Sudan University of Science and Technology (SUST)
College of Graduate Studies
College of Computer Science and Information Technology

Performance Improvement for Industrial Internet of Things Systems based on Optimization of Contention Access Period in Superframes

تحسين الأداء للنظم الصناعية لإنترنت الأشياء المبني على القيمة المثلى لفترة الوصول للمنافسة في الإطارات الفائقة

A thesis
Submitted in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY in Computer Science

By:
Yousuf Ruduan Hussein Ruduan

Supervisor:
Associate Prof. Dr. Salah Elfaki Elrofai Elfaki

April 2021

بسم الله الرحمن الرحيم

الآيـــــــات :

1- **قال الله تعالى** ﴿ قَالُواْ سُبْحَانَكَ لاَ عِلْمَ لَنَا إِلاَّ مَا عَلَّمْتَنَا إِنَّكَ أَنتَ الْعَلِيمُ الْحَكِيمُ ﴾

صدق الله العظيم

سورة البقرة – الآية ﴿32﴾

2- **قال الله تعالى:** اقْرَأْ بِاسْمِ رَبِّكَ الَّذِي خَلَقَ ﴿1﴾ خَلَقَ الْإِنْسَانَ مِنْ عَلَقٍ ﴿2﴾ اقْرَأْ وَرَبُّكَ الْأَكْرَمُ ﴿3﴾ الَّذِي عَلَّمَ بِالْقَلَمِ ﴿4﴾ عَلَّمَ الْإِنْسَانَ مَا لَمْ يَعْلَمْ ﴿5﴾ كَلَّا إِنَّ الْإِنْسَانَ لَيَطْغَىٰ ﴿6﴾ أَنْ رَآهُ اسْتَغْنَىٰ ﴿7﴾ إِنَّ إِلَىٰ رَبِّكَ الرُّجْعَىٰ ﴿8﴾ أَرَأَيْتَ الَّذِي يَنْهَىٰ ﴿9﴾ عَبْدًا إِذَا صَلَّىٰ ﴿10﴾ أَرَأَيْتَ إِنْ كَانَ عَلَى الْهُدَىٰ ﴿11﴾ أَوْ أَمَرَ بِالتَّقْوَىٰ ﴿12﴾ أَرَأَيْتَ إِنْ كَذَّبَ وَتَوَلَّىٰ ﴿13﴾ أَلَمْ يَعْلَمْ بِأَنَّ اللَّهَ يَرَىٰ ﴿14﴾ كَلَّا لَئِنْ لَمْ يَنْتَهِ لَنَسْفَعًا بِالنَّاصِيَةِ ﴿15﴾ نَاصِيَةٍ كَاذِبَةٍ خَاطِئَةٍ ﴿16﴾ فَلْيَدْعُ نَادِيَهُ ﴿17﴾ سَنَدْعُ الزَّبَانِيَةَ ﴿18﴾ كَلَّا لَا تُطِعْهُ وَاسْجُدْ وَاقْتَرِبْ ۩ ﴿19﴾.

صدق الله العظيم

سورة العلق

Dedications

I dedicate this thesis to my parents, my dear wife, my sons, and my daughter, also to my brothers and my sisters, who are always supporting, encouraging me, and they are still giving me a lot of support throughout my all years of education.

Acknowledgments

I wish to express my sincere gratitude and indebtedness to Associate Prof. Dr. Salah Elfaki Elrofai for his supervision, guidance, and encouragement throughout this study. His invaluable suggestions and constructive criticism from time to time during the preparation of this thesis enabled the author to present the thesis in this form. Also, we would like to thank Professor: Haitham S. Hamza at Cairo University, who gave me advice, valuable guidance, and led me to the IIoT field. I would like to thank my supervisor; he gave me valuable guidance until the completion of this thesis.

I want to thanks the member staff of the college of computer science and information technology for their kind helps towards obtaining a Ph.D. degree in computer science.

Finally, I extend my special thanks and appreciation to Professor Izzeldin Mohamed Osman.

Yousuf Ruduan Hussein

April 2021

Abstract

The Industrial Internet of Things (IIoT) is an emerging technology in recent years, which is widely utilized for control, manage the manufacturing environment, and monitor production lines in the smart factories at any time from every location over the global through an Internet connection. IIoT includes various physical objects of the real smart devices, which are deployed based on their functionalities. IIoT network has so many technical complex issues; one of the most essential issues is the performance, which affects the network throughput. Performance plays a major role as it can significantly improve the IIoT network's lifetime. Many research efforts have been done in this area to improve the IIoT network performance.

