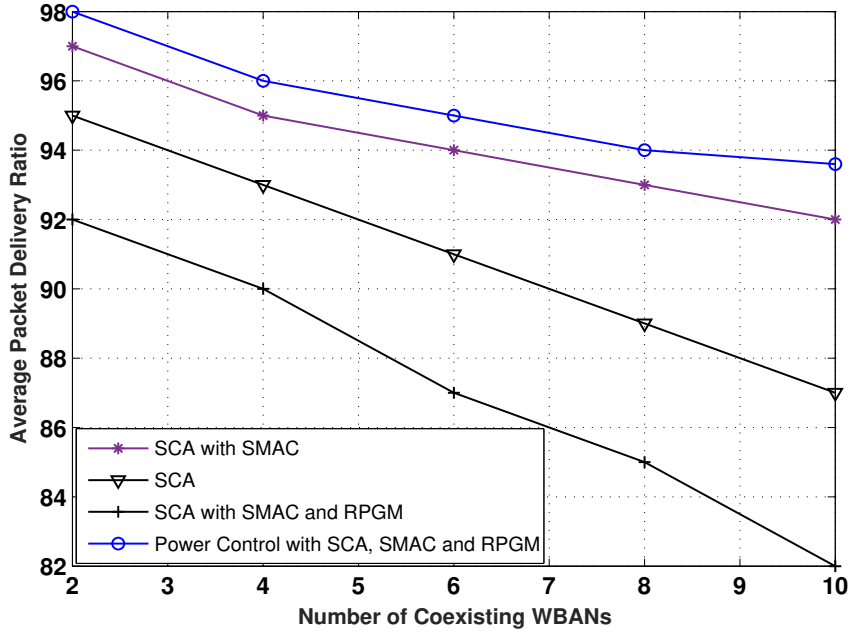


Figure 5.9: Average Packet Delivery Ratio versus the Number of Coexisting WBANs

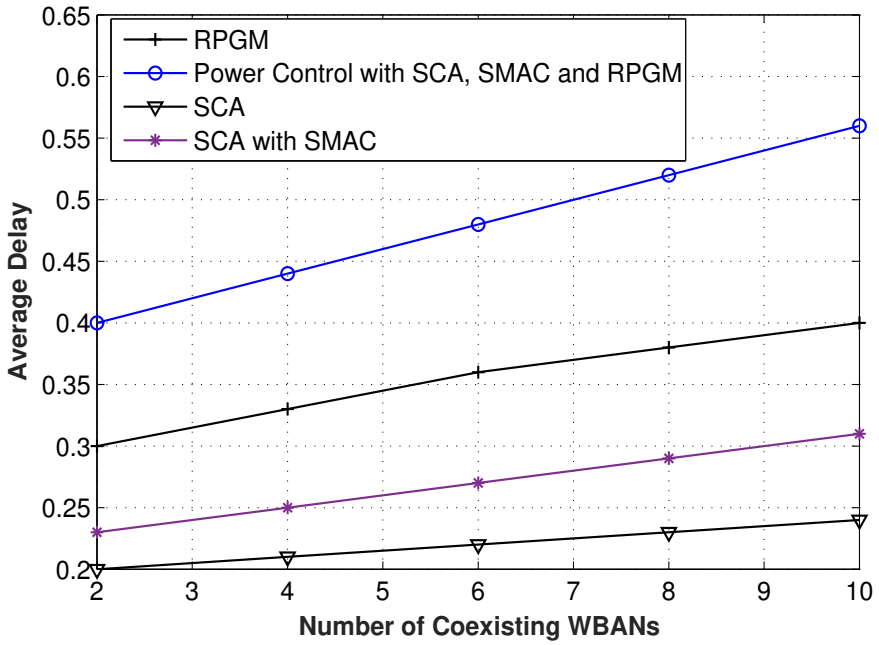


Figure 5.10: Average Delay (Seconds) versus the Number of Coexisting WBANs

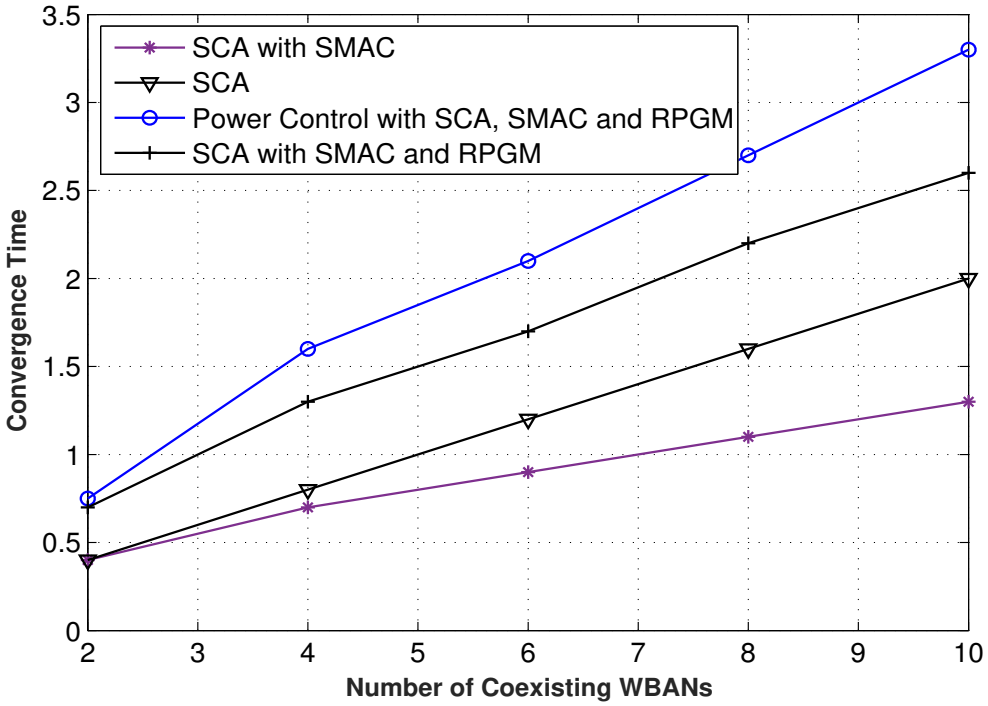


Figure 5.11: Average Convergence Time versus the Number of Coexisting WBANs

for coexistence. Thus Fig. 5.4 shows the proposed approach maintains reasonable results in all four cases.

Fig.5.5 demonstrates that using SMAC protocol on top of the SCA algorithm improves the packet delivery ratio due to the collision avoidance features embedded in it. However, the introduction of channel dynamics imposes variations within the network which requires novel channel assignment in some cases where the transmission of a certain WBAN can be terminated upon new changes in the network that leads to lower packet delivery ratio. In the case that the power control feature is also considered, as shown in Fig. 5.5 packet delivery ratio is enhanced as the power of the interfering sensor nodes will be reduced leading to less interference and therefore higher PDR.

Fig. 5.6 shows the average consumed energy at the sensor node versus the simulation scenario time for the four different cases. As can be clearly seen in this figure, the SCA with S-MAC scheme provides higher energy savings as it goes into sleep/idle mode at instances that it is not transmitting. However, in the case that mobility is induced into the network which implies changes in the interference region, which might require updated channel assignments, more energy is used. The most important message conveyed from Fig .5.6 is that variations in energy consumption is very low and can be neglected in return for massive gains in throughput and reuse. Fig.5.7 depicts the average convergence time for different stages of the protocol. As can be seen, there is only a slight increase of up to 80 milliseconds for embedding the power control feature as well as encountering mobility and SMAC on the SCA scheme with reassures the computational complexity.

Next, we evaluate the performance of the proposed scheme with different density of coexisting WBANs from 2 to 10. As expected and also demonstrated in Fig.5.8, the increase in the density of coexisting WBANs increases the power consumption, with the highest rate of energy consumption in the SCA scheme on its own. Whilst, the incorporation of SMAC with SCA has shown to decrease energy consumption as it introduces idle periods that avoid excess energy usage. The best attribute is the performance of the proposed protocol when mobility is introduced which shows less energy consumption that implies the introduction of network dynamics has been

well predicted in advance and taken care of ahead of time. There is only marginal degradation from this when transmit power control is introduced.

