Performance of IEEE 802.15.4 Beaconless-Enabled Protocol for Low Data Rate Ad Hoc Wireless Sensor Networks

A thesis as partial fulfilment of the requirements
of the degree of Doctor of Philosophy

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Dedicated to:
My miraculous late Father,
My outstanding Mother,
My humble late Parents in law,
and
My beloved Wife, Qiqi, and Ata

Acknowledgments

Foremost, praise be to God for all His Blessings and Guidance without which nothing is possible and going through the right path. I would like to use this opportunity to thank to His Prophets who guide people and me to the straight path of life.

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Abstract

This thesis focuses on the enhancement of the IEEE 802.15.4 beaconless-enabled MAC protocol as a solution to overcome the network bottleneck, less flexible nodes, and more energy waste at the centralised wireless sensor networks (WSN). These problems are triggered by mechanism of choosing a centralised WSN coordinator to start communication and manage the resources. Unlike IEEE 802.11 standard, the IEEE 802.15.4 MAC protocol does not include method to overcome hidden nodes problem. Moreover, understanding the behaviour and performance of a large-scale WSN is a very challenging task.

A comparative study is conducted to investigate the performance of the proposed ad hoc WSN both over the low data rate IEEE 802.15.4 and the high data rate IEEE 802.11 standards. Simulation results show that, in small-scale networks, ad hoc WSN over 802.15.4 outperforms the WSN where it improves 4-key performance indicators such as throughput, PDR, packet loss, and energy consumption by up to 22.4%, 17.1%, 34.1%, and 43.2%, respectively. Nevertheless, WSN achieves less end-to-end delay; in this study, it introduces by up to 2.0 ms less delay than that of ad hoc WSN. Furthermore, the ad hoc wireless sensor networks work well both over IEEE 802.15.4 and IEEE 802.11 protocols in small-scale networks with low traffic loads. The performance of IEEE 802.15.4 declines for the higher payload size since this standard is dedicated to low rate wireless personal access networks.

A deep performance investigation of the IEEE 802.15.4 beaconless-enabled wireless sensor network (BeWSN) in hidden nodes environment has been conducted and followed by an investigation of network overhead on ad hoc networks over IEEE 802.11 protocol. The result of investigation evinces that the performance of beaconless-enabled ad hoc wireless sensor networks deteriorates as indicated by the degradation of throughput and packet reception by up to 72.66 kbps and 35.2%, respectively. In relation to end-to-end delay, however, there is no significant performance deviation caused by hidden nodes appearance. On the other hand, preventing hidden node effect by implementing RTS/CTS mechanism introduces significant overhead on the network that applies low packet size. Therefore, this handshaking method is not suitable for low rate communications protocol such as IEEE 802.15.4 standard.

An evaluation study of a 101-node large-scale beaconless-enabled wireless sensor networks over IEEE 802.15.4 protocol has been carried out after the nodes deployment model was arranged. From the experiment, when the number of connection densely increases, then the probability of packet delivery decreases by up to 40.5% for the low payload size and not less than of 44.5% for the upper payload size. Meanwhile, for all sizes of payload applied to the large-scale ad hoc wireless sensor network, it points out an increasing throughput whilst the network handles more connections among sensor nodes. In term of dropped packet, it confirms that a fewer data drops at smaller number of connecting nodes on the network where the protocol outperforms not less than of 34% for low payload size of 30 Bytes. The similar trend obviously happens on packet loss. In addition, the simulation results show that the smaller payload size performs better than the bigger one in term of network latency, where the payload size of 30 Bytes contributes by up to 41.7% less delay compared with the contribution of the payload size of 90 Bytes.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ACK	Acknowledgment
AI-LMAC	Adaptive Information-centric L-MAC
AODV	Ad-hoc On-demand Distance Vector
APs	Access Points
BAN	Body Area Networks
BAS	Building Automation System
BE	Beacon Exponent
BI	Beacon Interval
BLE	Battery Life Extension
B-MAC	Berkeley Medium Access Control
BO	Beacon Order
BPSK	Binary Phase Shift Keying
BSN	Beacon Sequence Number
CAP	Contention Access Period
CBR	Constant Bit Rate
CCA	Clear Channel Assessment
CFP	Contention Free Period
CRC	Cyclic Redundancy Check
CTS	Clear to Send
CS	Carrier Sense
CSMA/CA	Carrier Sense Multiple Access
CW	Contention Window
DCF	Distributed Coordination Function
D-MAC	Data gathering Medium Access Control
DSDV	Destination-Sequenced Distance Vector

DSN	Data Sequence Number
DSR	Dynamic Source Routing
DSSS	Direct Sequence Spread Spectrum
ED	Energy Detection
E-MACs	EYES Medium Access Control
FCS	Frame Check Sequence
FFD	Full Function Device
FLAMA	Flow Aware Medium Access
GTS	Guaranteed Time Slot
IEEE	Institute of Electrical and Electronics Engineers
IFS	Inter-Frame Spacing
IoE	Internet of Everything
IoT	Internet of Thing
IoV	Internet of Vehicle
IWN	Interfering Wireless Network
ISM	Industrial, Scientific and Medical
LIFS	Long Inter-Frame Spacing
LLC	Logical Link Control
L-MAC	Lightweight MAC
LPDU	LLC Protocol Data Unit
LPL	Low Power Listening
LQI	Link Quality Indication
LR-WPAN	Low Rate Wireless Personal Area Network
MAC	Medium Access Control
MANETs	Mobile Ad-hoc Networks
MA-AODV	Mobility Aware AODV
MCPS	MAC Common Part Sub-layer
MCPS-SAP	MAC Common Part Sub-layer Service Access Point

MFR	MAC Footer
MHR	MAC Header
MIC	Message Integrity Code
MLME	MAC sub-Layer Management Entity
MMAC	Mobility-adaptive Medium Access Control
MMC	Machine-to-Machine Communication
MPDU	MAC Protocol Data Unit
MSDU	MAC Service Data Unit
MSNs	Mobile Sensor Networks
NB	Number of Back-off (periods)
NS2	Network Simulator-2
OLSR	Optimized Link State Routing
OSI	Open Systems Interconnection
PACT	Power Aware Clustered TDMA
PAMAS	Power Aware Multi Access protocol with Signalling
PAN	Personal Access Networks
PD	PHY Data
PD-SAP	PHY Data Service Access Point
PDR	Packet Delivery Ratio
PHR	PHY Header
PHY	Physical Layer
PIB	PAN Information Base
PLCP	Physical Layer Convergence Procedure
PLME	Physical Layer Management Entity
PLME-SAP	Physical Layer Management Entity Service Access Point
P-MAC	Pattern Medium Access Control
PMD	Physical Medium Dependent
POS	Personal Operating Space

PPDU	PLCP Protocol Data Unit
PSDU	PLCP Service Data Unit
PSSS	Parallel Sequence Spread Spectrum
QoS	Quality of Service
RF	Radio Frequency
RFD	Reduced Function Device
RI-MAC	Receiver-Initiated MAC
RTS	Request To Send
Rx	Receiver
SCP-MAC	Scheduled Channel Polling MAC
SD	Superframe Duration
SFD	Start of Frame Delimiter
SIFS	Short Inter Frame Spacing
SMACs	Self-organizing MAC for Sensor networks
S-MAC	Sensor MAC
S-MAC/AL	Sensor MAC with Adaptive Listening
SO	Super-frame Order
SPDU	SSCS Protocol Data Unit
SRD	Short Range Device
SSCS	Service Specific Convergence Sub-layer
STEM	Sparse Topology & Energy Management
TCL	Tool Command Language
TCP/IP	Transmission Control Protocol/Internet Protocol
TEEM	Traffic aware Energy Efficient MAC
T-MAC	Timeout Medium Access Control
TRAMA	Traffic Adaptive MAC
Trx	Transceiver
Tx	Transmitter

VoIP	Voice over IP
V2I	Vehicle-to-Infrastructure communication
V2V	Vehicle-to-Vehicle communication
WiseMAC	Wireless sensor MAC
WLANs	Wireless Local Area Networks
WMNs	Wireless Mesh Networks
WPANs	Wireless Personal Area Networks
WSN	Wireless Sensor Networks
Z-MAC	Zebra Medium Access Control

Chapter 1

Introduction and Motivation

1.1 Background

This chapter briefly presents the background of research gaps investigated, motivation of the research, and aim and objectives of the studies. Moreover, the main contributions and methodology to conduct the research are elaborated respectively in this chapter. Lastly, this chapter outlines and describes the thesis structure to provide readers with the easiest way to track any issues.

In the recent decades, wireless communication has been the most promising communication paradigm worldwide due to a very spectacular technological growth, a sharply reducing cost, and a very fast market penetration. Wireless access networks offer various connectivity to the networks and provide different type of features based on user requirements and the applications. Those wireless access technologies include mesh networks (WMNs) [1, 2], mobile ad hoc networks (MANETs) [3, 4], wireless sensor networks (WSNs) [5, 6], and worldwide interoperability for microwave access (WiMAX) [7, 8, 9]. All these wireless networks are categorised by different application domains and based on end users' bandwidth requirements, capacities and scalabilities.

A very rapid invention and development in wireless communication technologies, portable and compact devices i.e. tablets and smartphones, and tiny sensor motes have been accelerating the deployment of wireless sensor networks (WSNs). On the other hand, WSNs still has to face some resource constraints due to lack of power supply, memory capacity and bandwidth limitation. Therefore, the low power consumption is a critical issue in developing the medium access control (MAC) protocol for wireless sensor networks [10, 11, 12]. The IEEE 802.15.4 is one of many standards addressed to accelerate deployment of low rate wireless sensor networks [13].

Due to the lack of features for almost all of wireless communication standards, it was proposed by [14] a new approach network architecture named as dualWireless for low demanding applications of multi-hop energy-efficient networks. Every node in the proposed architecture belongs to dual wireless protocols where a permanent IEEE 802.15.4 protocol as a controller of the on-demand data communications over IEEE 802.11n protocol.

1.2 Research Motivations

The motivation of the research presenting in this thesis can be listed as follows:

1. The IEEE 802.15.4 standard defines the specification of physical (PHY) layer and medium access control (MAC) sub-layer for low rate wireless personal access networks (LR-WPANs) [13]. This standard has been accelerating the deployment of wireless sensor networks (WSNs) and development of supporting technologies as well. The main characteristics of WSN are low data rate, low power consumption, and low production and maintenance cost [15, 16, 17, 18]. On the wireless sensor networks, a coordinator should be assigned at first time to begin communication and then maintain the network resources. This causes some problems such as lack of flexibility, network bottleneck or traffic jam, and more energy consumption [19]. To overcome these problems, the networks must be distributed instead of centralised. Therefore, ad hoc WSN over the IEEE 802.15.4 beaconless-enabled protocol is an alternative solution [20].

2. Hidden nodes problem is one of the main constraints on ad hoc wireless network that has been encouraging many researchers to be more concerned on that field [21, 22, 23]. In most studies on wireless networks, the in investigation of that phenomenon is as one of considerations. A comparative study will also be performed to investigate the network overhead on ad hoc networks over different standard such as IEEE 802.11. For the beginning, all the scenarios will be implemented on static nodes wireless sensor networks. A preliminary evaluation of existing IEEE 802.15.4 protocol has been performed for the proposed low data rate ad hoc wireless sensor networks via several sets of simulation, including impact of varying data payload sizes.
3. In wireless sensor networks (WSNs), the coverage area of sensor node is very short where sensor communicates with a very low data rate and limited power. The performance of WSNs degrades when there are several nodes aggressively move within the network. The association efficiency can be affected when moving node regularly switches from one coordinator to another. The greater the number of mobile nodes with faster movement, the worst the node synchronisation process. This is caused by signal interference from other neighbouring nodes. Therefore, it increases the number of beacons lost and packet collisions. The existing research gives evidence that implementation of the IEEE 802.15 beacon-enabled mode has many constraints to meet the requirements such energy efficiency, scalability, reliability, and timelines [24]. In [25] it focuses on the IEEE 802.15.4 contention-based MAC protocol for WSNs and shows that it can suffer from a serious unreliability problem. Since the previous work implemented on small-scale network [20], therefore in this part of the thesis, the IEEE 802.15.4 beaconless-enabled protocol will

be implemented for a large number of static nodes on ad hoc wireless sensor networks.

1.3 Research Aim and Objectives

The main aim of the research presented in this thesis is to enhance the performance of low data rate ad hoc wireless sensor networks over IEEE 802.15.4 beaconless-enabled MAC protocol.

The works have been carried out by designing and then implementing the enhanced protocol of IEEE 802.15.4 for ad hoc wireless sensor network to meet the research objectives which are briefly explained and summarized as below:

1. To evaluate the proposed ad hoc wireless sensor network over IEEE 802.15.4 beaconless-enabled, then compare with the infrastructure and centralised wireless sensor network over IEEE 802.15.4 beacon-enabled protocol. Both of the protocols are implemented in the small-scale wireless sensor networks.
2. To compare the performance of the proposed ad hoc wireless sensor network over a very low data rate of the IEEE 802.15.4 MAC protocol to the ad hoc wireless sensor network over a high data rate of the IEEE 802.11 MAC protocol.
3. To study the performance of the proposed ad hoc wireless sensor network over IEEE 802.15.4 beaconless-enabled in the hidden node and unhidden node circumstances.
4. To measure the network overhead as side impact of implementation of handshaking RTS/CTS mechanism in contrast to the effort of avoiding hidden nodes appearance.
5. To evaluate the performance of large-scale low data rate wireless sensor networks over IEEE 802.15.4 beaconless-enabled protocol.

1.4 Main Contributions

This thesis has contributions to knowledge at least in three research issues, which are the IEEE 802.15.4 MAC protocol for ad hoc WSNs, hidden nodes problem, and deployment of large-scale WSNs. Those main contributions of this thesis are summarized and elaborated more detail as follows:

1. It solves the issues of network bottleneck, lack of flexibility and energy consumption on wireless sensor networks over the IEEE 802.15.4 protocol. The low data rate ad hoc wireless sensor network over IEEE 802.15.4 beaconless-enabled mode is deeply explored as an alternative to face such those problems. A comparative study has been conducted to evaluate the performance of existing IEEE 802.15 and IEEE 802.11 standard for ad hoc WSNs.
2. It arranges the three different scenarios aim to study the performance of beaconless-enabled wireless sensor networks (BeWSN) over IEEE 802.15.4 protocol in hidden nodes circumstances. Firstly, a scenario is arranged with various data inter-arrival times for beaconless-enabled ad hoc WSN over IEEE 802.15.4. Secondly, a scenario is set up for comparative evaluation of WSN in hidden nodes and unhidden nodes condition. Finally, an effectiveness study has been carried out to evaluate the implementation of RTS/CTS mechanism to avoid collision due to hidden nodes appearance. The two former experiments have been treated in a single-hop star topology, while the latter has been conducted in a multi-hop mesh topology.
3. It deeply investigates the issue of how big the number of nodes can involve in communication on wireless sensor networks supported by MAC protocol of the IEEE 802.15.4. In this thesis, the performance evaluation of IEEE 802.15.4 beaconless-enabled protocol also

considers the node deployment method. This aims to meet the requirement for initial deployment which should reduce the installation and maintenance cost, increase the flexibility of nodes placement, and guarantee the nodes become more self-healing and fault tolerant.

1.5 Research Methodology

In the first stage of the research, literature review of past and current works on the area of ad hoc networks and wireless sensor networks are extensively conducted to broaden the perspective on such areas of study. Furthermore, the IEEE 802.11 and IEEE 802.15.4 standards, MAC protocols, ad hoc networks, wireless sensor networks, and state of the art related to those addressed issues are deeply studied and intensively explored during this period.

Following the literature review phase, the implementation stage starts with an enhancement of the IEEE 802.15.4 medium access protocol and applies on the networks simulator. Network simulator2 (NS-2) version 2.34 is used to test and evaluate the proposed networks on the platform [26]. The code is compiled and tested under the Linux Kernel in the openSUSE platform. The network simulator NS2 is an open source discrete event simulator which provides interfaces to develop protocols at certain layer of the transmission control protocol/internet protocol (TCP/IP) protocol stack [27, 28]. Necessary modifications are made to various libraries, header functions and C++ files at MAC sub-layer to apply the proposed model.

In the testing stage, the tool command language (TCL) is used to write some scripts to generate the network topology and define the traffic model. Meanwhile, the two-ray ground reflection model is chosen as physical propagation model implemented in the NS2 network simulator. This propagation model considers both direct path and ground reflection path. Some literature proves that this propagation model is able to accurately give prediction for longer distance than of the free space model [29].

In the validation stage, the individual function of the protocols is tested in simulation environment and then the developed protocol is validated by comparison method between the proposed schemes with existing techniques. Finally, the obtained results are deeply analyzed and discussed by giving referred argumentations.

1.6 Thesis Structure

This thesis comprises of six chapters, where each chapter is inter-dependent. However, it is suggested for readers following the chapters in order for easier understanding of the contributions presented in this thesis. This **Chapter-1** begins with background and then followed by motivations, research objective, main contribution, methodology, and this thesis outline.

The **Chapter-2** provides a brief introduction to wireless sensor networks, fundamental concepts of medium access control and its applications in various communication protocols. A close-related literature on wireless sensor networks is then summarized and discussed to point out the strength and the weakness of each contribution. The review focuses on the IEEE 802.15.4 as the main protocol that used in the research. This chapter provides a fundamental related knowledge for the following chapters, where the beaconless-enabled mode of IEEE 802.15.4 protocol has been deeply explored and applied to solve the bottleneck problem, energy consumption, and lack of flexibility for applications of wireless sensor networks (WSNs). The chapter ends with summary of existing research and challenges on the IEEE 802.15.4 standard.

The **Chapter-3** presents a brief introduction to channel access mechanism in the IEEE 802.15.4 standard, the proposed ad hoc wireless sensor networks, and network simulator NS-2 version 2-34. Further, a comprehensive performance evaluation of ad hoc WSN over IEEE 802.15.4 standard and a comparative study with IEEE 802.11 standard are presented in this chapter. Following the simulation results and discussion, the chapter ends with the summary.

In the **Chapter-4**, it elaborates an enhancement of IEEE 802.15.4 beaconless-enabled protocol in hidden nodes circumstance. This chapter begins with brief overview of hidden nodes problem and then followed by problem statement and experimental set up. The results and discussion focus on the various inter-arrival times, impact of hidden nodes, and network overhead. The chapter ends with the summary.

The **Chapter-5** points out the investigation of the issue of how big the number of nodes can involve in communication on wireless sensor networks supported by MAC protocol of the IEEE 802.15.4. This chapter gives a brief overview of sensor nodes deployment model. Accordingly, implementation of IEEE 802.15.4 protocol for 101-node large-scale WSNs is extensively elaborated in the following section of this chapter. The chapter ends with the simulation results and the summary of this thesis part.

Finally, the **Chapter-6** consists of concluding remarks and suggestions. The chapter concludes the research findings and the main contributions. Lastly, future research is presented that might guide for the next direction of the research on mobile ad hoc wireless sensor networks (MAWSNET).

Chapter 2

Wireless Sensor Networks – An Overview

2.1 Introduction to Wireless Sensor Networks

In a few decades, several innovations and inventions in micro-electro-mechanical system (MEMS) technology, wireless communication, and digital electronics have significant influences in developing a tiny and smart sensor. The sensor is smaller, with limited storage capacity and computing capability and it is less expensive compared to conventional sensor. Later on, the trend of exponential growth in storage capacity of metal-oxide-semiconductors (CMOS) in one side, and miniaturization in other side has provided even more computing capacity of wireless devices. Those inventions followed by integration of wide range information technologies both hardware and software, networking, and programming have direct and indirect contributions to the large wireless sensor deployment. Therefore, researchers are now encouraged to apply this technology in ways that enable a new role for computing in science, including wireless sensor networks (WSNs) [6, 30, 31].

In the beginning era of sensor and actuator applications, sensor nodes are stand-alone devices without interconnecting to other devices or networks. Those sensors i.e. smoke or fire detectors, motion detectors, or temperature controllers are attached to the wall or roofs and respond to specified condition by delivering certain sign or alarm. Following the wide use of communication network for many applications, many researchers are interested in connecting those sensors with wireline communication networks and then extended to wireless networks. This was a starting point of the emergence of many never-ending new applications in military, habitat monitoring, health care, vehicle tracking, building automation, smart grid and smart city, manufacturing and industrial control.

Entering the 21st century, the emergence of wireless sensor networks has been attracting many researchers and manufacturers to develop hardware and software as well as protocols to support the very fast growing technologies of WSN. Various protocols and standards have been developed and released to accommodate the fast deployment of WSN for a huge range of applications to control and monitor physical environment aspects and to ease human interactions with the environment. Deployment of the sensors in a certain field of objects to collect data and track or monitor the environment results in lowering the cost and increasing the reliability compared with human intervention monitoring. Therefore, from the beginning the aim of medium access control (MAC) design is focus on how to minimize power consumption of sensor node to prolong its lifetime [32, 33, 34]. The IEEE 802.15.4 standard [13] then released firstly in 2003 as the standard of physical (PHY) and MAC which defines the requirements of low data rate, low cost, low maintenance, low power, self-organised and self-healing of large-scale wireless sensor networks.

2.1.1 WSN Characteristics

In the wireless personal area network (WPAN), it is by design to implement a sensor at very low power with limited processing speed, storage capacity, and communication bandwidth. Since wireless networking technologies have been mainly focused on high data rate and relatively for large coverage area, the emergence of WPAN is to fill the gap in the low power and low data rate networks as shown in Figure 2-1 [35].

In this thesis, it pays more attention to the low data rate over-the-air sensor networks with data transmission up to 250 kbps. In addition, because of power constraint in such sensor nodes within the network, they shall be densely deployed with a high degree of interaction among the sensor nodes [31]. Since the goal of sensor node deployment is related to specific task, such as monitoring, tracking, collecting data or identifying certain events, then sensor nodes are deployed either manually or by ad hoc. The ad hoc network deployment means that the nodes will form the network automatically and they communicate with their neighbours by following the routing path according to application requirements.

In a large-scale network, a node mostly connects to other nodes by wireless multi-hop communication because coverage area of each sensor is very short. The link among nodes in a multi-hop sensor network can be formed by radio, infrared or optical media [30]. Most of wireless sensors use radio links provided freely for the industrial, scientific, and medical (ISM) communication. Since sensors communicate with each other through limited wireless medium, a medium access control (MAC) protocol is then designed to provide fair access by sharing the allocated radio channels. In the initial phase of sensor network emergence, it operates over the wireless LAN MAC protocol. Furthermore, it is evolutionised with few enhancements so that it will be able to suit the energy-efficient MAC protocol for WSNs. Many studies and evaluations were carried out on the MAC protocols to cope with the energy-constraint since sensor nodes are to be left unattended for a longer time [32].

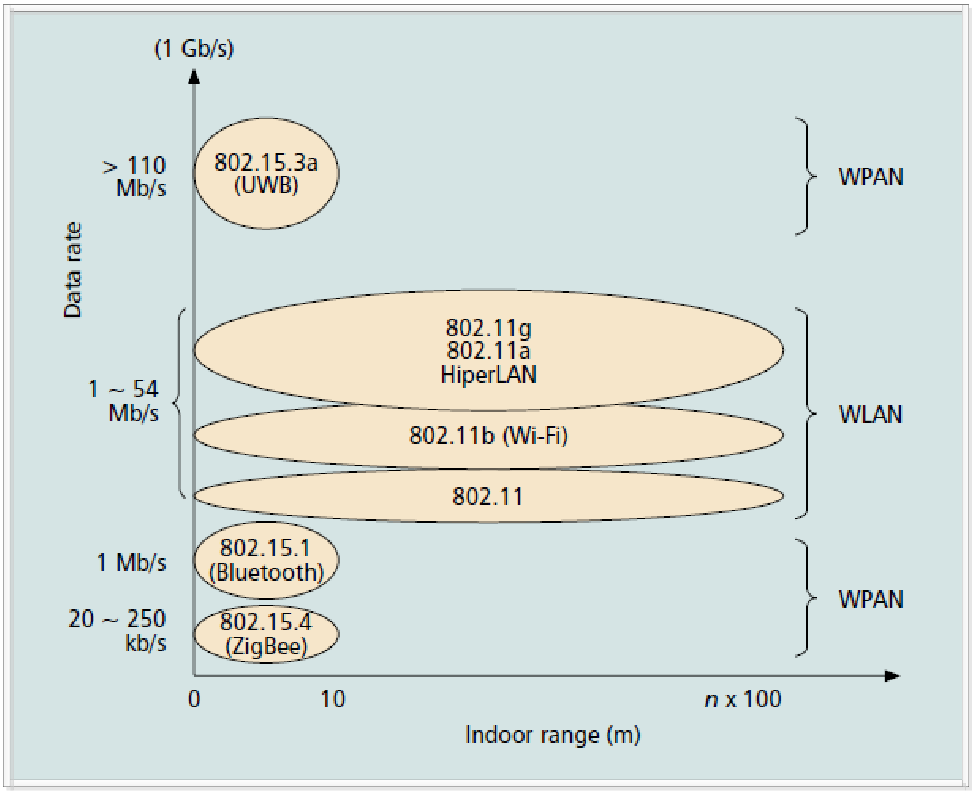


Figure 2-1: Wireless networking technologies with various bit rates and coverage areas.

2.1.2 WSN Hardware Architecture

The hardware architecture and configuration of a sensor node should consider the size-constraint. The required size may be smaller than even a cubic centimetre. Aside from the size, sensor node usually comes up with the ability to conserve energy, adaptively work in high density, and operates in self-configuration and self-healing without any human intervention for a long period.

Figure 2-2 shows a typical architecture of a sensor node (mote). A sensor node is made up of four main units: a sensing unit, a processing unit, transceiver unit, and a power unit. It might be equipped with additional component such as GPS (location finder), mobile unit, and power supplier. The main part of sensing unit is a sensor, which is complemented with converter from analog particular phenomenon to digital (ADC). Furthermore, the digital signals are fed to processing unit that consists of microprocessors and limited storage unit. The processing data is then transmitted through the radio transceiver to other sensor nodes on the networks. Another most important supporting unit for a sensor is power unit. This power unit is commonly attached to the mote as a battery unit; otherwise, it gets power from external power generator [30, 36].

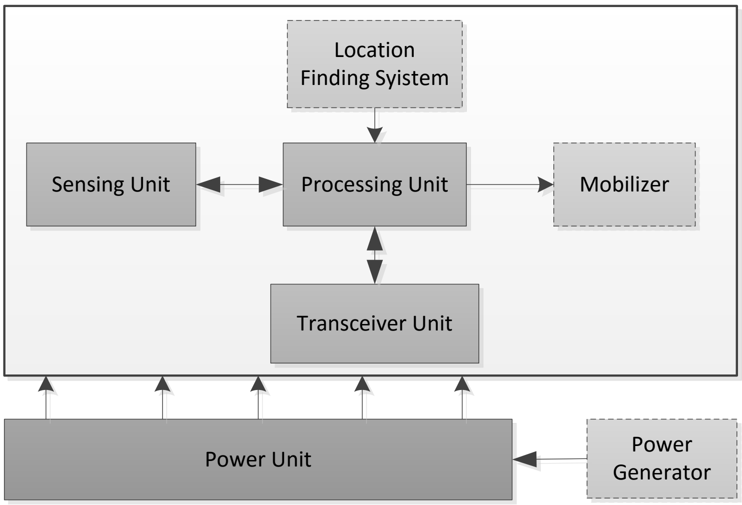


Figure 2-2: The main component of a sensor node: processor with memory, radio transceiver, sensor and power supply.