This thesis proposed the Contention Access Period Reduction Medium Access Control protocol (CAP Reduction protocol) for improving the performance based on the CAP size reduction. The proposed protocol leads to reduce the CAP portion. Thus the number of time slots, which assigned to the network nodes will decrease.

Moreover, this research attempts to estimate the performance of the IIoT network based on three metrics: throughput, packets delay, and energy consumption. To validate the proposed protocol, different experiments have been conducted based on the Cooja simulator, which works under the Contiki Operating System (OS). The proposed protocol is reduced the number of time slots by 50 %, increases throughput by 63.0 %, decrease the packets execution time by 33.7 %, and also reduces the overall energy consumption by up to 64.14 %.

مستخلص البحث

إنترنت الأشياء الصناعي (IIoT) هي تقنية نشأت في السنوات الأخيرة ، وهي تُستخدم على نطاق واسع للتحكم و إدارة بيئة التصنيع ومراقبة خطوط الإنتاج في المصانع الذكية في أي زمان و من أي مكان حول العالم من خلال الاتصال بالإنترنت. يتضمن إنترنت الأشياء الصناعية (IIoT) الكينونات المادية المختلفة للأجهزة الذكية الحقيقية ، والتي يتم نشرها بناءً على وظائفها. شبكة إنترنت الأشياء الصناعية (IIoT) لديها الكثير من القضايا التقنية المعقدة ، يُعدْ الأداء من أهم المشكلات التي تؤثر على أداء الشبكة. يلعب الأداء دورًا رئيسيًا حيث يمكنه تحسين عمر شبكة إنترنت الأشياء الصناعية بشكل ملحوظ. تم إجراء العديد من الجهود البحثية في هذا المجال لتحسين أداء شبكة إنترنت الأشياء الصناعية.

اقترحت هذه الرسالة بروتوكول التحكم في الوصول لخفض فترة الوصول إلى المنافسة (بروتوكول تقليل حجم CAP) لتحسين الأداء بناءً على تقليل حجم CAP. يؤدي البروتوكول المقترح إلى تقليل حجم CAP. وبالتالي فإن عدد ال (Time Slots) المخصصة لعقد الشبكة سينخفض.

علاوة على ذلك، يحاول هذا البحث تقييم أداء شبكة (IIoT) بالاعتماد على ثلاث مقاييس: الإنتاجية ، تأخير الحزم ، وإستهلاك الطاقة . للتحقق من صحة البروتوكول المقترح، أجريت تجارب مختلفة معتمدة على محاكاة (COOJA)، و الذي يعمل تحت نظام التشغيل (Contiki OS). يمكن للبروتوكول المقترح تقليل عدد ال (Time Slots) بنسبة 50٪ ، زيادة الإنتاجية بنسبة 63.0٪ ، تقليل زمن تنفيذ الحزم بنسبة 33.7٪ ، وتقليل إجمالي إستهلاك الطاقة بنسبة تصل إلى 64.14٪.

List of Contents

List of Figures

List of Tables

List of Terms and Abbreviations

No.	Abbreviation	Meaning
1	ACK	Acknowledgment
2	ASN	Absolute Slot Number
3	BP	Backoff Periods
4	BO	Beacon Order
5	BS	Base Station
6	CAP	Contention Access Period
7	CCA	Clear Channel Assessment
8	CFP	Contention Free Period
9	CSMA	Carrier Sense Multiple Access
10	CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
11	CPS	Cyber-Physical Systems
12	CPPS	Cyber-Physical Product Systems
13	CMS	Cyber Manufacturing Systems
14	CoAP	Constrained Application protocol
15	DSME	Deterministic Synchronous Multichannel Extension
16	EB	Enhance Beacon
17	FCS	Frame Check Sequence
18	Four G	Fourth Generation
19	GACK	Group Acknowledgment
20	GTS	Guaranteed Time slots
21	IE	Information Elements
22	IEEE	Institute of Electrical Electronics Engineering.