Fig.5.9 depicts the average packet delivery ratio (PDR) versus the density of co-existing WBANs. It can be noted that, as expected, as the number of coexisting WBANs increase the PDR decreases. But, as can be seen, the introduction of network dynamics has not deteriorated the performance of the proposed protocol. In fact, the introduction of SMAC has increased the packet delivery ratio. However, introducing network dynamics by deploying the RPGM model has led to a slight decrease in the packet delivery ratio compared to the SCA and SCA with SMAC scheme. This has been well overcome by incorporating power control in the proposed approach as the power control scheme reduces the power of sensory devices , therefore creating less radio interference in the new mobility scenario, and therefore higher packet delivery ratio, compared to incorporating the mobility model on the top of the SMAC and the SCA scheme on their own. This case with power control maintains a packet delivery ratio above 93% well above the 90% guideline in the IEEE 802.15.6 requirements.

The amount of delay versus density of coexisting WBANs is shown in Fig.5.10. It can be noted that, as expected, as the number of coexisting BANs increase the average delay increases. Also as expected, incorporating SMAC with the SCA scheme slightly increases the delay since it introduces idle periods and then needs to initiate again and there is a slight delay between the time the network goes into idle period and becomes active again which introduces this slight amount of delay. Also shown is the main drawback of incorporating power control, with a delay of over 500ms for 10 coexisting WBANs .

5.6 Conclusion

In this chapter, we have presented a social interaction based channel assignment for inter-WBANs interference mitigation. In other words, we have proposed a decentralized prediction algorithm for inter-WBAN communications using the smart channel assignment technique that captures the unknown dynamics and provides feedback to the coordinator of each WBAN , quickly updating its channel assignment based

on recent changes in the network. Unlike previous work, our WBANs channel assignment proposal is designed based on social interaction detection and prediction, which considers the unique features of social interaction in cyber-physical WBAN systems.

Firstly, we built the interference model based on social interaction information. Secondly, we modeled the social interaction and presented a methodology for interference mitigation based on network interaction distances. NS2 simulations were used to verify the correctness of our proposed model. Thirdly, we applied node-level power control at the interfering nodes to control the WBANs' transmission power effectively, using simple "Sample-and-Hold" channel prediction in order to mitigate the interference, as well as reduce circuit power consumption. The effectiveness of the proposed algorithm was further demonstrated. Theoretical analysis calculated the computation of the time instant at which coexisting networks initiate imposing interference on one another and the duration that such interference lasted.

Simulation results demonstrated that the proposed approach achieves more efficient usage of the scarce resources in WBANs, leading to major energy savings as well as a longer network lifetime. Additionally, simultaneous transmissions in coexisting WBANs allow for higher throughput and packet delivery ratio. We have shown that the proposed scheme can optimally update channel assignment to keep the interference level below a desired threshold. Simulation results have shown the efficiency of the proposed approach through four different mobility scenarios compared to the IEEE 802.15.4 approach. To conclude, the major advantage of this proposal was adding the feature of adapting to variations in channel dynamics and updating the channel assignment accordingly to avoid inter-network interference and energy drainage from nodes in a WBAN. In the following chapter, we will introduce a self-organization scheme for efficient coexistence of multiple WBANs with the need for a global coordinator.

Chapter 6

Self-Organization Amongst Multiple Co-existing Wireless Body Area Networks

6.1 Introduction

WBANs are designed to facilitate a vast array of applications from real-time healthcare to personal entertainment services. Hence, as WBANs become increasingly pervasive, their coexistence (inter-WBAN communication) is emerging as a major issue. Generally, due to the nature of WBANs and their high mobility it is unfeasible to allocate a global coordinator to control coexistence amongst multiple WBANs. In cases where co-located WBANs use the same channel (similar frequencies), transmissions can conflict; as the active periods can overlap Grassi et al. [2012]. Moreover, with the increase in the number of WBANs that can coexist in close proximity to each other, as well as the number of sensors deployed in each WBANs, makes interference mitigation even more challenging Movassaghi et al. [2014b].

The high mobility in WBANs can lead to variations in terms of topological changes (nodes joining/leaving the network), variations in traffic patterns and changes in overall load on the network Movassaghi et al. [2014c]. Additionally, the environment in WBANs is non-deterministic, which implies that taking the same action on the same state on two different occasions may lead to different states. Therefore adaptive spectrum allocation techniques must be deployed amongst coexisting WBANs to efficiently control these variations without coordination Movassaghi et al.

[2014d]. However, adaptive approaches require frequent exchange of information and lead to a linear cost for updating information. In addition, the broadcast nature of the radio spectrum and the limited radio bandwidth leads to interference between devices involved in communication across coexisting WBANs. Finally, power is a scarce resource in WBANs as sensors are battery-driven Movassaghi et al. [2014e].

The introduction of the IEEE 802.15.6 standard has been a breakthrough in the area by defining new PHY and MAC layer proposals for WBANs that provide ultra-low power, low cost, low complexity and short range wireless communication in or around the human body. The proposed standard requires the system to function properly within the transmission range of up to 3 meters when up to 10 WBANs are co-located Movassaghi et al. [2014a]; Sta. It also has to support 60 sensors in a $6m^3$ space (256 sensors in a $6m^3$ cube)Sta. Even though the standard provides a powerful foundation in the area, practical deployment of these networks requires novel WBAN-specific strategies to be devised.

For one thing, a huge number of WBANs need to function reliably in densely populated scenarios. The issue becomes even more challenging considering the mobility of WBANs, which implies these networks frequently move in and out of each others range Movassaghi et al. [2015a]. Unfortunately, existing proposals for inter-WBAN communication mainly rely on coordination or cooperation which leads to severe energy drainage. On the other hand, other existing wireless networks do not have the issue of distributed coordination and can access a centralized unit for communication amongst one another. Moreover, the decentralized approaches Werner-Allen et al. [2005].

The proposals in Werner-Allen et al. [2005]; Degesys et al. [2007]; Tyrrell et al. [2010]; Simeone and Spagnolini [2007] are not suitable for WBANs as they do not consider the social nature of WBANs, their stringent battery and memory resources as well as infeasibility of allocating a global coordinator amongst coexisting WBANs, Zhang et al. [2013]; Kim et al. [2013]; Fang et al. [2010b]; Zhang et al. [2010]. Additionally, a WBAN mainly has more frequent topology changes and a higher moving speed, whilst a Wireless Sensor Network (WSN) has static or low mobility scenarios. The only similarity between WBANs and Mobile Ad hoc NETworks (MANETs) is in

terms of the moving topology with group-based movement rather than node-based movement. Thus, due to the group-based movement and high mobility nature of WBANs they are not similar to WSNs or MANETs Cheng and Huang [2013].

Thus, in this chapter, a biologically inspired algorithm is presented for achieving global coordination amongst multiple coexisting WBANs with a single-hop star topology. Given a set of N_c coexisting WBANs that generate events periodically with a fixed period, coexisting WBANs converge to a state where all are evenly allocated a portion of the spectrum for their transmissions. The proposed algorithm is decentralized, simple and requires a little amount of fixed memory per coordinator node despite the network size. The proposed protocol is also robust to variations of coordinators leaving or joining the network as it self-adjusts to provide fairness for each coordinators transmissions. Our simulation and numerical results confirm that the proposed scheme rapidly achieves stability. To the authors' best knowledge, this is the first time such a self-organization approach is proposed for coexisting WBANs.

The following summarises the key contributions of this chapter:

- A simple, light weight approach for self-organization of multiple coexisting WBANs is proposed which is biologically inspired from the synchronicity of fireflies in nature.

- The proposed distributed, simple and lightweight solutions comply with the scarcity of resources in terms of channel availability by increasing the spatial reuse and reducing the overall network transmission delay

The rest of this chapter is organized as follows. In Section 6.2 the proposed scheme self-organization algorithm is described. Simulation results are provided in Section 6.3. Finally, Section 6.4 concludes the chapter.

6.2 Proposed Self Organization Scheme for Coexisting WBANs

6.2.1 Firefly Synchronicity

Our approach for self-organization amongst coexisting WBANs is somewhat based upon the concept of Pulse Coupled Biological Oscillators (PCO) inspired by fireflies synchronicity model introduced in Mirollo and Strogatz [1990]. Further discussion of how our approach differs from that in Mirollo and Strogatz [1990] follows. The synchronization concept is based upon the fact that each node performs as an oscillator with a constant time period T. More specifically, each node has an internal phase or time ϕ which starts at 0 and linearly increases with time until it reaches T. Thus, the phase variable is characterized by $\frac{d\phi}{dt} = \frac{1}{T}$.