The inventions and innovations in micro-electro-mechanical devices and integration of RAM and flash memory have tremendous implications for the better design of sensor nodes. For example, the TinyOS operating system [37] has encouraged the growth of applications in WSN. TinyOS was developed by University of California, Berkeley and is widely used in exploring system issues and pilot applications. The major characteristics of popular platforms that were designed over the past few years in terms of their processor speed, programmable and storage memory size, operating frequency, and transmission rate can be observed in Table 2-1. In addition, the timeline of those platforms development is presented in Figure 2-3. As can be tracked, the capabilities of those platforms significantly vary from time to time [38].

Table 2-1: Specification of several motes hardware

Mote Type	CPU Speed (MHZ)	Program Mem. (kB)	RAM (kB)	Radio Freq. (MHZ)	Data Rate (kbps)
Berkeley:					
WeC	8	8	0.5	916	10
Rene	8	8	0.5	916	10
Rene2	8	16	1	916	10
Dot	8	16	1	916	10
Mica	6	128	4	868	10/40
Mica2	16	128	4	433/868/916	38.4 kbaud
Micaz	16	128	4	2.4 GHz	250
Cricket	16	128	4	433	38.4 kbaud
EyesIFX	8	60	2	868	115
TelosB/Tmote	16	48	10	2.4 GHz	250
Shimmer	8	48	10	BT/2.4 GHz*	250
SunSpot	16-60	2 MB	256	2.4 GHz	250
BTnode	8	128	64	BT/433-915*	Varies
IRIS	16	128	8	2.4 GHz	250
V-Link	N/A	N/A	N/A	2.4 GHz	250
TEHU-112	N/A	N/A	N/A	0.9/2.4 GHz	N/A
NI WSN-3202	N/A	N/A	N/A	2.4 GHz	250
Imote	12	512	64	2.4 GHz (BT)	100
Imote2	12-416	32 MB	256	2.4 GHz	250
Stargate	400	32 MB	64 MB SD	2.4 GHz	Varies**
Netbridge NB-100	266	8 MB	32	Varies**	Varies**

*BTnode and Shimmer motes are equipped with two transceivers: Bluetooth and low-power radio.

**Stargate and Netbridge: data rate depends on the device communicates with.

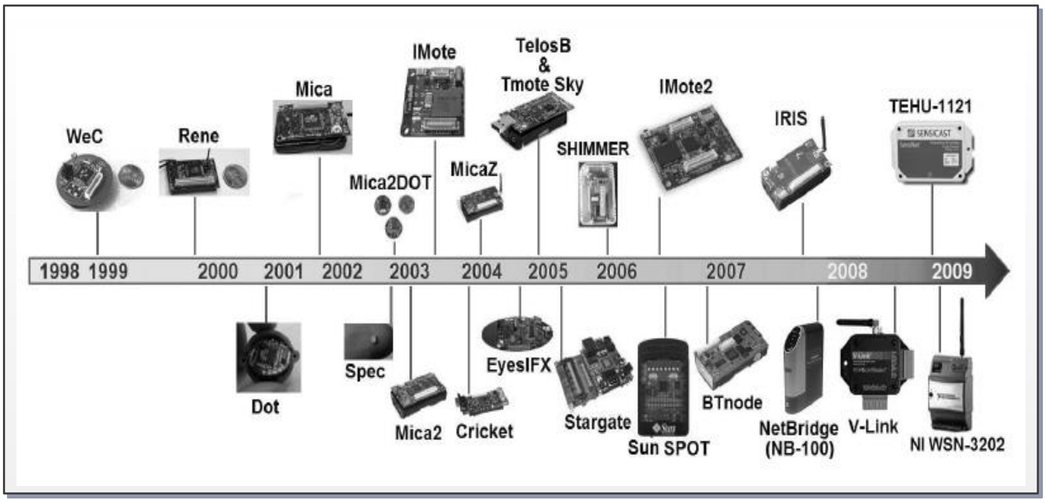


Figure 2-3: Timeline of sensor motes development.

2.2 MAC Protocol for WSNs

In wireless sensor network (WSN), every sensor node is designed to communicate each other without any human intervention and to be left unattended for long time. Because sensor nodes are equipped with limited energy and storage, therefore, most of the medium access control (MAC) protocols for WSN focus on energy saving, such as PAMAS [32], S-MAC [33], B-MAC [39] and the IEEE 802.15.4 MAC [13].

The MAC layer is a sublayer of the data link in the network protocol stacks. The MAC protocol is responsible to manage and control the sensor nodes' access within a shared radio channel using to communicate with neighbour nodes. In wireless technology, there are two categories of MAC protocol, namely contention-based and reservation-based medium access [38, 40]. In a contention-based protocol, each node competes for a shared channel. In consequence, collision can occur during the contention mechanism. Preventing the collision, a node should listen to the channel before transmitting a data packet. This procedure is commonly used in a carrier sense multiple access

(CSMA). Meanwhile, a reservation-based protocol implements either a time division multiple access (TDMA), a frequency division multiple access (FDMA), or a code division multiple access (CDMA) to avoid interference and collision.

In wireless sensor network, the issue of energy consumption and the power resources is a very crucial problem. Because power supply is commonly from batteries that attached in the sensor device, it is impractical to replace the exhausted batteries when the sensor nodes already deployed in the sensor field. Therefore, the main objective of MAC protocol design is to meet the requirement of energy-efficient instead of focusing on throughput improvement [41]. Various methods have been implemented on MAC design to solve the issue of energy consumption in WSNs by researchers from time to time such as in S-MAC [33], ASCEMAC [42], AS-MAC [43], DEEP [44], EMS-MAC [45], ES-MAC [46], and E^2MAC [47].

There are many reasons of energy waste such as collision, overhearing, control-packet overhead, over-emitting, and idle listening. One of the major sources of energy waste is idle listening. Therefore, technique to reduce the idle listening period by which node will be in sleep mode when no data transmission is the most popular method proposed by many researchers [41]. Even though it has introduced the duty-cycled MAC protocol to cope with energy issue due to idle listening and overhearing, MAC protocols for WSN still suffer from one or more issues such as additional latency. Recently, wake-up radio (WuR) systems have constituted a good alternative for tackling the issues to which duty-cycled MAC protocols are prone [48].

2.2.1 Contention-based Medium Access

Most of MAC protocols for WSNs are contention-based medium access, where slots allocated to nodes based on demand and contention mechanism.

The advantage of contention-based protocol is that it scales easily with changes of network size or topology. CSMA is very famous contention-based mechanism where a node should listen to the channel status whether it is busy or idle, before sending a packet. If it detects that the channel is idle, then a node will be ready to transmit. In contrast, a node should wait within a random time in non-persistent CSMA or continue listening until the channel is idle as implemented in 1-persistent CSMA.

MACA [49], IEEE 802.11 standard, and MACAW [50] are some examples of contention-based MAC protocols. In multiple access with collision avoidance (MACA) protocol, a duration field in RTS/CTS is introduced to indicate the list of ready data to send, so that neighbour knows how long to backoff.

Table 2-2: Comparison of MAC protocols in WSN implementing on Qualnet simulator

Protocols	Type	Energy Efficiency	Latency	Throughput
S-MAC	Contention based	Medium	Low	Low
EMAC	Contention based	High under variable traffic	High	Medium
Wise MAC	Contention based	Medium	High	High
DMAC	Contention based	Low	Low	Medium
TRAMA	Contention based	Low	Low	High
Modified SMAC	Contention based	High	Medium	High

The MACAW protocol is the enhancement of MACA. In this protocol, the receiver sends an acknowledgment (ACK) frame to the sender after receiving each data packet. This means to allow rapid link layer recovery from transmission errors. The CSMA-CA mechanism adopted by this MACAW introduces a new handshaking mechanism, which follows the sequence of RTS-CTS-DATA-ACK.

The IEEE 802.11 standard is dedicated for high data rate wireless LANs. The protocol adopts most of the features in CSMA-CA, MACA and MACAW within a distributed coordination function (DCF). Any various enhancements have been included in this standard, such as virtual carrier sense, binary exponential backoff, and fragmentation support. Some other examples of contention-based protocols in WSNs are IEEE 802.15.4, S-MAC and B-MAC. Parameters comparison of some contention-based MAC protocols implementing on Qualnet simulator is depicted in Table 2-2 [51].

2.2.2 Reservation-based Medium Access

In the wireless sensor network, many reservation-based protocols implement TDMA rather than FDMA or CDMA [40]. Preventing any collisions in TDMA, the channel is divided into slots based on the number of nodes but only one node can transmit data in a certain time. Therefore, the packets shall wait for their turn in the queue, which cycle through repeatedly.

The TDMA mechanism is more energy-efficient because it directly supports low-duty cycle operation of nodes. It also succeeds to hinder packet collisions. Besides, a node can conserve the power because it turns on the radio only during data transmission or reception period. Overhearing is also can be overcome by turning off the radio when neighbour node assigned the slots. Unfortunately, TDMA does not support direct peer-to-peer communication and is not adaptive to the network size or network topology changes.

The low energy adaptive clustering hierarchy (LEACH) is an example of the protocols that introduces TDMA mechanism in WSNs [52]. The LEACH protocol promotes 3 main techniques: (i) a new distributed cluster formation scheme, which enables self-organization for large-scale and densely networks; (ii) algorithm for adaptive clusters formation and cluster head rotation to uniformly distribute the energy load among all the nodes; and (iii) technique to optimize a distributed signal processing to meet a resource-efficient. Another example of a TDMA reservation-based protocol is the traffic-adaptive MAC (TRAMA) [34].

2.2.3 Some Other Examples of MAC Protocols for WSNs

In this section, it roughly describes several examples of MAC protocols for WSNs including some important features and contributions. Our focus is on energy conservation and collision avoidance promoted by the protocols. Accordingly, some MAC protocols for WSN are completely listed in Table 2-3 based on compilation from many sources [53, 54, 55, 56].

The first MAC protocol concerns on energy conserving, namely, the power aware multi access protocol with signaling (PAMAS) which was introduced in 1998 [32]. This enhanced protocol saves power by turning off the node's transceiver under certain circumstances. The development of PAMAS originally refers to MACA protocol by enhancing a separate signalling channel. In this new proposed scheme, the handshaking RTS/CTS frames takes place over a signalling channel that is different with the channel used for packet transmissions. This separate technique allows nodes to know when and for how long they can turn the power off. Nevertheless, it seems that PAMAS becomes a more complex protocol because apply two different channels.

S-MAC is inspired by PAMAS to reduce energy consumption by turning the radio off during data transmission by other node and only using in-channel signalling [33, 57]. In addition to apply the sleep and wake up scheduling to conserve energy, S-MAC also introduces a technique to ensure synchronisation among nodes by generating beacon frames, and implementing CSMA-CA to hinder packet collision. The synchronisation technique and beacon frames in S-

MAC protocol are then enhanced in the IEEE 802.15.4 standard where CSMA-CA is implemented with absence of handshaking RTS/CTS frames. To achieve the main goal of S-MAC design, the protocol comprises of four main modules: periodic listening and sleeping, collision avoidance, overhearing avoidance, and message passing.

In 2004, team from University of California at Berkeley introduced a new versatile low power MAC protocol for WSNs so-called B-MAC [40]. To achieve low power consumption, B-MAC protocol proposes an adaptive preamble sampling scheme to shorten duty cycle and minimise idle listening. It also employs low power listening (LPL) to increase power conservation. The idea of LPL technique is to turn the radio off, if it does not detect any preambles until the next sample. The protocol also uses clear channel assessment (CCA) to avoid collision, packet backoff for channel arbitration, and link layer acknowledgment for reliability. If the sending preamble is longer, then receiver will save energy by receiving short preambles less frequently. B-MAC has a set of interfaces, which allow services to tune their operations such as to adjust CCA, acknowledgments, and backoffs.

Lightweight MAC (L-MAC) [58] is a reservation-based protocol uses a TDMA technique. This is a collision-free protocol aims to reduce overhead of the physical layer. It focuses on reducing energy cost by minimising transceiver states switches, which allows the sleeping time for sensor nodes more adaptive to data traffic. The L-MAC protocol is based on a single channel transceiver, but later on, a multi-channel MAC protocol (MC-LMAC) [59] then designed to maximize the throughput of WSNs by coordinating transmissions over multiple frequency channels. The MC-LMAC utilizes the advantage of interference and contention-free parallel transmissions on different channels.

Table 2-3: Several MAC protocols and common network simulator used to evaluate the performance of WSNs

MAC Acronym	MAC Protocol Names	Implementation/ Environment	Development Year
SMACS	Self-organizing MAC for sensor network	-	2000
PACT	Power Aware Clustered TDMA	Simulation, WeC Mote	2001
STEM	Sparse Topology & Energy Management	Simulation	2002
S-MAC	Sensor MAC	Qualnet, GloMoSim, NS2, TOSSIM, Mote test-bed	2002
LPL	Low Power Listening	Mica	2001
Sift	Sift	NS-2	2003
T-MAC	Timeout MAC	MSP430, TNodes, GloMoSim	2003
TRAMA	Traffic Adaptive Medium Access	Qualnet, NS2	2003
WiseMAC	Wireless Sensor MAC	GloMoSim, simulation	2003
E-MACs	EYES MAC	OMNET++	2003
IEEE 802.15.4	IEEE 802.15.4	NS-2	2003
D-MAC	Data gathering MAC	NS-2	2004
L-MAC	Lightweight MAC	OMNET++	2004
B-MAC	Berkeley MAC	Mica2, NS2	2004
S-MAC/AL	Sensor MAC with Adaptive Listening	NS2, Mica2	2004
AI-LMAC	Adaptive Information-centric L-MAC	OMNeT++	2004
BitMAC	Bit MAC	BTnode	2005
MMAC	Mobility-adaptive MAC	NS2	2005
SCP-MAC	Scheduled Channel Polling MAC	Mica2	2005
FLAMA	Flow Aware Medium Access	Qualnet, Mica2	2005
µ-MAC	µ-MAC	NS-2	2005
P-MAC	Pattern MAC	NS-2	2005
TEEM	Traffic Aware Energy Efficient	Mote test-bed	2005
Z-MAC	Zebra MAC	NS-2 & Mote test-bed	2005
X-MAC	X MAC	TelosB, OMNeT++	2006
RI-MAC	Receiver-Initiated MAC	NS2. MICAz	2008
A-MAC	Another MAC	Epic, TelosB	2010

2.2.4 IEEE 802.15.4 Standard

The IEEE 802.15.4 protocol [13] defines the physical (PHY) layer and medium access control (MAC) sub-layer to support networks with simple devices which categorised as less power, low cost operation and maintenance, and operated typically in the personal operating space of tens meters. The emergence of this standard has influenced the faster growth of development and deployment of low data rate, low power and low cost wireless sensor networks.

The standard defines two different types of devices to build a wireless personal access network (WPAN), such as a full function device (FFD) and a reduced function device (RFD). An FFD device can talk to RFD and other FFD devices, and it operates in three mode of services, either as a PAN coordinator, a coordinator or a device. In contrast, an RFD device can only talk to an FFD device and is designed for extremely simple applications. Its source energy can be either from a battery or from a main power supply. As this thesis will concentrate on ad hoc wireless sensor network (WSN), all devices in ad hoc network are router-enabled FFDs to allow peer-to-peer communication.

The IEEE 802.15.4 standard supports a simple star and peer-to-peer topologies, where each topology has its own personal area network (PAN) coordinator with a unique ID. For a large-scale network, RFDs or sensors form the leaves to a cluster-tree topology, where the PAN coordinator becomes a root, and FFDs are appointed as coordinators as shown in Figure 2-4 [60]. An FFD in a LR-WPAN can use either a 64-bit IEEE address or a 16-bit short address assigned during the association procedure. In a 16-bit address, a single network can support up to 65,536 (or 2^{216}) devices [35].

The following subsections describe and elaborate more detail some important design features on the IEEE 802.15.4 physical layer and MAC sub-layer. The comprehensive specifications can be explored in [13] as a revision of the first released standard in 2003, and then followed by several amendments in 2009, 2011, 2012, and 2013, respectively.

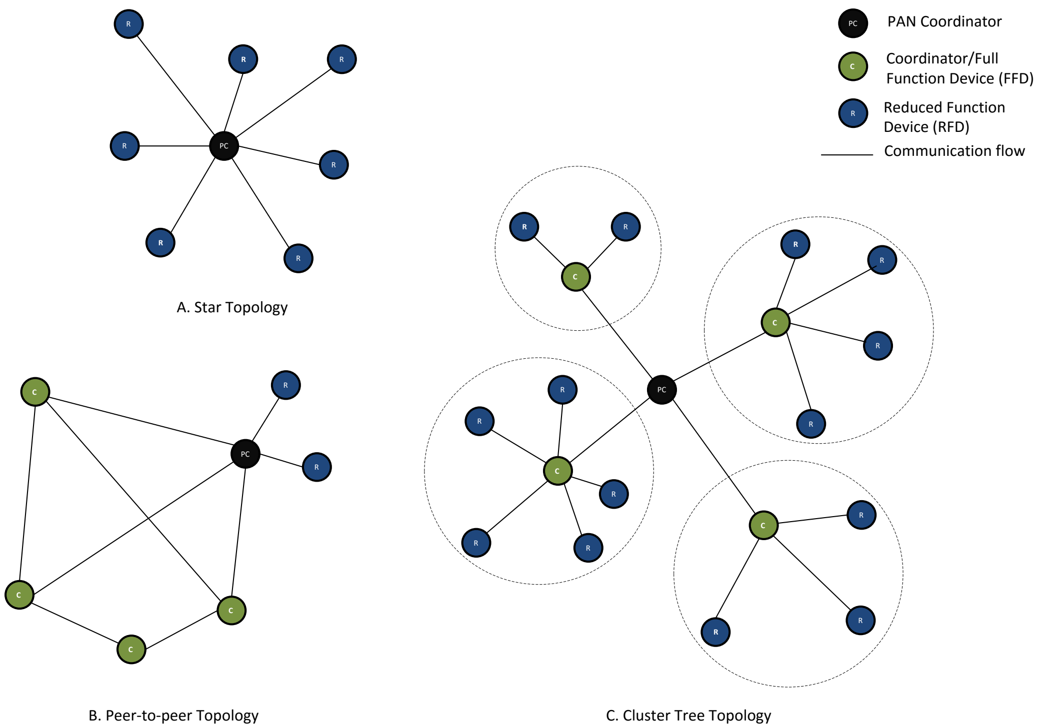


Figure 2-4: Illustration of network topologies supported by IEEE 802.15.4 standard.

2.2.4.1 Physical Layer

Wireless links under IEEE 802.15.4 can accommodate over-the-air data rates of 20 kbps, 40 kbps, 100 kbps, and 250 kbps in three license free industrial scientific medical (ISM) frequency bands. A total of 49 channels are allocated in the IEEE 802.15.4 standard, including 3 channels in the 868 MHz band, 30 channels in the 915 MHz band, and 16 channels in the 2450 MHz band. The ISM 2450 MHz is available worldwide, while ISM 915 MHz and 868 MHz bands are available in North America and Europe, respectively. The features of each frequency band are summarised in Table 2-4. The ISM 868 MHz, 915 MHz, and 2450 MHz bands are based on the direct sequence spread spectrum (DSSS) spreading technique, while ISM 868/915 MHz are also optionally based on parallel sequence spread spectrum (PSSS).

Table 2-4: Operating frequency bands, modulations, bit rates supported in IEEE 802.15.4 standard

PHY Frequency (MHZ)	Chip rate (kchip/s)	Modulation	Bit rate (kbps)	Symbol rate (ksymbol/s)	Symbols
868	300	BPSK	20	20	Binary
915	600	BPSK	40	40	Binary
868*	400	ASK	250	12.5	20-bit PSSS
915*	1600	ASK	250	50	5-bit PSSS
868*	400	O-QPSK	100	25	16-ary Orthogonal
915*	1000	O-QPSK	250	62.5	16-ary Orthogonal
2450	2000	O-QPSK	250	250	16-ary Orthogonal

*Optional

The physical (PHY) layer is an interface layer between the upper MAC sub-layer and the lower physical radio channel. It handles two services including the PHY data service and the PHY management service. The physical layer of the IEEE 802.15.4 is responsible for the following tasks [16]:

- ❖ **Activation and deactivation of the radio transceiver**: in this task, the PHY layer is responsible to switch OFF/ON the radio transceiver into the three states: transmitting, receiving or sleeping. The mode chosen depends on the MAC sub-layer command. The turnaround time of transmitting-receiving or vice versa takes less or equal to 12 symbol periods.

- **Energy detection (ED) within the current channel:** it results an estimation of the received signal power without any attempts to identify or decode signal within the channel. The energy detection time is equal to 8 symbol periods, which can be used by the network layer for clear channel assessment (CCA) purpose.
- **Link quality indication (LQI):** in the PHY layer, it uses LQI to measure the quality of sending packets. The LQI is proportional to the signal level, or a signal-to-noise estimation, or a combination of those methods where the value taking from 0 to 255. In the network simulator NS-2, it defines the LQI is as the equation below:

$$LQI = \left(\frac{E_{rx}}{E_{Th}}\right) * LQI_{min} \quad \text{(2-1)}$$

$$LQI_2 = \left(\frac{E_{rx}}{E_{Tot}}\right) * LQI_{max} \quad \text{(2-2)}$$

If $LQI > LQI_2$, then $LQI = LQI_2$ .... (2-3)

where LQI_{min} equals to 128 and LQI_{max} equals to 255. E_{rx} is the receiving power, E_{Th} is the receiving power threshold, and E_{Tot} represents the total power consumption of receiving packets.

- **Clear channel assessment (CCA)**: when a node starts transmitting data, the PHY layer should monitor the medium in either busy or idle by performing clear channel assessment. The CCA can be performed in one of the following 3 schemes:
  1. Energy detection scheme, where energy detection reports a busy medium if it detects that energy is above the value of ED threshold.
  2. Carrier sense scheme, where the medium is busy if it finds that a signal with modulation and spreading characteristics of the IEEE 802.15.4 is not similar with ED threshold.

3. Combination of carrier sense and energy detection scheme, when it detects a combination of modulating and spreading characteristics of the IEEE 802.15.4 signal with energy above the ED threshold, then it reports the medium is busy.

- **Channel frequency selection:** The PHY layer in IEEE 802.15.4 can select one of 49 channels and set the transceiver into a channel requested by upper layer during the channel selection process.
- **Data transmission and reception:** this is the essential task of the PHY layer where modulation and spreading techniques are involved in this task.

2.2.4.2 Medium Access Control Sub-Layer

The MAC sub-layer is an interface between the lower layer (PHY) and the upper layer (SSCS) which is service specific convergence sub-layer. The MAC sub-layer also provides two services of the MAC data service and the MAC management service. The detail tasks of MAC sub-layer are explained as below [16]:

- **Generate network beacons**: in the mode when beacon-bounded superframe is used, a coordinator can generate and sends out beacons periodically to synchronise the attached devices and for other purposes.
- **Synchronise to the beacon**: in beacon-enabled mode a device associated to a PAN coordinator are able to track the beacon for synchronisation purposes. This procedure is necessary to enable data polling, energy saving, and detection of orphaning nodes.
- **Support PAN association and disassociation**: this embedded association and disassociation in IEEE 802.154 MAC protocol aims to support self-configuration networks. Those functions allow to setup and create both self-configuring simple star and peer-to-peer network.

- **Support device security**: the MAC sub-layer support cryptographic mechanism based on symmetric-key cryptography to provide security services on specified incoming and outgoing frames when requested to do so by the higher layers. The standard supports 3 security services: data confidentiality, data authenticity, and replay protection.
- **Employ CSMA-CA mechanism**: the IEEE 802.15.4, similar with most other protocols for wireless networks, uses carrier senses multiple access with collision avoidance (CSMA-CA) mechanism for channel access.
- **Manage GTS mechanism**: in a beacon-enabled mode, a PAN coordinator can manage and allocate the slots of the active superframe to a device without any contention. These portions are called guarantee time slots (GTS) which is slotted during the contention free period (CFP) of the superframe.
- **Provide a reliable link:** to enhance the reliability of the link between two peers, the protocol employs various mechanisms such as sending acknowledgment frame, retransmission, using a 16-bit CRC to verify data, and implementing CSMA-CA mechanism.

The superframe comprises of an active period and an optional inactive period, and is bounded by network beacons as shown in Figure 2-5. An active duration of the superframe is divided into $aNumSuperframeSlots$ (default value 16) equally-sized time slots, during which frame transmissions are allowed, and the first slot of each superframe must be allocated to beacon frame. A contention access period (CAP), an optional contention free period (CFP) and beacon occupy the active period of the superframe. During the contention free period, PAN coordinator may assign up to seven particular time slots so-called guaranteed time slots (GTSs) to a specific device. In contrast, channel access during the CAP portion uses slotted carrier sense multiple access with collision avoidance (CSMA-CA) mechanism.

The beacon intervals are determined by two parameters, which are beacon order (BO) and superframe order (SO). The length of superframe so called beacon interval (BI) and the length of its active part known as superframe duration (SD) are defined as follows:

$BI = aBaseSuperframeDuration * 2^{BO}$ .... (2-4)

$for\ 0 \leq BO \leq 14$

$SD = aBaseSuperframeDuration * 2^{SO}$ .... (2-5)

In (2-4) and (2-5), $aBaseSuperframeDuration$ is equal to 960 symbols which corresponds to 15.36 ms, therefore, each symbol is equal to 0.016 ms [61]. The information regarding superframe specification in beacon frames is to ensure synchronisation among nodes. Figure 2-6 illustrate the beacon frame format and superframe specification field, while data frame format and physical packet in the IEEE 802.15.4 standard are shown in Figure 2-7.

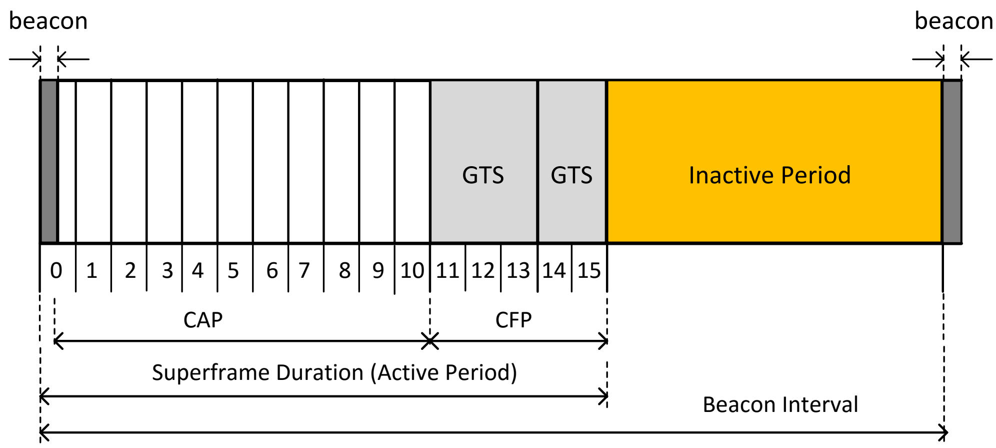


Figure 2-5: Superframe structure of beacon-enabled mode in the IEEE 802.15.4 standard.