No.	Abbreviation	Meaning
23	IETF	Internet Engineering Task Force
24	IoT	Internet of Things
25	IIoT	Industrial Internet of Things
26	ICPIoT	Industrial Cyber-Physical Internet of Things
27	I 4.0	Industry 4.0
28	IWSN	Industrial Wireless Sensor Network
29	LLDN	Low Latency Deterministic Network
30	LTE	Long Term Evolution
31	LR-WPAN	Low Rate Wide Personal Area Network
32	MAC	Medium Access Control
33	NNMI	National Network for Manufacturing Innovation
34	OPNET	Optimized Network Evaluation Tool
35	OS	Operating System
36	OV	Open Visualizer
37	PAN	Personal Area Network
38	PDR	Packet Delivery Ratio
39	PHY	Physical
40	PLM	Product Lifecycle Management
41	QoS	Quality of Service
42	RDC	Radio Duty Cycling
43	RFD	Reduced Function Device
44	RFID	Radio-Frequency Identification
45	RFS	Random-Frequency-Selection
46	RX	Receive
47	SD	Super-frame Duration

No.	Abbreviation	Meaning
48	SO	Super-frame Order
49	TCP	Transmission Control Protocol
50	TDMA	Time Division Multiple Access
51	TSCH	Time Slot Channel Hopping
52	TX	Transmit
53	UCB	University of California, Berkeley
54	UDP	User Datagram Protocol
55	UWB	Ultra-Wide-Band
56	WiFi	Wireless Fidelity
57	WLAN	Wireless Local Area Network.
58	WSN	Wireless Sensor Network
59	Z1	Zolertia Z1

.

Chapter One

Introduction

Chapter One

Introduction

1.1 Preface

This chapter intends to introduce the main ideas of the thesis. First, an overview of the Internet of Things (IoT), IIoT structure systems, and their differences between IoT and IIoT will be presented. Next, the communication protocols of IIoT have been discussed. Besides, the research scope presents in detail discussion. The problem statement is introduced, followed by the research objectives. Finally, the methodology, motivation of this thesis, and thesis contributions are described in more detail, concluded by the thesis organization.

1.1.1 Internet of Things

Recently, the Internet of Things (IoT) becomes is an essential technology due to its significant impact on human life [1]. The term IoT has been introduced in 1999 by Kevin Ashton to connect tiny devices to the Internet and persons to devices. Massive amounts of IoT objects will predict to be installed in machines, humans, vehicles, buildings, and environments. These objects include smartphones, tablets, cameras, smart sensors, and actuators [2], [3]. Wireless Sensor Network (WSN) is one of the most essential parts of the IoT, which is widely studied and applied wirelessly in different environments for compiling and exchanges data through the coordination among source nodes and sink nodes [4], [5]. The smart sensors are deployed to establish network connectivity to the Internet through internet protocol (IP), which is powered by batteries that make it subject to energy consumption constraints [6].

IoT definition is still under discussion, but there is a primary role of IoT devices through providing access to information and services over billions of heterogeneous devices (things), ranging from resource-constrained to powerful tools [7]. Theoretically, IoT means interconnect things and objects which are individually addressable and interact with each other using standard communication protocols [3], [8]. The new definition of IoT is a new way of addressing issues with remarkable social impact, relevant to new ways for educating, new ways of conceiving homes and cities on a human scale, and quickly responsive to the human needs, which are recent ways of addressing energy management issues, it is modern approaches for electronic healthcare. Rather people and objects have interacted with each other as peers. Objects interaction will allow for creating applications with a higher penetration rate and better virtual representation [9].

IoT is used for enabling monitoring and control of a myriad of interconnected devices. Managing huge heterogeneous resources of the IoT becomes a great challenge, especially in those cases that it operates on a limited battery [10]. IoT devices are more resource-constrained in terms of energy efficiency that requires to development of an appropriate operating system to build upon these devices [11]. The requirements of the operating systems for IoT nodes are to provide energy saving by using techniques just as radio duty cycling and minimizing the number of periodic tasks that need to be executed. Various kinds of IoT include identification, sensing, communication technologies, computation, services, and semantics [12].