In order to have a means of understanding when a transmission has initiated we introduce the concept of firing which basically implies the transmission has started. At $t = T$ the node "fires" and resets at $t = 0$ again. Since nodes in the network may start at different time intervals their internal state may differ. If no neighbors exist in the vicinity of a node, the node simply fires at $t = T$ again, whilst in the case where a neighbor exists in its vicinity it will need to adjust its firing phase. This amount of phase adjustment is decided upon based on the state function $f : [0,1] \rightarrow [0,1]$, also known as the firing function, and the value of the *Pulse Strength* $0 < \epsilon < 1$. In the case where the node of interest hears a neighbour fire at $t = t'$, it instantaneously jumps to a new internal time which is calculated as follows:

$$t'' = min(f^{-1}(f(t') + \epsilon), 1) \tag{6.1}$$

This implies if $t'' > T$, t is set to T and the node immediately fires and resets to $t = 0$.

6.2.2 The Self-Organization Protocol

We propose to utilize the concept of firefly synchronicity to achieve distributed management of the available spectrum amongst coexisting WBANs so as to avoid the

need for global management. However, our approach draws from existing proposals by considering this concept amongst coexisting wireless body area networks, specifically their coordinator which has a length T of data collected from its own sensors. Another main advantage of our proposal is that it achieves synchronicity and collision avoidance amongst coexisting networks in a small time and with the least information available, which implies avoiding excessive calculations and overhead on these networks with such stringent resources.

We assume that each WBAN reserves a fraction η of the time T for synchronization purposes. This time $\tau = \eta T$ is further divided into N time slots and the WBAN will fire in one of these slots. More specifically, when the WBAN cannot hear any firing from the other WBANs, it fires in the τ^{th} time slot.

We start with a simple scenario, where a WBAN_1 hears a firing of WBAN_2 in the middle of its transmission. Then WBAN_1 stops its transmission and allows WBAN_2 to continue its transmission. WBAN_1 also shifts its firing time one slot to the left. After time T, WBAN_1 is firing at time slot $N-1$, thus, WBAN_2 hears this firing and stop its firing, which is taking place in time slot N. Thus both WBANs knows that there are two WBANs in the area, and then decrease their transmission rate to one in each $2T$. Once WBAN_1 finish its transmission, it does not transmit any fire as it has to wait for T seconds. Therefore, WBAN_2 can fire and transmit successfully. This has been clearly shown in Fig.6.2.

This can be easily extended to the case that more than two users are coexisting. Let us assume that the number of WBANs is $N_c \leq N$. Then each WBAN which can hear the firing of ℓ other WBANs will shift its firing slot ℓ times to the left and decrease its transmission rate to once every ℓT. As WBANs stop their transmissions once the hear a firing in the middle of their transmissions, we claim that no two WBANs have the same firing slot. Thus, after the first round of transmission they will be synchronized. After that all the WBANs are synchronized and they don't hear any unadjusted firing, they shift their firing slot to slot N.

We can represent the coordinators of coexisting WBANs in each others range as beads moving clockwise on a ring with a period T shown in Fig.6.3, where each of the WBANs' require a duration of T for their own transmissions. However, as the

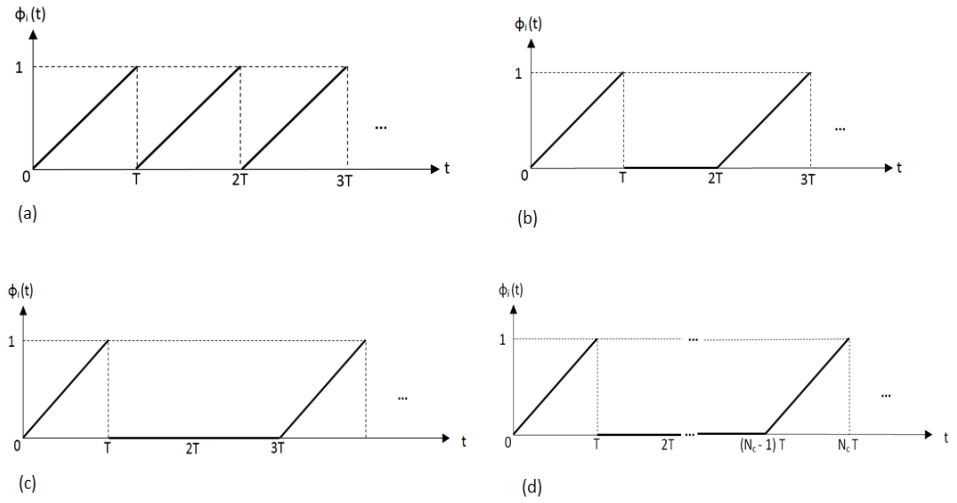


Figure 6.1: Transmission Patterns of a WBAN. (a) When no WBANs exist in the vicinity of a transmitting WBAN. (b) When one other WBAN exists in the coexistence of the WBAN of interest. (c) When two other WBANs exist in the vicinity of the WBAN of interest. (d) When $N_c - 1$ WBANs exist in the vicinity of the WBAN of interest.

number of coexisting WBANs increases the radius of the circle increases as follows:

$$
\begin{aligned}
2\pi R^{(1)} &= T \quad \text{for } \textit{one WBAN} \implies R^{(1)} = \frac{T}{2\pi} = R_0 \\
2\pi R^{(2)} &= 2T \quad \text{for } \textit{two WBANs} \implies R^{(2)} = \frac{2T}{2\pi} = 2R_0 \\
&\vdots \\
2\pi R^{(N)} &= N_c T \quad \text{for } N_c \textit{ WBANs} \implies R^{(N_c)} = \frac{N_c T}{2\pi} = N_c R_0
\end{aligned} \tag{6.2}
$$

We consider the following rules for the simulation and analysis of these networks:

Rule.1 When a WBAN fires, its neighbor WBANs instantaneously observe that event.

Rule.2 Nodes can instantaneously react by firing.

Rule.3 Each WBAN can compute f and

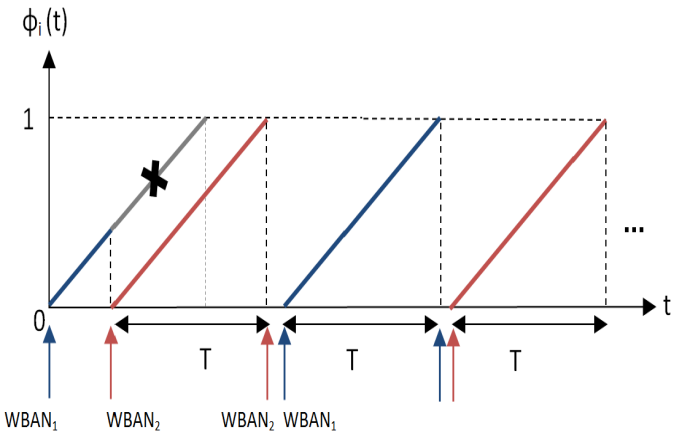


Figure 6.2: Example for scenario with two coexisting WBANs

Rule.3 All WBANs have the same time period T.

Rule.4 Each WBAN observes all events from their neighbor WBANs (no loss).

6.2.3 Example of the Proposed Self-Organization Protocol

6.2.3.1 *A WBAN moving into the coexistence of existing WBANs*

Let us assume that a set of coexisting WBANs are urrently synchronized. When a new WBAN enters the algorithm, it interrupts an existing WBAN's transmission with its firing message. All existing WBANs hear this unadjusted firing and realize that a new WBAN is joining them. The WBAN that was in the middle of its transmissions terminates its transmission, delays its transmission for the length of a WBAN's transmission, T, allows the new WBAN to continue with its transmission (which goes on for a T seconds interval). The cost of another WBAN coming into the coexistence of existing WBANs is a latency of one time period and the lost bandwidth that results from the interrupted data slot. All the other WBANs then shifts their firing slot one slot to the left. After one cycling interval of T, when the transmission of the new WBAN was finished, one of the existing WBANs which has to transmit at the current slot fires and continues with its transmission. All other WBANs then shift their firing slot one time to the left. After each period T the new WBAN hears the firing of one of the existing WBANs and thus after that all existing

