RESEARCH THESIS

Mitigating interference in coexisting IEEE 802.15.6 networks using superframe interleaving

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CERTIFICATE

We accept the work contained in this report as a confirmation to the required standard for the partial fulfillment of the degree of MS (CS).

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DECLARATION OF AUTHENTICATION

I state that the research work offered in this thesis is to the superlative of my own knowledge. All causes used and any help established in the research of this study have been acknowledged. I hereby verify that I have not yielded this material, either in whole or in part, for any other degree at this or any other institution.

Signature……………………..

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I thank Allah who provided me with strength and caliber to bring this thesis work to its successful completion.

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May Allah bless them all with eternal happiness.

DEDICATION

To My Father, Mother, Family and friends.

Abstract

IEEE 802.15.6 standard is designed for Wireless Body Area Network (WBAN). WBAN connects wireless sensor nodes in/on or around the body. WBAN is specially designed for monitoring e-health applications like temperature, blood pressure and fever etc. One of the basic concerns in IEEE 802.15.6 networks is coexistence of multiple BANs. This is a natural phenomenon because a network is around a single body therefore multiple BANs can be within the radio range of a single BAN. For example, in a sitting room, conference room, stadium and hospital BANs attached with different peoples can be within the radio range of each other. When multiple BANs coexist then the performance of an individual BAN is degraded due to interference with neighboring BANs. Interference decreases successful transmission of data, thus lowering the throughput and the energy of the devices is wasted which is a very precious resource for WBAN devices. This work is amid at studying the coexistence issues within the WBANs. IEEE 802.15.6 proposes different solutions including channel hoping, beacon shifting, and superframe interleaving for solving the issue of coexistence. The complete Superframe interleaving duration is divided in such a way that all neighboring BANs are given separate equal slots within the superframe. The superframe interleaving solution of IEEE 802.15.6 is able to accommodate only two BANs and assigns equal duration to each BAN. Superframe interleaving defined by IEEE 802.15.6 does not take into consideration the traffic load within a single BAN. For example, if there are two BANs each BAN equally share the bandwidth or superframe structure irrespective to the traffic requirements of a single networks. In this study, we have proposed a scheme for solving the coexistence issue by using dynamic active superframe interleaving. The scheme adjusts multiple superframes of interfering BANs according to the traffic load observed in each network. Hence, instead of assigning fix superframe duration to each BAN, duration is assigned according to each network's traffic requirement. Detailed simulation analysis using OPNET, concludes that proposed scheme provides less interference and higher throughput than simple interleaving used in IEEE 802.15.6.

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ABBREVIATIONS

ACK	Acknowledgement
BOP	Back off period
B2	Beacon 2
BP	Blood pressure
CCA	Clear Channel Assessment
CAP	Contention Access phase
CFP	Contention Free period
CIFS	Coexistence Inter Frame Space
ECG	Electrocardiography
EAP	Exclusive Access Phase
EEG	Electroencephalogram
EMG	Electromyogram
GTS	Guaranteed Time Slot
GPS	Global Positioning System
I-ACK	Immediate Acknowledgement
LR-WPAN	Low Rate Wireless Personal Area Network
MAC	Multiple Access Control
MAP	Management Access Phase
NB	Narrowband
PER	Packet Error Rate
PRR	Packet Reception Ratio
RIC	Random Incomplete Coloring
RAP	Radom Access Phase
SD	Super-frame Duration
SINR	Signal Interference Noise Ratio
UWB	Ultra-wideband
WMSN	Wireless Multimedia Sensor Network
WBAN	Wireless Body Area Network
WSN	Wireless Sensor Network
WPAN	Wireless Personal Area Network

Chapter 1

1. Introduction

1.1 Overview

Remote and automated health monitoring is one of the prime areas of wireless communication network. Wireless communication is sending information or commands between two or more devices that are not linked with each other with the help of any tangible means. Most common example of wireless communication is radio. Radio waves cover a short distance, few meters and thousands of kilometers or even millions of kilometers for deep space communication. Some examples of radio wireless technology are GPS, radio receiver, satellite television, cordless phones and broadcast television.

In early 1990's the idea of developing and implementing communications with human body as center gained popularity. This led to the birth of short range communication using IEEE 802.15.4 Wireless Personal Area Networks (WPANs) to execute communications around human body. IEEE 802.15 has proposed two types of WPANs, one is High data Rate (HR-WPAN) and second is Low data Rate (LR-WPAN).

Later, the term "BAN" came that referred to systems where communication is entirely within, on, and in the immediate proximity of a human body. WBANs aim to provide attractive and efficient alternate for conventional medical care system. A WBAN system can use WPAN wireless technologies as gateways to reach longer ranges. Through gateway devices, it is possible to connect the wearable devices on the human body to the internet. This way, medical professionals can access patient data online using the internet independent of the patient location.

In 2012, IEEE released the WBASN standard referred as IEEE 802.15.6 because it meets the medical requirements (proximity to human tissue) and relevant communication regulations for healthcare applications. IEEE 802.15.6 supports a variety of real-time health monitoring and consumer electronics applications. IEEE 802.15.6 aims to provide an international standard for low power, short range, and extremely reliable wireless communication within the surrounding area of the human body, supporting a vast range of data rates for different applications. Other wireless networking solutions like IEEE 802.11 and IEEE 802.15.4 do not support the extremely low power operation, prioritized medium access for critical data and short range communication requirements of Body Area Networks (BAN) [14].

IEEE 802.15.6 basically specifies the mechanisms and procedures for physical and Medium Access Layer (MAC) layers. The purpose of IEEE 802.15.6 is to provide an international standard for a short-range (i.e., about human body range 1-2m) having various data rates ranging up to 10Mbps [14]. The variation of data rates and criticality of different sensed information within a single small network leads to the challenges of traffic heterogeneity and reliability. As a result, IEEE 802.15.6 has classified the BAN traffics into three classes i.e. on-demand, emergency and normal data traffic. Normal traffic is based on routine data reporting between devices and the hub. On-demand traffic is initiated by coordinator to know certain information about sensor readings from the devices. Emergency traffic is the time bound senor data that is generated when an event occurs like heart attack. The reported data traffic is allocated a user priority (0 low to 7 high) by the application. Likewise, the superframe provides exclusive, random and polling based medium access. Reliable communication is another important feature of IEEE 80.15.6.

A WBAN expands over the whole human body and the nodes are connected through a wireless communication channel shown in figure 1. Typically WBAN consist of inexpensive and lightweight bio-sensors like breathing sensor, ECG (Electrocardiogram) sensor, blood pressure, blood glucose sensor and heartbeat etc. These bio sensors have different data rates and application requirements as shown in table 1 [15].

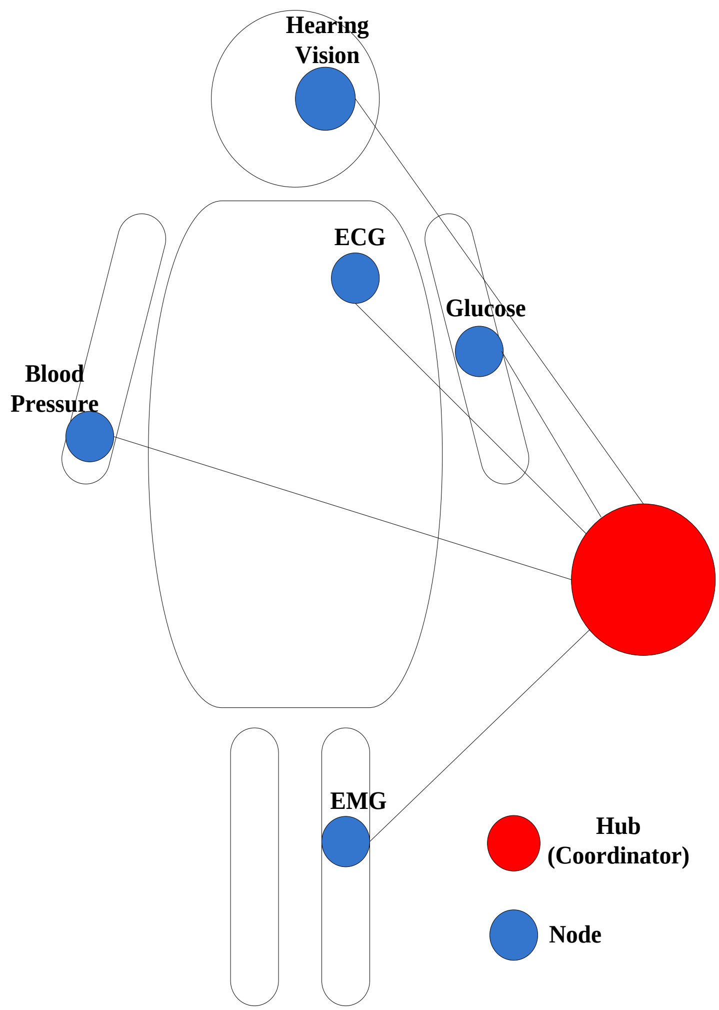

Figure 1: Wireless Body Area Network

Table 1: Shows the application-wise data rate in IEEE 802.15.6 [15].

Application-Type	**Sensor node**	**Data rate**
In-body application	Glucose sensor	Few Kbps
	Pacemaker	Few Kbps
	Endoscope capsule	>2Mbps
On-body Medical application	ECG	3Kbps
	SpO2	32Kbps
	Blood pressure	<10Kbps

Collectively, WPANs and WBANs can be termed as Low Power Lossy Networks (LLNs).LLNs is a general terminology that reflects low cost wireless networking solutions involving resource constrained devices with limited low quality wireless connectivity. However, LLNs have numerous applications for society from entertainment, health-care, agriculture, forests and roads etc. The afore mentioned wireless technologies along with the growth in embedded electronics has given birth to Internet of Things (IoT) [21].IoT connects every device to the internet by making use of the available wired and wireless technologies to provide sophisticated services for many applications[22,23]. In the IoT various wireless networks can coexist and exchange information over private or public networks

1.2 Motivation

WBAN offers many promising new applications in the area of remote health monitoring. In the medical field, for example, a patient can be equipped with a WBAN consisting of sensors that constantly measure specific biological functions, such as temperature, blood pressure, heart rate, electrocardiogram (ECG), respiration, and etc. One of the major concerns in WBANs is to solve coexistence problems. Homogenous coexistence that is the coexistence between the similar WBANs operating in the same channel is an important issue that can be solved by superframe interleaving proposed in IEEE 802.15.6. Superframe interleaving schedules interfering BANs using a simple approach in which two BANs are assigned different fixed time slots with in superframe. This simple scheme is not efficient because it supports only two interfering networks. Also, due to fixed superframe structure used in interleaving solution, the network utilization is low because one BANs may require more time duration than the other within the superframe. Hence, solutions are required for supporting superframe interleaving among multiple BANs.

1.3 Problem Statement

Mitigating the effect of interference due to coexistence in IEEE 802.15.6 to increase the network performance. IEEE802.15.6 proposes three techniques for coexistence mitigation: beacon shifting, superframe interleaving, and channel hopping. Superframe interleaving is the most effective way of mitigating homogeneous interference as it completely removes interference among neighboring BANs but the current IEEE 802.15.6 standard allows interleaving among two BAN's. Focus of our research is solving homogenous coexistence issue of interference in multiple BANs using dynamic superframe interleaving.

1.4 Thesis Organization

The thesis is organized as: Chapter 2 describes the detail overview of IEEE 802.15.6 and its applications. In Chapter 3, we discuss the existing work on interference mitigation techniques in different wireless networks. Chapter 4, presents the detailed operation of proposed technique that mitigates the interference in WBANs by modifying the superframe interleaving technique. Chapter 5, presents the simulation analysis of proposed technique. Last chapter concludes this work and provides future directions.

Chapter 2

2. Overview of IEEE 802.15.6

2.1 Introduction

IEEE 802.15.6 is a communication standard optimized for low-power (in-body/on-body or around the body) nodes for monitoring the health issues like temperature, blood pressure etc. The current IEEE 802.15.6 [14], define three PHY layers, i.e., Narrowband (NB), Ultra-wideband (UWB), and Human Body Communications (HBC) layers. The selection of each PHY layer depends on the application requirements. At the MAC sub-layer, IEEE 802.15.6 supports two different types of access mechanisms including: contention access and contention-free access. The contention access phase supports either a slotted ALOHA based access mechanism or CSMA/CA based access mechanisms. The contention-free access phase supports a scheduled uplink/downlink access scheme as well as an improvised polling/posting based access scheme.

The IEEE 802.15.6 network can operate in three different modes: beacon enabled mode with superframe boundaries, non-beacon mode with superframe boundaries, and non-beacon mode without superframe boundaries. Beacon mode with superframe boundaries contains different phases such as Exclusive Access Phase 1 (EAP1), Random Access Phase 1 (RAP1), EAP2, RAP 2, Managed Medium Access Phase (MAP) and Contention Allocation Phase (CAP) that are shown in figure 2.

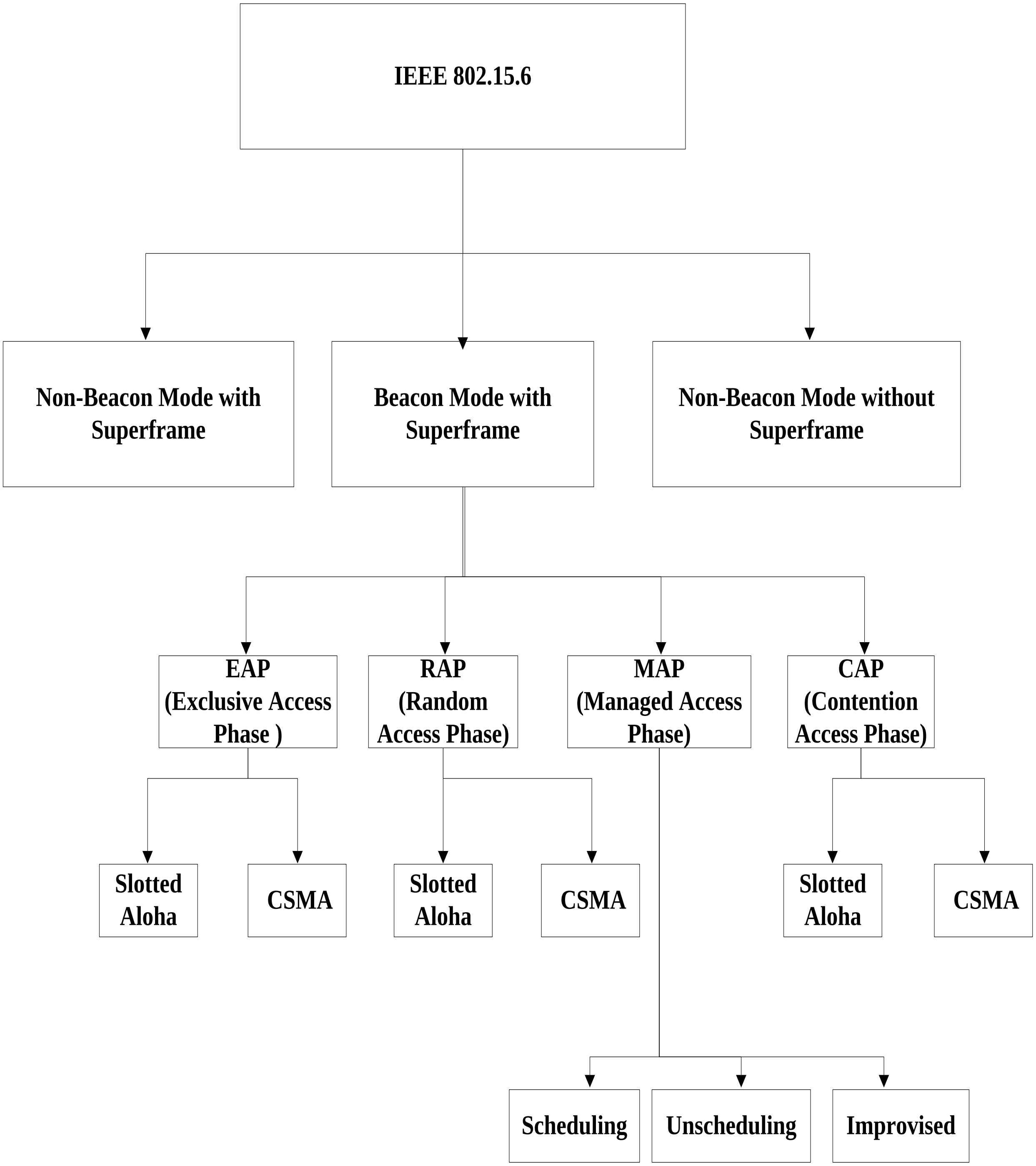

Figure 2: IEEE 802.15.6 Operational Modes

In this study, we focus on beacon mode with beacon period and superframe boundaries. IEEE 802.15.6 establishes a star topology based network which is controlled and maintained by a device termed as hub and data is directly exchanged between nodes and the hub as shown in figure 3.