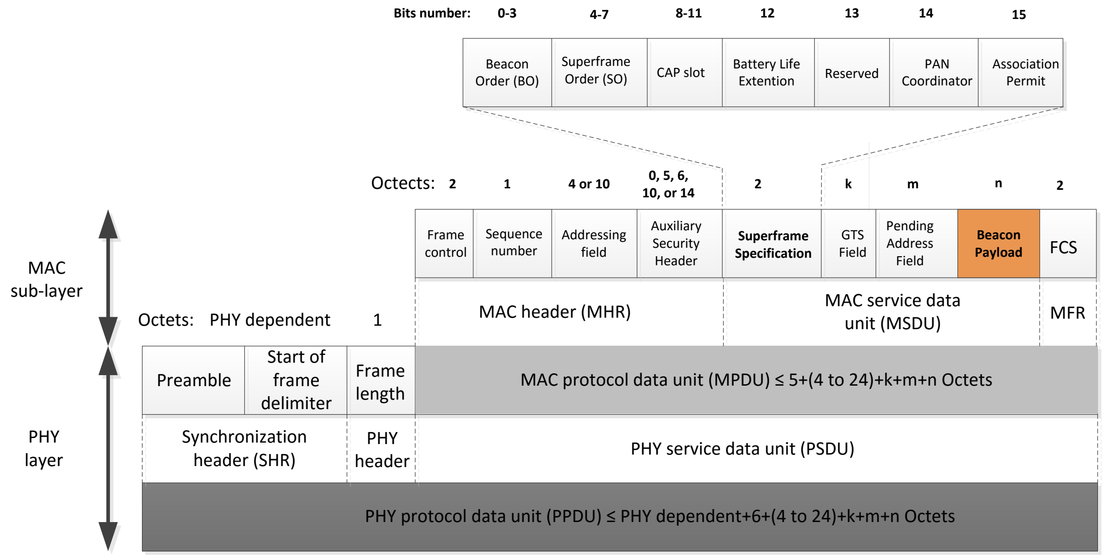


Figure 2-6: Beacon frame format with superframe specification and PHY packet.

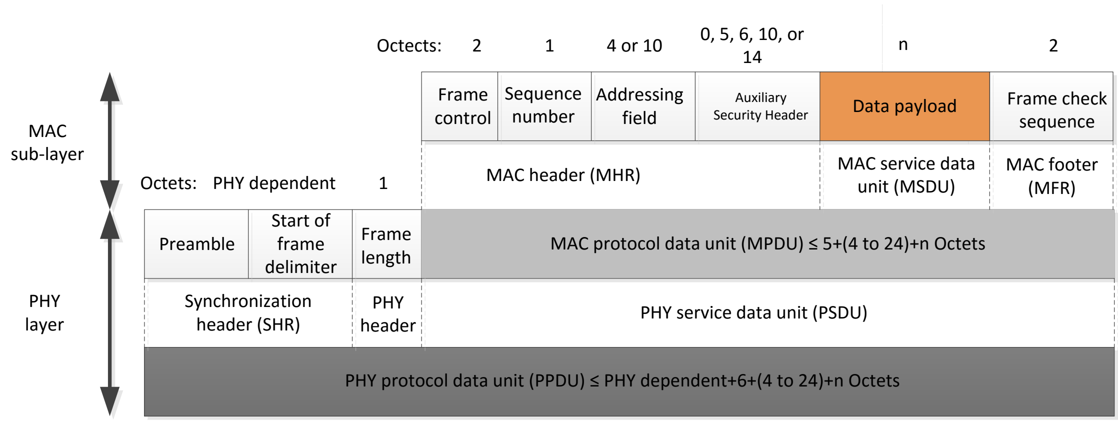


Figure 2-7: Data frame format and PHY packet in the IEEE 802.15.4 protocol.

Scanning through Channel: The IEEE 802.15.4 standard defines four types of channel scans where all devices are capable of conducting passive and orphan scans whilst full function devices should be able to perform energy detection

(ED) and active scans. All those types of channel scanning are elaborated more as follows:

1. **ED Channel Scan:** a PAN coordinator can select an appropriate channel within it starts communication in a new PAN. The channel selection is based on the measured peak energy in each requested channel. Therefore, the MAC sub-layer should discard all frames received over the PHY data service during the ED channel scanning.
2. **Active Channel Scan:** This channel scan allows a full function device to identify which coordinator transmits beacon frames within its coverage area. This scanning result is needed either to select a PAN identifier by a prospective PAN coordinator in order to begin a new PAN or it is used by a device before performing association procedure. All beacon frames should be kept whilst all frames received over the PHY data service shall be removed by the MAC sub-layer during this active scan. An FFD scanning shall not attempt to extract the pending data when a received beacon frame contains the pending address of the scanning device.
3. **Passive Channel Scan:** this passive channel scan is similar with active channel scan, yet it does not transmit the beacon request command. Besides, the passive scan is needed by a device prior to association.
4. **Orphan Channel Scan:** a device can attempt to relocate its coordinator by orphan channel scanning when it loses synchronisation with a coordinator. During an orphan scan, coordinator realignment command frame is kept by the MAC sublayer while it discards all frames received over the PHY data service. Meanwhile, if the specified set of logical channels has been scanned or a coordinator realignment command has been received by device, then the orphan scan should be terminated.

Association and Disassociation: The association process begins either with active or passive channel scan. Similar to the active scan, the passive scan allows a device to track location of any coordinator transmitting beacon frames within its coverage area. A suitable PAN is determined based on the scan results and characterized by its attributes which will be required by the next higher layer after an association is accomplished.

If a PAN coordinator allows devices to associate with, then it sets the $macAssociationPermit$ to TRUE. A device should try to associate with a PAN that is currently permitting association, respectively. When association is successful, then the device stores the short address of its coordinator in $macCoordShortAddress$ and the extended address is in $macCoordExtendedAddress$. Otherwise, association request commands will be ignored only if the PAN coordinator sets the $macAssociationPermit$ to FALSE. If the association is failed, then the device states the $macPANid$ to the default value $(0xffff)$.

The disassociation process might be initiated by either a coordinator or the device itself. In the first scheme, when a coordinator disassociates its associated device, it will transmit the disassociation notification command to the device using indirect transmission. Since the disassociation notification command frame is received by the device, it should then send an acknowledgement (ACK). Whether the ACK is received by the coordinator or not, it considers that the device is already disassociated. A PAN coordinator, therefore, deletes all references related to the disassociated device.

In contrast, the second scheme is when the device initiates to leave a PAN network. In this condition, device delivers a disassociation notification command to its coordinator. The coordinator sends back an acknowledgement to confirm the request. The device considers itself as disassociated, even though it does not receive the ACK. The device then removes all its references to the PAN.

Synchronisation: The standard provides procedure for coordinators to generate the beacon frame and for the devices to synchronise with a coordinator. The synchronisation can be performed both with beacons and without beacons.

In beacon-enabled network ($macBeaconOrder < 15$), all associated devices should synchronise the transmission with their coordinator after receiving and decoding the beacon frames. By this procedure, the associated devices are able to detect any pending messages or to track the beacons. The standard allows completing the beacon synchronisation with tracking or evenly without tracking.

A synchronisation problem happens in beacon-enabled network when a device fails to receive the beacon from its coordinator, or when the maximum transmission retries is failure. In this situation, the node decides to become an orphan device and then follows the orphaned device realignment procedure or re-associates with a new coordinator if the orphan scan comes to failure.

On the other hand, all devices operating on a beaconless-enabled PAN ($macBeaconOrder = 15$) are able to perform synchronisation by polling the coordinator for data and then follow the procedure to extract the pending data from the coordinator. The flowchart of node association and synchronisation is presented in Figure 2-8.

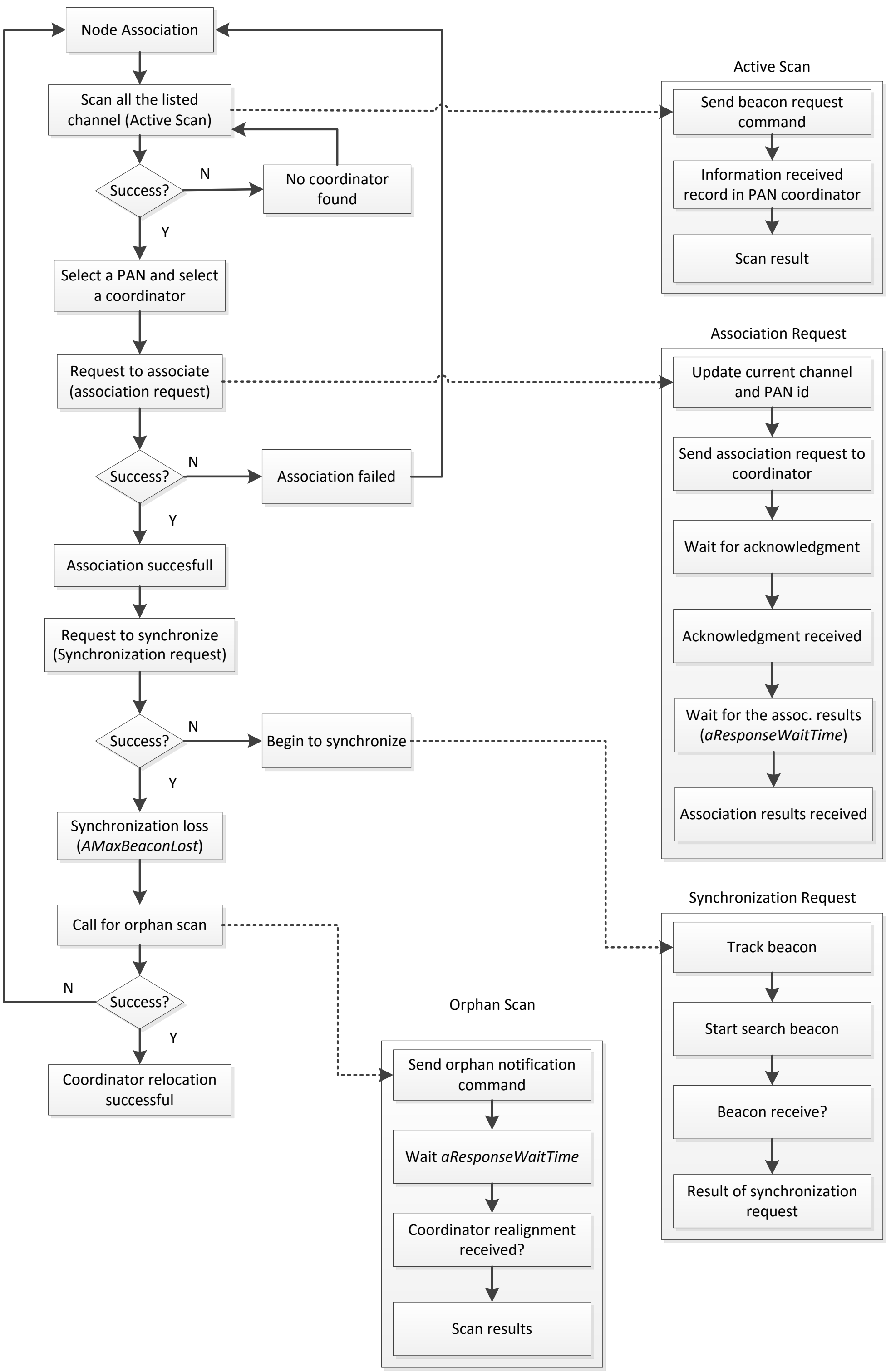


Figure 2-8: Association and synchronisation algorithm in IEEE 802.15.4 standard.

2.3 Some Applications of Ad Hoc WSNs

The main goal of wireless sensor network deployment is to capture some physical aspects of environment, which related to human life. In [6], WSNs application is classified into two main categories, which are monitoring and tracking objectives. The first category designed to monitor several indoor or outdoor environment aspects; wellness and health; power generation, distribution, and consumption; inventory, supply chain, and industrial process; and factory or structural building. The second application covers animals, humans, vehicles or traffics, data, and objects tracking. All those applications might work on densely static sensor nodes, some of them use mobile sensor nodes, or implement interactively between mobile and static nodes in the network. In the following sub-section, it will elaborate firstly some example of WSNs applications for healthcare, indoor environment, and traffic monitoring. Secondly, it gives more detail example of WSNs applications for search-and-rescue system and animal tracking.

2.3.1. Monitoring

There are several applications of ad hoc wireless sensor networks that can be categorised as monitoring-based application including healthcare monitoring [62] i.e. CodeBlue [63]; habitat monitoring [64]; indoor environment monitoring i.e. Povomon [39]; and traffic monitoring i.e. ScanTraffic [66].

CodeBlue is a wireless infrastructure implemented in TinyOS and deployed in the emergency medical care, which integrating low-power wireless vital sign sensors and end-user devices such as PCs, hand-held PDAs, or tablets. It is designed to be an information centre to support very large-scale ad hoc networks where thousands of mobile devices communicate with a reliable data delivery, a flexible naming and discovery mechanism, and a distributed security model.

The system still lacks of mobility where it just supports the low speed of movement like person walking and lack of energy conservation mechanism where the emergency event is used to wake the node up and to send data packet.

Figure 2-9: The Povomon implementation at the University of Trento Italy.

The Povomon is an open-data internet of thing (IoT) sensor network project, which aims to respond the need of environmental monitoring and intelligent sensing for buildings automation system and power grids management. In February 2014, the team from Department of Information Engineering and Computer Science, University of Trento North Italy firstly deployed the Povomon network, which consists of tiny sensor nodes at their building as can be seen in Figure 2-9.

The Povomon can monitor continuously various ambient quantities at the university building where hundreds people working and walking around. The Povomon network comprises of low power sensor nodes, which allows the flexible deployment of the sensor devices. Nowadays, the building environment aspect that monitored by the Povomon are lightening, vibration, temperature, and humidity. Besides, it also focuses on smart grids management of the entire buildings.

Implementation of wireless sensor networks for intelligent transportation system (ITS) so-called ScanTraffic was proposed by [66]. They develop some modular architectures including software to monitor, configure, and update the codes remotely. The prototype of ScanTraffic was deployed in the parking area and main intersection of the Pisa International Airport as can be viewed in Figure 2-10.

Figure 2-10: Deployment of ScanTraffic at the Pisa International Airport where several flow sensors placed at main intersection and parking sensors deployed in both indoor and outdoor parking lots.

2.3.2. Tracking

In this section, it elaborates more detail the two examples of ad hoc WSNs for tracking-based applications such as CenWits [67] and cattle tracking [68].

CenWits is a search-and-rescue application with occasional connectivity sensor-based tracking system implemented using Berkeley Mica2 motes. CenWits consist of mobile sensor, access point (AP), GPS receiver, and location point (LP). They main concept of CenWits is using witnesses to deliver all information measured and captured to the information centre. Therefore, the CenWits is designed to accurately determine and approximate the concentration area of search-and-rescue activities.

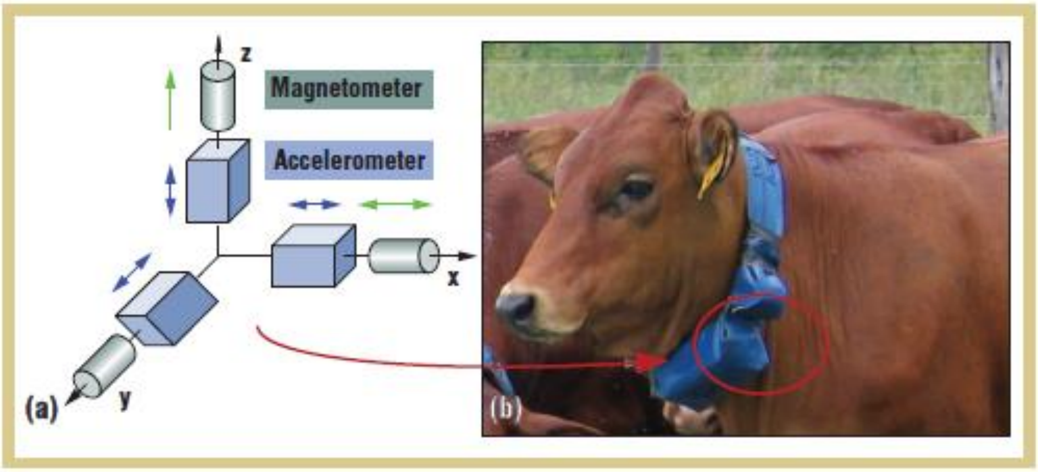


Figure 2-11: The sensor device is attached at the cow's collar to monitor animal-landscape interaction.

The CSIRO (Australia's Commonwealth Scientific and Industrial Research Organization) developed the application so-called smart farm that implemented wireless sensor network technology to animal agriculture aims to meet criterion of an optimal, profitable, and sustainable management of land and water resources. One of the supporting systems they have developed is cattle sensor network [68] where the sensor-based tracking application used to track the animal location where sensors are attached at the cattle's collar (Figure 2-11).

2.4 Research on IEEE 802.15.4 Standard

Since the IEEE 802.15.4 was released in 2003, several improvements and enhancements have been proposed by many researchers and developers including channel access mechanism implementing in the standard. A novel Markov chain for medium access control of the IEEE 802.15.4 protocol has been used by [69] to capture all major features of MAC mechanism to find the strengths and weaknesses of the channel access method. The Markov chain is used to model the contention access period (CAP) within a superframe structure, where it focuses on the slotted carrier sense multiple access with collision avoidance (CSMA-CA) mechanism. In order to improve the protocol performance in term of throughput, delay, and power conservation, it modifies the use of dual carrier sense specified in IEEE 802.15.4 MAC standard. In addition, a simulation tool was developed by [35] to evaluate the performance of slotted CSMA-CA related to some parameters. Furthermore, the parameters such as overheads, beacon orders (BOs) and superframe orders (SOs), backoff exponents (BOs), number of nodes, and frame size are then optimized to have a more flexible and adaptive slotted CSMA-CA mechanism for large-scale wireless sensor networks.

Throughput improvement and power conservation was achieved in [70] by adjusting the contention active period (CAP) in superframe structure for beacon-enabled mode in the IEEE 802.15.4 protocol. To cope with the weaknesses of fixed superframe active period, it developed mechanism to adjust the active duration size adaptively based on the data traffic information. Related to energy efficiency issue, the node is asleep even along the active period if there is no data transmission. Meanwhile, a channel management scheme using multi-dimensional scheduling (MDS) was proposed by [71] where the scheduled-based analysis was used to tune the superframe duration (SD) and beacon interval (BI) parameters in order to hinder beacon conflicts.

In the work [72], the performance of tree-topology WSNs over IEEE 802.15.4 beacon-enabled protocol is respectively evaluated by applying different traffic loads, and various beacon orders (BOs) with certain number of hops between source nodes and sink nodes. The evaluation indicates that the network suffers from high number of hops, while impact of the BOs is less significant than of the traffic loads.

In addition, a survey of various improvement of the IEEE 802.15.4 beacon-enabled protocol is widely presented [12]. It points out not only the distinguished strengths of IEEE 802.15.4, which contributes to its popularity in wireless sensor networks, but also several limitations that deteriorate its performance. The fact that network over IEEE 802.15.4 MAC protocol usually suffers from interference has motivated efforts to enhance this MAC protocol. Therefore, the paper also highlights some schemes they proposed to enhance the MAC protocol performance.

The IEEE 802.15.4 standard supports both beacon and beaconless modes. Whilst many researchers pay much more attentions to beacon-enabled mode, some of them are interested in exploring the beaconless-enabled mode. A dynamic scheme in the IEEE 802.15.4 protocol, which enables node to adjust its MAC configuration, based on the observing loss rate and latency for its recent packet generated by the node [73]. This approach effectively improves the network performance even though the network is under varying traffic load over short time-scales.

In [74] the authors present a performance evaluation of the IEEE 802.15.4 nonbeacon-enabled mode for internet of vehicle (IoV) application. Their works considered two major features, which are non-saturated traffic pattern and large-scale network of IoV applications. They contribute by identifying the CCA problem, developing a semi-Markov model, and then applying the model into two experiments including vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications.

Since all the previous literatures reviewed are focused on static WSNs, the following papers [24, 75, 76] took the node mobility into account on the proposals. Unfortunately, the moving sensor can severe the re-association and association processes in IEEE 802.15.4 standard. Therefore, the author of [24] investigated the impact of changing beacon order (BO) on throughput, speed, and energy for mobile nodes in WSN. In [75] it proposes a so-called mobile-supporting for sensor MAC (MS-SMAC) protocol where the speed of moving node is considered in decision to update the mobile node neighbour, adaptively. Meanwhile, design and implementation of a heterogeneous dynamic mobile sensor network (MSNs) platform, which comprises of static sensors, moving sensors, mobile gateways, and sink servers, are presented in [76]. The platform design aims to cope with the lack of current designs, where they are not adaptive enough to be implemented in various networking circumstances and applications.

2.5 Summary

In this chapter, it presents a brief overview of wireless sensor network including the emergence of wireless sensor networks, which was stimulated by a lot of great inventions and innovations in semiconductor manufacturing techniques, access network technologies, computing network and programming.

The chapter concentrates on elaboration of a very promising protocol for wireless sensor network among others which is the IEEE 802.15.4 standard. This standard supports a simple physical (PHY) layer and an energy efficient medium access control for several applications of wireless sensor networks.

This section aims to give broad view of the related MAC protocols, which support WSN application, focusing on MAC protocol for ad hoc wireless sensor network provided by IEEE 802.15.4 beacon-enabled mode. Finally, the ending part of this chapter gives example of applications of WSNs and presents several works accomplished by many experts and researchers. Nevertheless, many gaps and opportunities are still challenging on WSNS researches, nowadays and in the next future.

Chapter 3

Performance Evaluation of IEEE 802.15.4 Beaconless-Enabled MAC Protocol for Low Data Rate Ad Hoc Wireless Sensor Networks

3.1 Introduction

In a few recent decades, the tremendous worldwide growth of wireless communication industries has been a very attractive and a truly phenomenal. Mostly, information exchanged industries are currently integrating all voice, video, and data services as well as internet access and enjoy the revenue of several trillion dollars [77]. Meanwhile, a number of common problems are still challenging in all wireless access technologies, including traditional mobile phone access, wireless personal access, and wireless broadband multimedia access, such as fundamental problems of interference, spectrum scarcity, and scalability. The availability of spectrum is playing the main role; while time-by-time, the emerging of most applications requires bigger and bigger data and a real time data transfer. Such condition attracts many researchers to cope with these limitations [78, 79, 80].

Some potential wireless network applications have less requirement on network throughput or it is even measured in a few bits per second. Those applications include industrial control and monitoring; consumer electronics, building or home automation, and household power management; security and military sensing; asset tracking and supply chain management; intelligent agriculture; and health monitoring [81, 82]. Those applications require lower power consumption and less complexity wireless links, they hence need less power and lower cost devices. The low power consumption is a critical issue in developing the medium access control (MAC) protocol for wireless sensor networks [33, 10, 11, 83, 84]. The IEEE 802.15.4 is one of many standards addressed to accelerate deployment of low rate wireless sensor networks.

The mechanisms for data transfer depend on whether the network supports transmission of beacons or not. A beacon-enabled network is used for supporting low-latency devices, such as PC peripherals. If the network does not need to support such devices, it can elect not to use the beacon for normal transfers.

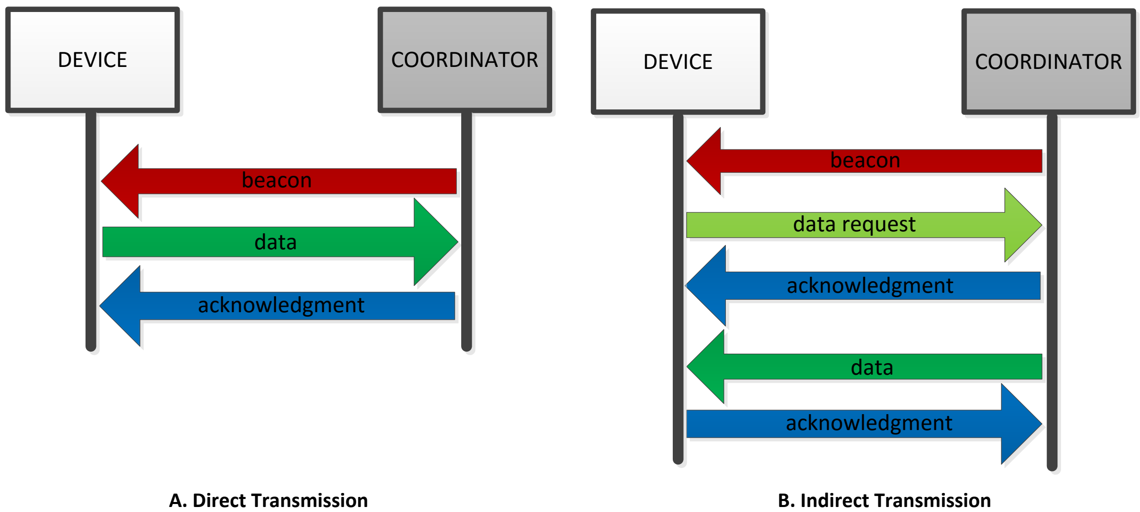


Figure 3-1: Data transmission in beacon-enabled mode: direct transmission and indirect transmission.

The IEEE 802.15.4 standard allows 3 modes of data transfer such as: (i) from devices to coordinator; (ii) from coordinator to devices; and (iii) among the devices in multi hop peer-to-peer networks. Figure 3-1 shows both direct and indirect data transmission for beacon-enabled mode, while Figure 3-2 points out data exchange scheme for beaconless-enabled mode. Those data exchange modes can be explained as below:

a) Direct data exchange: this scheme of data transmission commonly applies for all data transferring, either from devices to a coordinator, from a coordinator to devices, or between two peers. This mode of data transmission will be used in our experiment. (see Table 3-1)

b) Indirect data exchange: this mode of data communication only applies for data transferring from a coordinator to its devices.

c) Guarantee time slot (GTS) data transmission: this special scheme applies for data exchange at certain dedicated-slots provided by coordinator. The data transfer might be from devices to a coordinator or from a coordinator to devices.

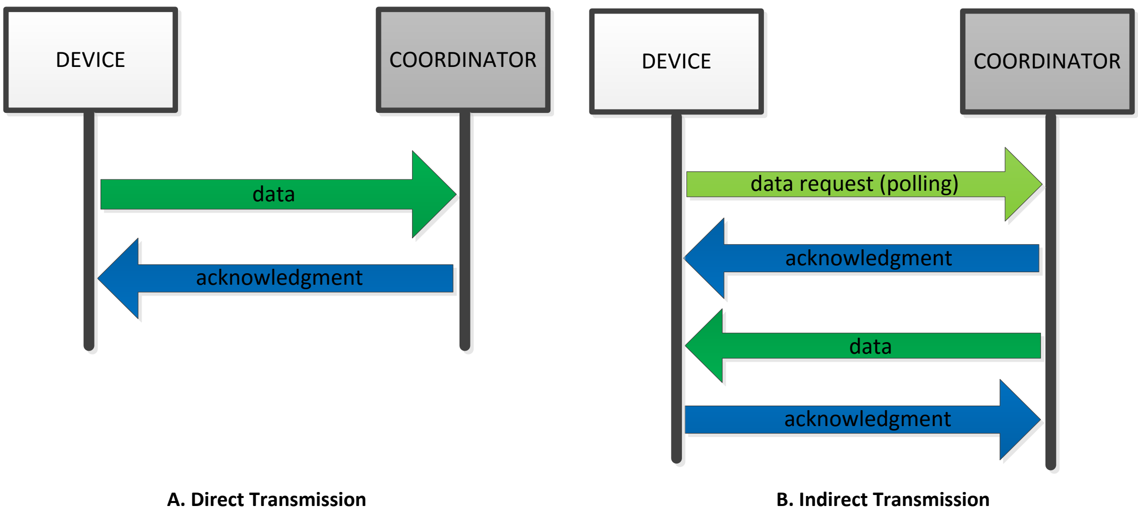


Figure 3-2: Data transmission in beaconless-enabled mode: direct transmission and indirect transmission.