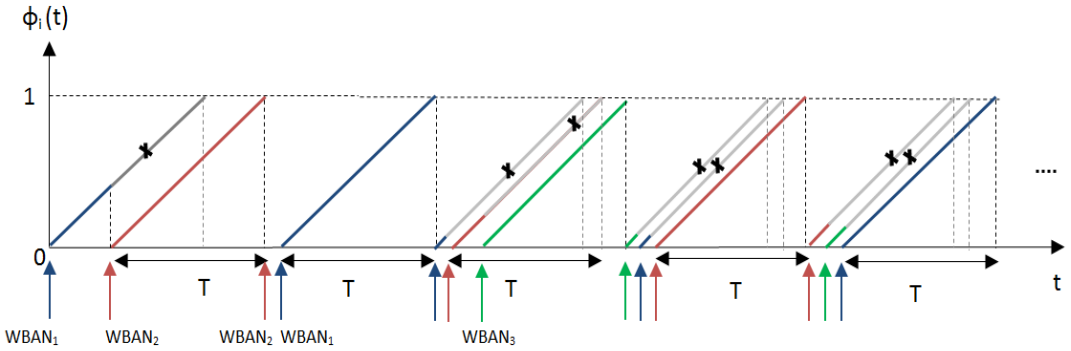


Figure 6.3: Example for scenario where a new WBAN is joining

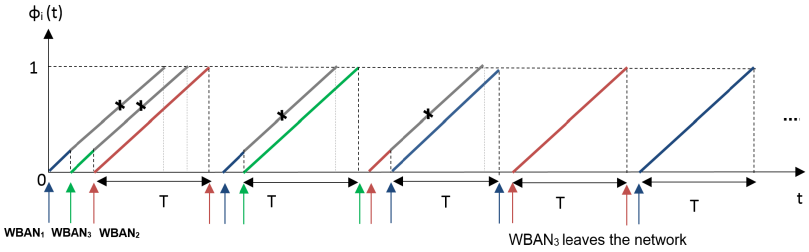


Figure 6.4: Example for scenario when one WBAN is leaving the coexisting WBANs

WBANs finish their transmission, it fires and thus will be synchronized with other WBANs as in Fig. 6.3.

6.2.3.2 *A WBAN moving out the coexistence of existing WBANs*

Let us assume that a WBAN is leaving a groups of WBANs of size N_c. Once a WBAN leaves the group, other WBANs cannot hear any firing in the time slot allocated to the WBAN which has just left the group. Then, they increase their transmission rate to once every $(N_c - 1)T$. Since the WBANs knows which WBANs left the group (from the missed firing signal), thus they adjust their timing slots to fully utilize the available bandwidth. Thus, if a WBAN decides to leave the coexistence of a number of WBAN networks, it can simply leave the protocol, sleep and re-enter whenever it needs to send again. Fig.6.3 shows an example of a WBAN moving out of the coexistence network.

Thus, our proposed approach allows for fair sharing of the superframe amongst all coexisting WBAN networks, even in cases where the size of the coexisting network varies or its mobility.

6.2.4 Simulation Results

In order to evaluate the performance of the proposed self-organization algorithm, we have performed simulations using the NS-2 simulator (version 2.34)ns2 with a one hop star topology within each WBAN for four different density of coexisting WBANs to be 1, 5, 10 and 20. In this section, we compare the performance of the proposed scheme in terms of delay, throughput, PDR and energy consumption. The parameters used for these simulations are provided in Table. 6.1.

Table 6.1: Simulation Parameters

Simulator	NS-2
Active Time of the Network	50
Simulation area	20m X 20m
Number of Sensor Nodes per WBAN	9
Number of Coordinators per WBAN	1
Number of WBANs	1, 5, 10, 20
MAC Layer Protocol	IEEE 802.15.4
Queue Size	100
Packet rate	8 packets/sec
Packet Size	1024 Bytes
Sensing Range	100 cm
Initial Energy	50 J

Fig .6.5 shows the average consumable energy per sensor in each WBAN versus the simulation time for the four different WBAN densities of low, middle, high and extremely high by considering N_c to be 1, 5, 10 and 20, respectively. As can be clearly seen in this figure, the proposed scheme provides more energy savings which is because of simplicity of proposed approach that does not require frequent cooperation and information exchange which leads to energy wastage. This feature is most advantageous to such networks with stringent battery requirements as battery replacements can be quite uncomfortable.

Fig. 6.10 depicts the average delay of each sensor per WBAN for transmission

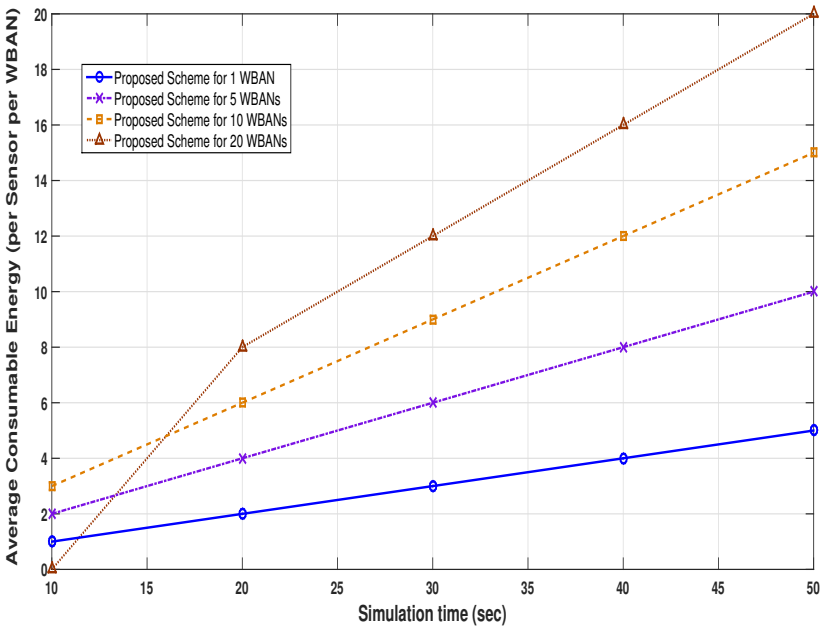


Figure 6.5: Average consumable energy of the proposed scheme versus active time of the network for different number of coexisting WBANs (Nc:1, 5, 10, 20)

versus the simulation time for the same density of coexisting WBANs. Negligible changes where noted which demonstrates the scalability of our algorithm for different densities of coexistence.

6.2.5 Conclusion about proposed self-organisation scheduling

We have proposed a collision-free approach for schedule assignment amongst multiple coexisting WBANs with no global coordination. Our approach is capable of achieving convergence with very low complexity and information exchange. In our proposed mechanism the coordinator of each WBAN is responsible for firing once it initialises its transmission, terminate its transmission upon hearing a fire and store the firing phase of its coexisting neighbors so as to minimize the convergence time whilst maximising reliability. Additionally, considering the stringent requirements of these networks specifically in terms of group based movement of the entire network as well as the WBAN communications channel, not only was our algorithm capable of achieving faster convergence compared to existing inter-network communication

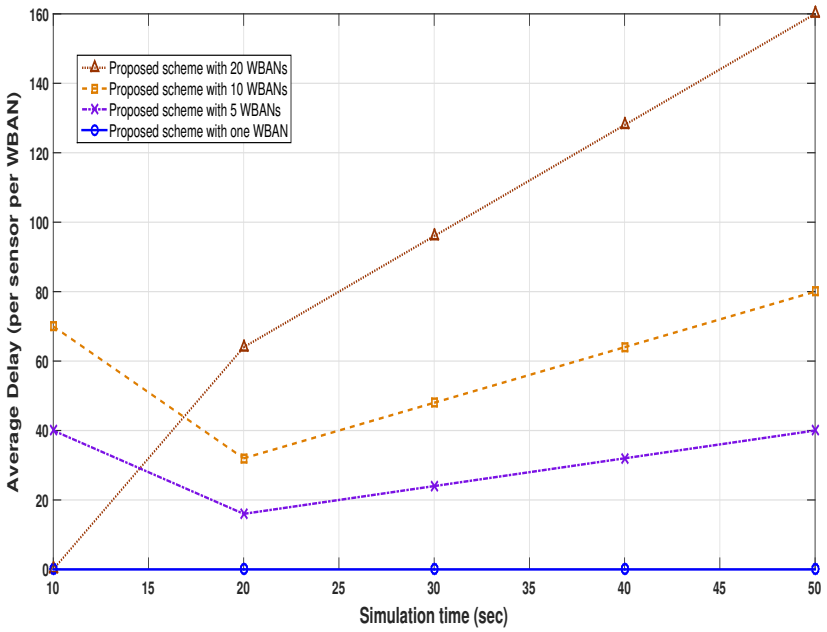


Figure 6.6: Average delay of the proposed scheme versus the active time of the network for different number of coexisting WBANs (Nc:1, 5, 10, 20)