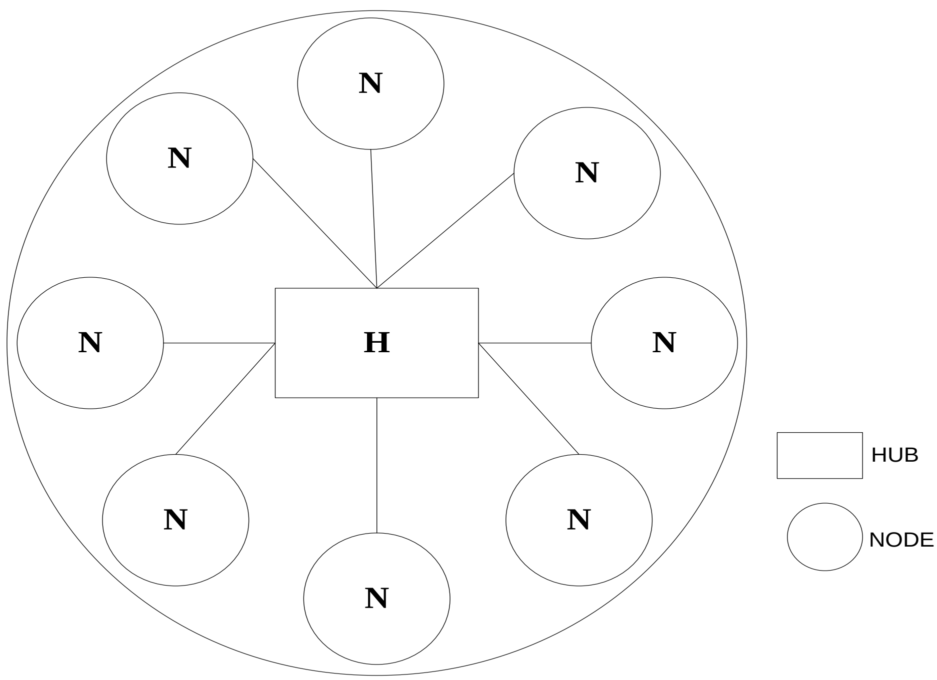

Figure 3: Architecture of WBAN

2.1.1 Beacon enabled mode

This mode is coordinated mode in which all the devices are synchronized with the hub and can provide higher throughputs with reduced energy consumption. Beacon frame provides different durations for medium access based on contention and contention free access. The superframe is comprised of EAP1/EAP2, RAP1/RAP2, MAP and CAP as shown in figure 4. EAP phase is used for emergency traffic and based on CSMA/CA or Slotted ALOHA. RAP phase is used for regular traffic and based on CSMA/CA or Slotted ALOHA. MAP phase is used for polling: uplink, downlink, bilink, and scheduling. CAP phase is used for coexistence if the CAP is non-zero length the hub shall transmit a B2 frame.

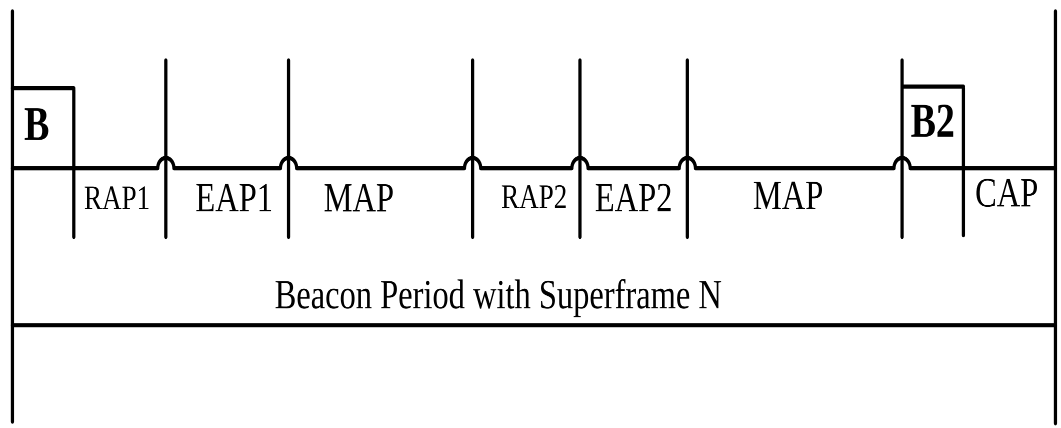

Figure 4: Beacon enabled mode with Superframe [14]

2.2 Coexistence in IEEE 802.15.6

When multiple BANs coexist, as shown in figure 5, then the radio range of neighboring BANs overlap due to which interference increases, throughput decreases and the energy of devices is wasted as the packets are dropped. IEEE 802.15.6 proposes different mechanisms for solving coexistence issues including: channel hopping, beacon shifting and superframe interleaving.

The coexistence solutions of IEEE 802.15.6 aim to address both homogenous and heterogeneous interference. Interference is referred as homogenous, when two similar type of wireless networks interfere with each other’s communication. For example, one WBAN interfering with another WBAN communication. In heterogeneous interference, two different types of wireless networks interfere with each other, for example, interference between IEEE 802.15.6 and IEEE 802.15.4 networks.

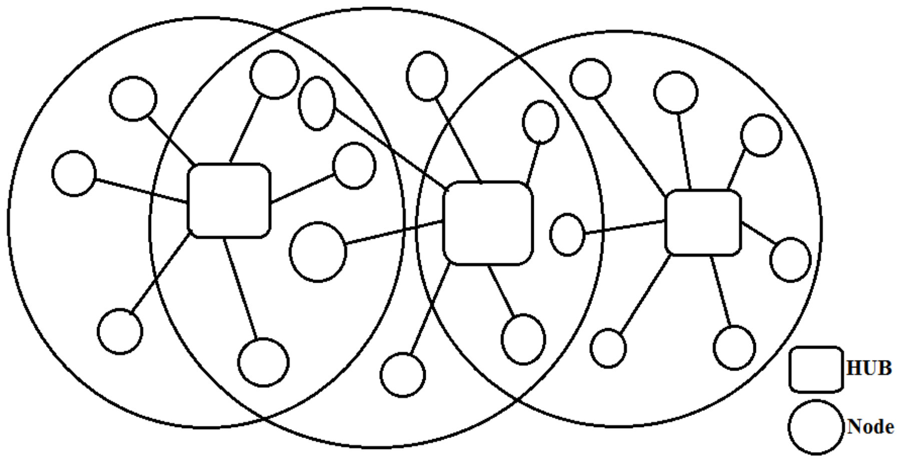

Figure 5: Coexistence among multiple BANs

2.2.1 Coexistence format

The B2 beacon in superframe structure, shown in figure 4, contains the coexistence fields that are shown in figure 6. The hub sets any of the beacon shifting, channel hopping or superframe interleaving bits to one, in order to inform nodes of the selected coexistence mitigation method.

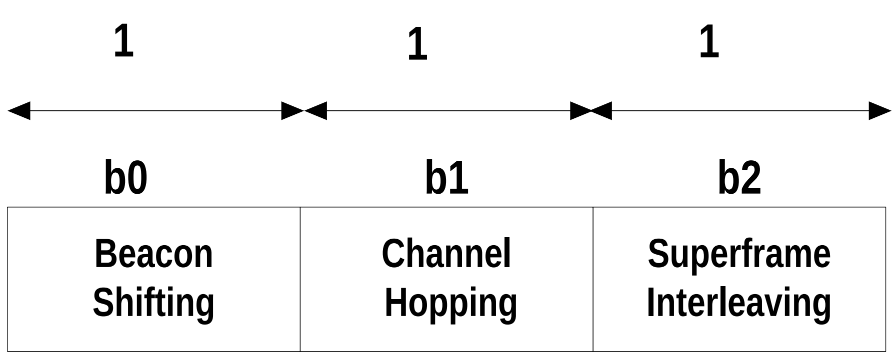

Figure 6: Coexistence mitigation technique selection [14]

2.2.2 Channel Hopping

In this technique, the interfering BANs use different frequency hopping patterns to change the communication channels and avoid interference. Channel hopping is not a very efficient solution because it requires tight hub to node synchronizations, energy is wasted when hoping is performed and overall throughput is less as compared to single channel operation.

2.2.2 Beacon Shifting

In this technique, just the beacon is shifted and complete superframe of coexisting BANs is not adjusted. IEEE 802.15.6 proposes beacon shifting as a solution to avoid beacon collisions when multiple BANs coexist. Beacon shifting technique recommends the use of different beacon shifting sequences for avoiding beacon collisions as shown in table 2.

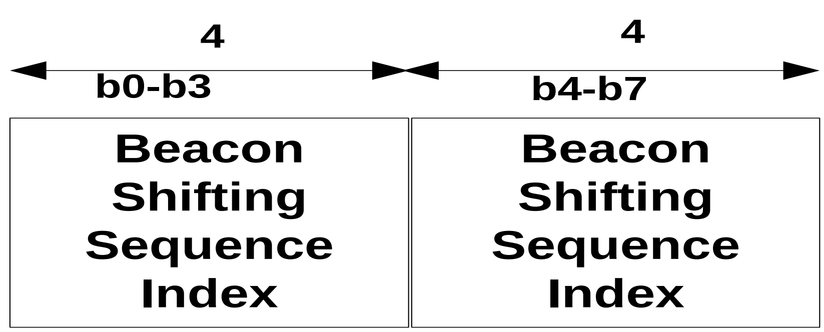

Figure 7: Sequence Format [14]

The beacon shifting index field and beacon shifting phase fields as shown in figure 7 are used for the selection of sequence and are broadcasted in beacon frames. Beacon shifting only aims to avoid beacon collisions and does not provide any solution for avoiding normal data packet interference.

Table 2: Beacon Shifting Sequence Field Encoding [11].

Beacon Shifting Index (m)	**Beacon Shifting Sequence Function of Sequence Phase n= 0,1,2,3,4………,15**	**Beacon Shifting Patterns "…." Represent Patterns are repeat**
0	$PN_0(n) = n \bmod 2$	$PN_0(n) = 0, 1, 0, 1, \ldots$
1	$PN_1(n)= 2^* PN_0(n)$	$PN_1(n) = 0, 2, 0, 2, \ldots$
2	$PN_2(n)= n \bmod 4$	$PN_2(n) = 0, 1, 2, 3, \ldots$
3	$PN_3(n)= [PN_0(n) + PN_2(n)]/2 \bmod 2 + [PN_0(n) + PN_1(n) + PN_2(n)]/ \bmod 4$	$PN_3(n) = 0, 1, 2, 3, \ldots$
4	$PN_4(n)=[PN_0(n) + PN_1(n) + PN_2(n)]/2$	$PN_4(n) = 0, 2, 1, 3, \ldots$
5	$PN_5(n)=\{PN_2(n) + [PN_0(n) + PN_2(n)]/2\} \bmod 4$	$PN_5(n) = 0, 2, 3, 1, \ldots$
6	$PN_6(n)= PN_0(n) + \{[PN_0(n) + PN_2(n)]/2 \bmod 2\}$	$PN_6(n) = 0, 3, 1, 2, \ldots$
7	$PN_7(n)= [PN_0(n) + PN_2(n)] \bmod 4$	$PN_7(n) = 0, 3, 2, 1, \ldots$
8-15	Reserved	Reserved

2.2.3 Superframe interleaving

In this technique, complete superframe of coexisting BANs are adjusted in such a way that all BANs use non-overlapping durations for operations. In fact, the superframe duration is subdivided into small equal sized durations and each BAN sends its own superframe within it. IEEE 802.15.6 uses two commands for initiating interleaving: active Superframe interleaving request and active superframe interleaving response.

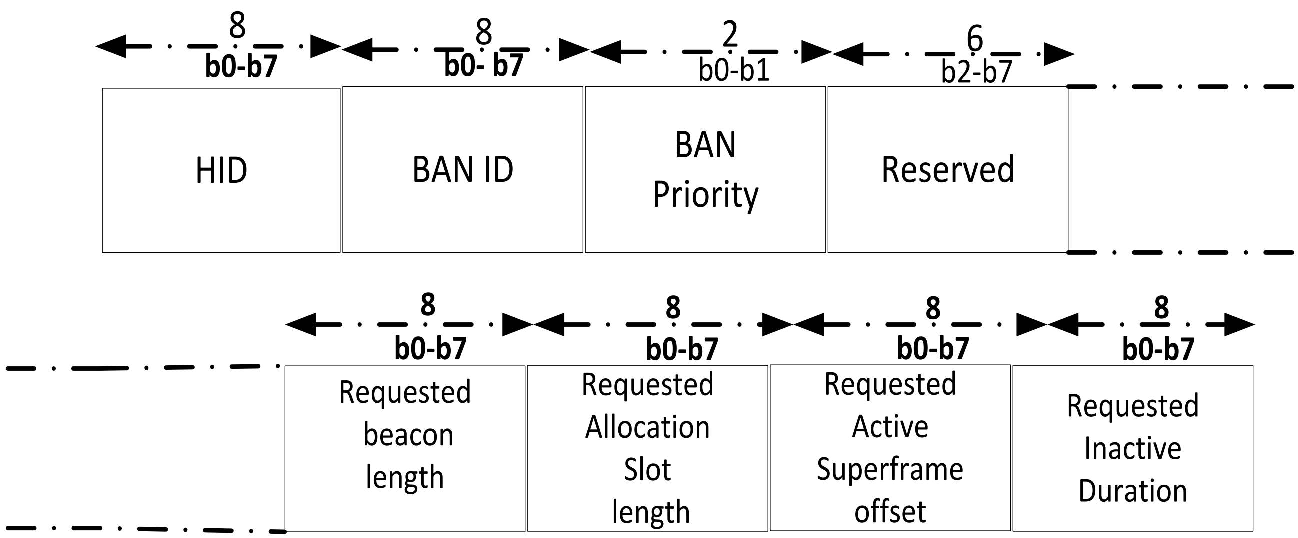

Figure 8:Command Frame Superframe Interleaving Request [14]

Active superframe interleaving request frame is shown in figure 8, which is optionally transmitted by a hub to another hub to request for channel sharing through active superframe interleaving. Active superframe interleaving response frame shown in figure 9, which is optionally transmitted by a hub to another hub in response to the request for channel sharing through active superframe interleaving. In complete superframe interleaving there is no beacon collision or data collision.