IoT applications in manufacturing systems called the Industrial Internet of Things (IIoT). The IIoT considers as the base of a new level of organization, management of industrial value chains that enables high flexibility, and resource-saving production as well as enhanced individualization for products at the cost of the massive production. The IIoT is a natural development of IoT; IIoT is a large scale of collection heterogeneous of resources, which include smart devices, machines, communication protocols, networks, and end-users. IIoT sensors are being disseminated increasingly in different kinds of industrial environments, for monitoring machines movement in the smart factory, sense and acquisition phenomena from their surrounding world, and the digital representation of products operations in the smart manufacturing. One of the most important parts of IIoT is the cyber-physical systems (CPS), which computes platforms that monitoring and control physical processes. CPS enables condition monitoring, remote diagnosis, and remote control of the production systems in real-time. IIoT is an emerging technology, it can be able to change industrial companies environments into a new term called smart factory [13], which considered as the main base for CPS, dynamically organizes and optimizes production processes with focuses on the resource-utilization costs, availability, material, and labor based on data generated and collected by an underlying CPS, even across company boundaries. In the context of smart factories, smart products know their own identity, history, specification, documentation, and also control their production process [14].

The architecture system of the IIoT network consists of three main layers. The first layer is physical, which is composed of several components such as smart sensors and actuators for collecting phenomena from their around environments. The second layer is a network that consists of many smart resources, which are used for data communications between devices ranging from the network layer to the application layer. The third layer is an application layer that utilizes big data analytics to introduce respected services to end-users [15]. IIoT is a promising technology that enables operators to understand how to optimize productivity or detect a failure before it occurs; potentially saving companies billions of dollars per year. The major IIoT applications are extended to motion control, machine-to-machine interactions, predictive maintenance, smart-grid energy management, big data analytics, and interconnected medical systems [8].

Many standard communication protocols have been developed to operate in each layer of the IIoT networking protocol stack [16], [17].

1.1.2 IIoT Communication Protocols

IIoT is a standardization technology that supports a heterogeneous set of communication protocols stack, widely setting up in every layer for establishing network connectivity, these protocols specifically provide services to end-users at an application layer [9]. Constrained Application Protocol (CoAP) is adopted at an application layer; CoAP is a better protocol for transferring streaming data between users and cloud platforms, which operate over Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) [18]. TCP and UDP are expected to be adopted in the transport layer that helps to maintain the sensor data flow [18], [19]. The Internet Engineering Task Force (IETF) and the Routing for Low Power and Lossy (RPL) Networks protocols have to be adopted [18] to work well at the network layer, which routes and foreword information on an appropriate path [18]. In the Medium Access Control (MAC) sublayer, the IEEE 802.15.4e protocol is developed, which can use a rigid slot structure with centralized and distributed scheduling to achieve high energy efficiency. The MAC sublayer manages collisions and helps in the energy operations of sensor nodes. In the physical layer, the most prominent standard in low-power radio technology is an IEEE 802.15.4-2006, which is expected to be sufficient for meeting the energy efficiency requirements of the machine to machine (M2M) devices [19]. The physical layer is very useful for connecting devices and preparing the radio, channel, modulation, transmission, and reception bits of data on the physical medium.

In the context of IoT sensors used in the IIoT applications; different methods are proposed and analyzed for improving performance based on the MAC sublayer communication protocols. The most popular MAC communication protocols are IEEE 802.15.4 and IEEE 802.15.4e, where the focuses of this study. IEEE 802.15.4 releases officially by the IEEE Working Group in May 2003 to meet the critical requirements of the IoT applications and wireless communication. The main objectives of the IEEE 802.15.4 are to provide variable data rates that reach up to 10 kbps, low-cost devices, low-power consumption, and extended coverage area [20], [21].

IEEE 802.15.4e amendment is published in 2012, for increasing the performance of the IEEE 802.15.4-2011 protocol [22] and can be supported by industrial markets [23]. The MAC sublayer protocols are defined as the superframe structure, and the nodes used the carrier sense multiple access with collision avoidance (CSMA/CA) as a channel access mechanism. The (CSMA/CA) is developed based on sensing the signal before transmission. The coordinator wants to transmit packets to the peripheral nodes, it will sense the channel if it is available for use or busy. If the channel is busy by the transmission of another packet, the coordinator waits some periods then tries to send it again [24]. Several studies are introduced a detailed explanation of the superframe structure [25], [26], [27], [28], [29], [30], and [31]. The superframe structure consists of two portions: an Active Period and optional an Inactive Period. In an Inactive Period, the devices enter the sleep state to save energy. The active period is divided into 16 equal-long timeslots, which include three main portions are Beacon portion, the Contention Access Period (CAP) portion, and the Contention Free Period (CFP) portion. The length of each superframe is equal to the numbers of the timeslots of the CAP, and the numbers of the timeslots of the CFP [28].