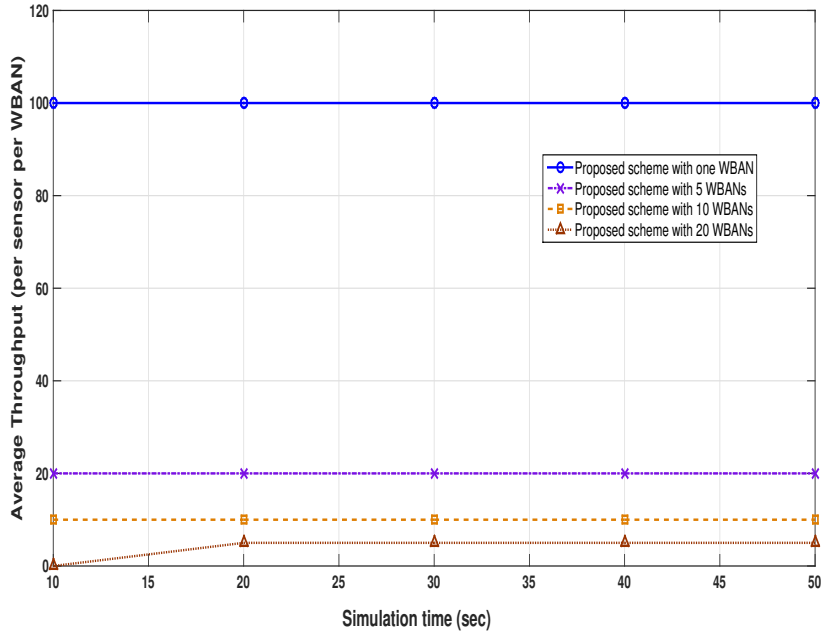


Figure 6.7: Average Throughput versus the active time of the network

mechanisms, but it was also capable of achieving a significantly better reliability. The other unique advantage of our algorithm is that is does not require an external global entity and self-adjusts itself to fully utilize the limited spectrum in WBANs. Further considering the computational burdens of these networks we also investigated reducing the computational complexity of the proposed solution. We demonstrated that our proposal can provide a significantly higher convergence time for collision free communications over traditional inter-network communication mechanisms. Considering the rapidly evolving growth of WBANs in recent years, there are yet more things to consider to allow for further improvement of such mechanisms. Exploring the different topological variations within each WBAN network, or proposing mechanisms to self-adjust to unequal channel allocation amongst all coexisting WBANs, are some of the directions which will be taken for further development of this work.

6.3 Biologically Inspired Self-Organization and Node-Level Interference Mitigation Amongst Multiple Coexisting Wireless Body Area Networks

This section presents a node-level self-organizing interference avoidance scheme (SIAC) between multiple coexisting wireless body area networks (WBANs) that incorporates self-organization and smart spectrum allocation. It follows a biologically inspired approach based on the theory of pulse-coupled oscillators for self-organization. The proposed scheme makes three major contributions as compared to the current literature. Firstly, it considers node-level interference for inter-network interference mitigation rather than considering each WBAN as a whole. Secondly, it allocates synchronous and parallel transmission intervals for interference avoidance in an optimal manner and dynamically adapts to changes in their coexistence. Finally, it achieves collision-free, self-organized communication with only information of the firing signal of each WBAN and does not require a global coordinator to manage its communications. It operates on a nodes traffic priority, received signal strength, and density of sensors within a WBAN. Simulation results show that

our proposal achieves a fast convergence time despite reduced received information. Moreover, SIAC is shown to be robust to variations in signal strength, number of coexisting WBANs and number of sensor nodes within each WBAN.

Thus, in this section we aim to leverage the inherent nature of these networks and enable their real-world deployment by addressing the following five challenges in WBANs:

- *Autonomy*: Since WBANs can be deployed in unattended areas or massively deployed in populated regions, they need to operate with minimum external aid. However, the social nature of these networks and their high mobility does not allow for their coexistence to be managed by a global coordinator.

- *Scalability*: The IEEE 802.15.6 standard for WBANs has defined the network to function efficiently within the transmission range of up to 3 meters with up to 10 coexisting WBANs, each consisting of up to 256 nodes Sta. Thus, WBANs need to function efficiently scaling up to a large number of sensors in each WBAN.

- *Adaptability*: Postural body movements (mobility) make interference even more challenging as WBANs move into and out of each other's range and lead to densely populated regions.

- *Self-organization*: Since a global coordinator cannot be assigned to manage the communication of multiple coexisting WBANs, they would need to self-organize their transmissions on their own.

- *Simplicity*: Due to the scarcity of resources in WBANs, the proposed protocol needs to be as simple as possible. This makes it extremely energy efficient and avoids excess computational complexity to enhance their battery lifetime.

This chapter aims to overcome the aforementioned challenges by incorporating an approach that takes all these factors into account. It draws from existing proposals by considering node-level interference mitigation rather than network-level synchronization. It allows self-organization for coexisting WBANs by using a model

based on pulse-coupled oscillators. The simplicity of the proposed approach and its operation based on the minimum amount of information exchange make it robust to different scales of deployment and also allow its adaptability to variations.

6.4 System Model

We model each WBAN by a circle of radius R, where the coordinator is located at the center while sensor nodes are uniformly located at random within the circle. We then define the intra-WBAN and inter-WBAN channel models similar to Movassaghi et al. [2014d]. The channel between the sensors and the coordinator in each WBAN (intra-WBAN) is modeled with gamma fading. The channel between the sensors and coordinators of different WBANs (inter-WBAN) is modeled by Rayleigh fading. For the small scale fading model between a pair of WBANs, we use the Jakes model with $f_D = 2Hz$ as its Doppler spread, where the Doppler fading parameter is $\frac{f_D}{f_s} = 0.01$ and the sampling rate at the receiver is $f_s = 200Hz$. Rayleigh fading uses fading coefficients of $CN(0,1)$ which are distributed around the shadowing path-loss which interprets as the shadowed path loss being the mean power of the fading coefficients.

We apply the Free Space Path Loss (FSPL) model based on the time varying nature of the channel and variation of distance with time due to intra and inter-network dynamics. The path loss exponent, n is set to be 2 and is stated to vary in different body locations based on investigated measurements. However, there will not always exist a line of sight path amongst the WBAN of interest and the interfering WBAN in cases where people are in random motion towards each other. Therefore, non-line-of-sight transmission or obstructed line-of sight are included as the shadowing effect and is applied as an offset to the FSPL. Table 1.1 shows the list of abbreviations and notations used throughout the chapter.

6.5 Biologically inspired Node-Level Self-Organization Amongst Multiple Coexisting Wireless Body Area Networks

A simple approach to avoid inter-WBAN interference is to assign completely orthogonal channels to coexisting WBANs (Inter-WBAN TDMA). However, a sensor in a specific WBAN may impose a higher interference level on its surrounding WBANs whilst other sensors of that WBAN may have a very low interference on co-located WBANs. In this case, sensor nodes with lower level of interference are not required to transmit orthogonally. This is the main objective behind proposing a node-level interference scheme, SIAC, which also contributes to higher speed of communication.

We consider a set of M number of coexisting WBANs denoted by $\{B_k|k = 1, ..., M\}$, where B_k refers to the kth WBAN. Each WBAN consists of a homogeneous set of N sensors denoted by $\{s_k^i|i = 1, ..., N\}$ and one central node known as the coordinator, where all sensor nodes transmit their data to the central node in their allocated time slot. We consider that the M coexisting WBANs use the same technology for communication with their sensor nodes referred to as (intra-WBAN communication). All WBANs are considered to utilize a similar superframe structure with the same superframe length (T). We assume that all sensor nodes have similar characteristics, a unique identification number (ID) and are initially provisioned with an equal amount of energy. The coordinator broadcasts a message in the R radius coverage area containing the ID of its sensor nodes, location in the buffer and their allocated time slot. The superframes are mainly regarded as uplink traffic from the sensors to the coordinator.

We propose to utilize the concept of Pulse-Coupled Biological Oscillators (PCO) inspired by the fireflies synchronicity model introduced in Mirollo and Strogatz [1990]. This model implies the phase, ϕ of each oscillator evolves continuously following its natural frequency ($\phi \in [0, 2\pi]$); when the phase reaches the end of the period, 2π, the oscillator fires, i.e., emits a pulse, and resets its phase to 0 ($f(0) = f(2\pi) = 0$). However, we define the synchronization concept at the coor-

dinator level of each WBAN. We consider the coordinator to collect the information from its sensor nodes and act as an oscillator with a constant time period T. More specifically, each node has an internal phase or time ϕ which starts at 0 and linearly increases with time until it reaches T. This internal phase difference relates to the variations in time where each WBAN wants to initiate its communication. Thus, the phase variable is characterized by $\frac{d\phi}{dT} = \frac{1}{T}$. At $t = T$ the node "fires" and resets at $t = 0$ again (Fig.6.8). Since nodes in the network may start at different time intervals, their internal state may differ. If no neighbors exist in the vicinity of a node, the node simply fires at $t = T$ again Movassaghi et al. [2015b].