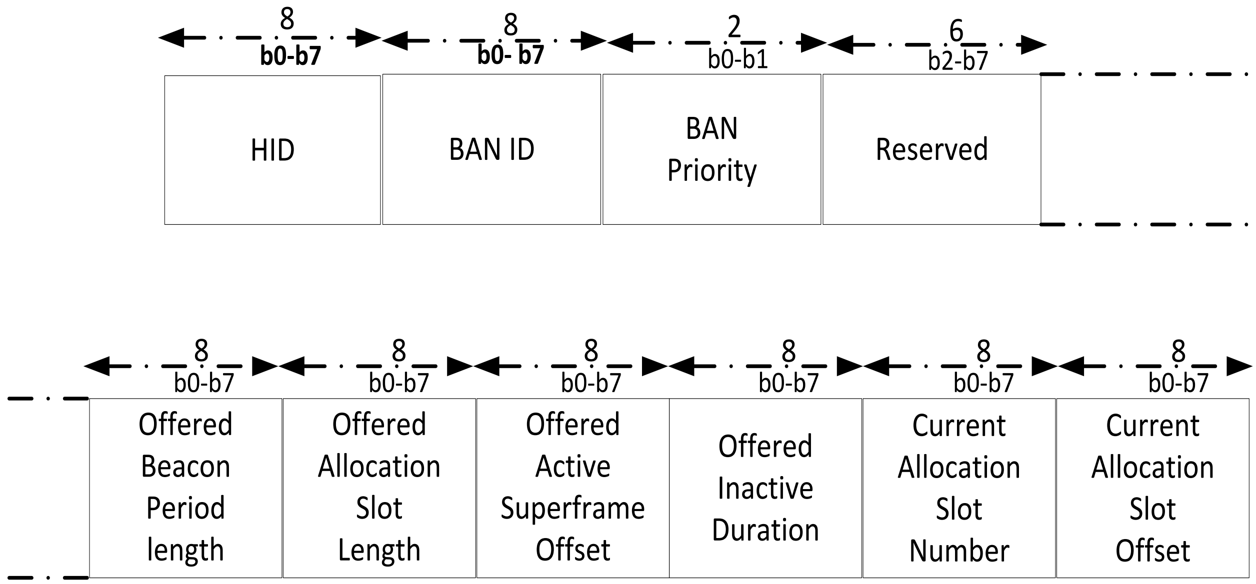

Figure 9:Command-Active Superframe Interleaving Response [14]

Chapter 3

Related Work

3.1 Introduction

In this chapter, we briefly describe the related work on WPAN and WBAN related to coexistence. The exertions of existing works are mainly focused on coexistence techniques. Apart from techniques defined by IEEE standards, the related work on mitigation of interference in WPAN and WBAN propose different schemes such as colouring algorithms [6] and game theory approaches [5]. Review of existing work on coexistence in PANs and BANs is presented in table 3.

Table 3: Review of existing work on coexistence in IEEE 802.15.6.

Paper Reference & Publish Year	**Objective**	**Metric**	**Proposed solution**	**BAN/ PAN**
[1], 2015	Coexistence in Homogenous Network	PRR and SINR	Prediction Algorithm	BAN
[2], 2015	Coexistence in homogenous network	PER, PRR, energy consumption	Comparison between TDMA based scheme and CSMA/CA based scheme	BAN
[3], 2012	Beacon Collision in Homogenous network	Shifting beacon broadcasting time, cluster coordinator	Simple Time Shift Scheme	PAN
[4], 2013	Coexistence in homogenous network	High-spatial reuse, fast convergence	Random Incomplete Coloring (RIC)	BAN
[5], 2015	Interference between homogenous network	Energy consumption	Game theoretic approach	BAN

[6], 2015	Coexistence between homogenous network	Short transmission cycle	Distributed Multi-coloring Algorithm	BAN
[7], 2015	Coexistence between homogenous network	Short Active	Long Active	PAN
[8], 2014	Coexistence in homogenous network	Energy Consumption	Survey of Coexistence	BAN
[9], 2014	Coexistence between heterogeneous network	Frequency	Nodes switch to concern channel for communication.	BAN/ PAN
[10], 2014	Coexistence between heterogeneous network	Time/delay	Delay called CIFS Coexistence Inter frame Space is added after DIFS in the superframe of the WLAN	BAN/ PAN
[11], 2014	Coexistence in homogenous network	interference signal strength (ISS)/ SIR	Fairness-based Throughput Maximization Heuristic (FTMH) And analytical model	BAN
[12], 2015	Coexistence in homogenous network	Throughput, energy, latency/ SINR	The inherent techniques (CSMA/CA and TDMA) are used together.	BAN
. [13], 2015	Coexistence in homogenous network	SINR	Dynamic Orthogonal channel assignment	BAN

Coexistence can be categorized into homogenous and heterogeneous: homogenous when interference is among same type of networks e.g., WBANs and heterogeneous when interference is among different type of networks using the same frequency spectrum e.g., BAN, PAN, LAN. Detailed survey on the co-existing issues and interference mitigation solution of WBAN is presented in [8]. The survey work classifies and compares the existing studies to analyze the coexistence issues.

In [1] prediction algorithm for multiple WBANs is proposed to solve homogenous coexistence problems. It relies on PRR (Packet Reception Ratio), SINR (Signal interference Noise Ratio) and “previous-state” layered upon naïve Bayesian classifier to predict the conditions of coexistence in a multiple WBAN. This algorithm approaches towards pre-emptive instead of reactive solution.

In [2], the work focuses on understand the effects of interference on WBANs. A mathematical model is built around IEEE 802.15.6 standard. Two non-collaborative: time shared and channel hopping, and one collaborative: CSMA/CA technique is used. Moreover, metrics like Packet Error Rate (PER), Packet Reception Ratio (PRR), energy consumption and latency are used for analytical analysis. The resultant model shows that in non-collaborative approach, channel hopping is better at all metrics even at lowest transmission power. In collaborative scenario, CSMA/CA performs much efficiently in terms of delay and PRR but it is not energy consumption efficient

Homogeneous interference of multiple WBANs is resolved using an unconventional coloring method: Random Incomplete Coloring (RIC) [4]. WBANs need both, high spatial reuse and fast convergence which are inversely proportional in conventional coloring. Theoretically RIC is applied in CPN (Central Processing Node) based IWS (Inter WBAN Scheduling), protocol with

TDMA framing structure. Simulation shows a significant decrease in collisions and increase in throughput. To tackle the beacon collision problem in IEEE 802.15.4 WPAN, the work in [3] proposes a Simple Time Shift Scheme (STSS) to avoid the beacon collision. STSS based on IEEE 802.15.4 keep original superframe structure and transmit the beacon frame over active period. This scheme uses a simple function to allocate a beacon frame transmission.

In [5], a game theoretic approach is considered to address the issue of coexistence in WBANs. The power control is modeled as a non-cooperative game where existentiality and uniqueness of Nash equilibrium are proved. Based on the upcoming results, a best response, least deterrence based power control approach is shaped to counter the coexistence in WBANs. In [6] the problem of coexistence is addressed and a solution in form of distributed multi-coloring algorithm is proposed. It also provides high spatial utilization by using available colors. To improve network performance in multiple WBAN environments, it proposed a distributed coloring algorithm which consists of initial coloring algorithm and multi-coloring algorithm.

The work [7] provides in-depth information based on simulations of homogenous beacon-enabled IEEE 802.15.4 network using contention-based slotted CSMA and contention free GTS allocations. The results highlight the underlying modes of interaction between interfering networks. In [9], the issue of dynamic homogenous/heterogeneous coexistence is solved using a distributed and collaborative mechanism called Dynamic Coexistence Management (DCM) mechanism. In this method a coordinator works as a coexistence manager when it detects a harmful coexistence and after collaboration it finds an optimal way for the superframe of the coexisting WBANs. Beacon replacement and channel switching are the core techniques used by the DCM for solving beacon collision and the data collision, respectively.

Heterogeneous coexistence of WBAN with 802.11 is resolved using the Coexistence Inter-Frame Space [10]. The CIFS is extra delay added after DIFS in IEEE 802.11 nodes, which try to give the transmission opportunity to IEEE 802.15.4 under wireless coexistence environment. The result shows the shorter CIFS cause lower transmission probability in IEEE 802.15.4. The IEEE 802.15.4 transmission probability reaches to 100 % when the CIFS around 1.2 ms. As a summary, table 3 list the existing works along with their objectives, metrics and proposed solution.

Fairness-based Throughput Maximization Heuristic (FTMH) [11] mitigates homogeneous interference to maximize throughput with fairness using non-linear programming problem technique. The super frame is divided into time slots and one sensor is assigned one time slots. Sensor can transmit data within assigned time slot. The slots are assigned in a non-linear fashion. In [12] the authors propose an interference mitigation scheme called Decentralized Interference Mitigation (DIM) which accumulates the benefits of CSMA/CA and TDMA method. The superframe comprises of beacon period, Superframe Period (SP) and CAP. The SP and CAP are dynamically adjusted according to the interference. The issue of slot allotment in SP is solved using low complexity sort and greedy algorithm.

In [13] introduces an interference alleviation technique among the relying nodes of coexisting IEEE 802.15.6 based WBAN by proposing a dynamic channel allocation scheme (DCAIM). In DCAIM, TDMA is used as access method for communication. The nodes in the communication range of a relay node is called relay region (RG). The RG, the relay node creates and broadcast the table of the nodes creating interference. These interfering nodes are assigned orthogonal channels /time slots which alleviate interference. This technique has overhead of creation of relay regions and broadcasting of table containing information of interfering nodes by the relay nodes.

Chapter 4

Proposed Interference Mitigation Scheme

4.1 Introduction

The objective of proposed scheme is to mitigate the interference among multiple BAN's. When multiple BAN's are active simultaneously and lies within the radio range of each other, then coexistence accord and communication will face interference. Content requirement between multiple BAN's can be flexible, different type of sensor's can be installed on/in, or around the body to monitor events like ECG, blood pressure, diabetes, asthma and heart attacks. In all the aforementioned events, the reporting rate and delay requirements of different events is variable. To overcome coexistence issue, IEEE 802.15.6 introduces a superframe interleaving technique as shown in figure 10. During superframe interleaving of IEEE 802.15.6 BAN 1 and BAN 2 have same duration in the shared superframe but we introduce dynamic superframe interleaving among multiple BAN''s.

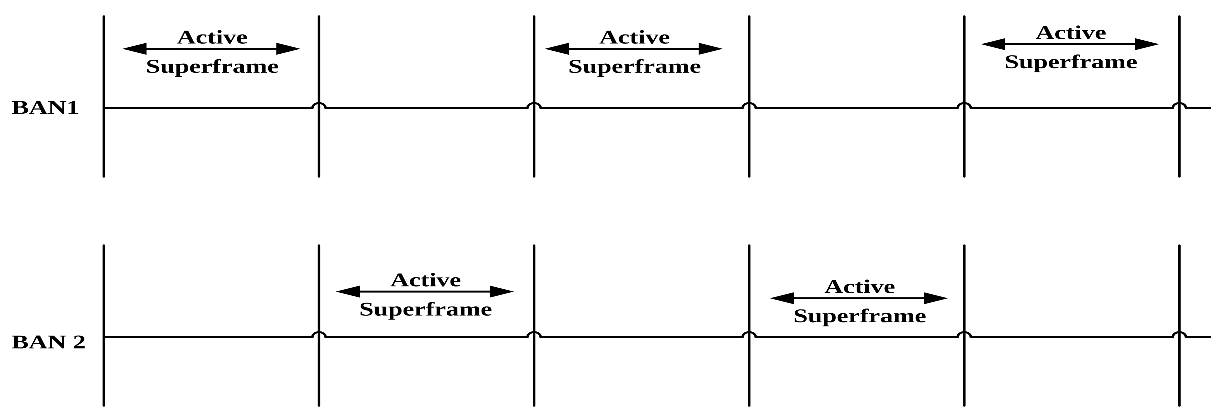

Figure 10: SuperFrameInterleaving

4.2 Network Model

The proposed algorithm operates in a star topology based IEEE 802.15.6 network. IEEE 802.15.6 offers three modes of communications but the proposed algorithm work in beacon enabled mode. Beacon-enabled mode is a coordinated and synchronized communication mode of IEEE 802.1.5.6. It supports relatively high data rate and consumes less energy of devices. The proposed scheme allows the use of all superframe specifications included in IEEE 802.15.6, such as EAP1, RAP1, MAP1, CAP and B2.

All network devices directly communicate with the HUB. HUB is responsible for network establishment and maintenance. Nodes generate events and have different content requirements based on the traffic priority type. Nodes are located at a fixed distance from hub and mobility is not considered. The proposed algorithm is designed to mitigate the interference in star topology based WBAN and to solve the coexistence problem by adjusting superframe interleaving technique.

In our solution, the coexisting BANs (Hubs / Coordinators) will create a cluster head. Cluster is a set of interfering BANs and one of the hubs is considered as cluster head. When multiple BAN's are active in same time and communicate with each other then one of the BAN became a cluster head and other BAN's are communication with cluster head. In figure 11,the five BAN's are active and these BAN's lie within the transmission range of each other, from these multiple BAN's one become a cluster head and other BAN's (BAN1, BAN2, BAN3, and BAN4) are member of cluster head BAN5. BAN6 is not the member of cluster head and can't communicate with them because it does not exist within the radio range of these BAN's. These multiple BAN's use superframe interleaving technique to mitigate the coexistence which occur when these BAN's are active at the same time. Coexistence among members of different clusters is not considered in this work. The focus of this scheme is mainly on coexistence mitigation instead of cluster formation or head selection.