3.2 Channel Access Mechanism

The IEEE 802.15.4 standard introduces two types of channel access mechanism, i.e. un-slotted CSMA-CA which is used on beaconless-enabled networks; and slotted CSMA-CA which is implemented on the network where the backoff slots should be aligned with beacon transmission. The CSMA-CA algorithm shall be used before data or MAC command frames transmission during contention access period. On the other hand, this CSMA-CA mechanism should not be needed for beacon, acknowledgment, or data frames transmission within contention free period. The two types of channel access algorithms can be learned from Figure 3-3 [13].

Figure 3-3 shows process of CSMA-CA algorithm in the standard IEEE 802.15.4 protocol. A node firstly initializes a number of backoffs, contention window and backoffs exponent. It waits for collision avoidance before transmitting data. After a random waiting delay has elapsed, then a clear channel assessment (CCA) should be started at boundary of a backoff period. If channel is idle, node may start its transmission, otherwise it backoffs for a random period until a maximum number of trials. If it still cannot access the channel, the algorithm terminates process with a channel access status failure.

In both slotted and unslotted mechanisms, the algorithm is implemented using time unit so called backoff period, where one backoff period is equal to a constant, i.e. *aUnitBackoffPeriod* (20 symbols). The CSMA-CA algorithm will attempt a maximum number of backoff before clarifying a channel access failure, i.e. *macMaxCSMABackoffs*, which can be varied from 0 to 5 (4 in default).

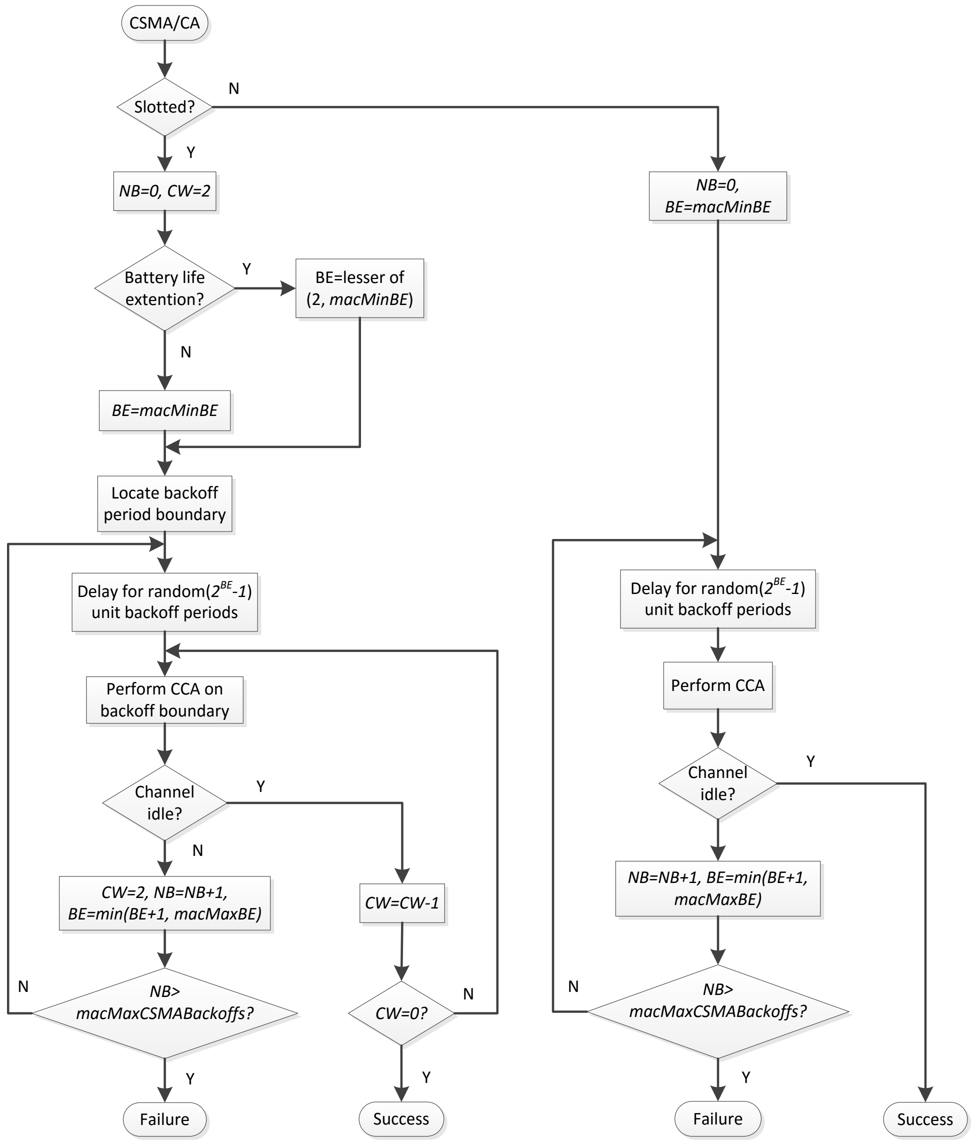


Figure 3-3: Carrier sense multiple access with collision avoidance (CSMA-CA) algorithm.

3.3 Ad Hoc Wireless Sensor Networks Overview

IEEE 802.15.4 standard supports both slotted and un-slotted CSMA/CA mechanisms. In the standard, there are two modes of communications supporting by IEEE 802.15.4, which are beacon-enabled and beaconless-enabled modes. The first mode can be operated on the so-called an infrastructure-based wireless network. In contrast, the second mode is able to build communication among nodes without firstly constructing the WPAN coordinator. This network is known as infrastructure-less or ad hoc wireless network [25].

The infrastructure-based wireless network is less efficient in costs related to purchasing and installing the resources. Therefore, this mode may not be suitable for dynamic environments in which people or devices need to communicate temporarily. This will cost more in areas without any pre-existing communication infrastructures such as in disaster areas, remote areas, or battlefields. In all those cases, the infrastructure-less or ad hoc mode provides the more efficient solution [25].

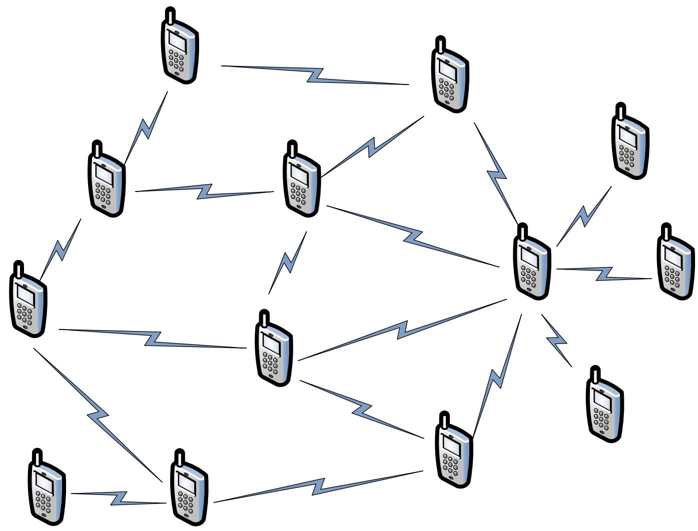


Figure 3-4: Example of ad hoc wireless sensor networks topology.

Wireless personal area networks (WPAN) comprises of at least a PAN coordinator, coordinators, and devices. A PAN coordinator, in general, has two functions: to handle multiple nodes association/disassociation and to allocate addresses when it is on beaconless-enabled mode network. The last function can be performed by each device that has a 64-bit address by default, while the first function can be handled by full function device (FFD) nodes. Therefore, ad hoc or beaconless wireless sensor network (BeWSN) has to be configured and supported by some FFDs or router-enabled devices. Ad hoc wireless sensor networks operate in any topologies such as star, mesh, or hybrid where all nodes homogeneously have such function of FFDs instead of RFDs (reduced function devices). An example of ad hoc wireless sensor network topology can be seen in Figure 3-4.

In ad hoc WSN network, each node can detect the default channel of all other nodes to find its neighboring nodes. When neighboring node identification process is completed, then peer-to-peer-communication could be started. Therefore, all nodes are always in active to keep engaging with the network.

3.4 Related Research

Development of network simulator NS-2 for IEEE 802.15.4 has enabled many studies on performance evaluation with various features [16, 35]. Also, in [15] the IEEE 802.15.4 MAC prototype on the NS-2 network simulator was implemented to provide simulation-based performance evaluation, focusing on its beacon-enabled mode for a star-topology network. A new dynamic channel management to avoid beacon collision was proposed in [71]. On the other hand, some papers [85, 86, 87] provided a lot of analytical models for beaconless-enabled mode of the IEEE 802.15.4 medium access control (MAC) protocol. Most of the previous works on IEEE 802.15.4 performance study were based on either the simulation or mathematical analysis. Therefore, Lee [18] carried out a preliminary realistic experiment. An investigation and mapping of the link quality distribution in an indoor building environment was conducted by [88]. A simple wireless sensor network was deployed in an indoor office building with concrete floors, brick walls and plasterboard internal partitions. Otherwise, in [19] Woon and Wan introduced ad hoc wireless sensor networks performance evaluation based on simulation and test-bed approach. Meanwhile, a WSN prototype [89] is presented to demonstrate its extended-range in different indoor environment and analyse the performance by both measurement and simulation. In addition, hidden nodes problem is one of the main constraints on ad hoc wireless networks, which have been attracting more concern of many researchers on developing and optimizing a plethora of techniques from time to time [21, 90, 91]. Also in the previous study, we considered this phenomenon which causes performance degradation [23]. Since most of researchers hitherto focused on static nodes, the authors of [24, 75] investigated the impact of changing beacon order (BO) on throughput, speed, and energy for mobile nodes in WSN, while [92] studied how network formation affected by mobility of sink nodes.

This chapter will elaborate a performance study of existing IEEE 802.15.4 protocol which has been performed [20] to evaluate the proposed low data rate ad hoc wireless sensor networks via several sets of simulation, including impact of the traffic loads and data payload sizes. A performance comparison with IEEE 802.11 protocol has been scrutinized to approach the potential problems might cause performance deterioration. Some changes and deficiencies of the previous study [20] will be pointed out in this chapter of the thesis.

3.5 Problem Statement

From time to time, wireless network has been evolved to cope with the increasing end-users demand in terms of data rate, scalability, reachability, mobility and ease of use. The recent advancements of wireless network access technologies provide a platform of ubiquitous communication for multiple types of data including voice, multimedia, and other web-based applications. However, the main challenges are scalability and air data rate of wireless communication due to the natural aspect of wireless medium and the availability of finite spectrum.

IEEE 802.15.4 defines the specification of physical layer and medium access control (MAC) sub-layer for low rate wireless personal access networks (LR-WPAN). This standard has been accelerating the deployment of wireless sensor networks (WSNs) and development of supporting technology as well.

The main characteristics of WSN are low data rate, low power consumption, and low production and maintenance cost. IEEE 802.15.4 employs a carrier sense multiple access with collision avoidance (CSMA-CA) mechanism and supports single-hop star networks and multi-hop peer-to-peer networks as well. In both network topologies, the first step to start communication is assigning the wireless sensor network (WSN) coordinator in order to manage and maintain network resources. This procedure can potentially cause network bottleneck in centralised WSN coordinator and consume more energy. Besides, it makes the networks less flexible with unrecoverable nodes. Therefore, in this thesis it proposes the IEEE 802.15.4 beaconless-enabled protocol for ad hoc wireless sensor networks as the solutions to cope with all those mentioned problems.

3.6 Performance Evaluation

The performance evaluation is conducted by simulation using network simulator NS-2 modeller, version 2.34 [26, 29]. The simulation settings and parameters are elaborated in the subsequence sections.

3.6.1. Network Simulator NS-2

The NS-2 simulator is a very famous simulation tool for researchers in the area of wireless sensor communication as well as for communication network generally [27]. NS2 is one of the discrete event network simulators widely used to study various real network scenarios. NS2 is open-source-based software and is originally designed to simulate wireline communication networks. It is then expanded and developed to simulate wireless networks including, wireless local area networks (LANs), mobile ad hoc networks (MANETs), and wireless sensor networks (WSNs). In [93], it points out that almost 57% of simulation-based papers have worked on networks simulator NS2 as a tool, which strongly proves that NS2 is a trusted and widely used network simulator.

The module of IEEE 802.15.4 protocol on the simulator NS2 was developed by collaboration team of Samsung and the City University of New York. Outline of module functions in the simulator can be found in Figure 3-5. A brief explanation of those modules is given as follows [16].

- *Wireless Scenario:* This module has some function such as: to select routing protocol and to define network topology; to schedule some events such as initialization of PAN coordinators, coordinators and devices; and to control the simulation. Some NS2 wireless functions can be defined in this module such as radio-propagation model, antenna model, interface queue, traffic pattern, link error model, and link and node failures. The user can set up some parameters in this module such as: superframe structure in beacon-enabled mode, radio transmission range, and animation configuration.
- *Service Specific Convergence Sublayer (SSCS):* This sub-layer is the interface between IEEE 802.15.4 medium access control sub-layer and the upper layers. The way to access all the MAC primitives is provided by this

service. It is an implementation specific module and its function should be tailored to the requirements of specific applications.

- *IEEE 802.15.4 PHY:* All 14 physical (PHY) primitives are implemented in this module.
- *IEEE 802.15.4 MAC:* This module implements all the 35 MAC sublayer primitives since it is the main module.

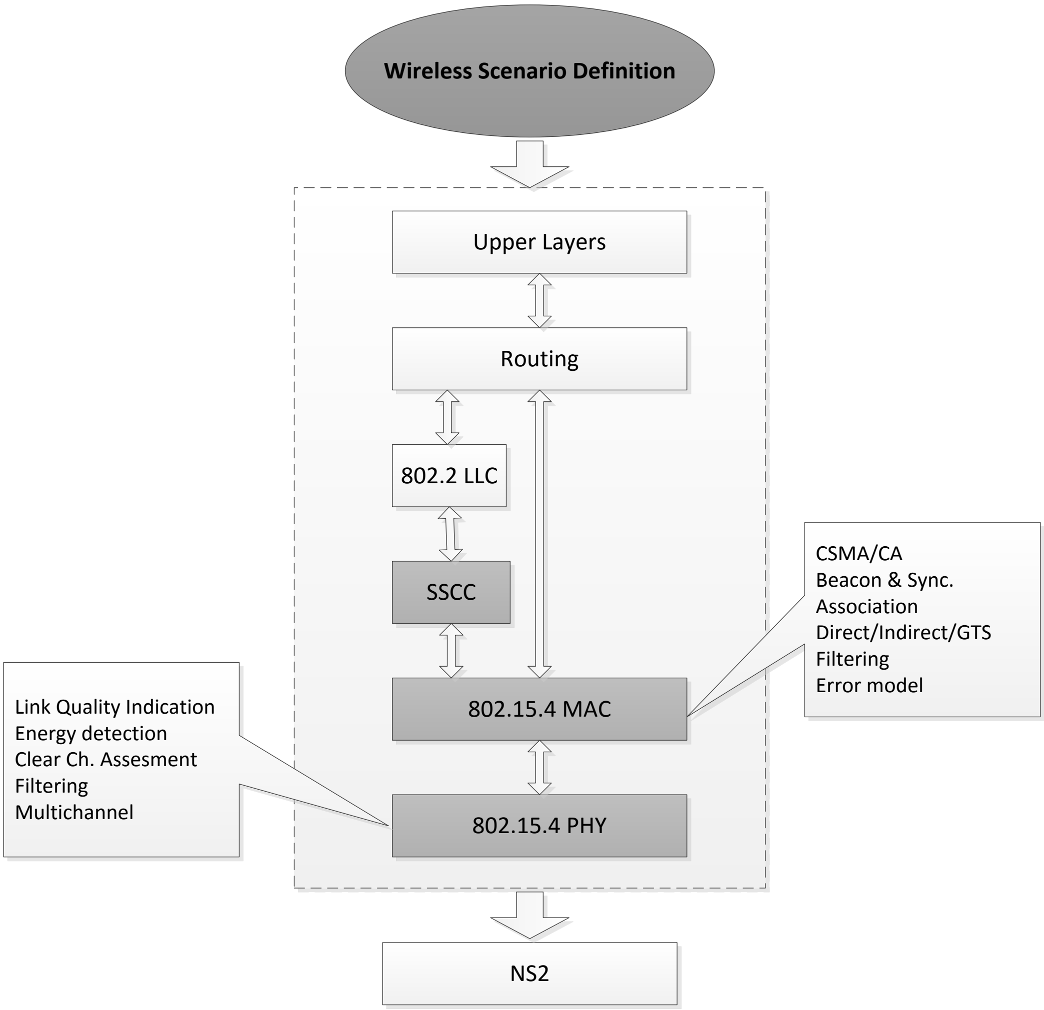


Figure 3-5: Network simulator NS-2 for IEEE 802.15.4.

3.6.2. Simulation Environment

In this part of our research, the two scenarios are designed to study performance behaviour of IEEE 802.15.4 protocol for ad hoc wireless sensor networks, including performance comparison with other protocol (i.e. IEEE 802.11). The first scenario is focused on the performance of two modes available in the standard of IEEE 802.15.4, which are the beacon-enabled mode for wireless sensor networks and the beaconless-enabled mode for ad hoc wireless sensor networks. The second scenario is set for ad hoc wireless network both over IEEE 802.15.4 and over IEEE 802.11 protocols respectively. The former is run in a nine-node single-hop star-topology network, while the latter is executed in a twenty-node multi-hop environment.

Table 3-1: Simulation parameters and environment set up in NS2 simulator

Simulation tool	NS2 version 2.34
Number of nodes	9 and 20 nodes
Network dimension	50m x 50m
Simulation time	500 seconds
Traffic model	Poisson distribution
Maximum queue	50 packets
Data transfer mode	Direct transmission
Maximum air data rates	IEEE 802.15.4 : 250 kbps IEEE 802.11 : 2000 kbps
Node mobility	Off
Acknowledgment	Off
Propagation model	Two ray ground

The duration of simulation is set to 500 seconds where the application traffic starts from 20 to 480 second. We prefer to generate Poisson distribution traffic in all our experiments rather than to use constant bit rate (CBR) traffic because it is too deterministic for static node wireless networks [16]. The other general setting of simulation can be found in Table 3-1.

Scenario 1: Firstly, we used beacon mode (slotted CSMA/CA) and all devices have capabilities as a coordinator (FFD), i.e. be able to handle association and relay data packets. Through simulation, we primarily study the effect of varying payload sizes on small-scale networks.

As shown in Figure 3-6, node 0 serves as the destination while another 8 nodes (node 1, 2, 3…, 7 and 8) are source nodes. Source nodes are in different ranges to the destination nodes and separated a few various metres from each adjacent node. The shortest distance from source to destination is 7 metres, while the longest one is 29 metres. This configuration is adopted from application of sensor networks for building automation system (BAS) [88]. All nodes can transmit within 40 metres (1.2017×10^{-7} W), so that all nodes can reach the destinations.

Secondly, the experiment is configured to show the proposed ad hoc network over IEEE 802.15.4 by setting the network to operate based on beaconless mode (un-slotted CSMA/CA). Using the similar treatment for both simulations then the results of the later experiment is compared with the former one.

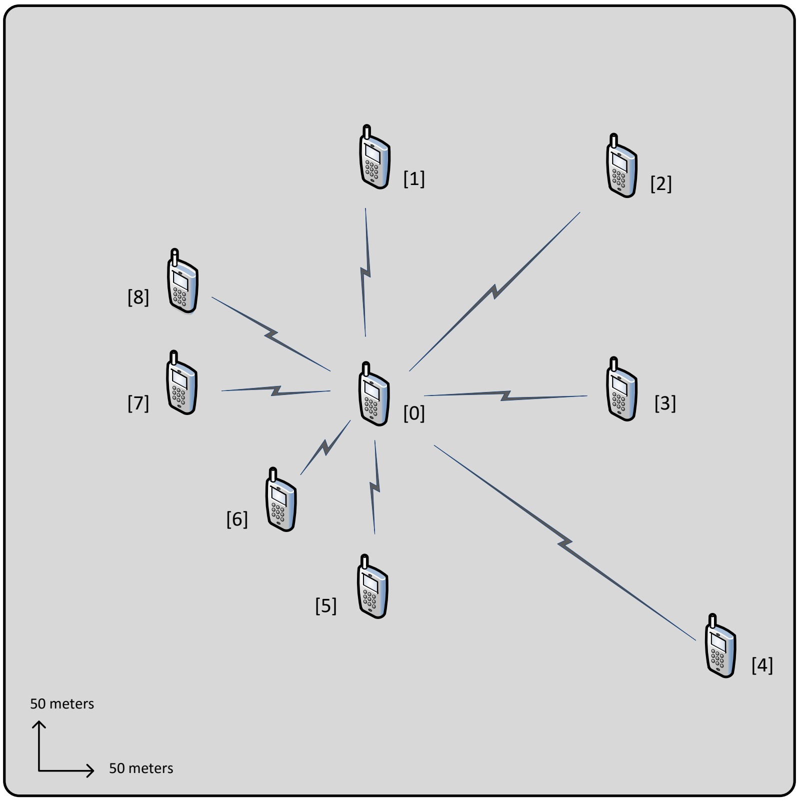


Figure 3-6: A single hop nine-node simple star topology.

Scenario 2: This scenario aims to evaluate performance of ad hoc wireless sensor network both over IEEE 802.15.4 and over IEEE 802.11 protocols. The performance is evaluated with respect to the following parameters:

- A twenty non-mobile node is randomly distributed in a 50 x 50 m^2 area, where the nodes deployment can be seen in Figure 3-7.
- Each node covers the area of 15 metres (or received power at destination is 8.54570 x 10^{-7} W).
- The IEEE 802.15.4 protocol works at maximum of low data rate of 250 kbps.
- The IEEE 802.11 standard operates at high data rate of 2000 kbps.

This experiment is conducted under the environment where it varies application traffic rates starting from 0.5 kbps to 27.3 kbps. It applies the packet size of 70 bytes and varies the inter arrival time of Poisson's data traffic.

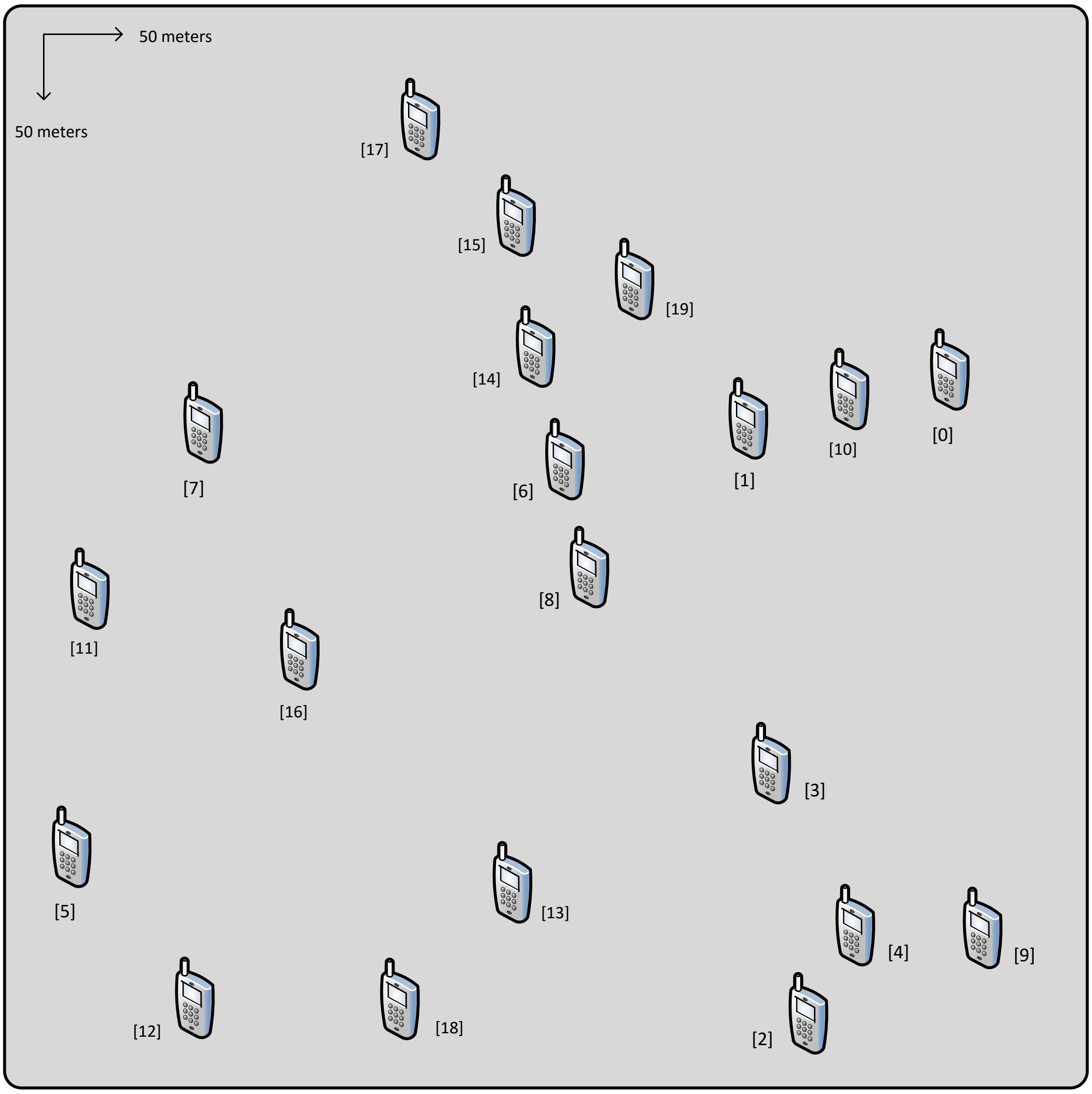


Figure 3-7: A multi-hop ad hoc wireless networks with 20 static sensor nodes.

3.6.3. Performance Metrics

We used the following 4-key performance indicators to evaluate the performance of IEEE 802.15.4 standard, such as:

- **Total throughput**: the total amount of data, in bits, which is received by each destination node on the network per second.
- **Packet delivery ratio or PDR:** the ratio of data packets successfully received at the destination nodes to those data packets sent by source nodes**.** Packet delivery performance of a wireless sensor network is a very critical issue to improve overall system performance and to explore the future development of WSN and its applications [94].
- **Total packet loss:** the whole numbers of packets that are degraded or lost during the time of communication among the nodes on the networks starting from time they are generated at the sink nodes until arriving at the destination.
- **Total end-to-end delay**: the entire delay of packets by computing the time elapsing since the packets are generated by source nodes up to the time they are received by destination nodes on the networks, including processing, queueing, and propagation delays.
- **Total energy consumption**: the mount of energy consumed by source nodes in the network through radio communication This metric can be calculated by setting the initial energy at the beginning of simulation and then measuring the residual energy at the end of simulation.

3.6.4. Simulation Results

The experiment results are divided into 2 parts and elaborated in details as below.

3.6.4.1 Performance Comparison between WSN and Ad Hoc WSN over IEEE 802.15.4 Protocol

This experiment is conducted on 9-node simple star network. Simulation of WSN is run under beacon-enabled mode that allows channel access using slotted CSMA-CA mechanism. Otherwise, ad hoc WSN works with un-slotted CSMA-CA mechanism where there is no PAN coordinator because all nodes are FFDs. In order to isolate the effects of MAC and PHY from those of upper layers, we just measure all metrics respect to MAC sub-layer and PHY layer and disable acknowledgment (ACK) transmission.

The results of simulations are then mapped on some graphs to show relation among parameters and those all performance metrics such as throughput, packet delivery ratio (PDR), packet loss, and end-to-end delay as shown in Figure 3-8, 3-9, 3-10, and 3-11, respectively.

Throughput is the very importance metric of performance because it reflects the effectiveness of data delivery in all kind of computer and communication networks. It can be calculated by the following formulation [95]:

$$Network\ Throughput = \frac{1}{T}\sum_{t=0}^{T}(NRx_t) \quad \text{(3-1)}$$

where T is total consumed time along communication among nodes and NRx_t is the whole data received at destination nodes within T time.