We consider each sensor has a predefined priority level (as described in Chapter 4) which contributes to the calculation of the rank of each WBAN which it broadcasts along with its interference list calculated as follows:

$$P_k = \left(\sum_{j=1}^{N} p(s_k^j) \right) \tag{6.3}$$

where $p(s_k^j)$ stands for the priority level of sensor j from $WBAN_k$ and P_k refers to the *rank* of each WBAN which implies its order of importance for transmissions. The higher the rank of a WBAN the sooner it gets to transmit amongst its collocated neighbors.

The coordinator of each WBAN takes charge of gathering channel state information which consists of intra-WBAN received signal strength (RSS) and inter-WBAN joint received interference strength (JRIS). Intra-WBAN RSS of B_k is denoted by $\{\gamma_k^i | i = 1, ..., N\}$, where γ_k^i represents the RSS from the ith sensor of the kth WBAN received at the coordinator of the WBAN of interest. The set of $M - 1$ sensors of each WBAN except for B_k is represented by s^i_{-k}, transmitting simultaneously with s_k^i; thus, the inter-WBAN JRIS from B_{-k} can be denoted by $\{\eta^i_{-k} | i = 1, ..., N\}$, where η^i_{-k} represents the vector of JRIS from s^i_{-k} to the coordinator of B_k. We assume the Control Frame Period (CFP) to be of an equal length of T for all WBANs which is divided into N time slots of equal length. Each sensor is allocated one time slot for transmitting its packets with a constant size.

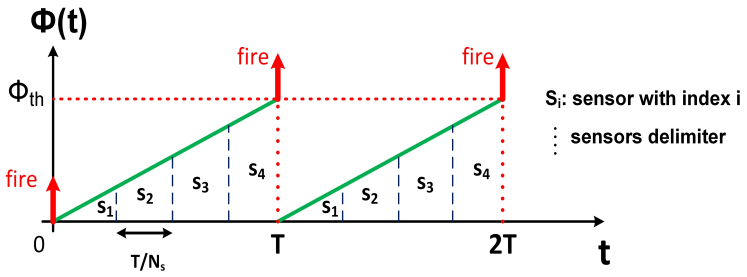


Figure 6.8: Transmission of Each WBAN Based on the Concept of Pulse Coupled Oscillators

The proposed approach can be described in the following three steps:

6.5.0.1 Step-1: Neighbor Discovery

In the first round, where an individual WBAN is transmitting and does not encounter another WBAN in its vicinity, it divides the CFP evenly amongst its N sensor nodes and allows them to transmit based on their initially assigned order. When the coordinator of the WBAN of interest hears a neighbor firing at $t = t'$, it instantaneously terminates its transmission and waits for a duration of T for the neighbor WBAN to fully transmit the data it has gathered.

6.5.0.2 Step-2. Information Exchange

Then, both WBANs transmit simultaneously for a duration of T which is when each WBAN is able to recognize which sensor nodes of the neighbor WBAN will be interfering with the WBAN of interest based on their RSS and JRSS values (Fig.6.2). More specifically, the coordinator of each WBAN finds the minimum received power from its sensors and compares it to the received power from sensors of other WBANs. If the received power of a sensor from other WBANs is larger than the γ_{th}, that sensor is added to the Inter-WBAN Interference list; otherwise, it is considered as a low interference node. We demonstrate which sensor of each WBAN imposes interference on which other WBAN in Fig.6.2.

Therefore, each coordinator can determine which of its sensors significantly interfere with the transmission of other WBANs. Also, each coordinator can verify which

Algorithm 5: Self-Organizing Interference Avoidance (SIAC)

Neighbor Discovery: for $i = 1$ *to* M

for $j = 1$ *to* N

if Sensor s_j^i exists in the interference list of $WBAN_k$

Record k as the index of the affected WBAN by s_j^i

WBAN-level ordering:

for$i = 1$ *to* M Find the rank of $WBAN_i$,(P_k), based on the accumulation of priority of its sensors $(p(s_k^j))$

Sort WBANs from highest priority ($P_k = 1$) to lowest priority ($P_k = M$)

Sensor-Level Ordering:

Round.1

for $P_k = 1$ to M Find the sensors that are interfering with $WBAN_k$

$WBAN_i$ has the highest ranked priority Sort the sensors based on the number of WBANs that they are interfering with, from the sensor interfering with largest number of WBANs to the sensor interfering with least number of WBANs.

Round.2

for $P = 1$ to M Initialize the firing time of $WBAN$ with priority P like inter-WBAN TDMA

if $P = 1$

for $j = 1$ to N Re-sort the sensors interfering with $WBAN$ so the time slots assigned are farther from the starting point of WBAN with $P = 2$

else

Re-sort the sensors interfering with WBAN with priority $(P - 1)$ so the time slots are assigned farther from end point of WBAN with priority $(P - 1)$

Determine the new firing time for WBAN with priority P

Re-sort the sensors interfering with WBAN with priority $(P + 1)$ so the time slots are farther from the starting point of WBAN with priority $(P + 1)$

sensors of neighbor WBANs impose significant interference on it. Each coordinator then creates a list, known as the interference list, consisting of all sensors which have a significant interference level Movassaghi et al. [2014c].

6.5.0.3 Step-3. Channel Assignment

This step initially involves ordering the transmission of coexisting WBANs by sorting them based on the level of priority of each WBAN (aforementioned rank value). Moreover, based on the interference list defined in the previous step, each WBAN sorts its sensor nodes through two stages. Accordingly, the first stage involves shifting the transmission of nodes that exist in the interference list of another coexisting WBAN to transmit either in the beginning or the end of the superframe, depending on their rank. For sensor-level ordering each WBAN needs to be aware of the priority level of its neighbor WBANs. According to this scheme, channel assignment for the highest ranking WBAN which will be transmitting first is different from other coexisting WBANs.

This means that for the WBAN with the highest level of priority (first-ranked WBAN) which is assigned to transmit first, the first slots are assigned for the communication of its interfering nodes. However, for the next WBANs that want to transmit after this WBAN, the interfering nodes will be placed at the end of the superframe. This sensor-level ordering is based on the number of affected WBANs by each sensor. In Fig 2, the affected WBANs are shown with text inside the sensor sections. In the second stage of sorting sensor nodes in each WBAN, the interfering nodes are sorted again to reach the most optimum order of sensor transmission within each WBAN, to yield the smallest required number of time slots for the coexistence of M WBANs and avoiding interference at the same time. The pseudo code associated with the proposed SIAC scheme is provided in Algorithm 5.

We have demonstrated an example of channel assignment in SIAC for a typical network shown in Fig.6.9 with three coexisting ($M = 3$), known as $WBAN_1$, $WBAN_2$, and $WBAN_3$, each consisting of four sensor nodes ($N = 4$). As illustrated in Fig.6.9, the priority of transmission of the coexisting WBANs based on the highest level of

priority is $WBAN_2$, $WBAN_1$ and $WBAN_3$, respectively. The overlapping area shown in the circle represents them existing in the interference region of one another. For instance, the third node of $WBAN_2$ (s_2^3) exists in the interference region and therefore the interference list of $WBAN_1$ and the second node of $WBAN_1$ (s_1^2) exists in the list of both $WBAN_2$ and $WBAN_3$, (s_2^3). Fig.6.9 illustrates the WBAN-level ordering as well as two-rounds of sensor level ordering also described in Algorithm 5.

In the channel assignment step, each WBAN assigns an equal amount of the time slot ($\frac{T}{N_s}$) to its sensor nodes. Also, each sensor marks which of its sensors' transmission imposes an interference on another coexisting WBANs. For this specific scenario, the third sensor of $WBAN_2$ (s_2^3) imposes interference on $WBAN_1$ and the fourth sensor of $WBAN_2$ (s_2^4) imposes interference on $WBAN_2$. The same procedure is done in $WBAN_2$ and $WBAN_3$. This information is exchanged between the coexisting WBANs. As mentioned earlier, with the predefined priority of $WBAN_2 > WBAN_3 > WBAN_1$, each WBAN would transmit based on their level of priority with the WBAN with the highest level of priority transmitting first. Hence, interfering nodes of $WBAN_2$ will be pushed to transmit in the beginning of the superframe whilst the next WBAN to transmit after $WBAN_2$, $WBAN_3$, will assign its interfering nodes to transmit last, and the same goes for $WBAN_1$.