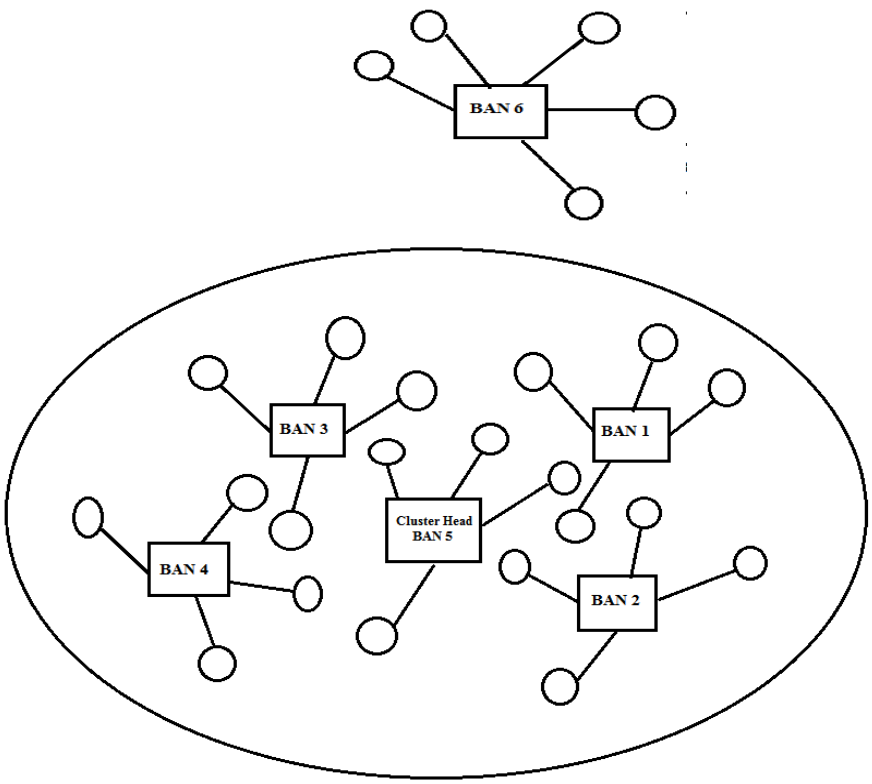

Figure 11: Coexistence scenario

In the proposed scheme, each BAN sends the information about Single Slot length that is “L” and number of slots in response frame. Single slot length is the duration of a single slot in the IEEE 802.15.6 superframe. There can be maximum of 255 slots in the IEEE 802.15.6 superframe. The beacon packet in each superframe lists the length of L and the number of a Slots that are to be used in the superframe. IEEE 802.15.6 defines L and number of slots before the network deployment and the aforementioned values do not change. In the proposed scheme, these values are dynamically selected after every superframe and are calculated based on the content requirement. The length of a single slot, total number of slots in the superframe and superframe duration are calculated using equation 4.1, 4.2 and 4.3. These values are fixed and defined by IEEE 802.15.6. T_{slot} is the length of single slot in seconds and depends on a minimum value (pAllocationSlotMin) and slot resolution (pAllocationSlotResolution) as defined in table 4.

Table 4: Symbols in proposed algorithm and their description

Symbols	**Description**	**Values**
$N_{preamble}$	The length of the preamble	90 bits
S_{header}	The length of the S header	1
N_{header}	The length of the N header	31 bits
$UP_{ppduBits}$	Data bits used by different priority levels	Data Size Received
$Symbol_{Rate}$	Symbol rate used for communication	600 ksps
$ACK_{ppduBits}$	Acknowledge bits used	40 bits
$P^{AllocationSlotMin}$	Length of single slot in seconds and depends on a minimum value	500µs
$p^{AllocationSlotResolution}$	Length of the single slot resolution	500µs
nSlot	Number of Slots	1-255

$$T_{SF} = nSlot \times T_{slot} \quad \text{Eq. (4.1)}$$

$$T_{slot} = (pAllocationSlotMin + L \times pAllocationSlotResolution) \quad \text{Eq. (4.2)}$$

$$L = (\frac{T_{slot} - pAllocationSlotMin}{pAllocationSlotResolution}) \quad \text{Eq. (4.3)}$$

In the proposed scheme, we calculate the estimated time for the successful transmission of single packet using equation 4.4. The time required for a successful transmission includes CCA time, data packet transmission time, acknowledgment packet transmission time, and inter frame spacing time $pSIFS$.

$$Estimated_{Time} = 2pSIFS + T_{pktAck} + T_{pkt} + (1 \times pCCA) \quad \text{Eq. (4.4)}$$

Where, T_{pktAck} , T_{pkt} is calculated using equation 4.6 and 4.5.

$$\mathrm{T_{pkt}} = (\mathrm{N_{preamble}} + \mathrm{S_{header}} \times \mathrm{N_{header}} + (\mathrm{UP_{ppduBits}} \div 2)) \div \mathrm{Symbol_{Rate}} \quad [14] \quad \text{Eq. (4.5)}$$

$$\mathrm{T_{pktAck}} = (\mathrm{N_{preamble}} + \mathrm{S_{header}} \times \mathrm{N_{header}} + (\mathrm{ACK_{ppduBits}} \div 2)) \div \mathrm{Symbol_{Rate}} \quad [14] \quad \text{Eq. (4.6)}$$

$$\mathrm{SF.ExpectedTime} = \mathrm{SF.Recieved_{pkts}} \times \mathrm{Estimated_{Time}} \quad \text{Eq. (4.7)}$$

Where $N_{preamble}$, S_{header} , N_{header} *and* $Symbol_{Rate}$ are defined in Table 4.

When BAN’s calculate the Single Slot length and number of slots then they send it to the Head BAN. When Cluster head receives the required information from the BAN’s, then it calculates the active and inactive period of each BAN by using equation 4.9 and send it to all BAN’s that are the member of cluster head. After receiving each BANs superframe time, cluster head calculates the total time required for its cluster using equation 4.8.

$$\text{One Cycle Time} = \sum_{i=1}^{N} \text{Superframe time of HUBi} \qquad \text{Eq. (4.8)}$$

$$\text{InactivePeriod of } SF_i = \sum_{i=1}^{N} \text{Superframe time of HUBi } - \text{ActivePeriod of } SF_i \qquad \text{Eq. (4.9)}$$

4.3 Operation of the proposed dynamic interleaving scheme

The proposed interleaving scheme uses the basic request/association and response procedure of IEEE 802.15.6. The IEEE 802.15.6 interleaving solution can provide interference mitigation between two BAN's only. Also, the superframe durations of the two interfering BAN's do not change in length (duration), simply they follow alternate pattern. First, one BAN transmits beacon and uses the network and then the other.

On the other hand, the proposed scheme allows multiple BAN's to co-exist with the help of clustering. Also, interleaving is dynamic therefore superframe duration of different interleaving BAN's can change as per requirement. This allow better QoS to BAN's that have more data to send as compared to BAN's that are not reporting any event.

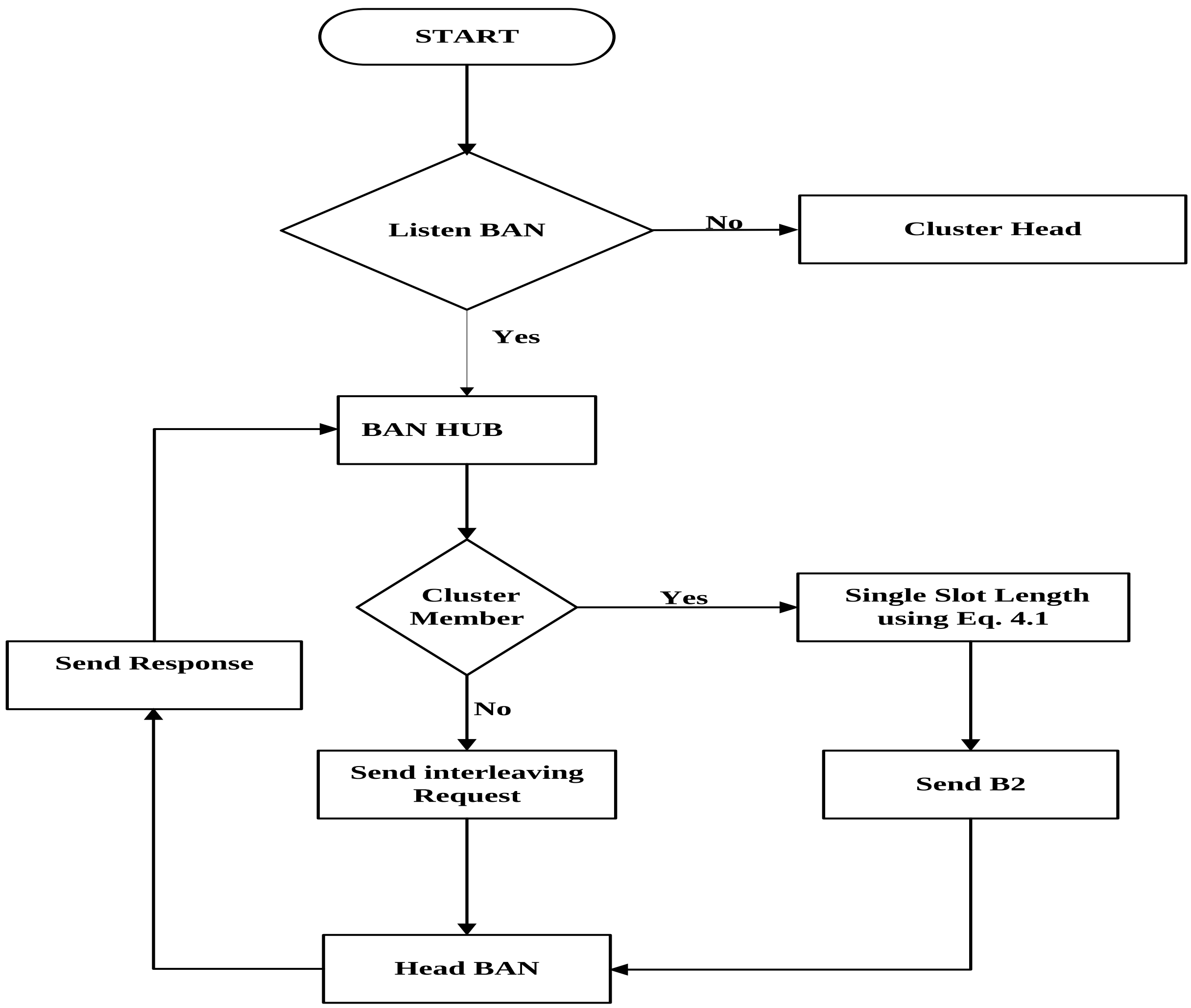

Figure 12: Flow chart of proposed scheme

Figure 12 explains the flow of information in the proposed algorithm in detail. When BAN is active, it listens for beacons of other BAN's. If any other BAN is not within the transmission range then this BAN becomes a cluster head. If any other BAN (Cluster head) already exists and lie within the transmission range then it sends membership request to the head BAN. The head BAN responds the membership/interleaving request and start communication with the help of superframe interleaving technique. This membership request frame includes information about single slot length and number of slots. Slots define the superframe duration that's why we use slot length to adjust the superframe duration. If cluster head receives the membership request then it sends the response frame to the requested BAN and stores the information about the requested BAN's. This response frame includes the active and inactive durations of BAN's. IEEE 802.15.6 explains active superframe interleaving request frame and response frame.

If cluster head receive multiple membership requests from other BAN's then cluster head sends the response frame to the newly activated BAN's. All other BAN's that are already the member of cluster head will receive the response frame that contains the new information about the active and inactive duration of superframe of each BAN.

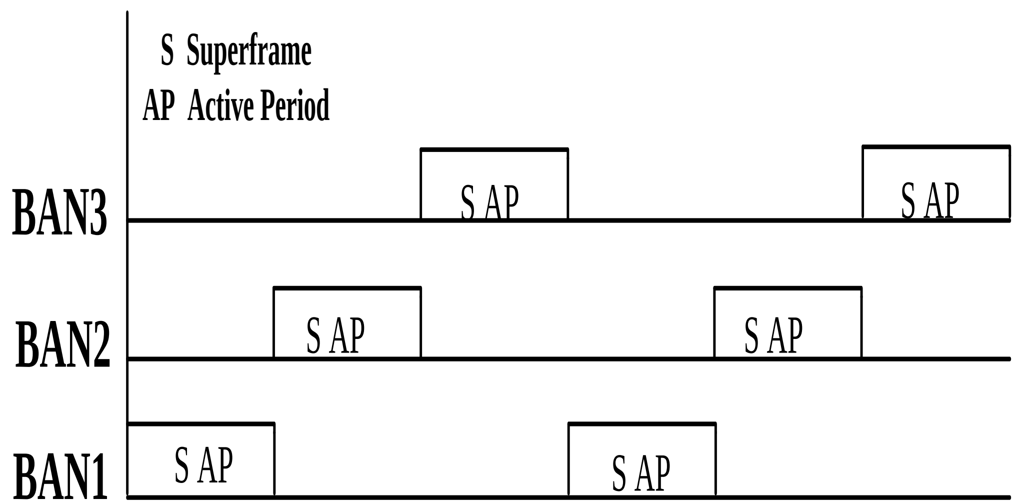

Figure 13: Dynamic Superframe Interleaving

In figure 13 the active period of multiple BAN's are shown that use proposed dynamic superframe interleaving technique. Firstly activated BAN is the cluster head (BAN 2) and other BAN's, BAN 3 and BAN 4 are inactive mode. After the activation of BAN 2 (cluster head), BAN 3 is activated and BAN 2 (cluster head) and BAN 4 are inactive mode and after the activation of BAN 3, BAN 4 is activated, BAN 2 (cluster head) and BAN 3 are in inactive mode.

Proposed algorithm for IEEE 802.15.6 superframe interleaving technique to mitigate the coexistence. The pseudocode of dynamic superframe interleaving algorithm presented in figure 14 and is same as shown in figure 12.

```
Start
If (head BAN)
{
  If(Coexistence == True)
  {   Listen B2
       Send Response Frame
  }
  Else
  {    Listen Response Frame
       Send Response Frame
  }
}
Else
{
   If(Coexistence == True)
   {  Change L value with respect to eq.
      Send it in B2
   }

   Else
   {    Listen Beacon
        Send Request Frames
   }
}
```

Figure 14: Proposed Algorithm

Chapter 5

Results and analysis

5.1 Introduction

In this chapter, detailed simulation analysis and performance evaluation of proposed algorithm is discussed and compared with extended IEEE 802.15.6. Original IEEE 802.15.6 standard provides superframe interleaving for two networks only whereas we have extended the same algorithm for more than two networks. Hence, we can compare proposed algorithm results with extended IEEE 802.15.6. Comparisons are based on end-to-end latency, packet delivery ratio, and throughput. The simulation analysis is performed using network simulator OPNET 14.5 [18]. We have analyzed different simulators (NS-2) for the implementation of IEEE 802.15.6, but only OPNET 14.5 supports the IEEE 802.15.6 implementation. There is another simulator that supports the DRAFT of WBAN and it is OMNET++, but it doesn't provide complete superframe implementation.

The network used in simulation analysis is star topology based WBAN, in which all nodes can communicate with HUB directly. The WBAN HUB is placed in center of the network topology, whereas the other nodes are placed around the hub. Multiple BAN's are active at the same time and these BAN's exist within the transmission range of each other. For simulation, we take consider four BAN's. Beacon-enabled mode of communication is used by all HUB and each HUB broadcasts periodic beacon for it network devices. Each beacon contains superframe duration along with information about EAP, RAP and MAP interval.