As depicted in Figure 3-8, of both WSN and ad hoc WSN increase sharply when we introduced small load, then throughput decrease gradually for the bigger payload size.

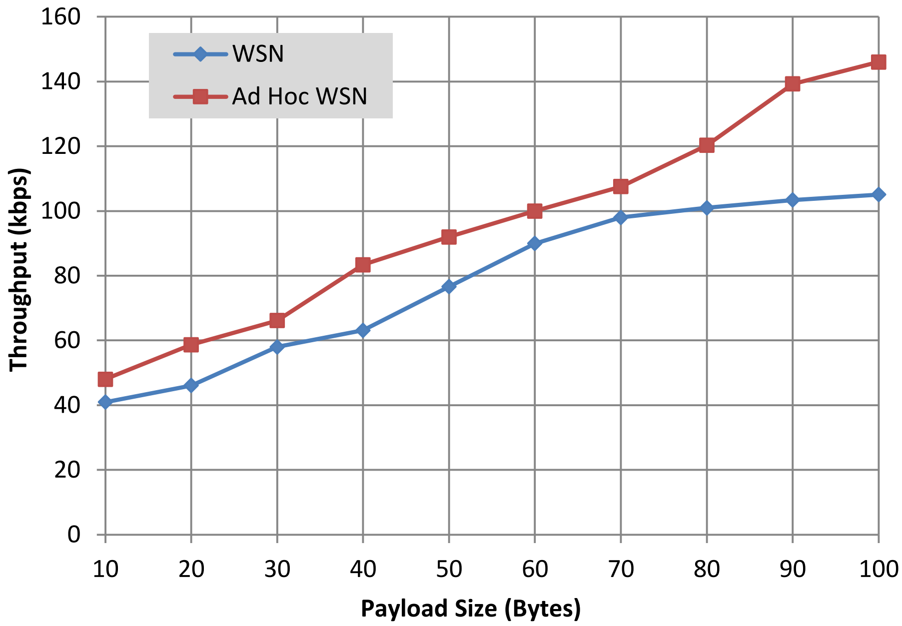


Figure 3-8: Throughput comparison between WSN over 802.15.4 beacon-enabled MAC protocol and ad hoc WSN over 802.15.4 beaconless-enabled MAC protocol.

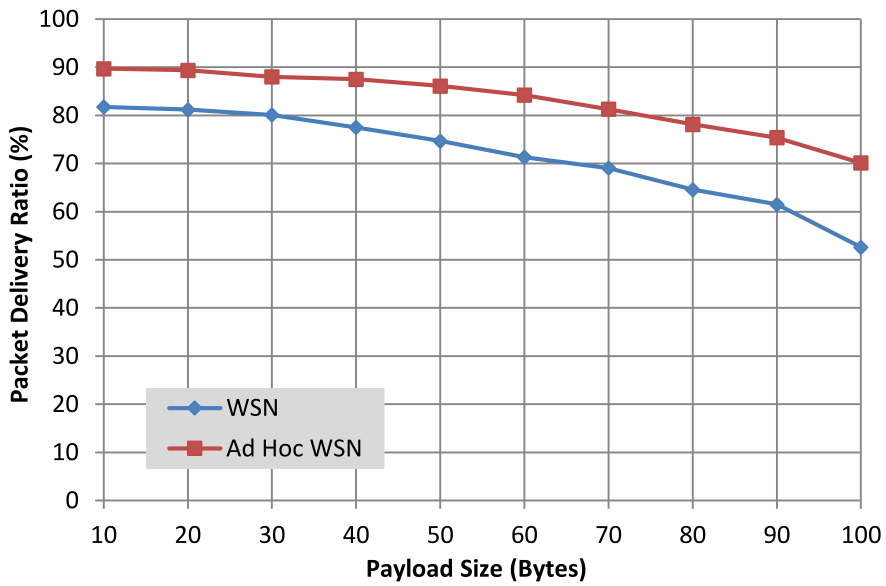


Figure 3-9: Packet delivery ratio (PDR) comparison between WSN over 802.15.4 beacon-enabled MAC protocol and ad hoc WSN over 802.15.4 beaconless-enabled MAC protocol.

Furthermore, packet delivery ratio (PDR) reflects the data transmission efficiency and can be computed as [94]:

$$PDR = \frac{N_{Rx}}{N_{Tx}} x 100\% \quad \text{(3-2)}$$

where N_{Rx} is the total number of data packets successfully received by sink node and N_{Tx} is the total amount of data packets transmits at source node.

If it refers to the packet delivery ratio of both WSN and ad hoc WSN (see Figure 3-9), then it finds that successful received-packet is smaller for larger payload size. This can be explained that collisions occur more frequent when networks handle larger payload size. This also proved by the number of packet loss of wireless sensor networks is by up to 34.1% much higher than that of ad hoc WSN, as it is shown in Figure 3-10.

Overall, ad hoc WSN performs better than WSN in this proposed small scale networks as it improves throughput and delivery ratio by up to 22.4% and 17.1% respectively.

Meanwhile, end-to-end delay measures the average time consumed by data packet starting from leaving the source node and arriving at the destination node. This can be expressed as follow [95].

$$E2E\ Delay = \frac{1}{N} \sum_{i=1}^{N} (Rx_i - Tx_i) \quad \text{(3-3)}$$

where N denotes a number equal to the last number of packet transmitted by source nodes, Rx_i represents the time since the i^{th} packet left the source node, and Tx_i is the time when the i^{th} packet received at sink node.

From the result of simulation, the bigger payload size applied on network, the longer time needed to process packet transmission which will affect network latency as can be seen in Figure 3-11. In this point of view, WSN achieves less latency by up to 2.0 ms.

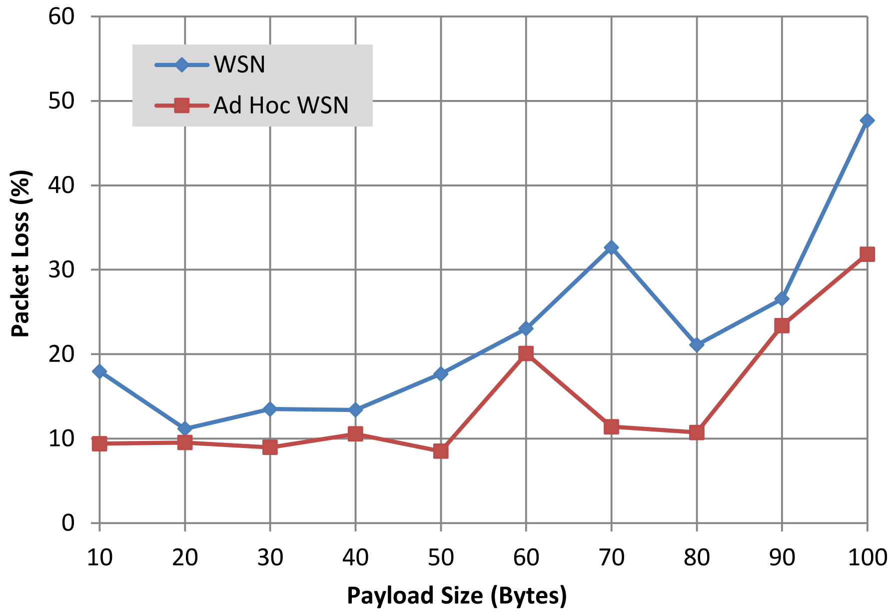


Figure 3-10: Packet loss comparison between WSN over 802.15.4 beacon-enabled MAC and ad hoc WSN over 802.15.4 beaconless-enabled MAC protocol.

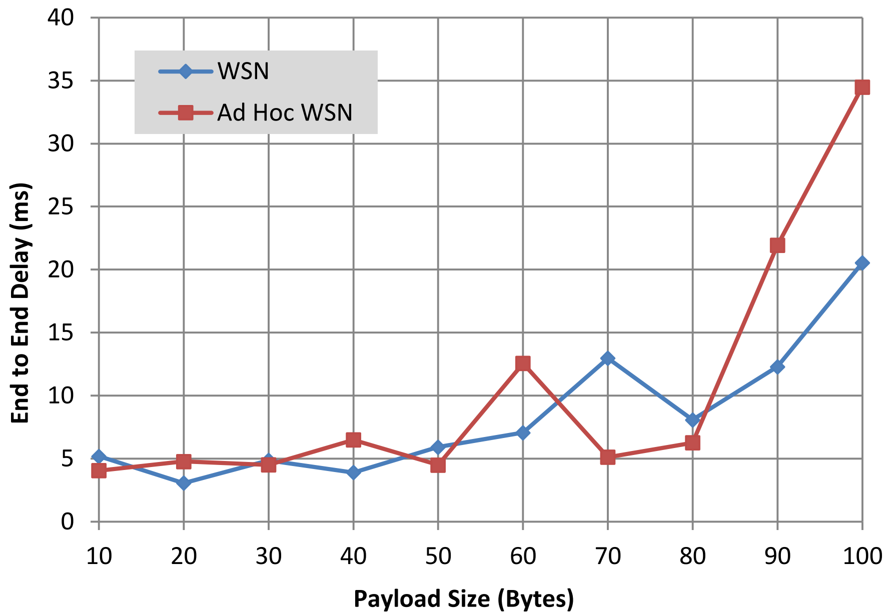


Figure 3-11: End to end delay comparison between WSN over 802.15.4 beacon-enabled MAC protocol and ad hoc WSN over 802.15.4 beaconless-enabled MAC protocol.

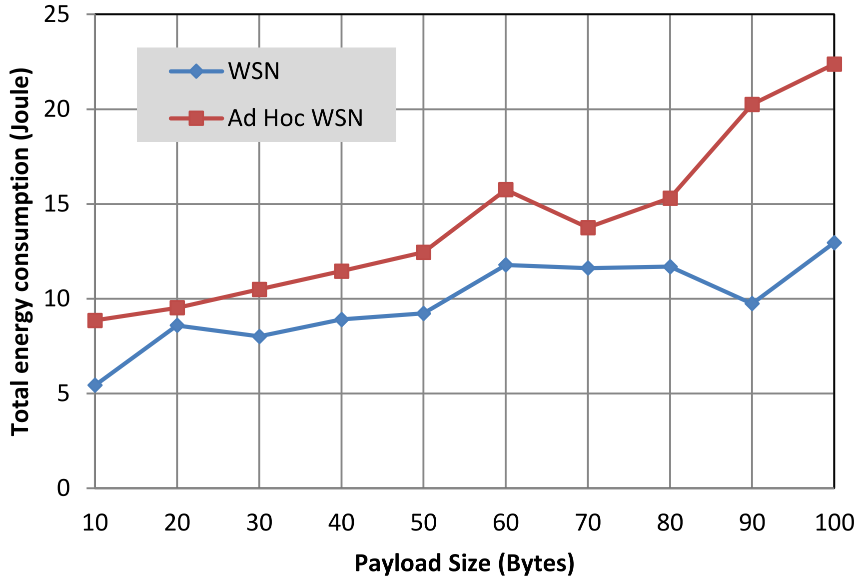


Figure 3-12: Total energy consumption comparison between WSN over 802.15.4 beacon-enabled MAC protocol and ad hoc WSN over 802.15.4 beaconless-enabled MAC protocol.

The total energy consumption by all source nodes on the network, given as P_T, can be computed by collecting all energy (E) consumed by N source nodes during the simulation time the simulation time. The equation for the total energy consumption is written as below:

$$P_{T=} \sum_i^n E_i \quad \text{.....(3-4)}$$

where this equation totals up the energy consumed in all source nodes when they transmit data packets.

It can be seen from Figure 3-12 that ad hoc WSN outperforms WSN in term of total energy consumption. In this case, ad how WSN reduces the energy consumption on average by up to 43.2% compare to that of WSN.

3.6.4.2 Performance Comparison between Ad Hoc WSN over IEEE 802.15.4 and over IEEE 802.11 Protocol

This experiment is carried out based on scenario 2, where there are 20 non-mobile nodes. This experiment aims to study the performance of ad hoc over IEEE 802.15.4 and over IEEE 802.11 MAC protocols by varying payload size starting from 0.5 kbps to 27.3 kbps. The performance results are pointed out on some graphs as can be seen in Figure 3-13 to Figure 3-16.

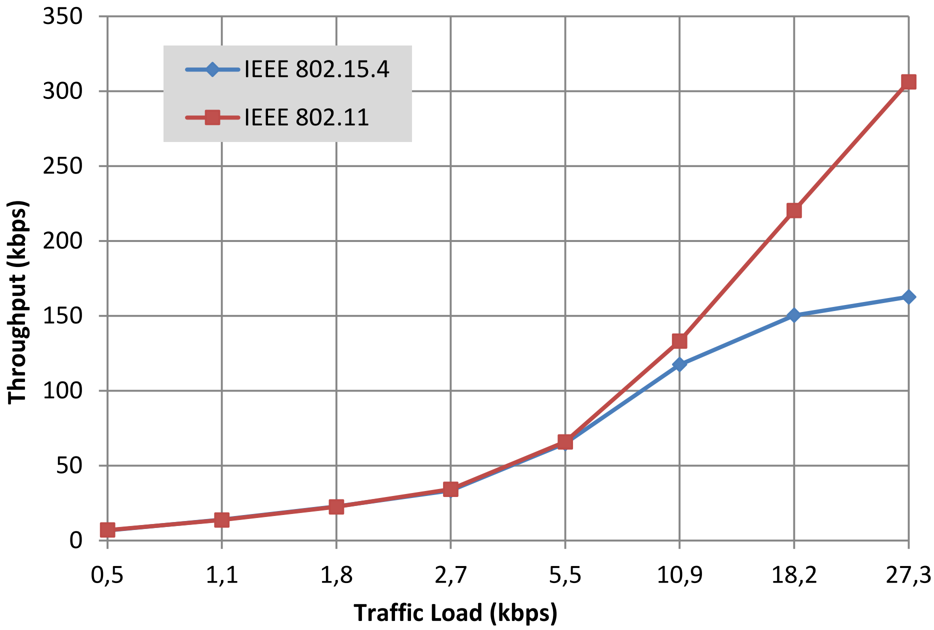


Figure 3-13: Throughput comparison between ad hoc WSN over 802.15.4 and over 802.11 MAC protocol.

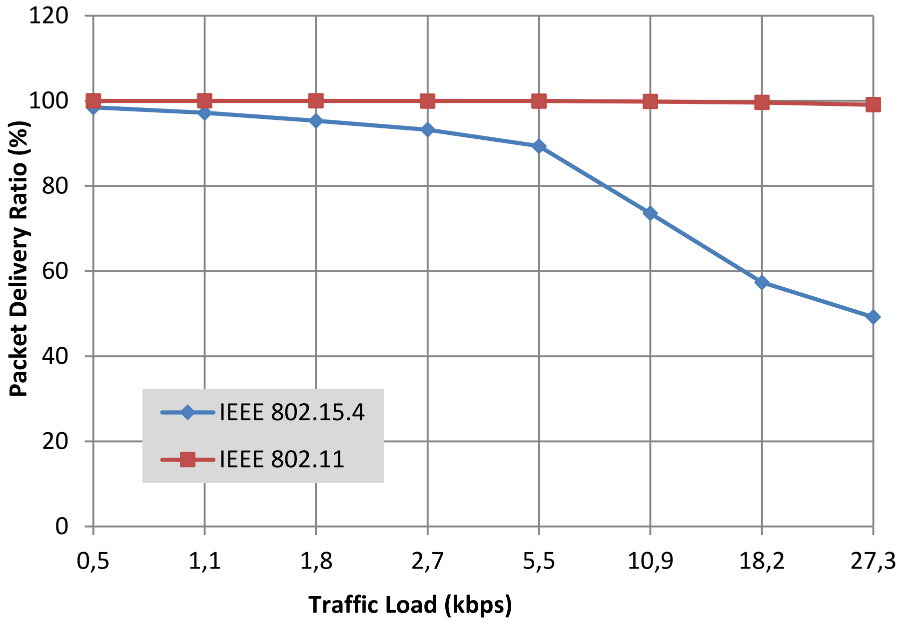


Figure 3-14: Packet delivery ratio (PDR) comparison between ad hoc WSN over 802.15.4 and over 802.11 MAC protocol.

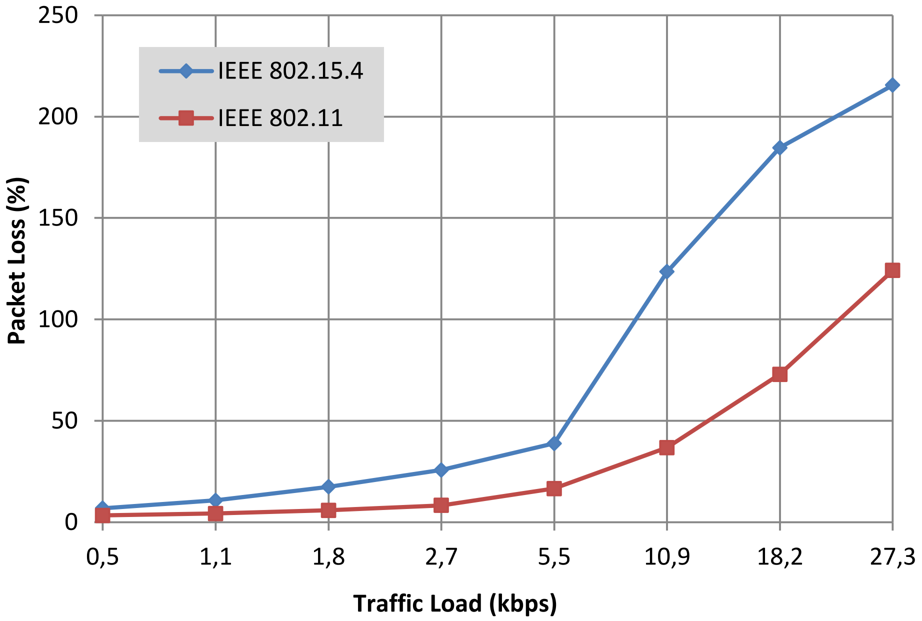


Figure 3-15: Packet loss comparison between ad hoc wireless sensor networks over 802.11 and over 802.15.4 MAC protocol.

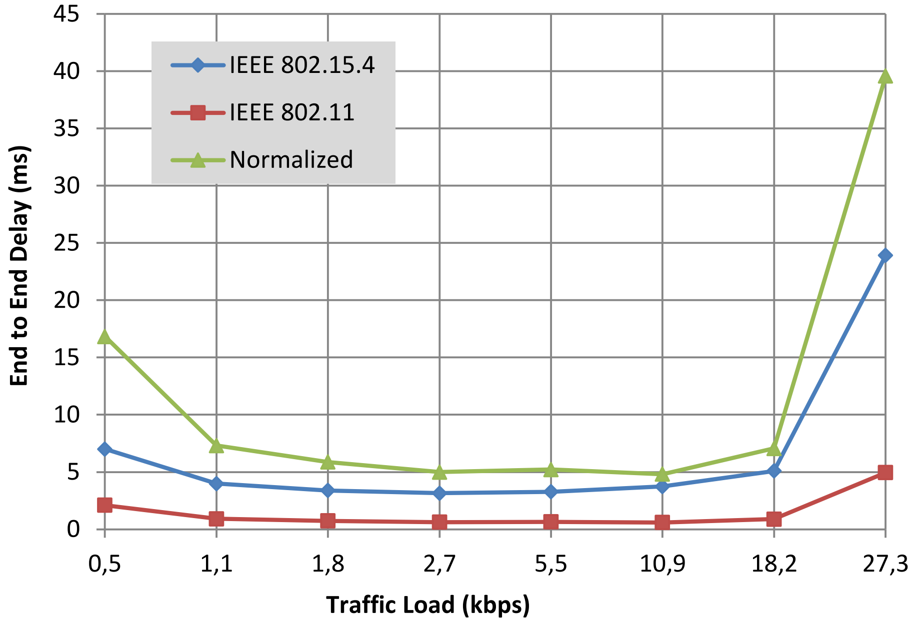


Figure 3-16: End to end delay comparison between ad hoc WSN over 802.15.4 and over 802.11 MAC protocol

Figure 3-13 shows that when the traffic load of 5.5 kbps or smaller is introduced to the network, total throughput of ad hoc over IEEE 802.11 is similar to that of IEEE 802.15.4. Yet, ad hoc over IEEE 802.11 performs better than that of IEEE 802.15.4 for traffic load greater than 5.5 kbps.

Increasing traffic loads on ad hoc over IEEE 802.15.4 will decrease the probability of successfully receiving packets. The PDR goes down about 49.2 % when adding traffic loads from 0.5 kbps to 27.3 kbps. In contrast, the decreasing PDR is less than 1% on ad hoc over IEEE 802.11 as shown in Figure 3-14. This tendency also is clearly shown by the number packet loss of ad hoc network over IEEE 802.15.4 where it increases sharply since the traffic load is more than 5.4 kbps as depicted in Figure 3-15.

As can be seen in Figure 3-16, the total end-to-end delay on the IEEE 802.11 protocol is smaller than on the IEEE 802.15.4 standard. However, this comparison is not quite fair because of the different air data rate of both protocols. The IEEE 802.15.4 protocol operates at low air data rate of 250 kbps, while the IEEE 802.11 standard works at high data rate of 2000 kbps. After normalizing the delay according to air data rates, it is not surprised that delay produced by IEEE 802.11 is greater than that of IEEE 802.15.4 as shown by normalized IEEE 802.11 graph in Figure 3-16. From this point of view, average delay induced by IEEE 802.11 protocol is 1.68 times longer than by IEEE 802.15.4 standard.

3.7 Summary

In this chapter, the low data rate ad hoc wireless sensor network over IEEE 802.15.4 beaconless-enabled mode has been deeply explored to overcome the network bottleneck problem at the centralised WSN coordinator and to reduce the total energy consumption.

From the results of such simulations, it concludes that in small-scale networks, ad hoc WSN over 802.15.4 performs better than WSN in term of 4-key performance indicators such as throughput, PDR, packet loss, and energy consumption by up to 22.4%, 17.1%, 34.1%, and 43.2%, respectively. Nevertheless, WSN achieves less end-to-end delay; in this study, we found it reduces by up to 2.0 ms less delay than of ad hoc WSN. However, some applications are delay tolerant while some others are not. This issue of latency will be significantly considered for some certain applications of ad hoc wireless sensor networks.

The ad hoc wireless sensor networks work well both over IEEE 802.15.4 and IEEE 802.11 protocols in small-scale networks with low traffic loads. The performance of IEEE 802.15.4 for higher payload size will decline since this standard is dedicated to low rate wireless personal access networks.

Chapter 4

Enhancement of IEEE 802.15.4 Beaconless-Enabled Protocol for Wireless Sensor Networks in Hidden Nodes Environment

4.1 Introduction

The IEEE 802.15.4 [13] employs a carrier sense multiple access with collision avoidance (CSMA-CA) mechanism and supports single-hop star networks and multi-hop peer-to-peer networks as well. In both network topologies, to start communication among nodes, a wireless personal area network (WPAN) coordinator should be selected and it further manages and maintains the network resources. This procedure can potentially cause network bottleneck in the centralised WSN coordinator and need more energy consumption. Besides, it makes the networks less flexible, non-self-healing, and unrecoverable nodes.

There are 2 modes of communication supported by IEEE 802.15.4 protocol such as beacon-enabled mode and beaconless-enabled mode. The first mode is so called as an infrastructure wireless network where it needs infrastructure of communication before starting communication among nodes. In contrast, the second mode is named as infrastructure-less or ad hoc wireless networks where every node has a capacity to be coordinator and manage the communication among nodes on the network.

Wireless personal area networks (WPAN) comprises of a PAN coordinator, coordinators, and devices. A PAN coordinator, in general, has two functions: to handle multiple nodes association/disassociation and to allocate addresses when it is on beaconless-enabled mode network. The last function can be performed by each device that has a 64-bit address by default, while the first function can be handled by full function device (FFD) nodes. Therefore, ad hoc or beaconless-enabled wireless sensor network (BeWSN) has to be configured and supported by some FFDs or router-enabled devices. Ad hoc wireless sensor network can operate in any topologies such as star, mesh, or hybrid where all nodes homogeneously have such function of FFDs instead of RFDs (reduced function devices).

Every node, in ad hoc wireless sensor network, can detect the default channel of all other nodes to find its neighbouring nodes. When the neighbouring nodes identification process is completed then it can start peer-to-peer communication on the networks. Therefore, all nodes must be in active or listening state to keep connecting with the network.

In this thesis, it focuses on the mechanism of handling the hidden nodes problem. In relation to this problem, as the very famous standard, the IEEE 802.11 MAC protocol uses extended distributed control function (DCF) to alleviate the hidden nodes problem through a virtual carrier sensing mechanism that is based on two control frames: request-to-send (RTS) and clear-to-send (CTS). By using the RTS/CTS mechanism, nodes may become aware of transmissions from hidden nodes and learn how long the channel will be used for these transmissions.

4.2 Hidden Nodes Problem in Wireless Networks

CSMA mechanism does not cope with the hidden nodes and exposed nodes problem adequately [21]. Figure 4-1 shows a typical hidden nodes scenario [25]. It is assumed that node B is in the transmitting range of both A and C, but node A and C are unable to hear each other. Let say A is transmitting to B. If C has a frame and attempt to transmit to B, based on CSMA mechanism, it senses the medium and will find the channel is free because C cannot hear A's transmissions. Therefore, it will transmit the frame at the same time, thus causing a collision at the destination (node B).

On the other hand, this scenario may cause other problem so called exposed node. If node B is transmitting to node A, then node C will sense the transmission and find the channel is busy because of B's transmission. Therefore, it defers to transmit to other node (i.e. node D), although this transmission would not cause a collision at node A. The exposed nodes problem may reduce networks utilization efficiency.

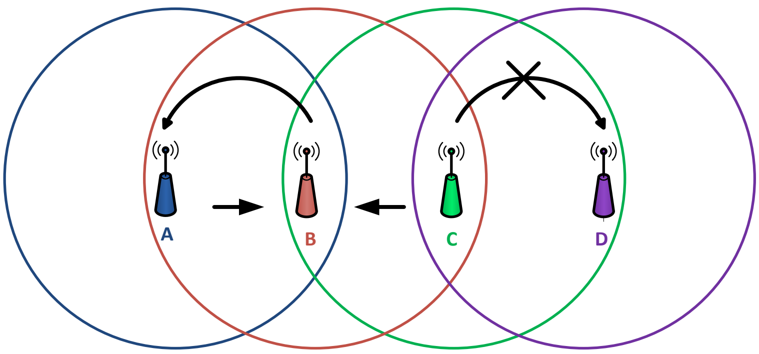


Figure 4-1: Illustration of hidden and exposed nodes problem.

4.3 Related Research

Development of NS-2 simulator for IEEE 802.15.4 protocol has encouraged many researchers to conduct studies, performance analysis, and investigations with various features [15, 16, 96]. A new dynamic channel management to avoid of beacon collision was proposed in [71]. Most of the previous work on the IEEE 802.15.4 performance study was based on either simulation or mathematical analysis. Therefore, a preliminary realistic experiment was conducted by [18]. Since most of researchers focused on static nodes, researchers in [24] investigated the impact of changing beacon order (BO) on throughput, speed, and energy for mobile nodes in WSN, while in [92] presented how network formation affected by mobility of sink nodes. Otherwise, a proposal of ad hoc wireless sensor networks was initiated and evaluated in [19] based on simulation and test-bed approach.