In the second phase of sensor-level ordering, as per the pure strategy of scheduling of the sensors are re-sorted to decrease the number of time slots required for one round of transmission of all coexisting WBANs. The main objective here is to save the time slots in one round of transmission as much as possible. In other words the proposed channel assignment would minimize the delay between the firings of coexisting WBANs acquired by the appropriate pure strategy. This adjustment is implemented by a bilateral comparison of the WBAN of interest and its coexisting WBANs (except for the first ranked WBAN).

6.6 Simulation Results

We consider a similar network to the one in Movassaghi et al. [2014c]. We have considered variations in the density of coexisting WBANs ranging from 4, 5, 7 and 10, respectively. We consider different sensor node densities of low, middle, high and extremely high by N ranging from 2 to 20. We also consider that all sensor nodes excluding the coordinator in a WBAN have similar transmit power (P_t). We define the outage, $Pr_{out,i}$, to denote the probability that the total signal-to-interference-ratio at time instant t is smaller than an γ_{th} at $WBAN_i$ (B_i) which can be calculated as follows:

$$Pr_{out,i} = Pr\left(\frac{\gamma_k^i}{\sum_{j=1}^{N-1}\eta_{-k}^j} < \gamma_{th}\right) \tag{6.4}$$

As stated throughout the chapter, $WBAN_0$ places a sensor node in the interference list if the received interference power from that sensor is larger than a threshold $SINR_{th}$ and γ_j denotes the joint received signal strength from a sensor node in $WBAN_j$ at $WBAN_0$.

The main trade-off that motivated us for this research was the capability of achieving a significantly higher speed of communication due to lower delay. This is at a slight cost for higher throughput and reliability requirements in critical health-care at an outage probability of 1%, and also a slight cost at 10% outage probability, which corresponds to the the packet error rate of 10%, the maximum PER allowed in the IEEE 802.15.6 guidelines. Fig.6.11 illustrates the outage probability versus a range threshold $SINR$ for full shadowing for three coexisting WBANs, each consisting of 20 sensor nodes over three different average inter-WBAN distances $d = 2, 5$ and 9, respectively. As can be seen, the outage probability overlaps for different inter-WBAN distances for a wide range of SINRs, which implies variations in distance does not affect the efficiency of our proposed approach since we are achieving the same outage as the distance changes.

Fig.6.10 shows the inter-network latency versus the number of sensor nodes in a

WBAN for 4, 5, 7 and 10 coexisting WBANs. The proposed approach is compared to the case where all WBANs transmit back to back to one another as in conventional WBANs that deploy inter-WBAN TDMA. As can be seen, the proposed approach achieves a much lower delay, which is highlighted even more with the increase in the number of sensors in each WBAN. Similar results are obtained with the increase in the number of coexisting WBANs.

From a *fairness* point of view, which refers to equal use of the allocated channel for the transmission of each sensor, all sensors have equal opportunity to transmit their data to the coordinator. In other words, the number of transmissions associated with each sensor is equal for all WBANs. In addition, the computation cost of the proposed algorithm is quite low. The only cost is related to sorting sensors in each WBAN based on their interference level from coexisting WBANs and re-sorting the orders of the sensors in the second phase to find their appropriate pure strategy. Hence, the order of complexity is quite low in the range of $O(N^2)$ which is acceptable for WBANs.

6.7 Conclusion

In this work a biologically inspired node-level channel assignment was proposed for inter-WBAN interference mitigation at the node-level. In our proposed method, SIAC, sensor nodes that cause interference to neighbor WBANs are allocated orthogonal channels whilst others are allowed to use the rest of the time slots until all are occupied. Our approach aims to reduce the time between consecutive transmissions of each WBAN to improve the network speed and reduce the inter-network latency. SIAC has been further evaluated by computer simulation showing up to 30% faster speed (reduction in delay) than the conventional orthogonal channel assignment between coexisting WBANs. This allows for more efficient usage of the limited resources in these networks. Another main advantage of our proposal is that it avoids collision amongst coexisting networks in a self-organized manner within a small time and with the least information available.