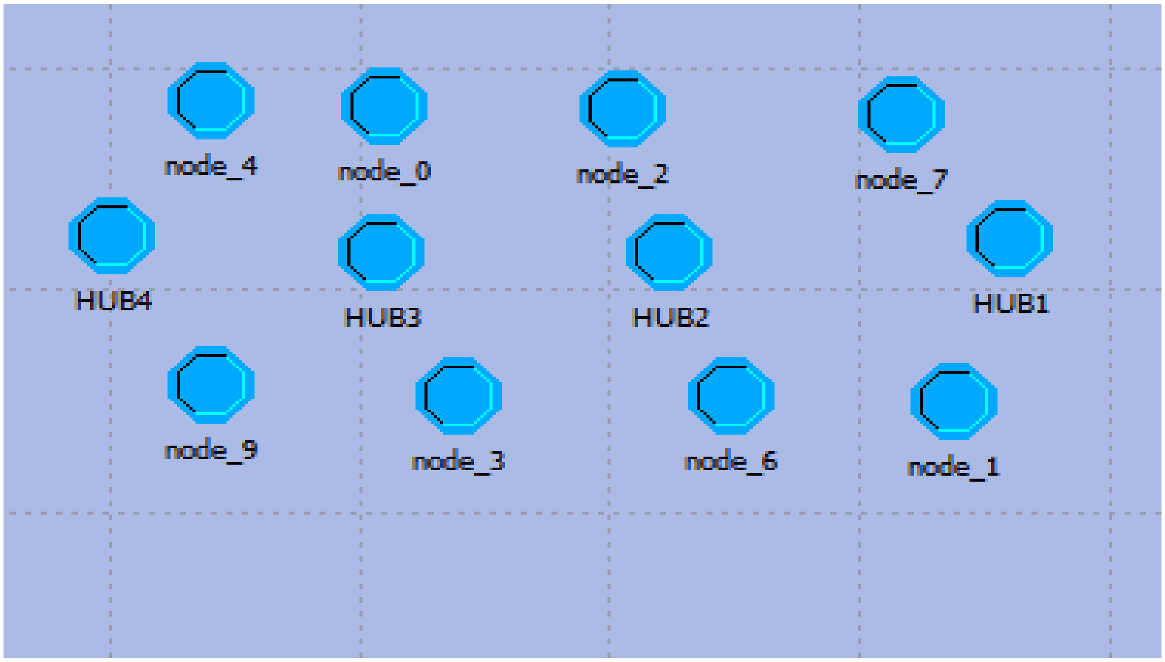

Figure 15: Simulation Network Topology

Figure 15 shows different BAN's, whereas all Hubs are within the radio range of each other. Node 7 and 1 are connected with HUB 1, node 2 and 6 are connected with HUB 2, node 0 and 3 are connected with HUB 3 and node 9 and 4 are connected with HUB 4. The maximum link capacity supported by each WBAN is 971.4kbps. Frequency band used for operating is 2400 MHz to 2483.5 MHz in our simulations.

Table 5: Modulation Parameters

Packet component	Modulation (M)	Symbol rate = 1/Ts (ksps)	Code rate (k/n)	Spreading factor (S)	Information data rate (kbps)
PSDU	π/4-DQPSK (M = 4)	600	51/63	1	971.4

Only three types of traffic priorities are used UP7, UP6 and UP5 because in EAP only UP7 traffic is communicated whereas in RAP all traffic priority from UP7 to UP1 can be transmitted. Hence in order to create contention between different traffic in RAP duration only UP7, UP6 and UP5 is used. The energy parameters of nodes are monitored according to the common sensors. The modulation parameters are shown in table 5. The general simulation parameters used are shown in table 6.

Table 6: Simulation parameters

Parameter	**Value**
Simulation time	500 s
Frequency band	2.4 GHz
Traffic Type	UP5,UP6 and UP7
Packet Size (bytes)	100,150,200
Number of BAN's	4
Link capacity	971.4 kbps
Initial energy	34560 Joules
Data Rate(kbps)	156.25, 234.36,312.5
Transmit mode	17.4 mA
Receive mode	24.8 mA
Sleep mode	6.1 µA
Idle mode	26.1 µA
Buffer Size	Variable

In the remaining of this section, simulation results of proposed algorithm are compared and analyzed with extended IEEE 802.15.6 superframe interleaving technique. Two types of data reporting periodic and continuous is used. First, we will discuss periodic data reporting results and later on we will discuss continuous data reporting results.

5.2 Periodic data reporting

Periodic data reporting means transmitting data for a certain interval then stopping data generation, to observe the performance of dynamic and extended IEEE 802.15.6 scheme. In table 7, the periodic data reporting pattern of different HUBs, with respect to time is shown. It is noticeable that in periodic data reporting, HUB takes turn during communication and only one HUB is active during a certain duration. Hence, no inter-HUB interference will be observed during communication. However, contention among different traffic generated by a single network will exist as two different priority data is being communicated at the same time. It is important to simulate the periodic data reporting pattern because proposed algorithm adjusts the superframe according to traffic requirements in terms of packets per second.

Table 7: Periodic Data Reporting Parameters

	UP 5	**UP *6***	**UP 7**
MSDU Interval Time (seconds)	0.005 (200 pkts/sec)	0.005 (200 pkts/sec)	0.005 (200 pkts/sec)
MSDU Size (bits)	800 (100 bytes)	1200 (150 bytes)	1600 (200 bytes)
HUB 1			
Starting Time	400 Second	200 Second	50 Second
Ending Time	500 Second	300 Second	150 Second
HUB 2			
Starting Time		300 Second	50 Second
Ending Time		500 Second	250 Second
HUB 3			
Starting Time		400 Second	150 Second
Ending Time		600 Second	350 Second
HUB 4			
Starting Time	400 Second	200 Second	50 Second
Ending Time	500 Second	300 Second	150 Second

5.2.1 Drop packets of proposed scheme with buffer size 10

The drop packet results of proposed schemes per BAN is shown in figure 16. The buffer size is 10 packets per node. The data reporting is periodic that's why it shows fluctuation in packets drop rate. The results of drop packets of dynamic extended scheme is better than the extended IEEE 802.15.6, because the size of superframe is constant in extended IEEE 802.15.6 whereas, superframe size in dynamic extended scheme is not constant and it changes according to the traffic. So, the throughput of dynamic extended is better than the extended IEEE 802.15.6 because throughput is directly dependent on the packets drop rate. When the drop rate is increased the throughput is also increased.

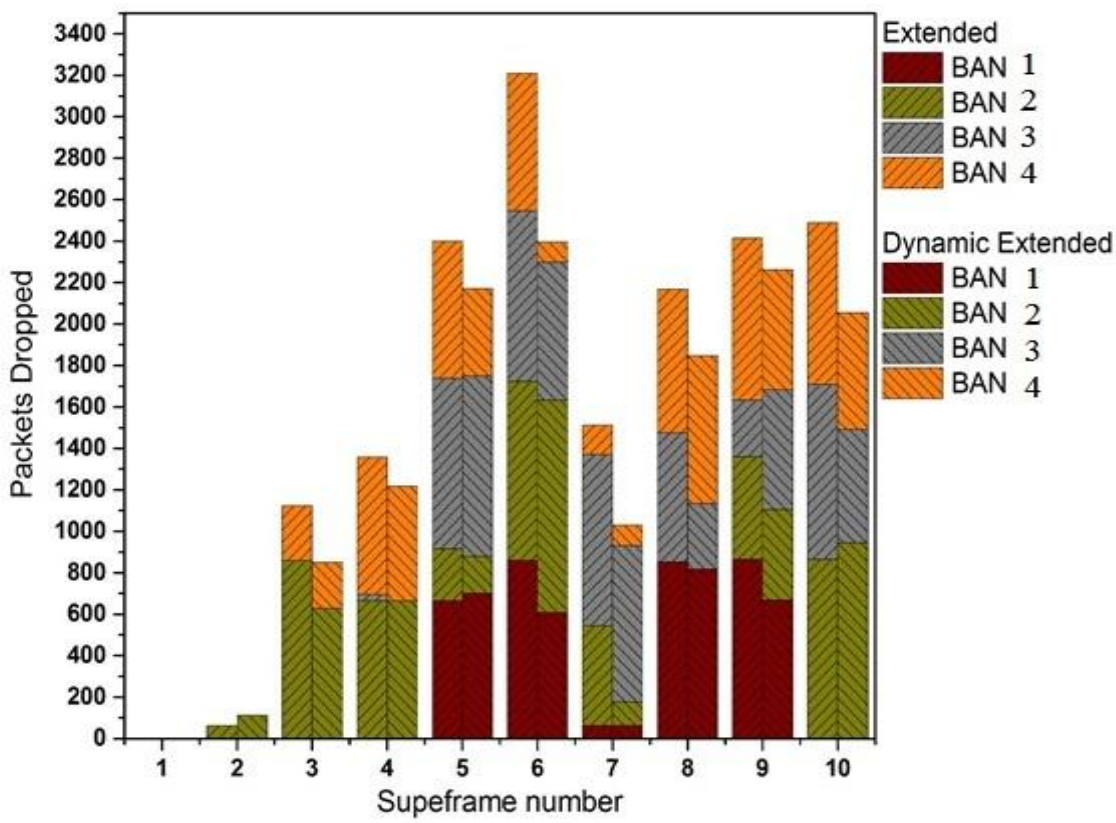

Figure 16: Packets dropped during periodic data reporting with buffer size 10

5.2.2 Drop packet of proposed schemes with buffer size 30

Figure 17 shows the comparison between proposed schemes, these are extended IEEE 802.15.6 and dynamic extended IEEE 802.15.6 with buffer size 30. The result of drop packet in dynamic extended is better as compared to extended IEEE 802.15.6. When we increase the buffer size the results in dynamic and extended IEEE 802.15.6 schemes is better than the buffer size 10 as shown in Figure 16.

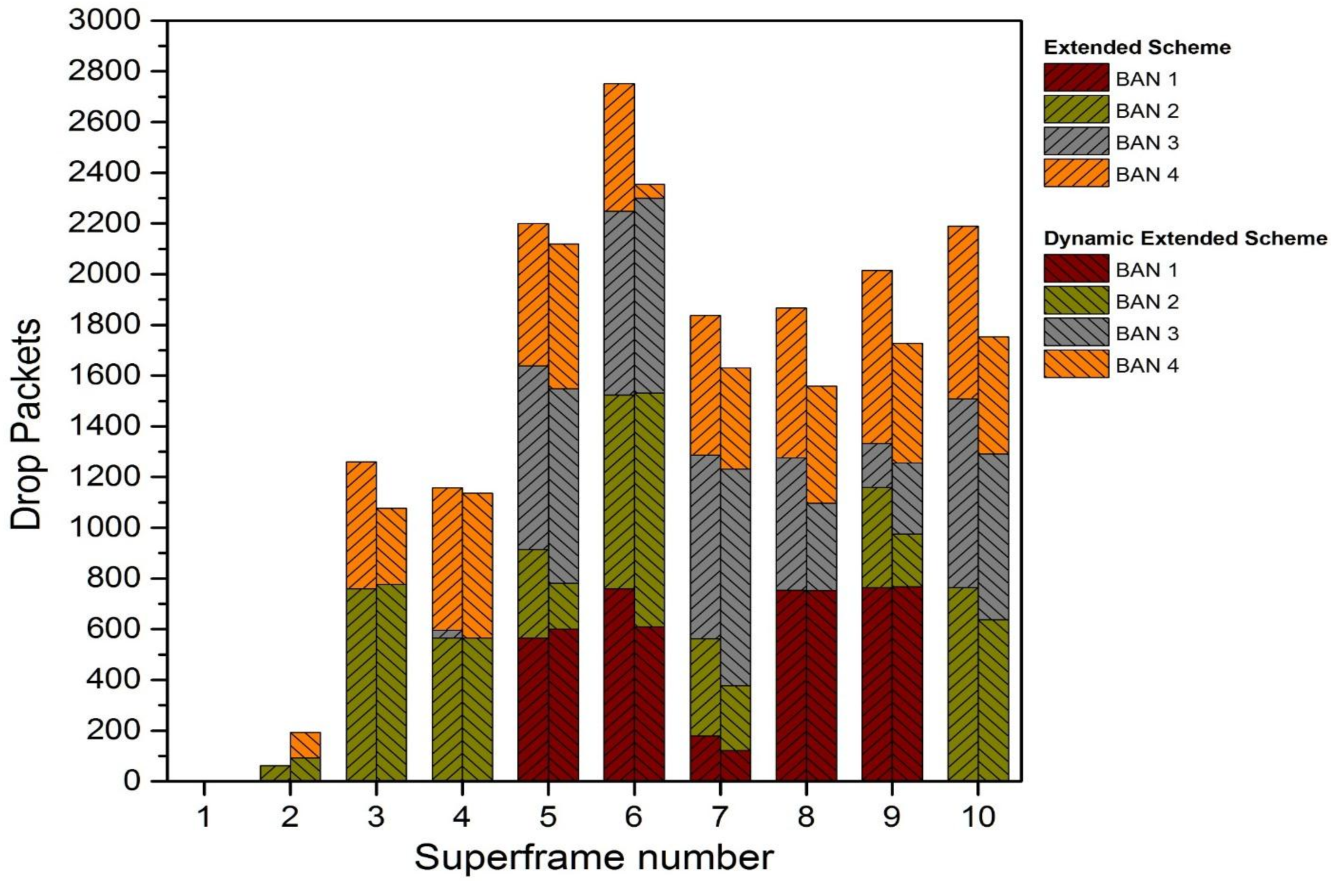

Figure 17: Packets dropped of periodic data reporting with buffer size 30

5.2.3 Drop packet of proposed schemes with buffer size 50

Figure 18 refer to the result of extended IEEE 802.15.6 using buffer size 50 for different BAN's. Superframe in dynamic extended scheme is not constant and it changes according to the traffic. So the results of dynamic extended is better than the extended IEEE 802.15.6.