However, one of the critical issues that hinder the development of IIoT networks is performance. Many research efforts have been made in this area that aimed to improve the performance-based superframe structure of the IEEE 802.15.4 and the IEEE 802.15.4e. This thesis proposed a CAP reduction MAC protocol to reduce the number of time slots in order to improve performance and it gives an optimal distribution of the devices based on the superframe structure of the IEEE 802.15.4e.

1.2 Thesis Scope

This research is directed toward improving the performance of the IIoT sensors that are deployed in the smart factory. IIoT promotes such goals by fostering research into technologies, methods, concepts, and tools that will improve operational efficiency, flexibility, reduce costs, and improve the quality of human life. Now a day, it becomes a crucial tool for all smart industries. The performance of the IIoT nodes becomes a very critical issue. The thesis will propose technical solutions for the IIoT systems in order to address the performance issue, which is composed of throughput, packets delay, and energy consumption. The scope of the thesis is focused on the MAC sublayer for the IIoT system based on the superframe structure of the IEEE 802.15.4e DSME protocol.

1.3 Problem Statement

Some important issues of the IIoT networks are performance, reliability, scalability, robustness, network lifetime, latency, throughput, and mobility that need to be addressed. One of the most essential criteria for an IIoT system is to design and develop a reliable network with reasonable timely data transfer between the nodes and the base station node depends on the communications protocols. IEEE 802.15.4e in particularly suffers from performance degradation, which depends on the distribution of the sensors. This study attempts to enhance the performance by an optimal distribution of the sensors to improve system throughput, packets delay, and energy consumption.

1.4 Thesis Significance

IIoT is played a vital role in the areas ranging from agricultural to smart healthcare technology, where smart healthcare becomes one of the most important medical services recently, which utilizes for remote monitoring and tracking patients that help the doctors to give timely advice to the patients as diseases of Cardiology, Cancer, Diabetes diseases, and COVID -19 patients. Moreover, one of the best-known IIoT deployments that are deployed for measuring the consumption of machine units for aircraft to replace them with new ones, this operation helps for reducing preventive maintenance. The significance of the thesis comes as a result of improving the performance of the IIoT system. Despite the complex applications, which are clarified through this study, the adoption of IIoT is growing rapidly.

1.5 Thesis Objectives

The major objective of this thesis is to develop a new technique for improving the performance of the IIoT network based on the IEEE 802.15.4e protocol. The proposed technique is deployed for computing an optimal value of the Contention Access Period (CAP) to reduce the number of time slots per superframe so as to achieve an acceptable optimal distribution of the sensors.

1.6 Thesis Contributions

The contribution of this thesis is developing a MAC protocol for improving the IIoT network performance based on the IEEE 802.15.4e protocol by reducing the time slots of the CAP period. This reduction depends on the values of the superframe order (SO), the SO value is setting up as a variable value. The proposed protocol improves the performance of the IIoT network that is tested under a Cooja simulator, which gives an optimal distribution of the sensors. Accordingly, throughput is maximized, packets delay is minimized and the energy consumption is reduced. Moreover, the overall total costs has been decreased

1.7 Thesis Methodology

The experimental method is used to address the problem formulations of this thesis. Firstly, a literature study is conducted to review different technologies to get an understanding of IIoT systems technology, IEEE 802.15.4e, IIoT architecture, Contiki-OS, and the necessary components of the Cooja simulator. Secondly, the process of setting up a simulation to conduct experiments and gather quantitative data was also conducted. IIoT has complex issues, it is used in high connected heterogeneous nodes, which causes performance degradation in wireless communication, thus throughout is decreased and the packets delay is increased. In order to develop a technical solution to this issue, a new CAP size-reduction MAC protocol is proposed for reducing the time slots per superframe. The proposed protocol can reduce the CAP duration by increasing the superframe order (SO). If SO is increased, the CAP is decreased, and the CFP is increased. When the CAP was reduced, the number of time slots per the CAP duration is minimized. Simultaneously, it maximizes the bandwidth. To evaluate this protocol, several experiments are done by using the Cooja simulator, which is a Linux-based simulation tool used for measuring three main metrics are throughput, packets delay, and energy consumption. Tmote Sky and Zolertia Z1 are smart sensors, which are utilized through all experiments for comparing the performance of the proposed protocol with the classical performance of an original MAC protocol in terms of the throughput, packets delay, and energy consumption.