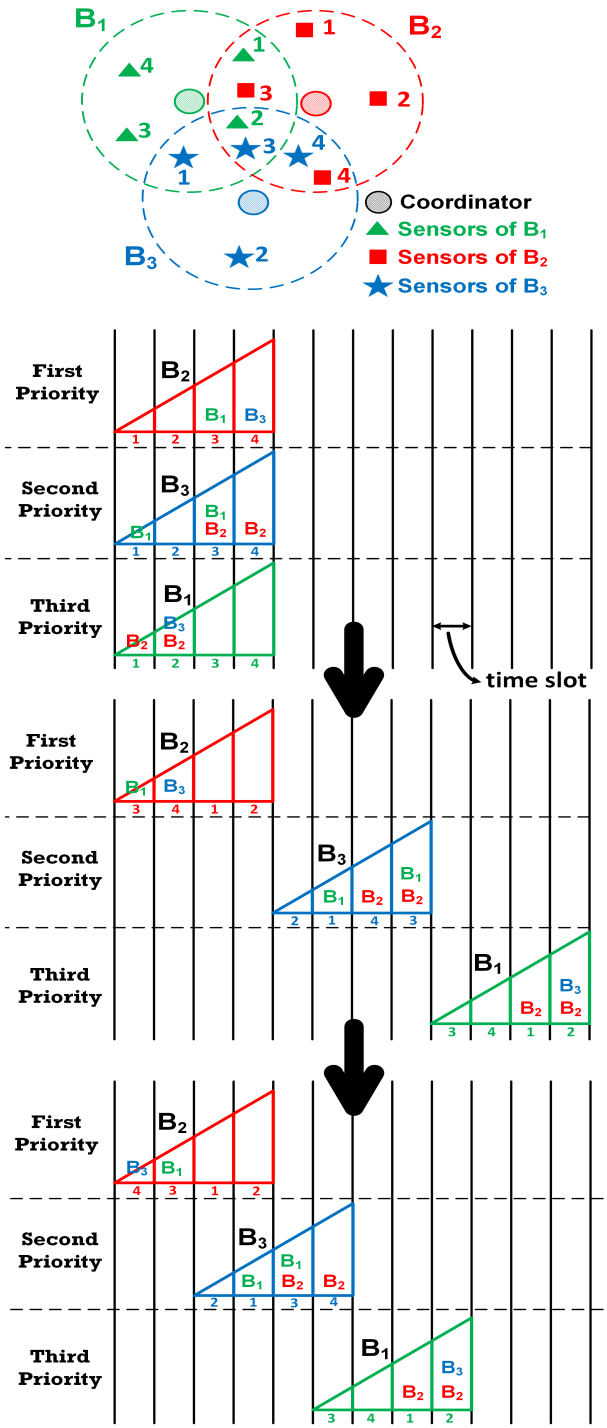


Figure 6.9: Channel Assignment in SIAC

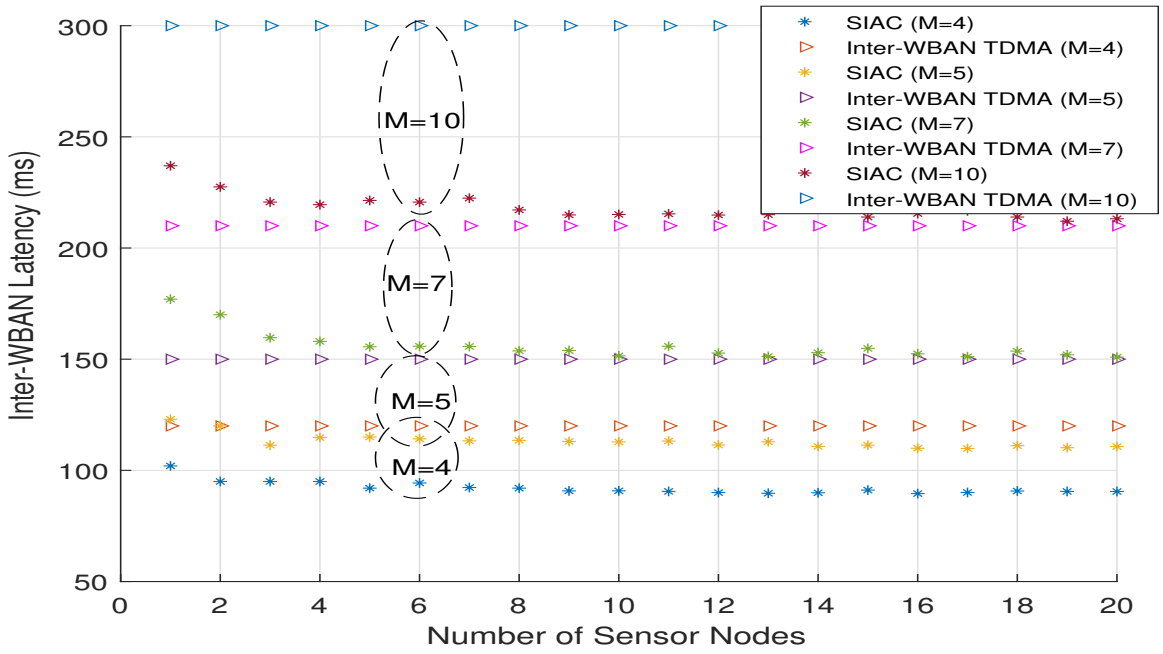


Figure 6.10: Delay versus number of sensor nodes in each WBAN for 4 coexisting WBANs

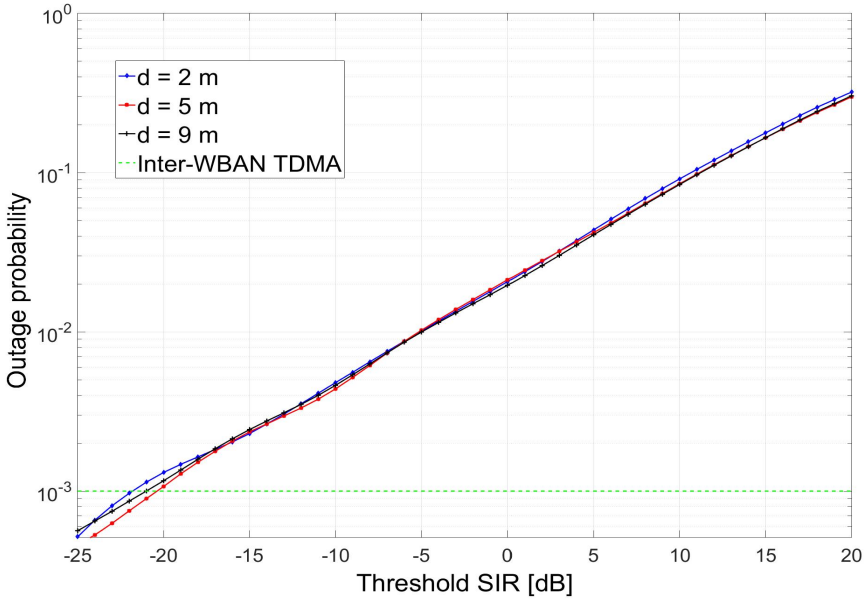


Figure 6.11: Outage Probability versus SIR values

Chapter 7

Conclusions and Future Work

The real-time monitoring and large-scale deployment characteristics of wireless body area networks will provide an ultimate communication paradigm for a wide area of applications from health-care to entertainment. In this thesis we have investigated efficient communication amongst coexisting WBANs to allow for their practical deployment. The intrinsic properties and current characteristics with respect to research into these networks are studied in terms of: standard requirements; challenges with their wide-spread use; phases of communication establishment amongst them; accepted modes of communication; communication architecture; mobility scenarios; PHY and MAC layer proposals; different phases of communication establishment for their coexistence; and power management. We then describe the current state of the art for interference mitigation amongst coexisting WBANs. The proposed approaches are classified into 6 main categories and the distinction between them in each category is further described, which provides a better understanding as to why these networks are not adopted yet in most people's everyday lives whilst they can immensely enhance quality of life. In this context, this thesis has addressed several shortcomings for the energy, interference and coordination-aware communication of WBANs. Hence, this thesis provides an in-depth understanding of these networks and how to enable their efficient coexistence.

7.1 Summary of Contributions

An opportunistic and smart spectrum allocation scheme for interference mitigation has been proposed, which deals with the issue of coexistence of multiple wireless

body area networks. The proposed approach allows sensor nodes of coexisting WBANs that do not exist in the interference coverage of coexisting WBAN networks to transmit simultaneously, and all other sensor nodes in all WBAN networks to transmit orthogonally. Through exhaustive simulation and analysis, this approach has been shown to significantly enhance the system performance in terms of throughput and delay as well as offering much higher spectral efficiency that fulfills the variations of channel conditions and high-data rate requirements of these networks as well as resulting in a higher network lifetime and much longer depletion time. We further investigated adaption of the proposed protocol to a node's priority, packet length, number of nodes in each WBAN and its SINR value to allow for adaptive spectrum allocation while dealing with the issue of channel assignment for interference avoidance amongst coexisting WBANs. We then used the interference signal that falls into the network as a source of energy and harvested that for future transmissions. Later on clusters were proposed to be formed amongst pair-wise WBANs such that colors were assigned to expand the resource usage even more by allocating distinct colors and therefore distinct channels.

We have also investigated the postural body movements of these networks within each WBAN, and relative to other WBANs, and we have devised a prediction algorithm that encounters these variations and adapts its resource allocation accordingly. The decentralized prediction algorithm proposed captures the unknown dynamics and provides feedback to the coordinator of each WBAN. Next, the collision-free approach for schedule assignment was enhanced to progress across multiple coexisting WBANs with no global coordination, whilst achieving convergence with very low complexity and information exchange. This collision-free approach was biologically inspired by the synchronisation of fireflies in nature whilst it minimised the convergence time and maximised reliability. Additionally, considering the stringent requirements of these networks specifically in terms of group based movement of the entire network as well as the WBAN communications channel, not only was our algorithm capable of achieving faster convergence compared to existing inter-network communication mechanisms, but it was also capable of achieving a significantly better reliability. The other unique advantage of our algorithm is that is does not require

an external global entity and self-adjusts itself to fully utilise the limited spectrum in WBANs. Further considering the computational burdens of these networks we also investigated reducing the computational complexity of the proposed solution. We demonstrated that our proposal can provide a significantly higher convergence time for collision free communications over traditional inter-network communication mechanisms. Considering the rapidly growth and evolution of WBANs in recent years, there are yet more things to consider to allow for further improvement of such mechanisms, which will be described in the following section.

7.2 Future Work

This work has questioned, and appropriately addressed the assumptions, protocols and solutions for efficient coexistence of WBANs . In this section potential future work, following from the contributions made, is outlined:

- *Scalability*– Based on existing MAC, routing, and transport protocols, the network performance, indexed by throughput, end-to-end delay, and fairness, is typically not scalable with either the number of nodes or the number of hops in the network. This problem can be alleviated by increasing the capacity of network nodes. Typical approaches include applying multiple channels/radios per node or developing wireless radios with higher transmission rate. However, these approaches do not truly enhance the scalability of WBANs, because the relative performance with respect to increased network capacity is not actually improved. Therefore, in order to achieve scalability, it is essential to develop and fully integrate new MAC, routing, and transport protocols for co-located body-to-body networks.

- *Self-organization and self-configuration*– Self-configuration requires all protocols to be distributed and collaborative. Otherwise, WBANs will lose their autonomic feature. However, current WBANs can only partially realize this objective.

- *Security*– Due to wireless ad hoc architectures, WBANs may be vulnerable to se-

curity attacks in various protocol layers. However, current security approaches may be effective to a particular attack in a specific protocol layer, but lack a comprehensive means to prevent or counter attacks in different protocol layers. Thus fully secure implementation across the whole protocol stack is an important area for ongoing research.

- *Network integration*– Current WBANs have very limited capabilities for integration into heterogeneous wireless networks. Integration into multiple, different, heterogeneous wireless networks is still an on-going task for WBANs, due to the difficulty in building multiple wireless interfaces and the corresponding gateway/bridge functions on the same hub/coordinator router. Software radios may be the ultimate solution to this problem, as such this requires significant further research.

- *Priority of Coexisting WBANs*– In order to better formulate the traffic that needs to be transferred amongst coexisting WBANs, other than considering the priority of data collected from nodes within a WBAN, an interesting aspect could be assigning a priority score to each of the coexisting WBANs and then updating resource allocation accordingly.

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