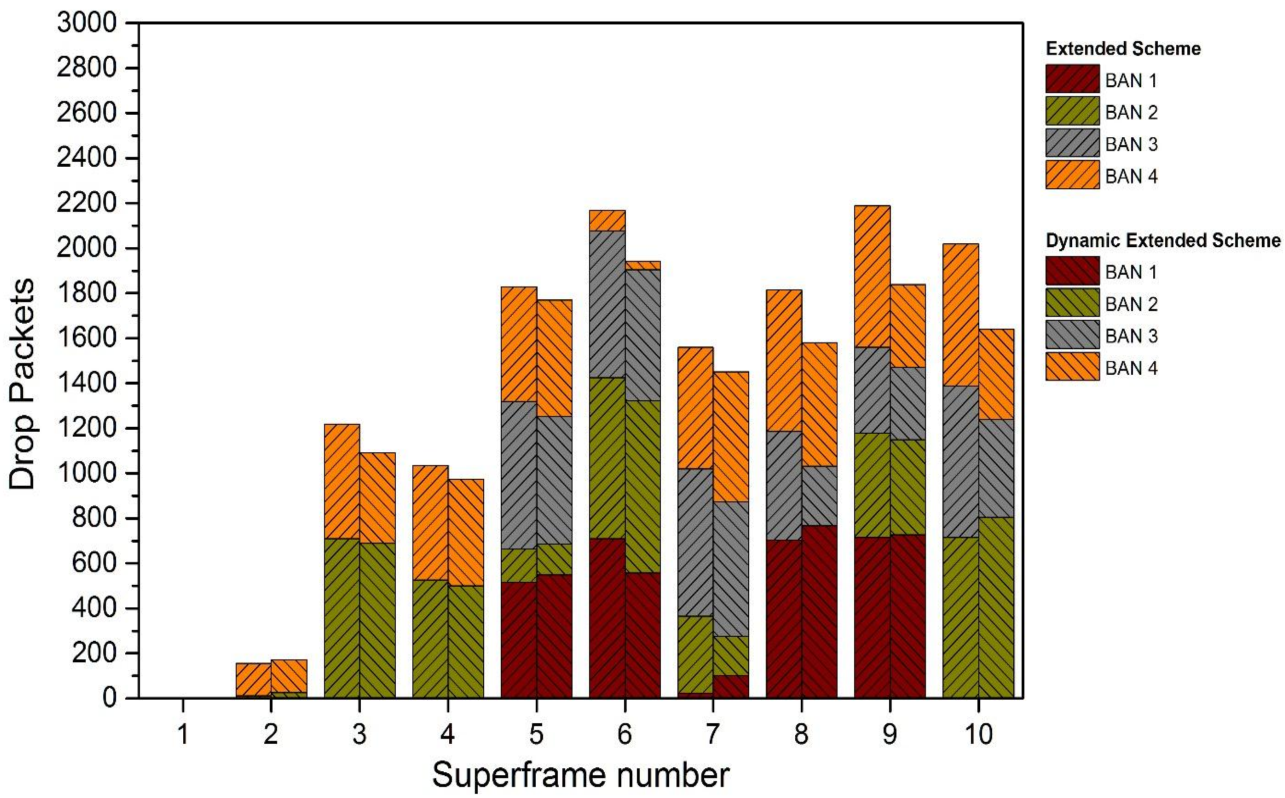

Figure 18: Packets dropped of periodic data reporting with buffer size 50

5.2.4 Latency of proposed schemes with buffer size 10

Latency of extended IEEE 802.15.6 and dynamic IEEE 802.15.6 is shown in Figure 19 by using buffer size 10 for different BAN's. Figure 19 clearly highlights that latency of dynamic scheme is better than the result of extended IEEE 802.15.6. Due to periodicity of data reporting in dynamic extended IEEE 802.15.6 latency is increased as compared to extended IEEE 802.15.6, as shown in figure 19, superframe 6, 9 and 10 latency result in dynamic scheme is little higher than the extended IEEE 802.15.6, because the superframe duration in extended is constant and in dynamic extended IEEE 802.15.6 is not constant so the superframe duration is according to the traffic.

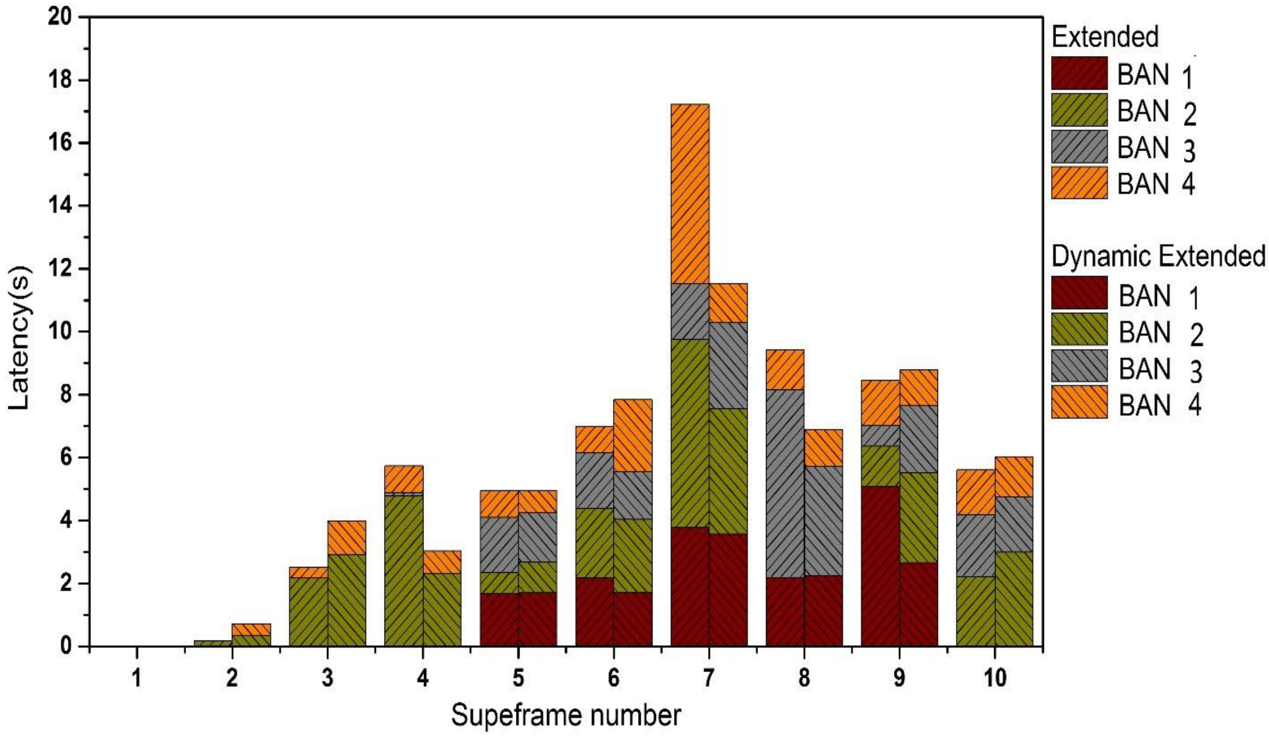

Figure 19: Latency of periodic data reporting with buffer size 10

5.2.5 Latency of proposed schemes with buffer size 30

Figure 20 presents the result of latency between the extended and dynamic IEEE 802.15.6. The result of latency in dynamic IEEE 802.15.6 is better than the extended IEEE 802.15.6, because dynamic adjustment gives more time to BANs with data as compared to BANs with no or less data.

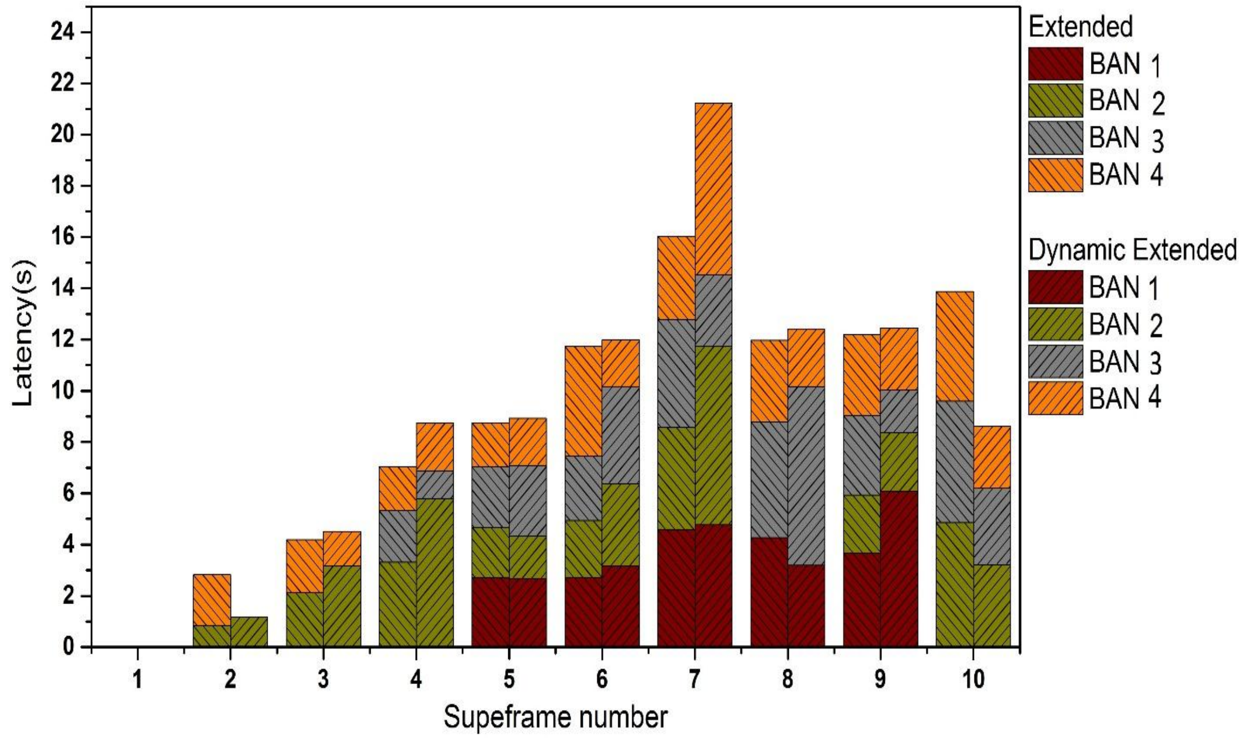

Figure 20: Latency of periodic data reporting with buffer 30

5.2.6 Latency of proposed schemes with buffer size 50

Figure 21 analyze the simulation results of latency with buffer size 50 in extended and dynamic IEEE 802.15.6 schemes. In a single communication channel, four BAN's are used for calculating the latency in coexistence environment. Latency of dynamic extended scheme is better than extended IEEE 802.15.6 scheme.

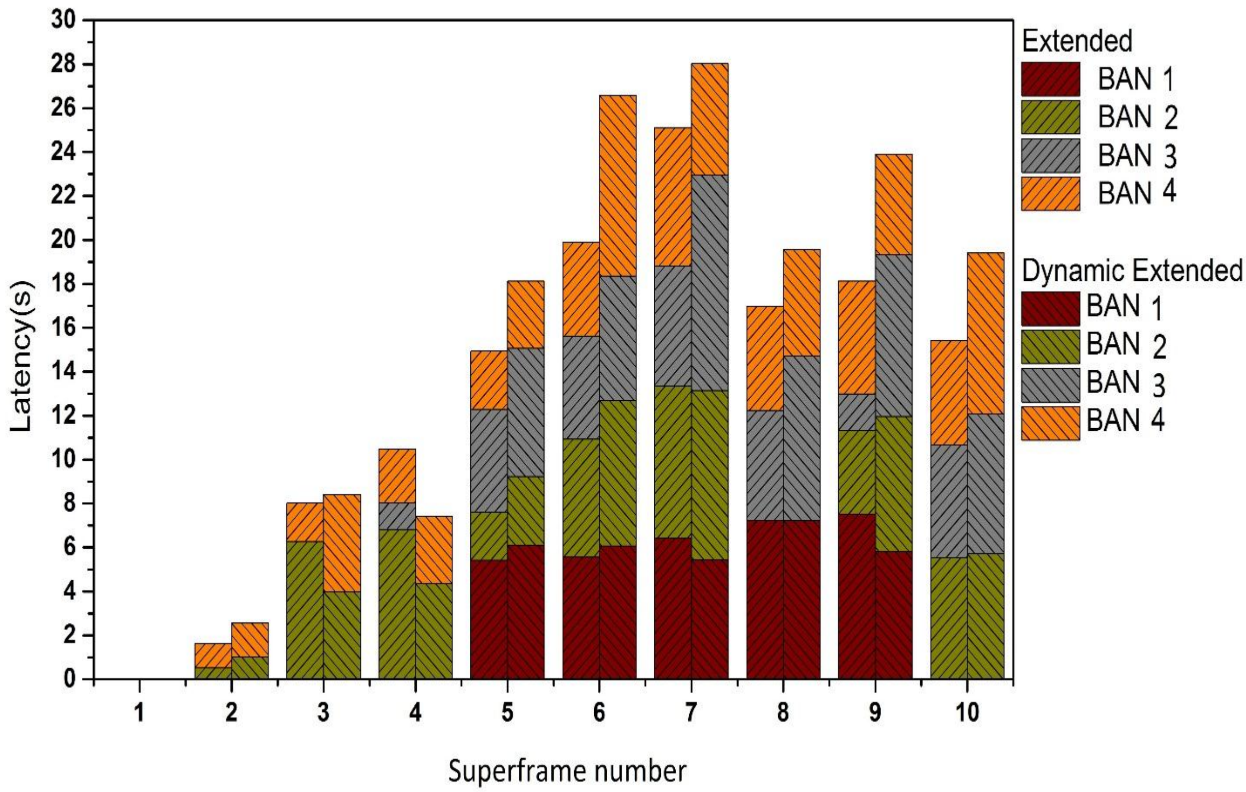

Figure 21: Latency of periodic data reporting with buffer 50

5.2.7 PDR of proposed schemes

Figure 22 shows the packet delivery ratio of extended IEEE 802.15.6 and dynamic IEEE 802.15.6. PDR is above 50% in both schemes but in dynamic extended it is quite higher than the extended IEEE 802.15.6. PDR is higher in dynamic IEEE 802.15.6 because it is traffic aware and it adjusts BAN's superframe according to traffic. Cluster head calculates the traffic requirement on its HUB and assigns new superframe sizes to other BAN's in the communication channel. That's why its results in terms of PDR is better as compared to extended IEEE 802.15.6 as shown in Figure 22.

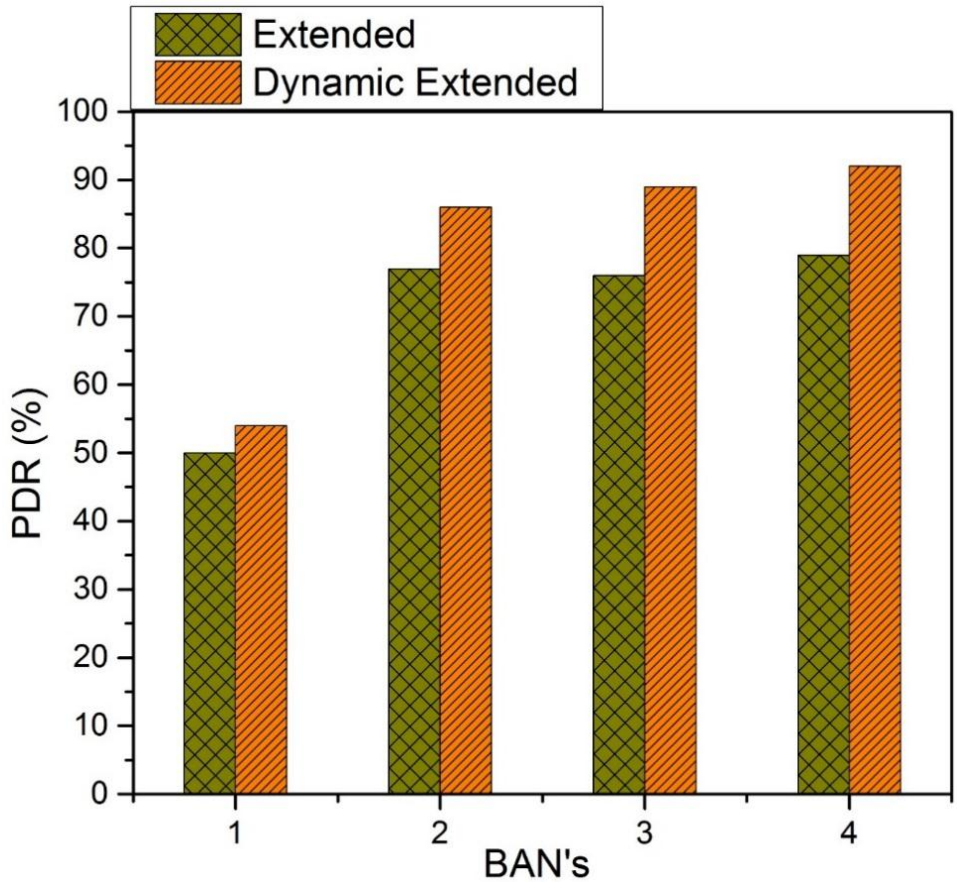

Figure 22: PDR of proposed schemes with buffer 30

5.3 Continuous data reporting

In this section, continuous data reporting is used with constant rate and the results can be analyzed and compared to the performance between the extended IEEE 802.15.6 and dynamic IEEE 802.15.6. In continuous data reporting only UP7 data traffic is used. Reason of using the only UP7 is to generate data traffic in all phases of superframe, but in UP6 traffic is not generating in all phases. Table 8 shows the simulation parameters for continues data reporting. We use a different buffer size for different BAN's to analyze the performance and results to generate data continuously for dynamic IEEE 802.15.6 and extended IEEE 802.15.6.