In [20], it presents comparison study of ad hoc wireless sensor networks over both of IEEE802.15.4 and IEE 802.11. Moreover, the evaluation study is then focused on hidden nodes problem for on beaconless-enabled wireless sensor network (BeWSN) over IEEE 802.15.4 [23]. Hidden nodes problem is one of the main constraints on ad hoc wireless network that has been encouraging many researchers to be more concerned on it [21, 90, 97, 98, 99, 22, 91, 100]. A mechanism to recover quickly when the networks suffer from hidden node collisions was proposed by [101]. Another main problem in WSN is control packet overhead. These control packets are very important to make communication among nodes possible. Nevertheless, transmitting and receiving those control packets will cause overhead on the networks. Since the overhead has extra cost in communication, therefore control messages and long headers in frames should be avoided as much as possible [51]. Meanwhile, an analysis in [102] considered using RTS/CTS in IEEE 802.15.4 protocol which is combined with packet concatenation for non-beacon-enable mode. The stochastic model is presented in [103] for the impact of hidden nodes, under certain conditions, on the packet loss probability and latency in a beaconless IEEE 802.15.4 network. The carrier sense multiple access with collision freeze (CSMA/CF) protocol is developed by [104] to responsively alleviate aggravated collision on the network with hidden-nodes problem.

This chapter explores detail of comparative study hidden that has been conducted in [25] and extends with some considerations. A comparison study of implementing RTS/CTS method is carried out to measure the network overhead.

4.4 Problem Statement

IEEE 802.15.4 standard supports both beacon-enabled and beaconless-enabled modes. The beaconless-enabled MAC protocol for low rate ad hoc wireless sensor network has been deeply explored as an alternative to overcome network bottleneck problem. Unlike IEEE 802.11 standard that provides RTS/CTS handshaking mechanism, the IEEE 802.15.4 MAC protocol does not include any methods to overcome hidden nodes problem.

Since the hidden nodes problem has been encouraging many researchers to conduct more studies on that phenomenon, this thesis elaborates a comparative study of the IEEE 802.15.4 beaconless-enabled wireless sensor network (BeWSN) in hidden nodes environment. In this investigation, the study of IEEE 802.15.4 beaconless protocol for WSN in hidden nodes environment is taken as the main concern. In addition, comparison study is performed to investigate network overhead on ad hoc networks over IEEE 802.11. All those scenarios are implemented on static nodes wireless sensor networks. A comprehensive evaluation of existing IEEE 802.15.4 protocol has been performed for the proposed low data rate ad hoc wireless sensor networks via several sets of simulation, including impact of varying data payload sizes and traffic load.

4.5 Performance Evaluation

In this section, it presents the performance evaluation that has already been conducted by simulation approach using network simulator NS-2 [26, 27, 29]. The simulation settings and parameters are elaborated in the subsequence sections.

4.5.1 Simulation Environment

Three different experiments are designed to comparatively study the performance of beaconless-enabled wireless sensor networks over IEEE 802.15.4 protocol in accordance with hidden nodes appearance on such networks. The first scenario is arranged for beaconless-enabled ad hoc WSN over IEEE 802.15.4 with various data inter-arrival times. The second scenario is then set up for comparative evaluation of WSN in hidden nodes and non-hidden node situation. The last scenario is set up to measure overhead impact on the network caused by sending handshaking (RTS/CTS) frames which means to prevent hidden nodes effect. The two former experiments will be treated in a single-hop star topology, while the latter will be executed in a multi-hop mesh topology.

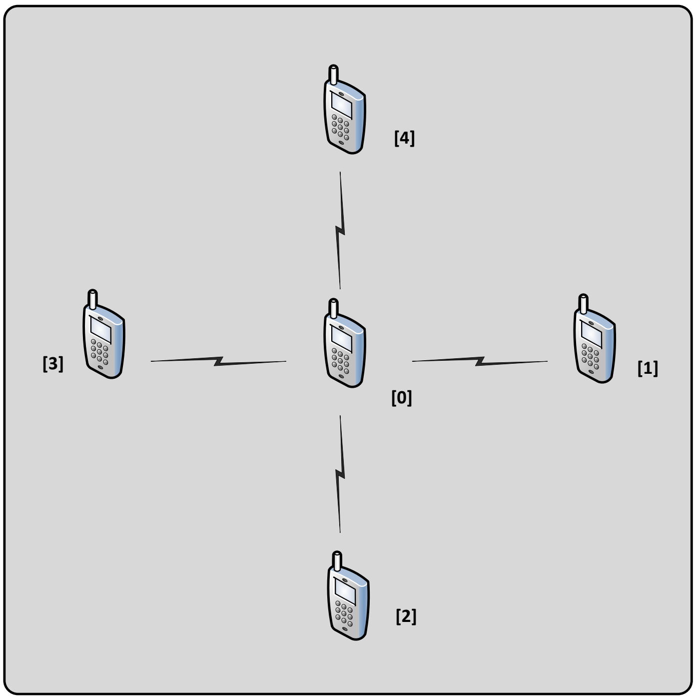


Figure 4-2: A five-node simple star topology.

The duration of simulation is set to 500 seconds where the application traffic starts from 20 to 480 second. It prefers to generate Poisson distribution traffic in all our experiments rather than to use constant bit rate (CBR) traffic because it is too deterministic for static node wireless networks [16]. The other general settings of simulation are as follows [23]:

- Data transfer mode : direct transmission
- Network dimension : 50m x 50m
- Maximum queue : 50 packets
- Node mobility : off
- Acknowledgment : off
- Propagation model : two-ray ground.

Experiment-1: The IEEE 802.15.4 MAC beaconless mode (un-slotted CSMA/CA) is implemented on the simulation. All devices are set up to have the abilities as coordinators (FFDs) so that they are able to handle association and to relay the data packets. Through this simulation, it intends to find some appropriate parameters that are suitable for the next experiment (i.e. experiment-2) on comparative study between hidden nodes and unhidden nodes environment. The network topology is designed as shown in Figure 4-2, where node 0 serves as the destination while the others (node 1, 2, 3, and 4) are the source nodes. In this step, all source nodes are placed where they can cover the destination node in the range of 10 metres and separated about 14.4 metres from each adjacent node. Since all source nodes have transmission power within range of 12 metres (or power at receiver: 1.33527×10^{-6} W) so that all nodes should not 'hear' any others transmission. This condition causes all source nodes are hidden to each other and this is so called hidden nodes environment. In this experiment it tries to find the best fit parameter such as inter-arrival time of data. It will compare the inter-arrival time from the longest to the shortest, i.e. 100 ms, 30 ms, 20 ms, and 10 ms while it treats the network to be more saturated by increasing the payload size from 10 Bytes to 100 Bytes, gradually.

Experiment-2: In this experiment, the scenario is designed to comparatively study the impact of hidden and unhidden nodes on beaconless-enabled ad hoc wireless sensor networks over IEEE 802.15.4. As it has been conducted in experiment-1 (see Figure 4-2), node 0 still serves as the sink node while others are as source nodes. In this part of studies, by simulation approach, it intends to prove some impacts of varying payload sizes gradually from 10 Bytes to 100 Bytes on small-scale networks. Based-on the previous result and network stability, it generates the traffic with inter-arrival time of 30 ms. The other conditions are likely similar to the experiment-1, where the 'behaviour' of the network is kept to be hidden nodes environment. To enable a comparative study, the second configuration is set up to avoid any opportunities of hidden nodes appearance on the network. All source nodes and a destination node are then separated by range of 7 metres. A transmitter of each node can cover 15 metres (or power at receiver: 8.54570×10^{-7} W) so that all of nodes are in the range each other. In other word, there are no hidden nodes found on the evaluated network. The result of the later scenario is then compared with the former one, which is implemented on hidden nodes environment.

Experiment 3: The goal of this experiment is to measure overhead impact on the network caused by sending handshaking (RTS/CTS) frames which means to prevent hidden nodes effect. We studied implementation of RTS/CTS mechanism on ad hoc over IEEE 802.11 protocol since such handshaking mechanism is absence in IEEE 802.15.4 standard. The performance study is carried out by simulation on the following parameters:

- A 20-static-sensor node is randomly distributed and deployed on the area of 50x50 m^2 (see Figure 4-3).
- Each node can transmit to the maximum of coverage area of 15 metres (or received power at destination is 8.54570×10^{-7} W)
- The IEEE 802.11 MAC protocol operates at high data rate of 2000 kbps.

The simulation is conducted under the environment of Poisson distribution where we vary application traffic rates starting from 0.1 packets per second (pps) to 20 pps. Furthermore, such performance is measured on different sizes of data packets, which are classified as low size (20 Bytes), medium size (50 Bytes), and large size (100 Bytes).

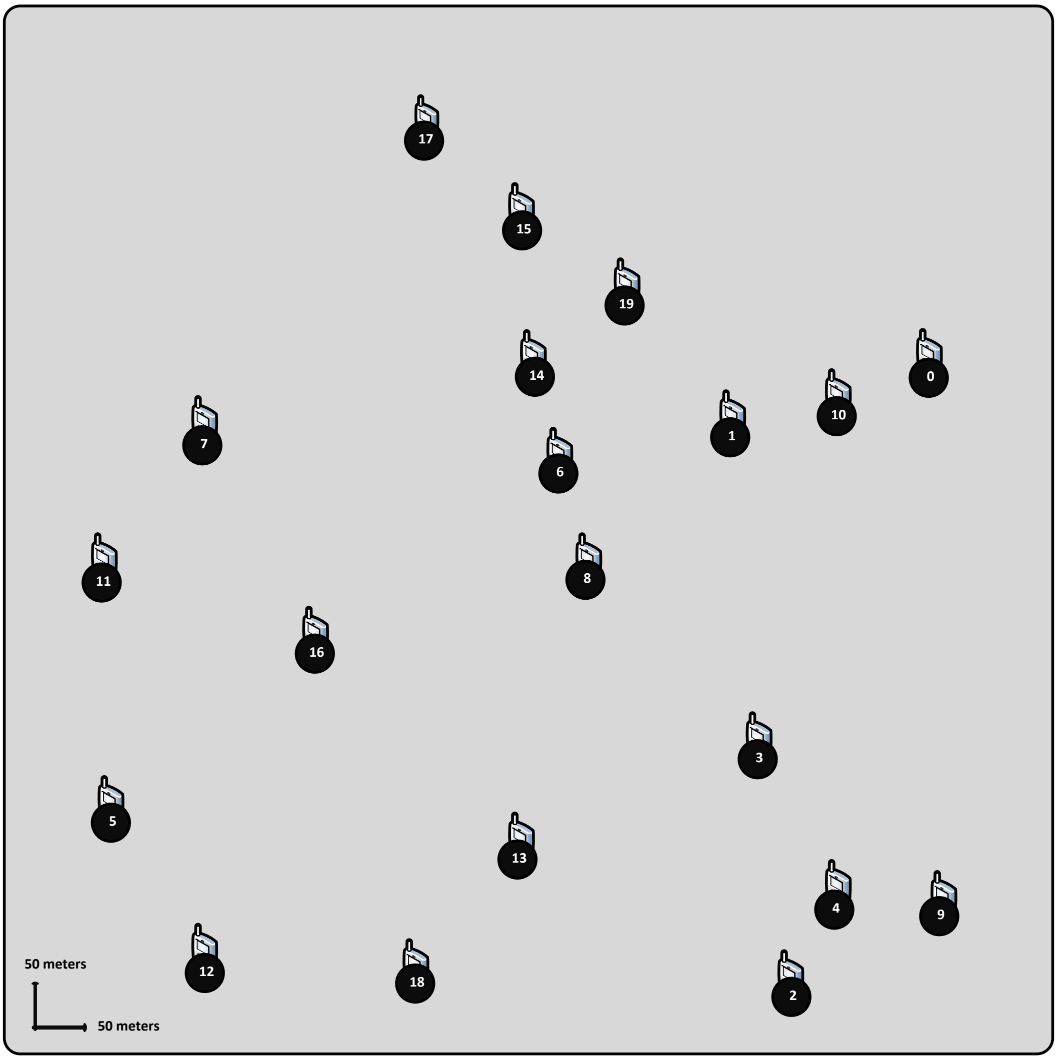


Figure 4-3: A multi-hop 20-node ad hoc wireless networks.

4.5.2 Performance Metrics

We used the following 5-key performance metrics to evaluate performance of the IEEE 802.15.4 standard, such as follows:

- **Throughput**: the total amount of data, in bits, that is received by each destination node in the network per second.

- **Packet delivery ratio or PDR**: the ratio of data packets successfully received in the destination nodes to those data packets sent by source nodes.
- **Packet loss**: the whole number of data packets that have been lost or degraded during the transmission process since it is generated at the sink nodes.
- **End-to-end delay**: the total delay computed in entirely networks, including processing, queueing, and propagation delay.
- **Network overhead ratio**: the ratio of handshaking packets (RTS/CTS frames) sent on the networks to all other data packets sent by source nodes.

4.6 Simulation Results

This section presents investigation results to study the impact of hidden nodes problem on ad hoc wireless sensor networks over IEEE 802.15.4 beaconless-enabled mode. The evaluation is based on the previous 3-experiment and will be elaborated in details as follows.

4.6.1 Inter-arrival Time

This experiment is conducted on a five-node simple star network with the layout of hidden nodes environment. The results of simulation are analysed by plotting them on the following graphs as depicted in Figure 4-4 to 4-6. Those figures clearly show some related impacts of hidden nodes among parameters and those performance metrics such as throughput, packet delivery ratio (PDR), and end-to-end delay.

Throughput, as depicted in Figure 4-4, of all inter-arrival times (IAT) tends to increase in the initial of introducing small payload sizes to the networks. It then declines gradually for the bigger payload sizes. It can also be seen that on the IAT 10 ms, the total throughput is the highest because in this condition the source nodes send data more frequent rather than others. Otherwise, the increasing of throughput on the IAT 30 ms is more stable compare to others.

Referring to the packet delivery ratio or PDR of all the inter-arrival times (see Figure 4-5), it finds that successful received-packet is smaller for larger payload size and shorter inter-arrival time. When it introduces the payload size from 10 Bytes to 100 Bytes, it reduces almost a half of the PDR of all IATs. In addition, it can calculate that on IAT 100 ms, the PDR is on average of 30% bigger than that of IAT 10 ms. This result explains that collisions often occur when the networks handle a larger payload size with more frequent data arrival.

Meanwhile, the more frequent the data arrive to the network, the longer time needed to process the data transmission, which will affect to the network latency as shown in Figure 4-6. From the simulation it finds that the IAT 100 ms, 30 ms, 20 ms, and 10 ms introduce network latency by on average of 4.03 ms, 4.67 ms, 8.48 ms, and 29.44 ms respectively. The result from Figure 4-6 is quite interesting where for the IAT 10 ms, the delay for 40 Bytes, 50 Bytes, and 50 Bytes are 86.6 ms, 70.6 ms, and 76,78 ms respectively. This spike results can be explained that on the high data traffic with inter arrival time of 10 ms, the network is not stable because the IEEE 802.15.4 is not suitable for high data rate.

Overall, the hidden nodes problem on beaconless-enabled WSN has become a serious aspect to be considered in design of MAC protocol for certain applications.

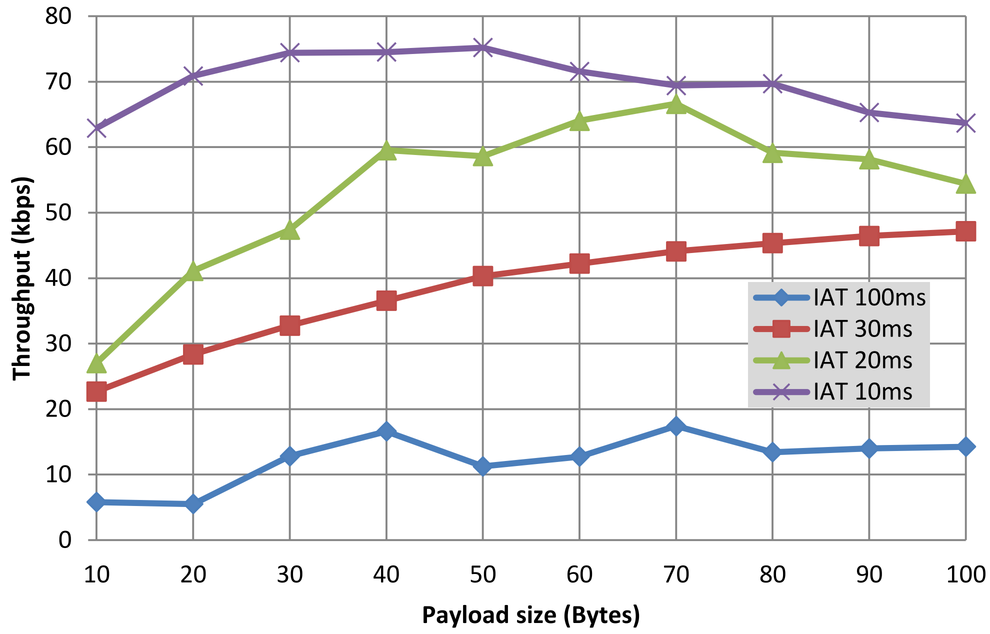


Figure 4-4: Impact of hidden nodes on throughput for various data inter-arrival time.

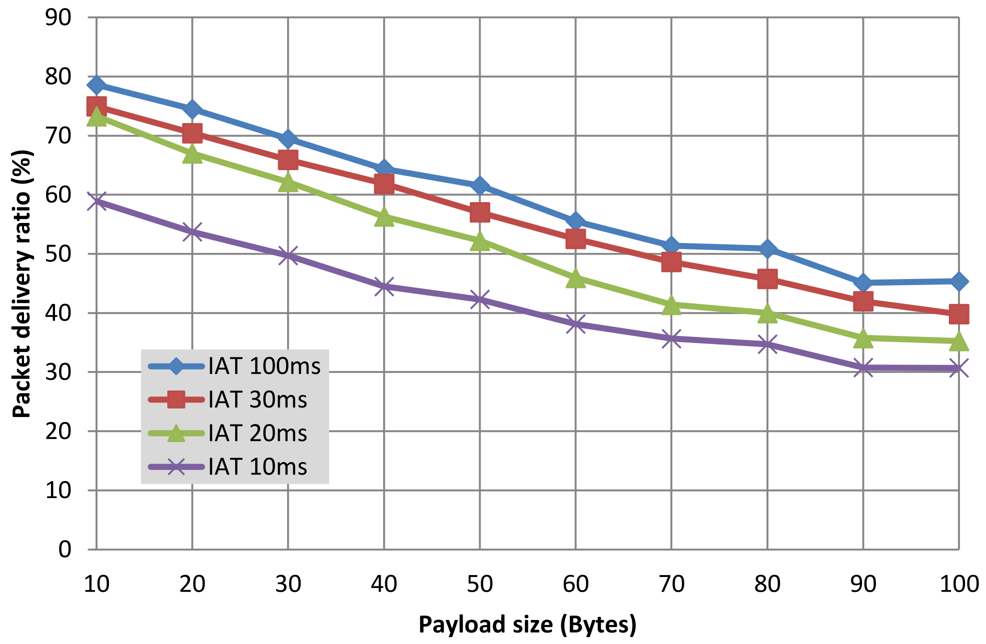


Figure 4-5: Impact of hidden nodes on packet delivery ratio for various data inter-arrival time.

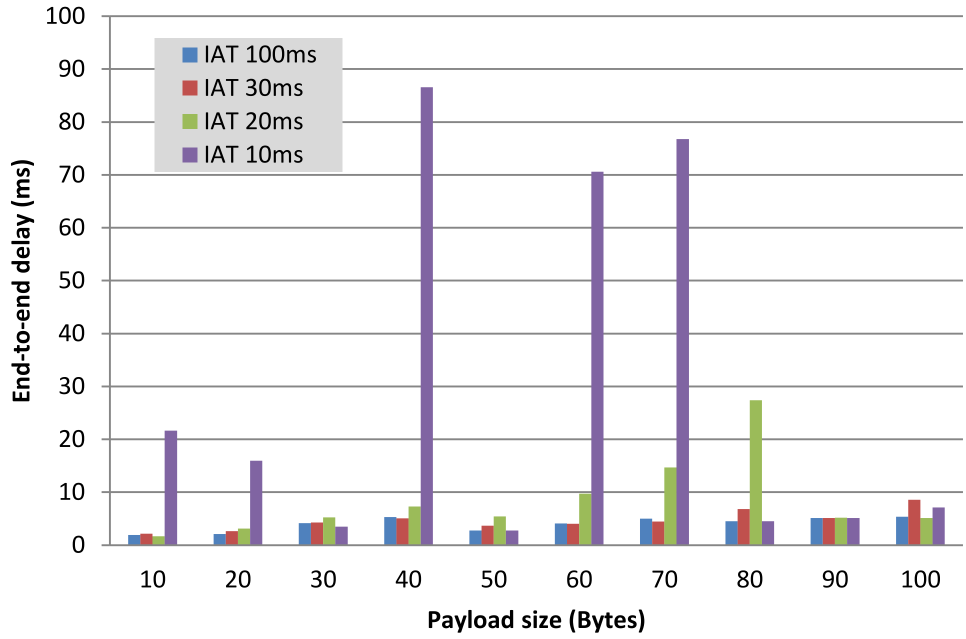


Figure 4-6: Impact of hidden nodes on end-to-end delay for various data inter-arrival time.

4.6.2 Performance Comparison in Hidden Nodes and Unhidden Nodes Environment

This evaluation is based on experiment 2 where, for the first step, all nodes put in the range where each node can hear another. In other words, there are unhidden nodes on this proposed network. After completing the first step, then it continues to the next one where such network environment is created to show hidden nodes impact. After all, it is able to directly compare the results with the previous findings.

Figure 4-7 shows that throughput, on ad hoc network with hidden nodes environment, slightly increases when it introduces gradual payload size from the lowest (10 Bytes) to the highest (100 Bytes). On the other hands, throughput sharply increases for the same treatment on unhidden nodes environment. The gap of throughput between both environments is starting from 12.50 kbps (on the lowest payload size) to 72.66 kbps (on the highest payload size). This indicates that throughput significantly drops as an impact of hidden nodes appearance. It explains that a more collisions occur on such networks due to existence of hidden nodes.

The impact of hidden nodes problem on deterring network performance is clearly seen in Figure 4-8. It shows that performance of ad hoc network with hidden nodes drops as indicated by decreasing PDR value by up to 35.15%. In contrast, the declining of packet delivery ratio is less than 7.5% on networks without hidden nodes. It also proves that the more packets collide on the networks, the less packets successfully deliver to the destination.

From Figure 4-9 we can see that performance of ad hoc networks deteriorates in term of packet loss. It seems that packet loss on network without hidden nodes slightly swings in between 10% to 14%. On the other side, packet loss is much bigger on hidden nodes environment and gradually goes up by 18.8% starting from 12.6% to 31.4%.

Meanwhile, in perspective of end-to-end delay as can be seen in Figure 4-10, there is no significant performance deviation due to hidden nodes phenomenon.

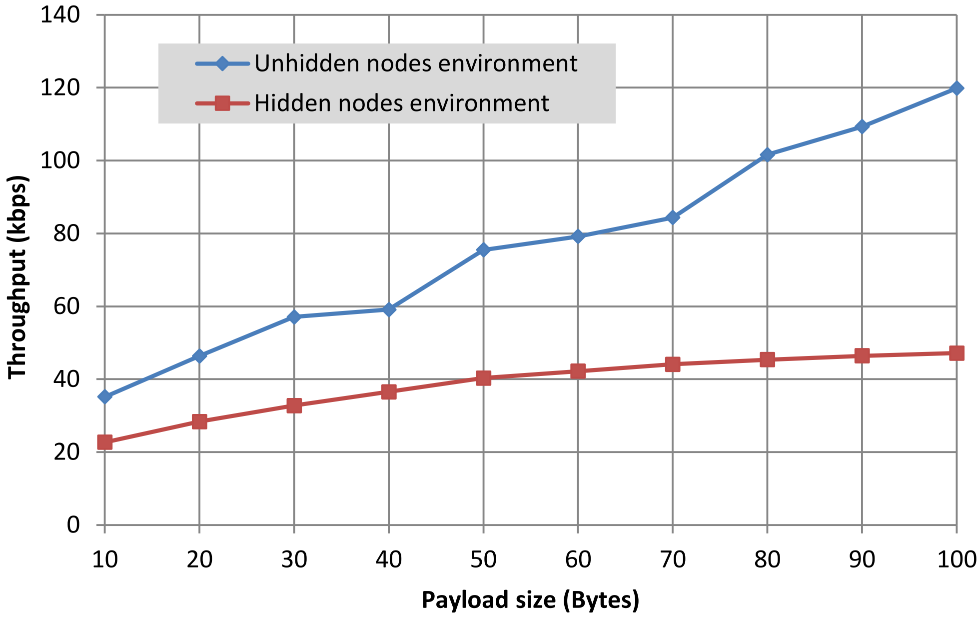


Figure 4-7: Throughput comparison in hidden nodes and unhidden nodes environment.

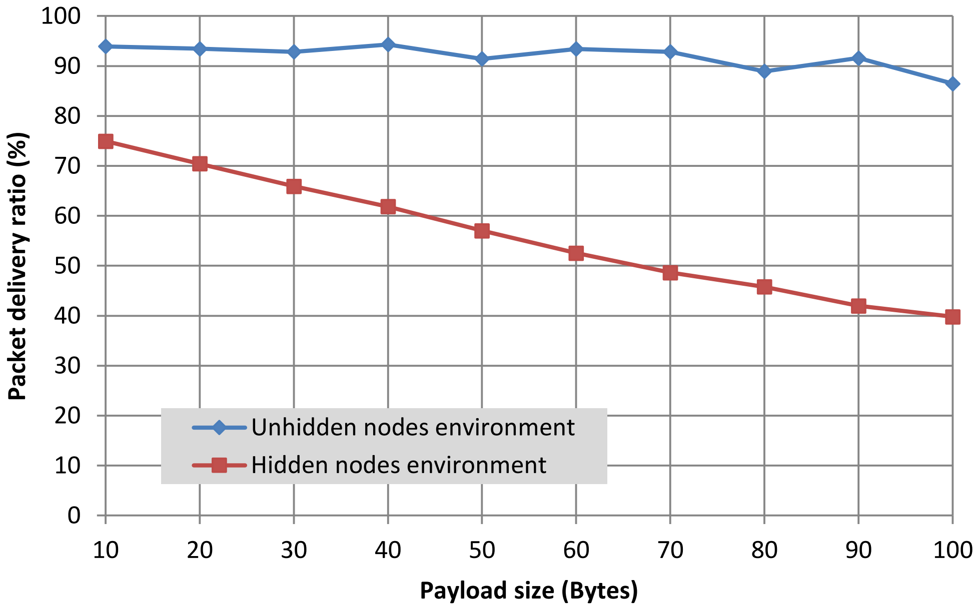


Figure 4-8: Packet delivery ratio comparison in hidden nodes and unhidden nodes environment.