1.8 Thesis Organization

This research is organized as follows: -

Chapter 2 provides background and a literature review of IEEE 802.15 .4e MAC modes (DSME, TSCH, D) protocol. Also discuss the superframe structure of the IEEE 802.15.4e.

Chapter 3 describes the basic knowledge of IIoT, Industry 4.0. Cyber-Physical System, Cyber Manufacturing System, IIoT communication technologies, and Smart Factory.

Chapter 4 formally introduces the new CAP size-reduction MAC protocol based on the superframes, design specific technique for decreasing the number of time slots, then decrease the number of the sensors. This chapter also provides an experiment setup and then presents how throughput, execution time, and energy consumption can be measured based on the IEEE 802.15.4e protocol.

Chapter 5 focuses on the results of the experimental measurements, which begins by providing the first comprehensive comparisons of the performance parameters of IIoT sensor nodes based on a particular operating system. In conclusion, Chapter 6 provides a summary of this research and a listing of the significant contributions as well as some suggestions for future research directions that can build upon this work. Appendices are provided that include the Cooja simulator background and source program for throughput, packets delay, and energy consumption.

Chapter Two

Background & Literature Review

Chapter Two

Background & Literature Review

2.1 Background

The purpose of this chapter is to introduce the basic knowledge of the standard MAC sublayer protocols and the literature review, which presents the methods related to the fields of the performance of the IIoT network. These methods were systematically analyzed and classified based on scientific literature into three categories:- Firstly the general proposed methods for improving performance, secondly the proposed methods for improving the performance related to the IEEE 802.15.4 protocol, and finally the method for addressing the performance issues of the IEEE 802.15.4e protocol.

2.1.1 MAC Sublayer Protocols

In the context of the communications domains, where the processing usually can be done on the information either sent, stored, or utilized beneficially. This processing gives birth to a new era called the networks; initially wired and then wireless communications [32]. Entering the wireless domain, there are numerous network technologies are proposed for different applications, amongst these technologies is WSN, which consists of small electronics devices called nodes that communicate wirelessly using radio waves [33]. These nodes communicate directly with each other through the service provided by an important layer known as the MAC sublayer. The MAC sublayer is an essential part of the data link layer (Layer 2) of the open system interconnections (OSI), the OSI is a layered networking framework that does how communications should be done amongst heterogeneous systems. The data link layer which includes two sublayers: the Logical Link Control (LLC) and the MAC sublayer, as illustrates in fig. (2.1). The LLC is used for addressing and multiplexing, while the MAC sublayer manages access to the physical network medium, and its fundamental target is to reduce packets collisions in the medium [18], [34], where the focuses of this thesis. MAC sublayer is proposed by IoT IEEE 802.15 working group, it is a sublayer of the IoT protocol stack, and it has a responsibility for wireless communications in the IIoT networks.