Table 8: Simulation parameters for Continuous data

Parameter	Value
Simulation time	550 seconds
Frequency band	2.4 GHz
Traffic Type	UP7
Packet Size	100 B
Number of BAN’s	4
Link Capacity (kbps)	971.4
Data Rate (kbps)	156.25
Initial energy	34560 Joules
Transmit mode	17.4 mA
Receive mode	24.8 mA
Sleep mode	6.1 µA
Idle mode	26.1 µA

For achieving the maximum results and output of our proposed scheme, we generate data continuously by using only one type of traffic that is UP7. Continues data reporting parameters are shown in table 9.

Table 9: Continuous Data Reporting Parameters

	UP 7
MSDU Interval Time (seconds)	0.0025 (400 pkts/sec)
MSDU Size (bits)	800 (100 bytes)
HUB1	
Starting Time	50 Second
Ending Time	550 Second
HUB2	
Starting Time	50 Second
Ending Time	550 Second
HUB3	
Starting Time	50 Second
Ending Time	550 Second
HUB4	
Starting Time	50 Second
Ending Time	550 Second

5.3.1 Drop packet of proposed schemes with buffer size 10

Figure 23 shows the drop packets of extended and dynamic scheme using continues data reporting with buffer size 10 for different BAN's. When we use dynamic IEEE 802.15.6 then throughput gets better as compared to when we use extended IEEE 802.15.6, because the throughput is dependent on packet drop rate, when packet drop rate decreases the throughput increases. Packets are only dropped when buffer size is relatively small in size.

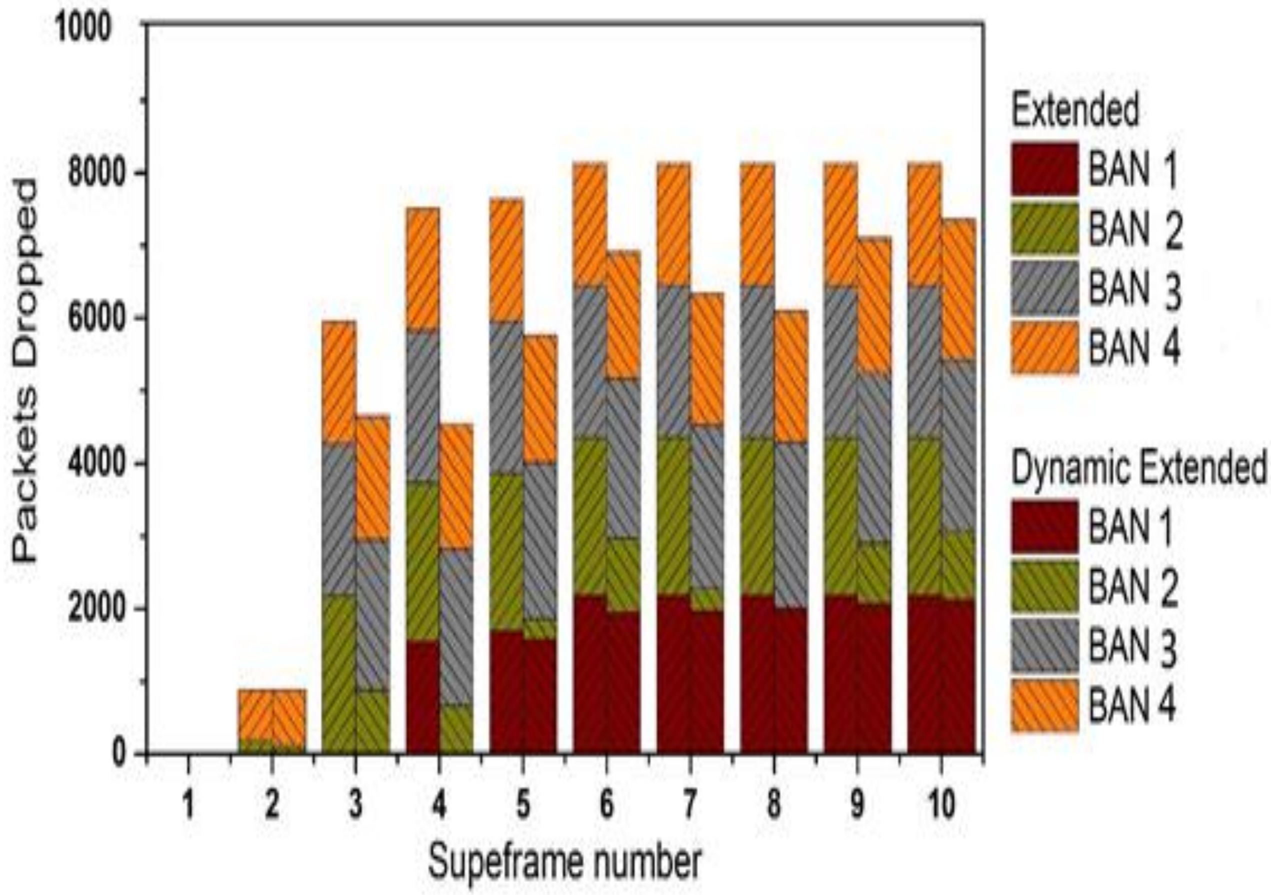

Figure 23: Drop packets of continuous data reporting with buffer size 10

5.3.2 Packet drop of proposed schemes with buffer size 30

Packets drop ratio is shown in Figure 24 with size 30 of extended IEEE 802.15.6 and dynamic extended IEEE 802.15.6 scheme.

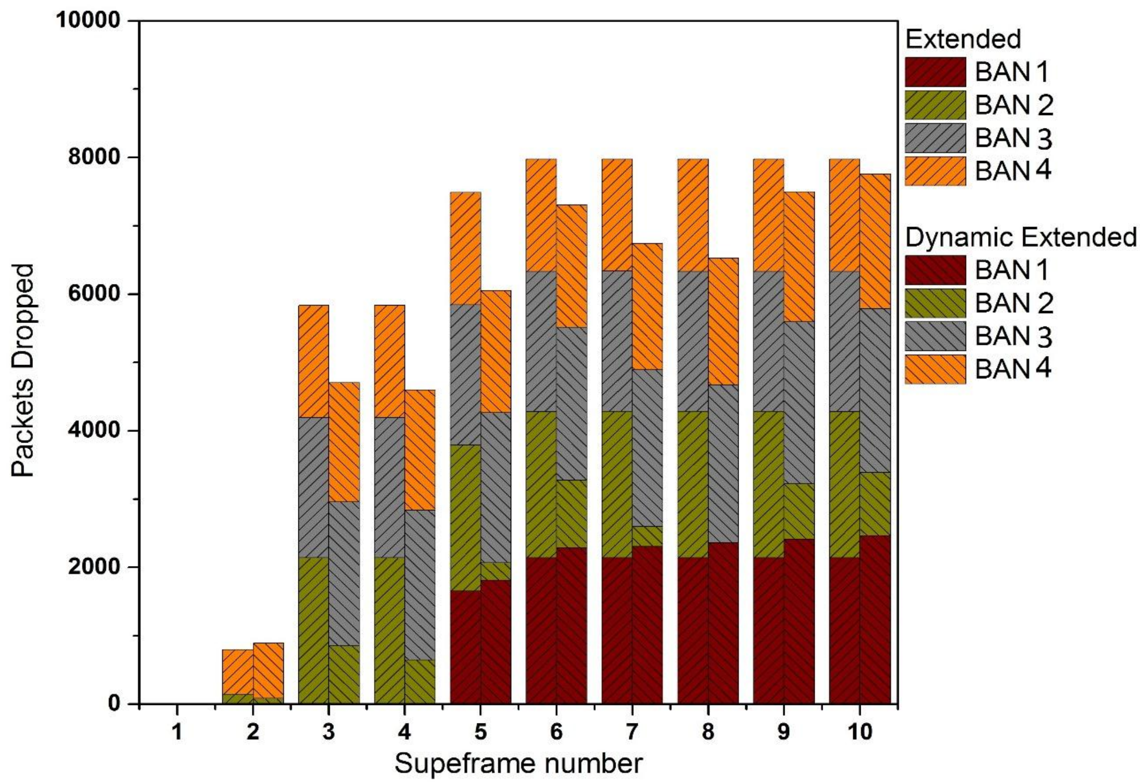

Figure 24: Drop packet of continuous data reporting with buffer size 30

5.3.3 Drop packet of proposed schemes with buffer size 50

Packets drop ratio is shown in Figure 25 and provides the comparison between extended scheme and dynamic extended IEEE 802.15.6 scheme. We analyze the performance of proposed dynamic scheme with proposed extended IEEE 802.15.6 using the buffer size 50.

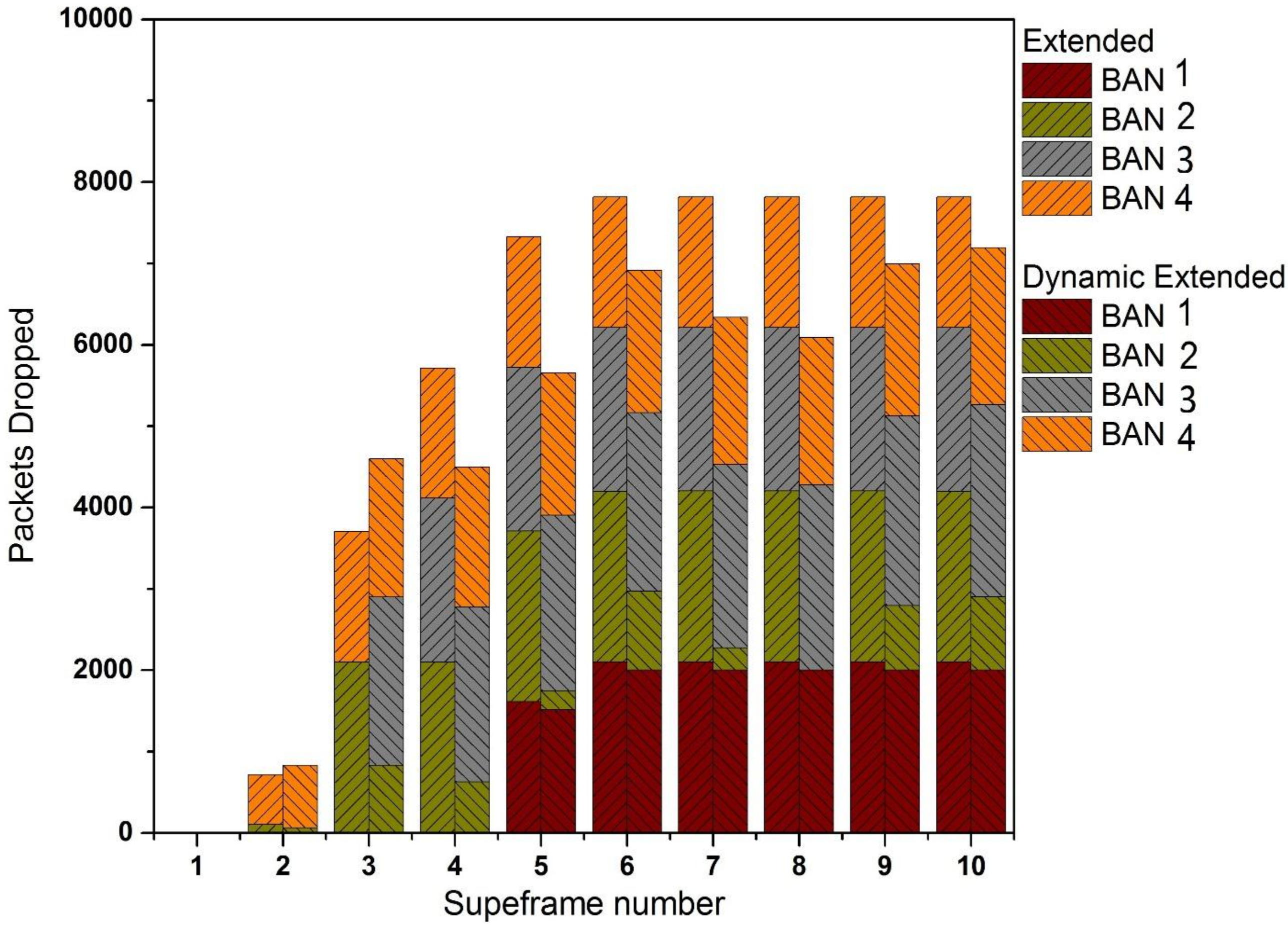

Figure 25: Drop packet of continuous data reporting with buffer size 50

5.3.2 Latency of proposed schemes with buffer size 10

Latency of extended proposed scheme is increased when we increase the buffer size because the latency is directly dependent on the overall packets that are stored in buffer. Latency is low when buffer size is small and it increases when buffer size is increased. Figure 26 show the simulation results of latency in extended IEEE 802.15.6 and dynamic IEEE 802.15.6. Result of latency in extended IEEE 802.15.6 is better than the dynamic IEEE 802.15.6 because in extended scheme superframe is constant but in dynamic extended scheme superframe is vary according to traffic.