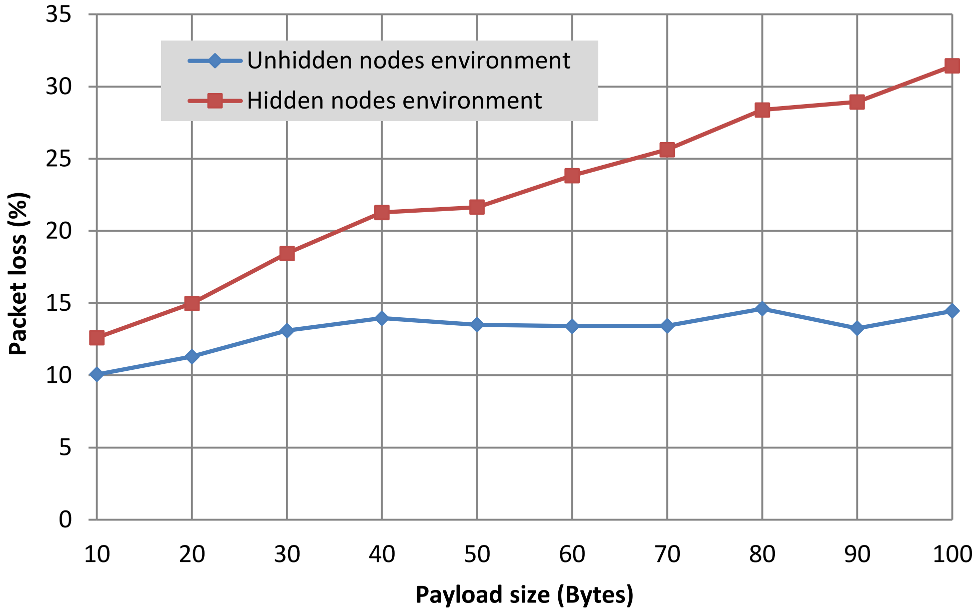


Figure 4-9: Packet loss comparison in hidden nodes and unhidden nodes environment.

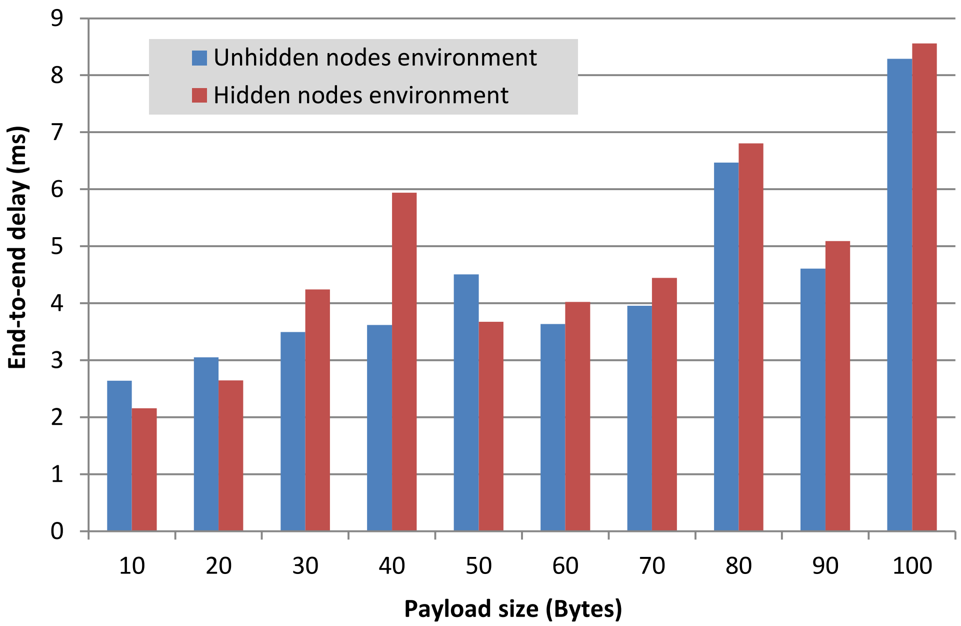


Figure 4-10: End-to-end delay comparison in hidden nodes and unhidden nodes environment.

4.6.3 Network Overhead

The third experiment aims to measure network overhead caused by implementation of mechanism to prevent hidden nodes effect on ad hoc wireless network over the IEEE 802.11 protocol. The experiment is carried out based-on scenario-3, where there are 20 non-mobile nodes, which deploy randomly on the area of 50x50 m^2. Evaluation result is indicated by fraction of number of RTS/CTS frames to number of application packets received by destination nodes. It confirms that introducing shorter packet size into proposed network will raise the network overhead ratio up.

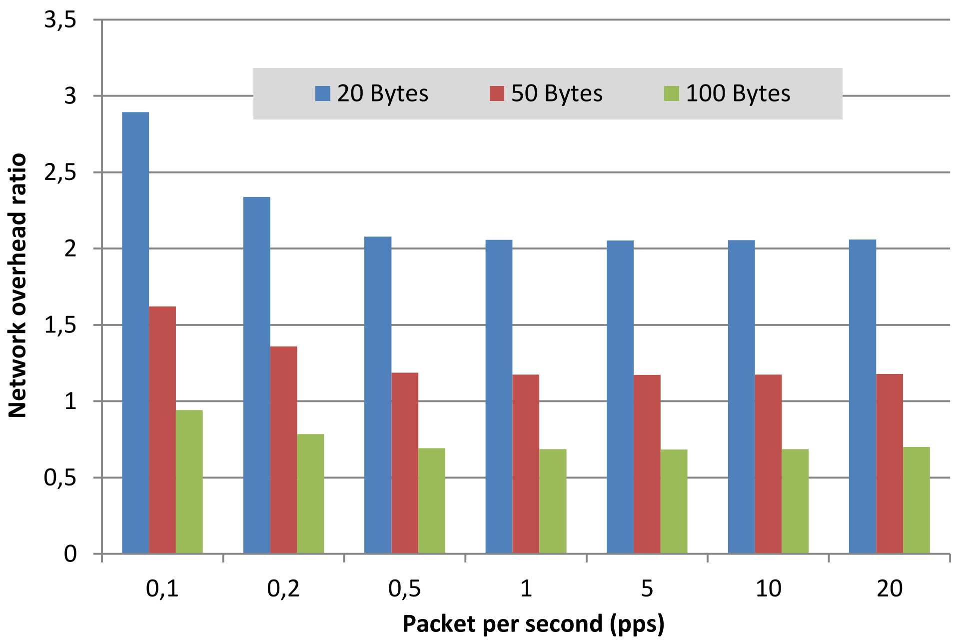


Figure 4-11: Overhead impact of handshaking mechanism implemented on ad hoc networks to overcome hidden nodes problem.

From Figure 4-11, it can be clearly seen that overhead ratio on network with packet size of 20 bytes is tripled than that of 100 bytes. At the same time, the average of overhead ratio on packet size of 50 bytes is almost doubled than that of 100 bytes. This means that, in the networks which employ handshake mechanism, if we reduce the packet size of application data, it will increase the number network overhead. Therefore, conventional RTS/CTS mechanism should not be included in the MAC protocol for low data rate wireless sensor networks such as IEEE 802.15.4 standard.

4.7 Summary

This chapter elaborates a comparative study of the IEEE 802.15.4 beaconless-enabled wireless sensor network (BeWSN) in hidden nodes environment. Investigation of network overhead on ad hoc networks over IEEE 802.11 is also presented. A comprehensive performance evaluation through simulation is applied based on some performance indicators such as throughput, packet delivery ratio, packet loss, end-to-end delay, and overhead ratio.

The result of studies we conducted indicates that performance of beaconless-enabled ad hoc wireless sensor networks deteriorates as indicated by degradation of throughput and packet reception by up to 72.66 kbps and 35.15%, respectively. Those deterring performance is due to hidden nodes appearance on the networks. Meanwhile, in relation to end-to-end delay, there is no significant performance deviation caused by presence of hidden nodes.

Preventing hidden node effect by implementing RTS/CTS mechanism will add significant overhead on network that applies low packet size. Therefore, this method is not suitable for IEEE 802.15.4 protocol, which is dedicated to low data rate wireless sensor networks.

Chapter 5

Implementation of IEEE 802.15.4 Beaconless-Enabled Protocol for a Large-scale Wireless Sensor Network

5.1 Introduction

There two main goals should be considered when design and develop the medium access control (MAC) protocol. Firstly, since a huge number of sensor nodes are densely deployed in sensor network, the MAC protocol aims to establish communication link among nodes for data transfer. Secondly, the MAC should be designed to fairly manage and efficiently maintain communication resources among sensor nodes [5, 11].

The IEEE 802.15.4 MAC protocol supports low data rate, low-cost less-maintenance devices, and low energy consumption wireless sensor networks. In wireless sensor networks, the IEEE 802.15.4 MAC protocol is also responsible to associate and synchronise the communication process between a coordinator node and some associated nodes [14, 35].

The main difference between conventional wireless network and wireless sensor network is the coverage area where in WSN the sensor node has a very short coverage with a very low data rate and limited power. Degradation in performance of WSN happens when there are several nodes aggressively move within the network. The association efficiency is influenced when mobile node regularly switches its coordinator. The greater the number of mobile nodes with faster movement, the worst the node synchronisation process. This is caused by signal interference from other neighbouring nodes; therefore, it increases the number of beacon losses and packet collisions [24].

The work presented in this chapter considers those evidences that implementation of the IEEE 802.15 beacon-enabled mode has many constraints related to the number of nodes involving in the network and mobility issue.

5.2 Sensor Node Deployment Model

Sensor node deployment is one of the crucial issues in wireless sensor networks since this step of installation has significant contribution to the overall network performance. The chosen deployment model of sensor nodes depends on the purpose of wireless sensor networks implementation and the characteristic of area or environment where the sensor nodes will deploy. In general, there are two methods of spreading the sensor nodes i.e. random model or follow a certain pattern.

The random sensor deployment method is commonly used in WSN for outdoor applications and in a very remote and difficult environment. These applications include WSN for habitat monitoring, sensor network for disaster mitigation, volcano monitoring, etc. The coordinate of sensor location after deployment follows one of certain distribution such as normal distribution, uniform or Poisson distribution. Figure 5-1 shows an example of random deployment using aircraft to spread the sensor nodes. The aircraft drops down such sensor nodes mostly from the centre of the intended area, so that most of sensor will distribute in the centrum part of the deployment area [105].

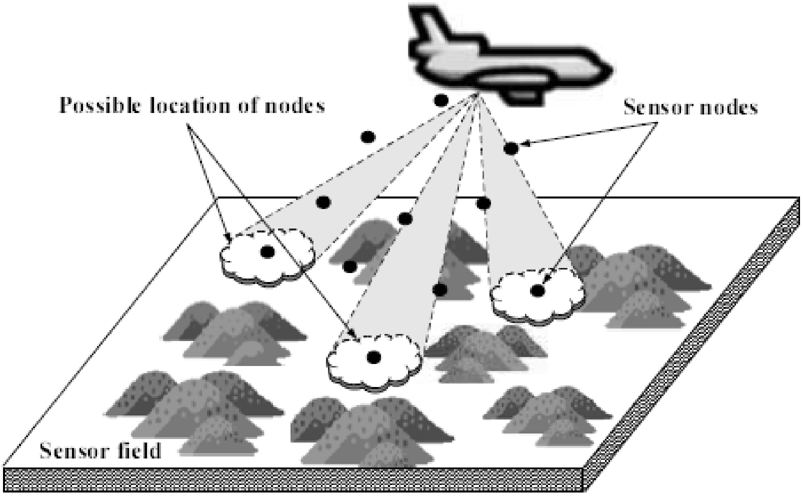
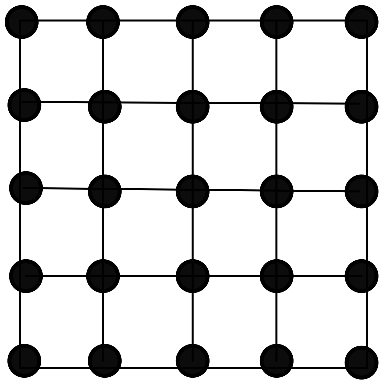


Figure 5-1: Example of random node deployment; the cloudy regions show the possible area of sensor deployment, while the dots mean the intended location of sensors.

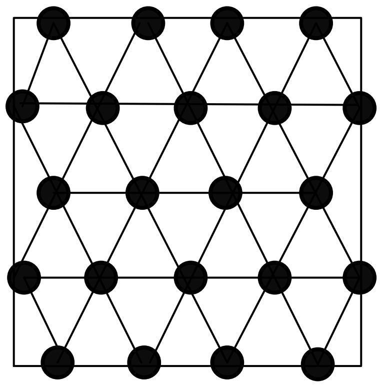
On the other hand, deployment model following a certain pattern is typically implemented for indoor application of wireless sensor network. Some pattern of deployment is depicted in Figure 5-2. The area per node (APN) of those patterns denoted by γ and calculated as below [106]:

$$\gamma = \frac{A_p}{N_p} N_n \quad \text{(5-1)}$$

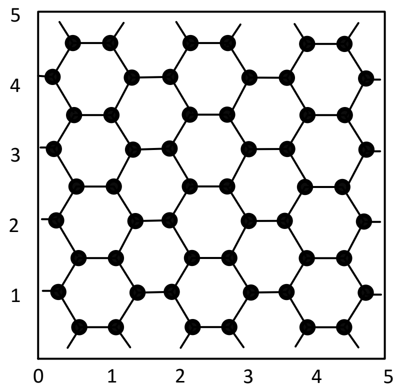
where A_p states the area of the pattern, N_p indicates the number of nodes that compose a pattern, and N_n represents the number of pattern blocks that share a node. As the example, in hexagonal pattern (see Figure 5-2) the value of $N_p = 6$ and $N_n = 3$. Meanwhile, in triangular lattice pattern, we know the number of $N_p = 3$ and $N_n = 6$. Additionally, in square pattern we find that $N_p = 4$ and $N_n = 4$.



a). Square Pattern



b). Triangular Pattern



c). Hexagonal Pattern

Figure 5-2: Example of sensor node deployment patterns; square, triangular, and hexagonal model.

Let declare $\gamma^{ROM}(r_c, r_s, \theta)$ as the APN in a rhombus based topology with acute angle θ that provides both coverage and connectivity with a communication radius of r_c and a sensing radius of r_s. From the equation (5-1), we find that:

$$\gamma_{MAX}^{SQU} = r_s^2\left(min\left\{\sqrt{2}, \frac{r_c}{r_s}\right\}\right)^2 \qquad (5\text{-}2)$$

$$\gamma_{MAX}^{TRI} = \frac{\sqrt{3}}{2} r_s^2\left(min\left\{\sqrt{3}, \frac{r_c}{r_s}\right\}\right)^2 \qquad (5\text{-}3)$$

$$\gamma_{MAX}^{HEX} = \frac{3\sqrt{3}}{4} r_s^2 \left(min \left\{ 1, \frac{r_c}{r_s} \right\} \right)^2 \quad (5\text{-}4)$$

It has been conducted in [107] a comparative study of several sensor nodes deployment methods in wireless sensor networks. From the calculation, it proves that sensor deployment based on equilateral angular pattern is better than that in the form of square as a rule. The efficient coverage area (ECA) of triangular as a rule is up to above 90%, in contrast with the latter one that is below 90%.

5.3 Related Research

A lot of studies have been carried out by many students and researchers which pay more attention on performance evaluation of the IEEE 802.15.4 standard for multi-purposes wireless sensor networks. The never-ending development of various features and new embedded-services to the existing protocol of WSN is still attractive and challenging for many researchers. The new innovation and value-added in the existing protocol has been enriching both physical layer and MAC sub-layer in such way to meet some particular requirement of certain applications.

The IEEE 802.15.4 MAC protocol supports two mode of operation which are either in beacon-enabled mode or beaconless-enabled mode. Many researches have been conducted on both schemes.

The prototype of IEEE 802.15.4 beacon-enabled protocol is implemented in the NS-2 network simulator with a CMU wireless extension [15]. The network topology used in the simulation is a 49-node simple star topology and evaluation focus on the super-frame structure with synchronisation. The simulation shows that the lower the duty cycle, the more the saving energy, but this costs a higher latency and a lower bandwidth significantly. Furthermore, related to the synchronisation, there is tradeoff between beacon tracking and non-tracking methods and depends on duty cycle and data rates.

Several researches on performance evaluation of the IEEE 802.15.4 standard seem to be more attractive for many research students, researchers, manufacturers, and professionals since [16] developed IEEE 802.15.4 modules on NS-2 simulator and carried out several sets of simulations to study its performance. They studied the protocol performance, both slotted and un-slotted CSMA/CA and/or beacon and beaconless-enabled modes. Almost all performance metrics are comprehensively evaluated such as packet delivery ratio, network overhead, hop delay, association rate and efficiency, orphaning rate, collision rate and distribution, and duty cycle.

Another analysis based on an accurate OPNET simulation model of slotted CSMA/CA mechanism over IEEE 802.15.4 beacon-enabled mode has been performed by [61]. Some findings from the studies come up regarding the protocol performance as the following: (i) the backoff algorithm of in beacon enabled mode is not flexible enough for large-scale wireless sensor networks and inadequate to avoid the collisions; and (ii) additional overheads are introduced by lower superframe order (SO) due to more channel clear assessment (CCA) deference and collision; and (iii) the higher the beacon order (BO), the longer the network latency.

The work in [108] proposed two mechanisms to improve throughput and energy efficiency the IEEE 802.15.4 standard by enhanced CSMA-CA algorithm. An enhanced collision resolution (ECR) mechanism is developed in order to adjust the backoff exponent (BE) which reflects the level of channel contention. Furthermore, an enhanced backoff (EB) algorithm is proposed to enable the range of backoff counters shifted so that reduces redundant backoff and clear channel assignment (CCA) by utilizing the CCA outcome.

Since the most of the previous works focused and explored more on static node rather than consider node mobility. Thus, in [24] an observation is carried out to evaluate the reliability and suitability of the IEEE 802.15.4 standard for mobile sensor circumstances.

Because the beaconless-enabled mode less attractive for researcher, then [19] introduced ad hoc wireless sensor networks performance evaluation based on simulation and test-bed approach. The proposed ad hoc wireless sensor on small-scale networks over IEEE 802.15.4 beaconless-enabled is explored deeply to overcome the network bottleneck problem at centralised WSN coordinator [20].

Implementation of IEEE 802.15.4 is evaluated using OMNET simulator for industrial applications in [109] by investigation of performance in various beacon order (BO) and super-frame order (SO) with different traffic load. The primary goal of study is to meet industrial requirements, which are reduced end-to-end delay and less power consumption issue.

In [110] a wireless sensor network was developed to improve the performance of data-centre and to optimize energy consumption for an efficient and optimal data-centre environmental monitoring. It presents a small 10-node size network that was designed for temperature and humidity monitoring in the data-centre building at Argonne National Laboratory, Chicago Illinois USA. Meanwhile, the paper [65] presents the deployment of ad hoc wireless sensor network for indoor environmental quality monitoring. The main objective of this work is to balance the inhabitant comfort level and power demand. The proposed system is also a small-size network which consists of 19 sensor nodes continuously measure some environment parameters such as temperature, humidity, light, vibration, and carbon dioxide levels in working areas.

5.4 Problem Statement

In the network over IEEE 802.15.4 beacon-enabled protocol, it is very difficult to maintain a long connection between a coordinator and sensor nodes, especially when a sensor in mobile with high speed. Moreover, because the coordinator has short distance of coverage, the sensor nodes will be easily disconnected and unsynchronised with its coordinators. By losing the synchronisation means that all schedules for being active or turning off the radio transceiver is not available for the nodes which is very important in perspective of energy conservation. Consequently, the node drains the energy so quickly because it becomes idle for long period [24].

In beacon-enabled mode, a WSN coordinator starts communication by sending beacon message to all nodes and then it continues its responsibility to manage and maintain network resources. In this scheme, the network bottleneck problem potentially arises in centralised WSN coordinator and consumes more energy. It also makes the networks less flexible with unrecoverable nodes respectively. Since our previous work implemented on small-scale network [20], therefore, in this chapter we propose the IEEE 802.15.4 beaconless-enabled for a large-scale ad hoc wireless sensor networks.

Deploying sensor nodes is a complex and multifaceted job, especially in large field with unpredictable circumstances. Therefore, pre-deployment test through simulation and/or test bed will help to illustrate the real environment. Through this simulation, it reflects the intrinsic characteristic of a large-scale wireless sensor network. On the other side, understanding the behaviour and performance of a large-scale WSN is a very challenging task because of the following reasons: (i) a very complicated behaviour of the network and its nodes; (ii) lack of common infrastructure for event recovery; and (iii) less sufficient operational efforts for classifying the losses [94].

In this work, the performance evaluation of IEEE 802.15.4 beaconless-enabled protocol also considers the node deployment method. This aims to meet the requirement for initial deployment which must reduce the installation and maintenance cost, increase the flexibility of node placement, and become more self-healing and fault tolerant [30].

5.5 Performance Evaluation

In this sub chapter, it points out the performance evaluation that has already been performed by simulation approach using a very well-known network simulator NS-2 version 2.34 [26, 27, 29]. The simulation settings and parameters are elaborated in the subsequence sections.

Table 5-1: Two hops communication arrangement

Source Node	Sink Node	Source Node	Sink Node	Source Node	Sink Node	Source Node	Sink Node	Source Node	Sink Node
64	**28**	**85**	**45**	**78**	**11**	**99**	**59**	**16**	**4**
76	**36**	**93**	**17**	**90**	**22**	**83**	**39**	**32**	**0**
88	**48**	**77**	**10**	**98**	**58**	**56**	**51**	**13**	**1**
96	**20**	**89**	**21**	**82**	**38**	**72**	**68**	**29**	**0**
80	**9**	**97**	**57**	**63**	**27**	**53**	**52**	**14**	**2**
92	**24**	**81**	**37**	**75**	**35**	**69**	**65**	**30**	**0**
100	**60**	**62**	**26**	**87**	**47**	**54**	**49**	**15**	**3**
84	**40**	**74**	**34**	**95**	**19**	**70**	**66**	**31**	**0**
61	**25**	**86**	**46**	**79**	**12**	**55**	**50**	**8**	**7**
73	**33**	**94**	**18**	**91**	**23**	**71**	**67**	**5**	**6**

5.5.1 Simulation Environment

In this experiment, all the 101 static sensor nodes are deployed on the area of 80 metres x 80 metres. The nodes are arranged to form a mesh network with triangular pattern as shown in Figures 5-3. The sensor node deployment is adopted from the topology used by [16]. Meanwhile, the simulation scenario is designed where the communication from source node to destination node happens only in 2-hop communication refers to Table 5-1. The distance among the adjacent node is 7 metres and each node has transmission power to cover the distance of 9 metres (power at receiver: 2.37381x10^{-6} W).

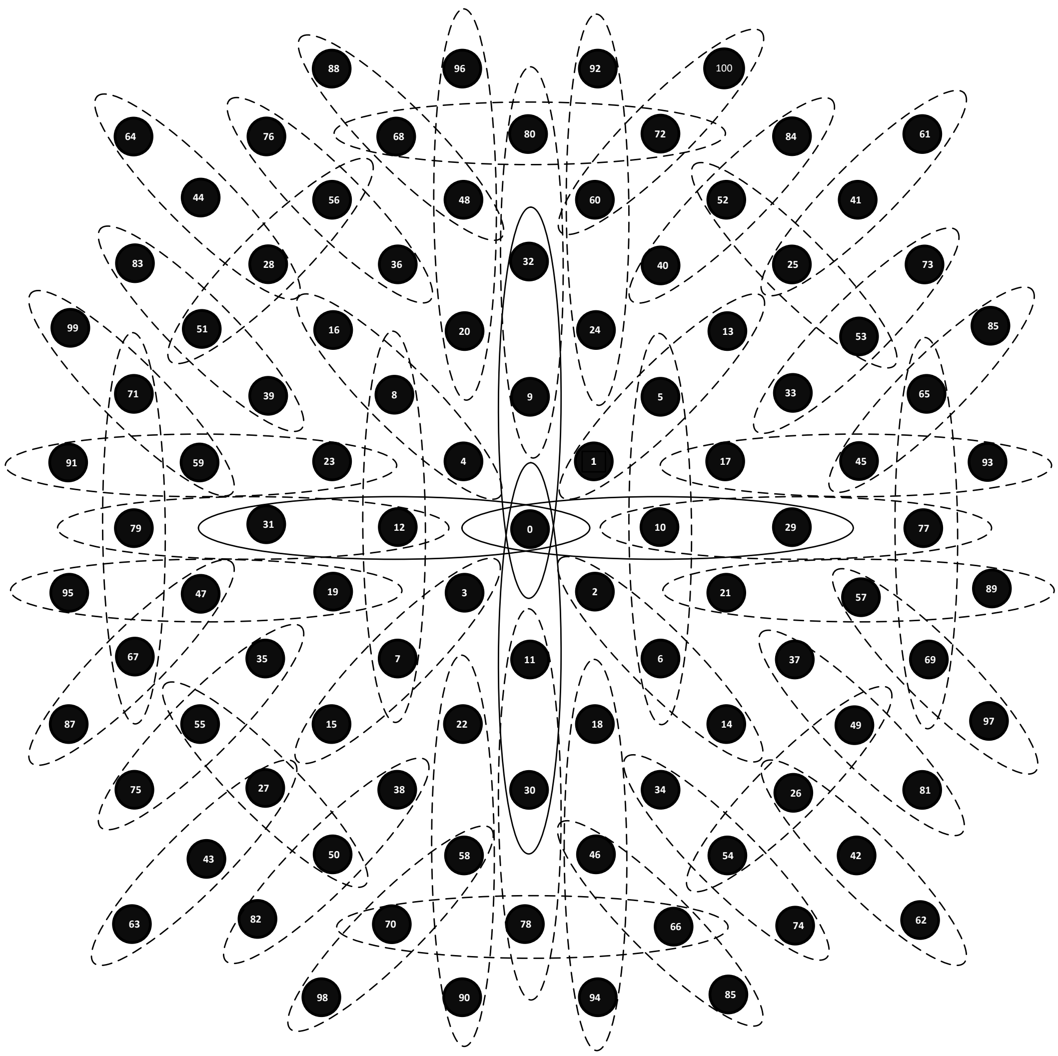


Figure 5-3: Design topology of implementing 802.15.4 beaconless-enabled protocol on a large-scale wireless sensor network with 101 nodes.

The experiment implements the proposed network based on beaconless-enabled mode. The aim of the experiment is to prove that beaconless-enabled mode of IEEE 802.15.4 protocol is not only suitable for small-scale WSN [20] but also adaptable for large-scale WSN. Various performance metrics, which are very important in communication networks, are investigated and then evaluated such as network throughput, packet loss, and network latency.

This experiment is conducted under the environment where it introduces gradual number of nodes connected on the networks starting from 5 to 50 connections. Each connection comprises of two-hop communication. We apply three different payload sizes to find the most applicable size for the proposed network. Those are classified as low (30 Bytes), middle (60 bytes and varied the inter arrival time of Poisson's data traffic. We also employ Poisson's data traffic which distributes data packet exponentially with inter arrival time of 0.1 millisecond. Detail of all parameters used within the simulation is depicted in Table 5-2.

Table 5-2: Some parameters used in the simulation

Parameters	Value
Networks simulation	NS2 version 2.34
Simulation duration	500 s
Traffic runs	20 to 480 s
Network dimension	80 m x 80 m
Number of nodes	101 nodes
Distance among nodes	7 m
Node mobility	Off
Node coverage range	12 m
Antenna	Omnidirectional
Radio propagation model	Two ray ground
Data bit rate	250 kbps
Traffic model	Poisson distribution
Packet size	70 Bytes
Number of connections	Varied from 5 to 50
Number of hops	2 hops
Acknowledgment (ACK)	On
Retransmission	On

5.5.2 Performance Metrics

Some performance metrics as performance indicators of proposed networks in the simulation can be defined as below:

- **Average network throughput:** the whole number of generated packets (in bits or bytes) by source nodes that are successfully received by destination nodes for a certain period (in second). In this simulation, communication among nodes is designed to be homogeneous as 2 hops range from source to sink node.
- **Packet delivery ratio:** the ratio (in percentage) of data packets successfully received at the destination nodes to those data packets sent by source nodes**.** Packet delivery performance of a wireless sensor network is a very critical issue to improve overall system performance and to explore the future development of WSN and its applications [94].
- **Number of dropped packet:** The failure packet measured in this experiment is based on the number of packet generated by source nodes and packet successfully received at destination nodes or packet forwarded at intermediate nodes.
- **Average packet loss:** the average numbers of packets that are degraded or lost during the time of communication among the nodes on the networks starting from time they are generated at the sink nodes until arriving at the destination.
- **Average network delay:** the average delay of packets by computing the time elapsing since the packets are generated by source nodes up to the time packets are received by destination nodes on the networks, including processing, queueing, and propagation delays. This metric refers to the total delay of data packets occurred inside the network caused by retransmission, hop count, queueing, and other factors such as environment factors [111].