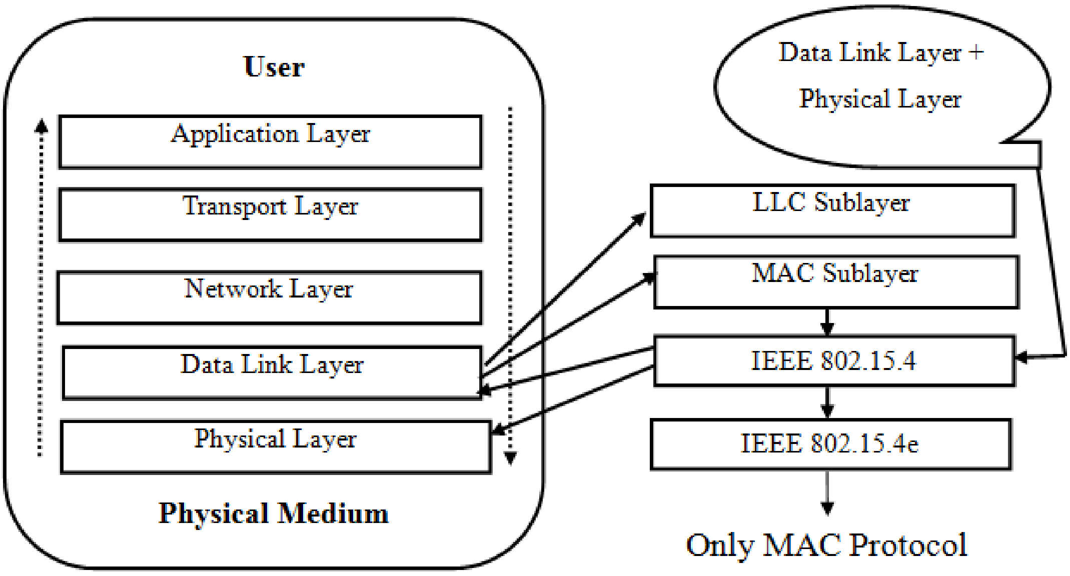


Fig. 2.1: The IoT Layers [18].

The MAC sublayer acts as an interface between the physical layer (PHY) and the LLC sublayer. The MAC sublayer can be divided into two different portions: contention-based MAC and time-divided. In contention-based MAC, nodes need to know if the channel is available or busy by other transmissions before sending frames, this operation can usually be used by the CSMA/CA mechanism, CSMA/CA technique is used broadly adopted in different communications technologies. Contention-based MAC protocols allow several nodes to share the same channel without being pre-coordinated [35].

The second portion of the MAC sublayer is time-division, where devices share the same radio frequency by using it at different times. This technique is called the Time-Division Multiple Access (TDMA). Time is usually divided into different slots known as timeslots, it has the same duration. In the time-division based solutions, nodes need to agree on the duration of a time slot [36].

Several wireless communication protocols support different kinds of applications as data communications, video, and voice. Each of these protocols set a trade-off between properties such as throughput, latency, energy efficiency, and radio coverage that aimed to define an application well. WSNs usually do not impose stringent requirements in terms of bandwidth; they require minimized energy consumption so that the overall network lifetime is prolonged. Meeting the QoS requirements such as throughput, latency, and energy consumption are considered the main objectives of WSN protocols and their modern technologies. This thesis will not discuss cluster-based approaches such as the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol [37] and the Group TDMA protocol [38], which require the overhead of cluster establishment and maintenance. Also, it will not discuss multi-channel solutions such as the Power-Aware Multi-Access with Signaling (PAMAS) [39].

This thesis presents two emerging wireless communications technologies provided by the MAC sublayer that is implemented for building robust IIoT networks. The most popular MAC sublayer protocols are IEEE 802.15.4 protocol and IEEE 802.15.4e protocol.

2.1.2 IEEE802.15.4 MAC Protocol

To realize the quality of services (QoS) needs of industrial communication over a few years; several standards aiming at a low data rate, low cost, and low-power wireless communications [17] have developed. A typical example is the IEEE 802.15.4 [27], which has been developed to meet the critical requirements of IoT applications [25], [28]. This protocol defines only the physical and data link layers. The following sections briefly explained three key tangible layers of the IEEE 802.15.4 as illustrated in fig. (2.2).

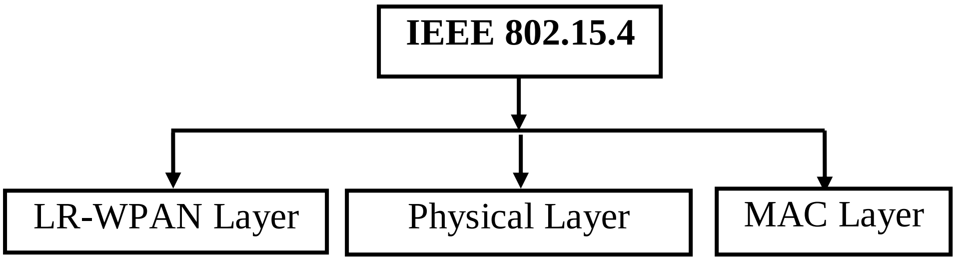


Fig: 2.2: IEEE 802.15.4 Layers

2.1.2.1 Wireless Personal Network Layer

The IEEE 802.15.4 [40] standard, devices can be classified into Fully Function Devices (FFD) and Reduced Function Devices (RFD). The Fully Function Devices (FFD) includes all the capabilities such as routing, association, and information of a network. The coordinator is the FFD that typically represents the main controller to which other devices can be associated. It is responsible for the time synchronization of the entire network. Besides, a FFD represents a Coordinator providing local synchronization services and routing to its neighbor's nodes. The Reduced Function Device (RFD) acts as the end node of an IEEE 802.15.4 network. A RFD is intended for applications that are extremely simple, such as a light switch or passive infrared sensors which are generally synchronized up with a coordinator and are not capable of routing functionality [41].