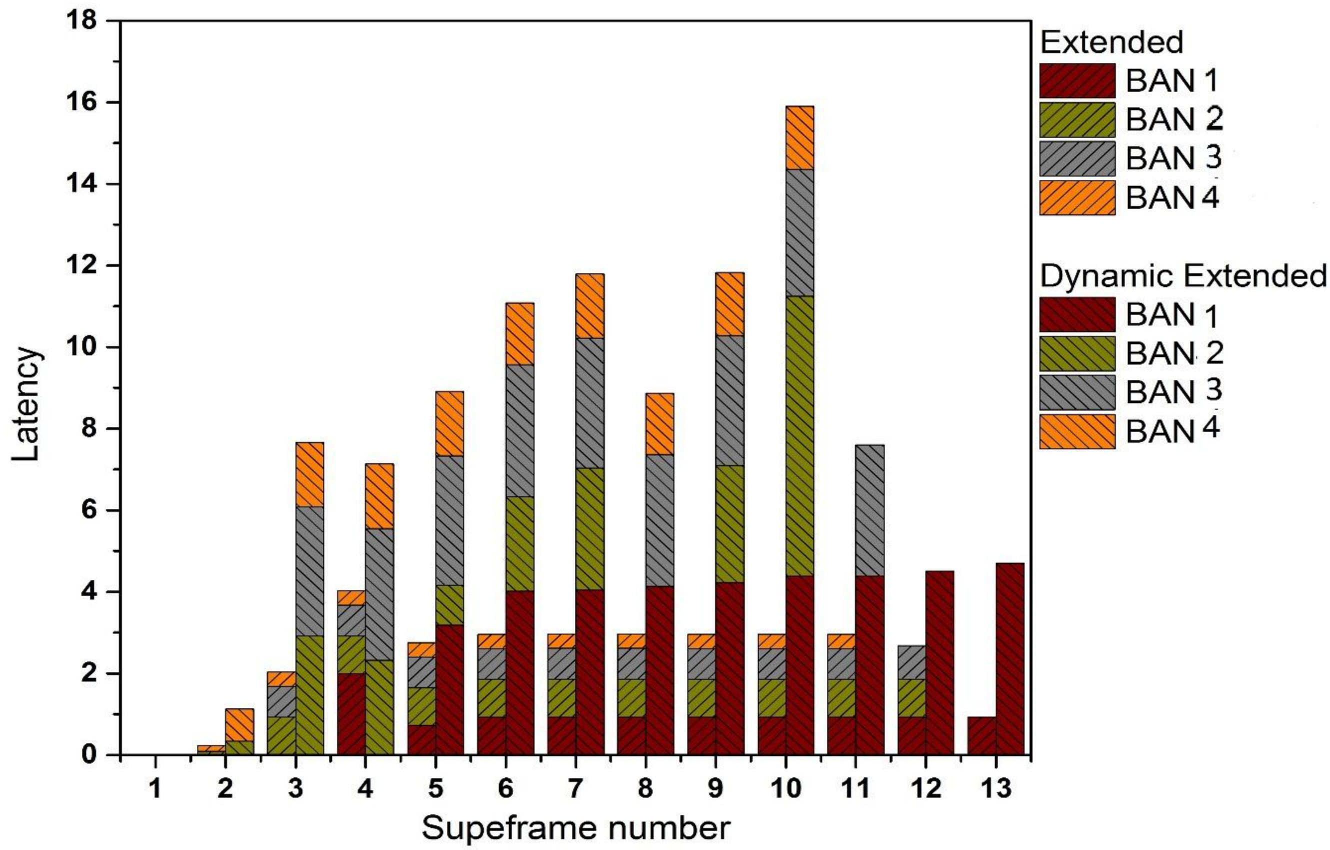

Figure 26: Latency of continuous data reporting with buffer size 10

5.3.3 Latency of proposed schemes with buffer size 30

The latency of proposed schemes is shown in Figure 27. We use multiple BAN's with buffer size 30 to analyze the latency of proposed schemes. Buffer size effect the latency, when we increase the buffer size then latency is also increase. When BAN2 BAN4, BAN7, and BAN12 using the extended IEEE 801.15.6 scheme with buffer size 30 the latency is constant but in dynamic extended IEEE 802.15.6 is not constant then latency is change in each superframe.

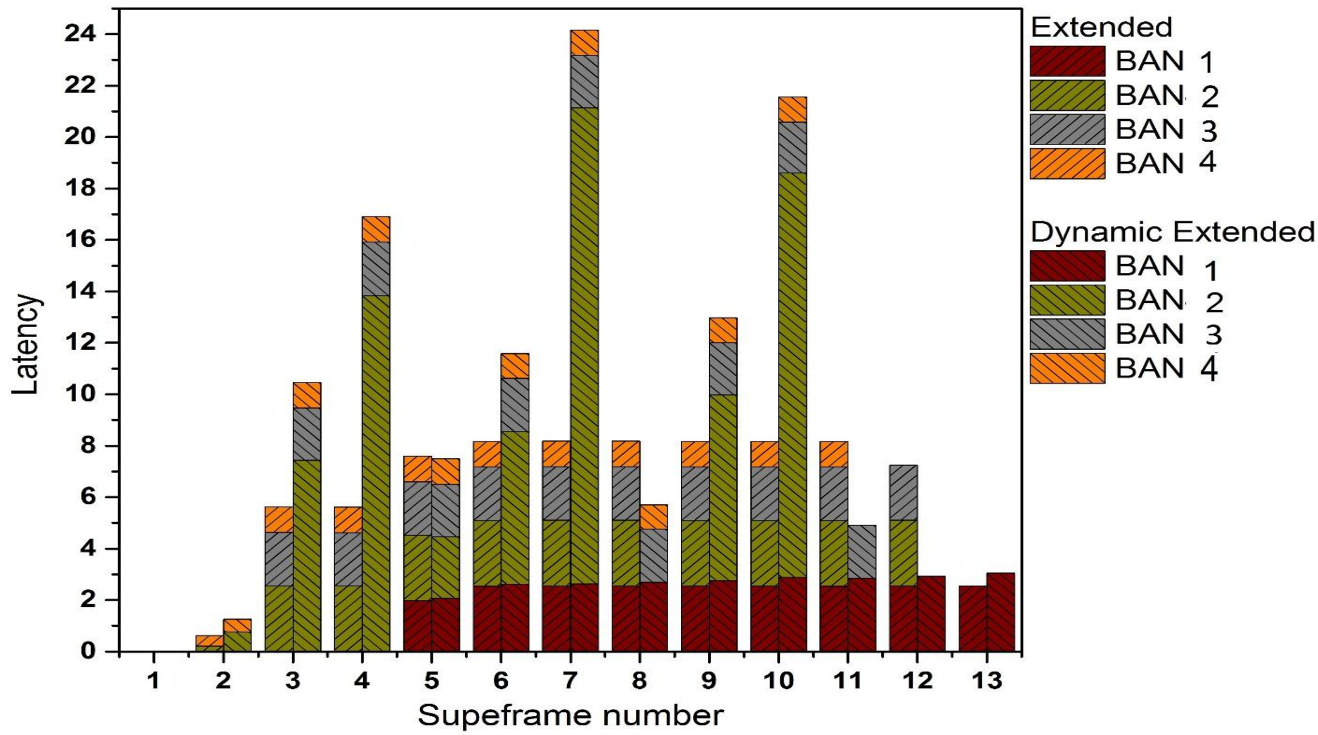

Figure 27: Latency of continuous data reporting with buffer size 30

5.3.4 Latency of proposed schemes with buffer size 50

Figure 28 shows the result of latency between the proposed dynamic scheme and extended IEEE 802.15.6 scheme. When we analysis the result of latency in dynamic IEEE 802.15.6 is vary according to the superframe duration because the duration of superframe is changing according to the data generated but in extended the result of latency is not change because the duration of superframe is not changing according to the traffic, so the result of latency is vary as compared to extended.

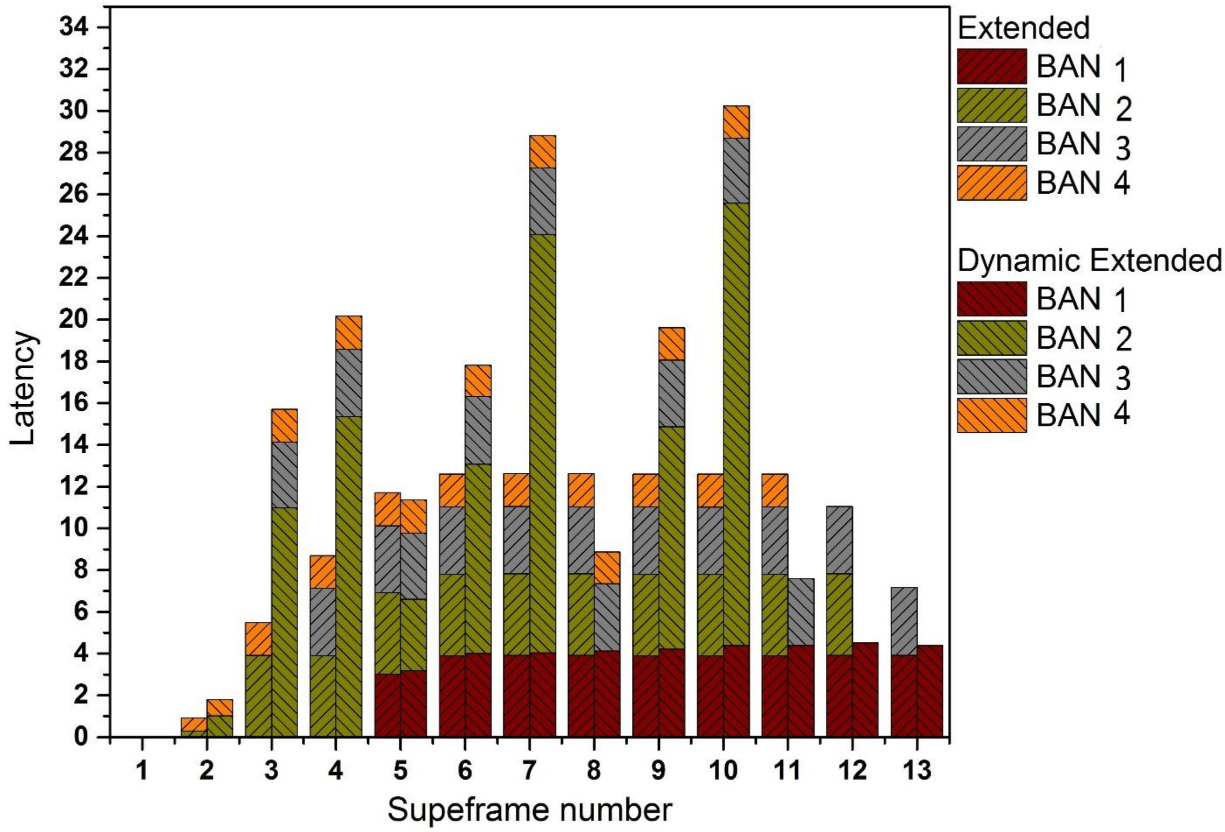

Figure 28: Latency of continuous data reporting with buffer size 50

5.3.5 Packet delivery ratio with buffer size 30

Packet delivery ratio of both schemes with buffer size 30 is shown in Figure 29. In continuous data reporting, PDR of dynamic extended IEEE 802.15.6 scheme is much better than the extended IEEE 802.15.6. Dynamic extended scheme shows better results because its cluster head is also adjusting the superframes according to the each BAN traffic requirement.

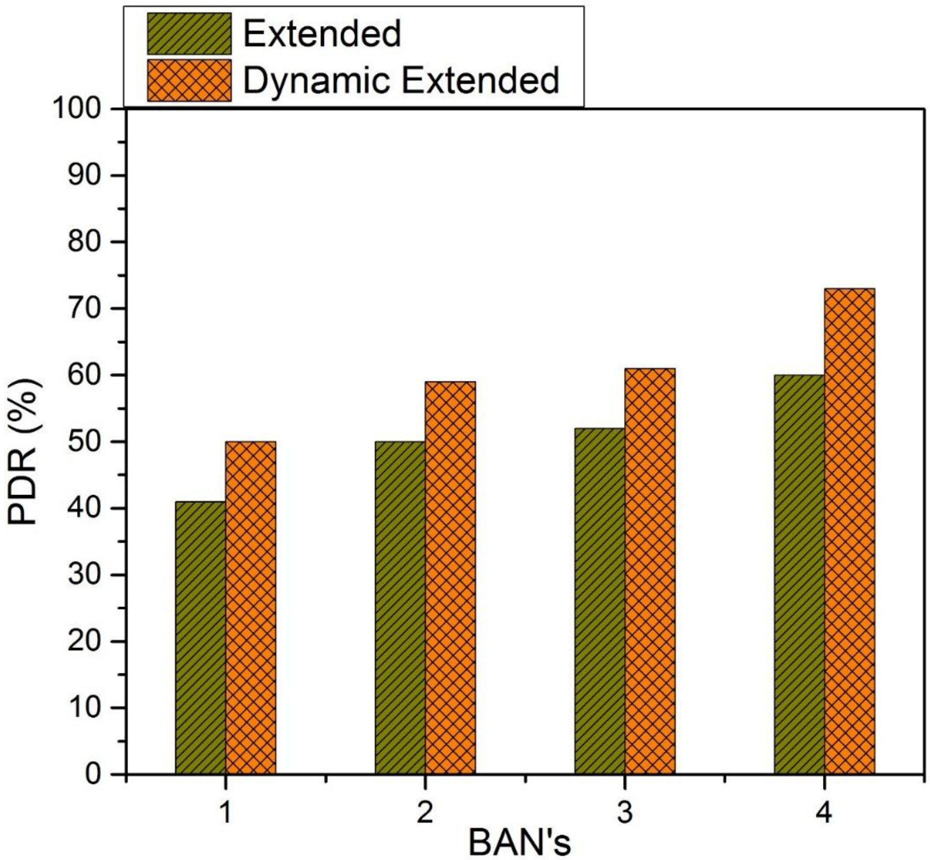

Figure 29: Packet delivery ratio with buffer size 30

Chapter 6

Conclusion

The problem of coexistence is well known and studied in wireless networks for more than two decades. However, IEEE 802.15.6 is a relatively new standard for WBANs and due to the nature of short distance communication in BANs interference is imminent in these networks. In IEEE 802.15.6 three techniques are proposed to avoid coexistence between BAN's. First technique is channel hopping in which BANs constantly change communication channels. Second technique is beacon shifting in which multiple patterns of beacon shifting are introduced and these patterns are assigned to individual BAN's. The last technique is superframe interleaving that completely mitigates the interference between multiple BAN's by adjusting sharing the communication channel on turns. IEEE 802.15.6 proposed the interleaving solution for only two BAN's.

Proposed algorithm play a vital role in improving the performance by mitigating the coexistence between the homogenous networks in WBAN.

In this work, we have developed an extended and dynamic IEEE 802.15.6 scheme in which more than two BANs can use the superframe interleaving technique. The work assumes a cluster of BAN networks in which the BAN head performs interleaving among neighbouring BANs. Each BAN calculates it's superframe requirement and request for interleaving to its cluster head. The head BAN allocates the superframe duration in the interleaved superframe to all the BAN hubs. The head BAN dynamically adjusts the active duration of each BAN in its cluster according to its traffic requirements. Thus, dynamic superframe allocation is proposed in the existing superframe interleaving procedure of IEEE 802.15.6.

Detailed simulation analysis is performed in OPNET and the performance of the proposed dynamic superframe interleaving is found better than the existing IEEE 802.15.6 interleaving. The proposed scheme is able to substantially increase the overall packet delivery ratio of interfering BANs.

In our proposed scheme, we assume that the first BAN in a communication channel is the cluster head. In future work, selection of cluster head can be made more efficient by considering multiple parameters for cluster head selection. Also, algorithms for cluster head rotation and tackling changes in the cluster with mobility are interesting areas for future research in WBANs. Another, important aspect for future research is the application of superframe interleaving in heterogeneous networks as the proposed scheme only addresses the interference problem in homogeneous WBANs.

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