5.5.3 Simulation Results

This section presents the implementation of IEEE 802.15.4 beaconless-enabled protocol for large number of nodes (101 nodes) communicating on wireless sensor networks. Those results include all performance metrics such as average network throughput, packet delivery ratio (PDR), number of dropped packet, average packet loss, and average network delay as shown in Figure 5-4, 5-5, 5-6, 5-7, and 5-8, respectively. The following sub-sections present and elaborate detailed results of those experiments.

5.5.3.1 Average Network Throughput

Figure 5-4 shows the average throughput which is gathered from the experiment. It presents generally that throughput goes up when there are more nodes communicating on the networks. Furthermore, the performance of IEEE 802.15.4 MAC beaconless-enabled protocol obviously better on large-scale ad hoc WSN for the bigger payload size in term of achieved network throughput. From the figure, it calculates that the average throughputs are 440.1 kbps, 323.8 kbps, and 235.2 kbps for the payload size of 90 Bytes (upper), 60 Bytes (middle), and 30 kbps (low), comparatively.

As shown in the Figure 5-4, the throughput increases for all increment number of nodes, which also increase the number of radio channels using to communicate each other in the networks. This condition allows nodes on the network to produce a larger aggregate throughput. From the figure, the increment of network throughput starting from 5 connections to 50 connections are 615.0 kbps, 451.1 kbps, and 334,.6 kbps for the upper payload size (90 Bytes), middle payload size (60 Bytes), and low payload size (30 Bytes), respectively.

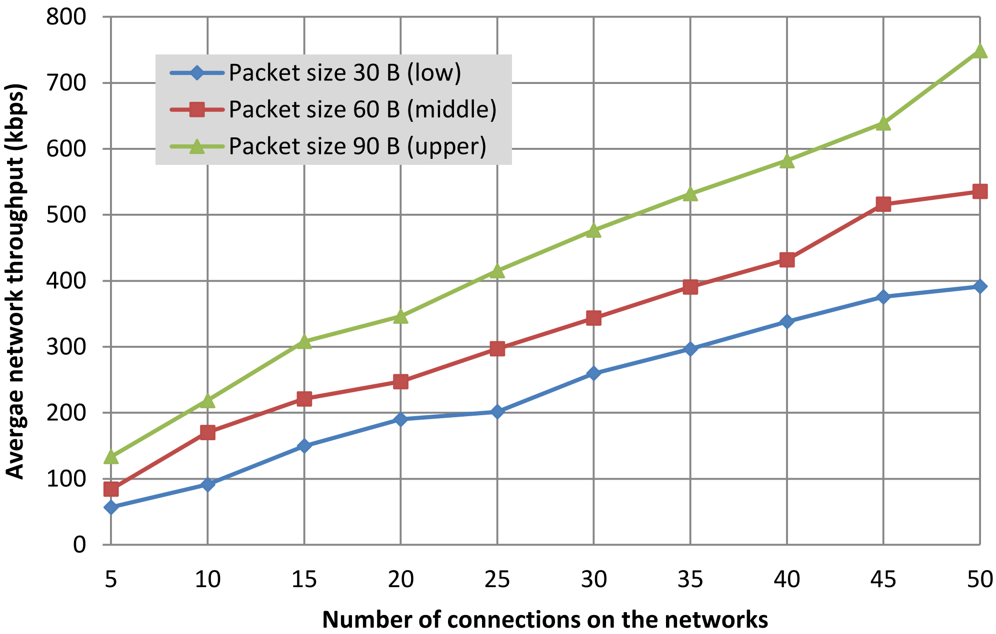


Figure 5-4: Average network throughput on a large-scale wireless sensor network with various number of connections among nodes.

5.5.3.2 Packet Delivery Ratio

Packet delivery ratio (PDR) or known as packet delivery fraction (PDF) is an important performance metric of any protocols because it indicates the significance of achieved throughput on the end-to-end paths. Figure 5-5 depicts a comparison of significant correlation of three packet sizes, which are categorised as low, middle, and upper sizes to the performance of proposed networks in term of packet delivery ratio. The figure also shows that the probability of successful data delivery seriously degrades with the increment of connections on the networks.

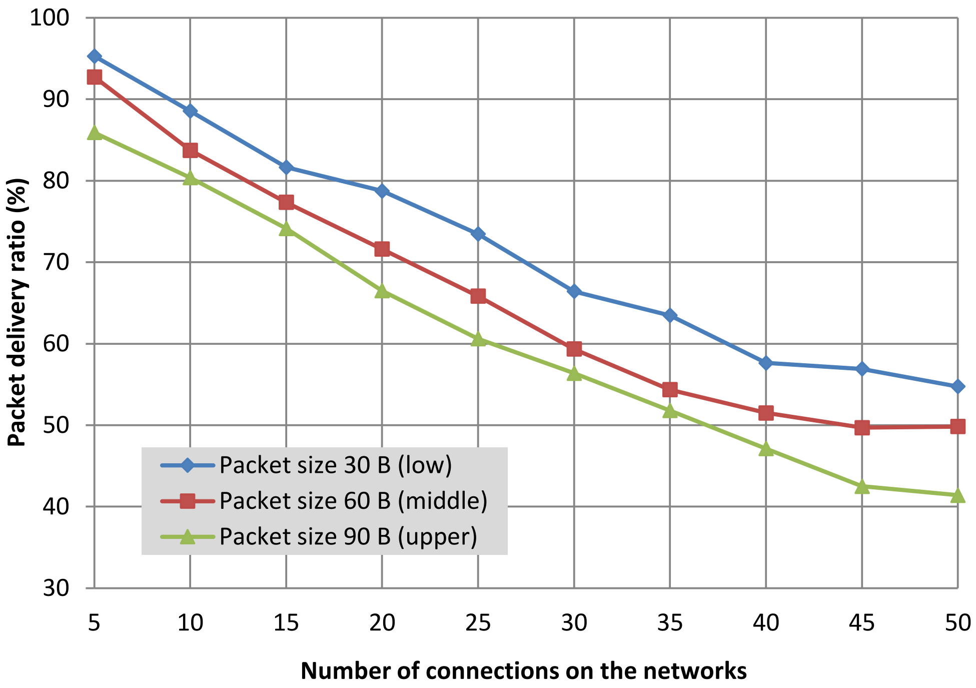


Figure 5-5: Packet delivery ratio on a large-scale wireless sensor network with various number of connections among nodes.

As shown in Figure 5-5, the three different sizes of packet start their performance with different PDR, where the lower packet size performs better than the middle or the upper packet sizes. However, when the number of connections increases, the PDR starts dropping for all packet size. The more the number of connections the more network congestions and collisions occur on the network. From the figure, when the number of connection grows up from 5 to 50 connections, then the value of PDR decreases by up to 40.5%, 42.9, and 44.5% for the low, middle, and upper payload size, respectively. Overall, on the small payload size of 30 Bytes, IEEE 802.15.4 protocol performs better to carry up to 95.3% data on low congested network and up to 54.8% on extremely congested network as compared to the protocol performance on upper payload size of 90, which deliver successful data up to 85.9% and 41.4%, respectively.

5.5.3.3 Number of Dropped Packet

Figure 5-6 shows the amount of data dropping (in 1000 packets) during the simulation for the proposed large-scale ad hoc WSN over IEEE 802.15.4 protocol with several payload sizes. In Chapter 3 of this thesis, the proposed small-scale ad hoc WSN over IEEE 802.15.4 protocol outperforms to the WSN over the same protocol in all the previous performance metrics, except the network latency. Meanwhile, Figure 5-6 proves that in the large-scale ad hoc WSN, the protocol IEEE 802.15.4 performs better with lower payload size in terms of data dropping. It calculates that the average of dropping packet on low payload size (30 Bytes) is not more than 202.9 kilo-packets (k-pkts). In contrast, the dropping data on upper payload size (90 Bytes) is up to 271.8 k-pkts. Meanwhile, the moderate dropping data occurs on the middle payload size (60 Bytes) which is about 231.2 k-pkts.

Result in Figure 5-6 shows that there are fewer data drops at smaller number of nodes connected on the network compare with the larger number of connections. The increasing numbers of dropped packets when the network employs gradual connections starting from 5 to 50 connections are 476.7 k-pkts, 478.7 k-pkts, and 618.03 for payload size of 30 Bytes, 60 Bytes, and 90 Bytes, respectively. This shows that the protocol works better at lower payload size and on smaller-scale network. This explains that the larger the size of networks the more the chances of collisions and transmission errors which leads to more dropping of packets.

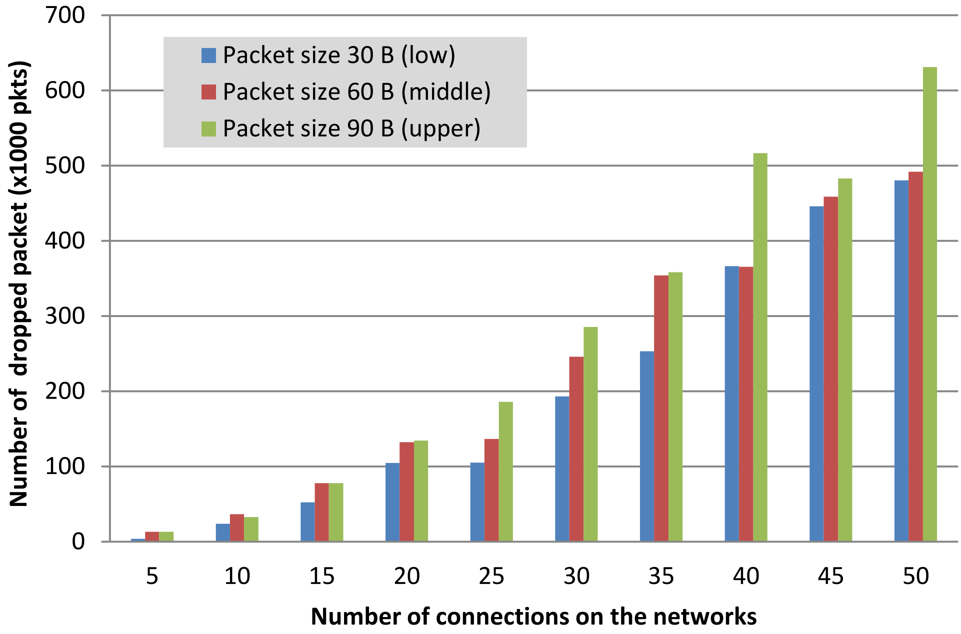


Figure 5-6: Number of dropped packet on a large-scale wireless sensor network with various number of connections among nodes.

5.5.3.4 Average Packet Loss

A large number of nodes which communicate on the networks may affect the occurring collision rate. This trend can be seen in Figure 5-7 where packet loss rate goes up significantly when the number of nodes involving in communication increases as well.

From Figure 5-7, it can calculate that average packet loss is higher for upper packet size rather than of low packet size. The average packet losses measured from the simulation are 119.2%, 139.6%, and 161.2% for the low (30 Bytes), middle (60 Bytes), and upper (90%) of packet size, respectively.

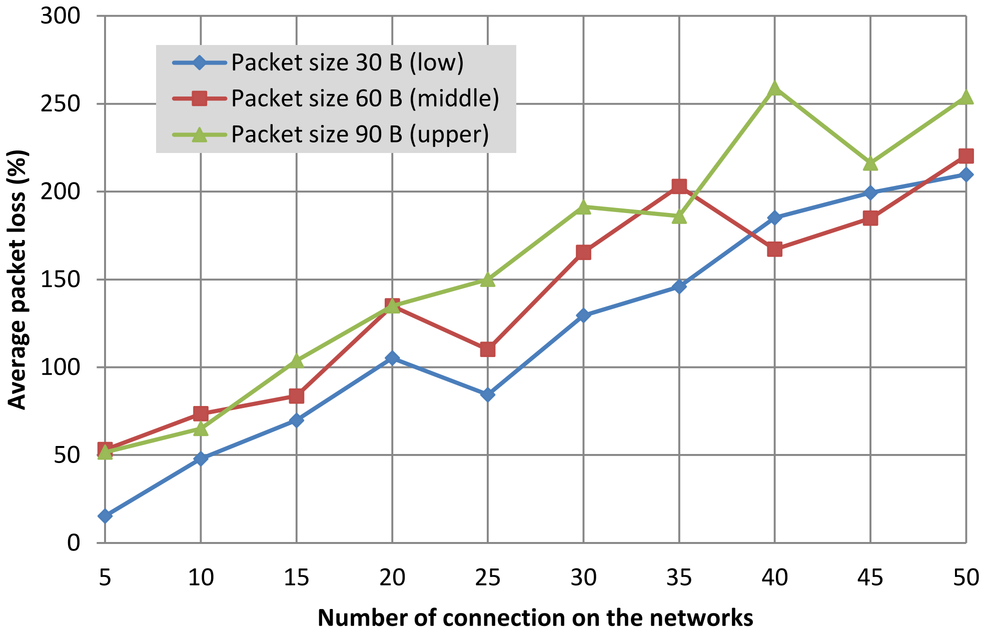


Figure 5-7: Average packet loss on a large-scale wireless sensor network with various number of connections among nodes.

5.5.3.5 Average Network Delay

Figure 5-8 compares the average network delay of the implementation of IEEE 802.15.4 beaconless-enabled MAC protocol in a 101 nodes wireless sensor network. As can be seen from the figure, the average delay experienced by the packets is greater for the bigger packet size and larger number of nodes connecting in the networks. When the number of connected nodes increase then the more hops should be passed by packet from source node to the destination node. Consequently, there is more transmission and queuing delays on the path experienced by each packet and then they contribute more latency to the network.

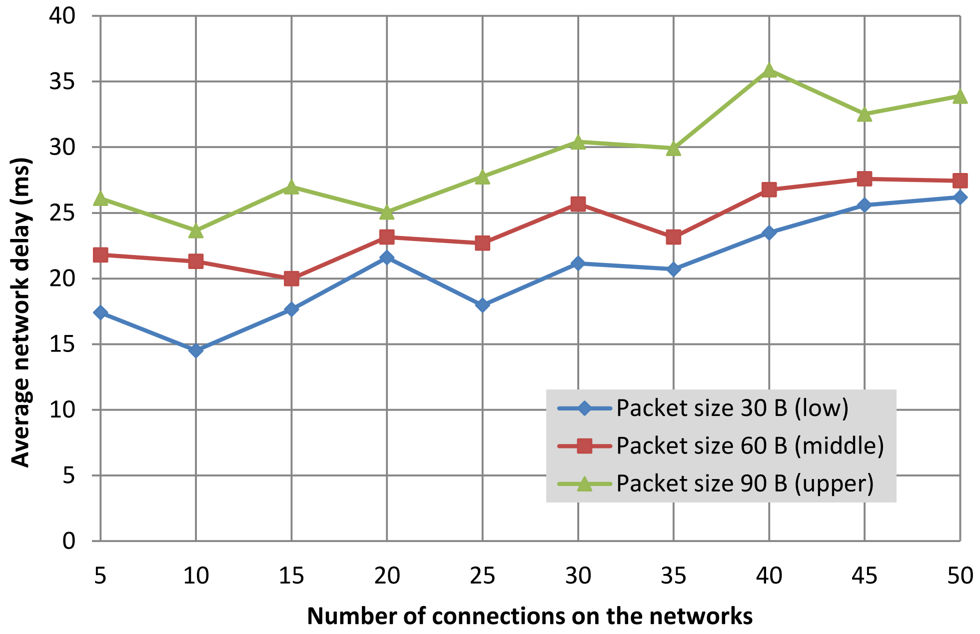


Figure 5-8: Average network delay on a large-scale wireless sensor network with various number of connections among nodes.

The average network delay for different number of connections on the evaluated network, as shown in Figure 5-8, points out that the smaller payload size performs better than the larger size by producing less latency in the networks. Overall, the average network delay measured from simulation are 20.6 ms, 24.0 ms, and 29.2 ms for low packet size of 30 Bytes, middle packet size of 60 Bytes, and upper packet size of 90 Bytes, respectively.

5.6 Summary

This chapter presents an evaluation study of a 101-node large-scale beaconless-enabled wireless sensor networks over MAC sub-layer of IEEE 802.15.4 protocol using network simulator NS-2 version 2.34.

From the experiment, it finds that when the number of connection densely grows up, then the probability of packet delivery decreases by up to 40.5% for the low payload size and not less than 44.5% for the upper payload size. Meanwhile, for all sizes of payload applied to the large-scale ad hoc wireless sensor network, it points out a stable increasing throughput whilst the network handles more connections among sensor nodes.

In term of dropped packet, the evaluation result confirms that there are fewer data drops at smaller number of nodes connected on the network compare with the larger number of connections. It also calculates that, on low payload size of 30 Bytes, the protocol outperforms not less than 34% better than on upper payload size. This concludes that the protocol works better at lower payload size and on smaller-scale network. The same trend is obviously seen for the performance metric of packet loss.

The simulation results show that the smaller payload size performs better than the bigger one by producing less latency in the networks. The payload size of 30 Bytes contributes less than 41.7% compared with the contribution by payload size of 90 Bytes.

Chapter 6

Conclusions and Future Research

This chapter presents the main conclusion and a summary of research done in each chapter with some contributions to the knowledge. Since the research topic on the field of WSNs is a never-ending work, then this chapter also highlights a potential further investigation as a guidance to the next research direction.

6.1 Conclusions

This thesis focuses on the enhancement of the IEEE 802.15.4 beaconless-enabled MAC protocol to cope with some issues of network bottleneck, less flexible nodes, and more energy waste at the centralised wireless sensor networks. The thesis has expanded three main contributions in each chapter i.e. the first contribution in Chapter 3, the second contribution in Chapter 4 and the third contribution in Chapter 5. All the three contributions are elaborated more details on the section 6.1.1, 6.1,2, and 6.1.3, respectively.

6.1.1 Ad Hoc Wireless Sensor Networks

In this part of the research, it solves the issues of network bottleneck, lack of flexibility and energy consumption on wireless sensor networks over the IEEE 802.15.4 protocol. The low data rate ad hoc wireless sensor network over IEEE

802.15.4 beaconless-enabled mode is deeply explored as an alternative to face such those problems. A comparative study has been conducted to evaluate the performance of existing IEEE 802.15 and IEEE 802.11 standard for ad hoc WSNs.

The result of the first part of simulations confirms that ad hoc WSN over IEEE 802.15.4 beaconless-enabled mode performs better than WSN over beacon-enabled mode in a small-scale network. In term of throughput, successful data delivery, and energy consumption, the ad hoc WSN performs better than WSN in the proposed small-scale network as it improves by up to 22.4%, 17.1%, and 43.2%, respectively. The ad hoc WSN also outperforms the WSN by mean of the percentage of packet loss where it drops fewer packets by up to 34.1%. Nevertheless, WSN achieves less end-to-end delay than ad hoc WSN. It shows that the bigger payload size applied on network, the longer time needed to process packet transmission which will affect network latency. In this point of view, WSN contribute less latency by up to 2.0 ms.

From the result of the second part of simulations, it indicates that ad hoc wireless sensor networks work well both over IEEE 802.15.4 and IEEE 802.11 protocols in small-scale networks with low traffic loads. Meanwhile, for higher payload size, the performance of IEEE 802.15.4 protocol declines since this standard is dedicated to low rate wireless personal access networks. This can be seen from the declining of successful receiving packets (or PDR), which goes down by up to 49.2% when traffic added to the network over IEEE 802.15.4 protocol from 0.5 kbps to 27.3 kbps. In contrast, the decreasing PDR is less than 1% on ad hoc over IEEE 802.11 protocol.

6.1.2 Hidden Nodes Problem

The simulation has implemented three different scenarios with aim to study the performance of beaconless-enabled wireless sensor networks (BeWSN) over IEEE 802.15.4 protocol in hidden nodes circumstances. Firstly, a scenario is arranged with various data inter-arrival times for beaconless-enabled ad hoc WSN over IEEE 802.15.4. Secondly, a scenario is set up for comparative evaluation of WSN in hidden nodes and unhidden nodes condition. Finally, an effectiveness study has been carried out to evaluate the implementation of RTS/CTS mechanism to avoid collision due to hidden nodes appearance. The two former experiments have been treated in a single-hop star topology, while the latter has been conducted in a multi-hop mesh topology.

From the simulation result, it shows that the performance of ad hoc wireless sensor networks deteriorates as indicated by degradation of throughput and packet reception due to hidden nodes appearance. It calculates that the throughput and PDR decline by up to 72.66 kbps and 35.15%, respectively whilst the packet loss goes up by 18.82%. Fortunately, in relation to end-to-end delay, there is no significant performance gap caused by presence of hidden nodes.

The last experiment in this part of thesis proves that preventing hidden node effect by implementing RTS/CTS (request-to-send/clear-to-send) handshaking mechanism is not suitable for IEEE 802.15.4 protocol, which is dedicated to low data rate wireless sensor networks.

6.1.3 Implementation in Large-scale WSNs

The thesis further investigates the issue of how big the number of nodes can involve in communication on wireless sensor networks supported by MAC protocol of the IEEE 802.15.4. In this thesis, the performance evaluation of IEEE 802.15.4 beaconless-enabled protocol also considers the node deployment method. This aims to meet the requirement for initial deployment which should reduce the installation and maintenance cost, increase the flexibility of nodes placement, and guarantee the nodes become more self-healing and fault tolerant.

For all sizes of payload applied to the simulation of a large-scale ad hoc wireless sensor network, it points out a stable increasing throughput whilst the network handles more connections among sensor nodes. In addition, when the number of connection densely grows up, then the probability of packet delivery decreases by up to 40.5% for the low payload size and not less than 44.5% for the upper payload size.

In term of dropped packet, on the low payload size of 30 Bytes, the protocol outperforms about 34% better than on upper payload size of 90 Bytes. This concludes that the protocol works better at lower payload size and on smaller-scale network. The similar trend is obviously seen for the performance metric of packet loss.

The experiment results also confirm that the smaller payload size performs better than the bigger one by producing less latency in the networks. The payload size of 30 Bytes contributes less than 41.7% compared with the contribution by payload size of 90 Bytes.

6.2 Future Research

The research and investigation on wireless sensor networks is never-ending works. Several recommendations, which may guide to the future research directions on wireless sensor networks, are also deliberated in the following section. The future works related to the current findings and results will be elaborated more detail as below.

6.2.1 Mobile Ad Hoc Wireless Sensor Networks

All of the proposed designs and experiments in this thesis are based on static sensor nodes because of the simplicity reason and wide range of static WSN applications. Otherwise, many applications comprise of mobile sensors with static coordinator or both mobile sensors and mobile coordinator. Since we proposed ad hoc or infrastructure-less wireless sensor networks, then the protocol should consider mobility for all sensor nodes with full function devices.

Several improvements in MAC protocols for mobile sensor networks (MSNs) are still challenging nowadays and the next future [112]. The problems arise due to the low coverage area, low speed of mobile sensor node, and complex switching process with adjacent nodes. A few existing literatures presents the enhancement of MAC protocols to support mobile sensor nodes whilst some of them still point out some gaps. One of the issues is that the MAC design related to energy saving is not suitable for network utilization because mobile nodes should be in idle for longer time [113].

Since the coverage of a sensor network with static sensor nodes has been extensively investigated, then [114] identified and characterized the dynamic aspects of network coverage related to sensor movement. Authors also proposed a game theoretic approach and derived optimal mobility strategies to detect random stationary targets. Furthermore, [115] have investigated area coverage in mobile sensor networks where every sensor has various sensing range. The investigation overwhelmed asymptotic coverage under uniform deployment model and *k*-coverage under Poisson deployment model. Meanwhile, [116] proposed an iterative approach to locate the coordinate of mobile sensors with the guidance of moving beacons in WSNs. Most of those studies concentrate on development of certain mechanisms related to the mobile sensor devices. In the next future, however, we propose design of MAC protocol to support improvement of throughput and prolong sensor lifetime of the so-called mobile ad hoc wireless sensor networks (MAWSNET).

6.2.2 Less Delay and Collision LDR-MAWSNET

In [45] the MAC protocol named as EMS-MAC (enhanced mobility-aware sensor medium access control) has been introduced to handle mobility issue on wireless sensor networks. The MAC protocol enhances mechanism to detect the mobile node movement using a combination technique between the received signal strength indicator (RSSI) and the link quality indication (LQI). Accordingly, authors proposed a pseudo active zone so-called the mobility-zone to extend the original idea of the active zone in the previous mobility-aware sensor MAC (MS-MAC) protocol [117].

In [118] the theoretical analysis of collision occurrence in two neighbouring WPANs has been developed and the necessary and sufficient conditions have been provided to avoid collisions happening in adjacent WPANs over IEEE 802.15.4 MAC protocol.

In the low data rate mobile sensor networks (MSNs) with high beacon orders (BO), the probability of data and beacon collision occurrence is merely rare. Nonetheless, collision might happen more often when there is huge number of nodes with faster movement. Therefore, in the very dense networks, avoiding data collisions in the networks will be very beneficial for lowering network latency and reducing data retransmissions. The adaptive adjustment of receiving power threshold is one of promising techniques to be implemented to control the collision [119].

Accordingly, in the next works, we consider the collision problem and its impact on latency on the proposed low data rate mobile ad hoc wireless sensor networks (LDR-MAWSNET).

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List of Publications

A. Published Papers

[1] V. P. Selvan, **M. S. Iqbal,** and H. S. Al-Raweshidy, “Performance analysis of linear precoding schemes for very large multi-user MIMO downlink system”, in Proceeding the 4th International Conference on Innovative Computing Technology (INTECH 2014), Luton-UK, pp.219-224, 13th -15th August 2014. DOI:10.1109/INTECH.2014.6927765.

[2] **M. S. Iqbal** and H. S. Al-Raweshidy, “Performance evaluation of IEEE 802.15.4 standard for low data rate ad hoc wireless sensor networks”, The 2nd International Conference on Control, Automation, and Information Sciences (ICCAIS 2013), Nha Trang Vietnam, pp.300-304, 25th -28th November 2013. DOI:10.1109/ICCAIS.2013.6720572.

[3] **M. S. Iqbal**, A. Masrub, V. P. Selvan, and H. S. Al-Raweshidy, “A performance enhancement of IEEE 802.15.4 standard to overcome hidden nodes effect on low data rate ad hoc WSNs”, in Proceeding the 3rd International Conference on Innovative Computing Technology (INTECH 2013), London, pp.360-364, 29th -31st August 2013. DOI:10.1109/INTECH.2013.6653642.

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B. Submitted Papers

[1] **M. S. Iqbal**, V. P. Selvan, and H. S. Al-Raweshidy, "A comprehensive evaluation of IEEE 802.15.4 beaconless MAC for low rate low power ad hoc wireless sensor networks", IET Wireless Sensor Systems (submitted May 2016).

[2] **M. S. Iqbal**, V. P. Selvan, and H. S. Al-Raweshidy, "A comparative study of IEEE 802.15.4 beaconless protocol for wireless sensor networks in hidden nodes environment", Wireless Networks: The Journal of Mobile Communication and Information (submitted May 2016).

[3] **M. S. Iqbal** and H. S. Al-Raweshidy, "Enhanced IEEE 802.15.4 beaconless-enabled MAC for a large-scale wireless sensor network", Telecommunication Systems (submitted May 2016).