2.1.2.2 Physical Layer

IEEE 801.15.4 operates in three different frequency bands are a 2.4 GHz, which has 16 channels, 915 MHz which has 10 Channels, and 868 MHz it contains only one channel. The data rate also varies depending on the bands that are used. The 2.4 GHz band can be operated with a data rate of 250 Kbps; the 915 MHz operates at 40 Kbps, and while the 868 MHz bands operate at 20 Kbps. The physical layer has responsibilities for the activation and deactivation of the radio transceiver, measurement of the link quality, clear channel assessment (CCA), and channel selection [42].

2.1.2.3 MAC Layer

The MAC layer for IEEE 802.15.4-2011 standard is emerged to work using a non-beacon enabled mode or a beacon-enabled mode depends on the CSMA/CA as a channel access mechanism. The CSMA/CA has two types:- The slotted CSMA/CA refers to performing CSMA-CA while there is a superframe structure used in this mode. The unslotted CSMA/CA algorithm is used when there is no superframe structure. In the case of a Non-beacon-enabled mode, all devices can simply send their data using Unslotted-CSMA/CA, in this mode, there is no superframe structure is used. In the beacon-enabled mode, devices are used CSMA-CA as a channel access mechanism for network interconnection, Beacon frames are periodically generated by the Coordinator to synchronize associated devices and to identify the PAN [24], as illustrated in fig. (2.3).

A Beacon frame is the first part of a superframe structure of IEEE 802.15.4. The superframe of the IEEE 802.15.4 includes an active period and an inactive period, in an inactive portion, where the coordinator switches to sleeping mode. During an active period of a superframe, all data is exchanged between the nodes and the PAN coordinator using slotted

CSMA/CA. If the node uses slotted CSMA/CA it can be capable to compute the backoff delay of the transmission frames, which depends on the random number of backoff periods (BP), before accessing the medium for transmission, it performs two (CCA).

2.1.3 Superframe Structure of IEEE 802.15.4

The superframe boundaries are defined using beacons sent from the coordinator to ask the nodes to connect the network. The duration between two beacons known as beacon interval (BI). The active period includes two operations, called the contention access period (CAP) and the contention-free period (CFP). In the CAP period, the nodes in the network contend to connect the network using the slotted CSMA. CAP and CFP both are equal to 16-timeslots used by the nodes for networking access with high needs of (QoS). The idle period prolongs the lifetime of the battery since the node goes to sleep mode [25]. At the end of the idle period, the nodes have been waking up. This indicates to the beginning of the next superframe cycle. The active period of the superframe duration (SD), where the CFP, guaranteed time slots (GTSs) are implemented to allow the devices to operate on the channel within a portion of the superframe allocated to that device. After that, the GTS is required by the device to the coordinator for data transmission and data reception. If the GTSs are available, they can be allocated to the devices according to their requests. Also, the superframe structure includes two key parameters: a macBeaconOrder (BO) and a macSuperframeOrder (SO). The SO indicates the duration of the active period of the superframe with the beacon frame transmission time. The BO is the cyclic time when the coordinator communicates using beacons [43]. Thus, the time between two beacons frame transmissions is expressed as follows:

$$BI = aBaseSuperframeDuration \times 2^{BO} \qquad (2.1)$$

$$SD = aBaseSuperframeDuration \times 2^{SO} \qquad (2.2)$$

$$\text{for } 0 \leq SO \leq BO \leq 14.$$

where BO = 15 implies non-beacon mode, only on-request frames of the beacon are transmitted. The aBaseSuperframeDuration (SD) is the number of symbols that constitute a superframe when the SO is set to zero. The superframe structure is illustrated in fig. (2.3). During the superframe interval, the nodes in the wireless personal area network (WPAN) are transmitting beacons by contending for medium access using slotted CSMA-CA. For real-time and time-sensitive applications, the IEEE 802.15.4 enables the allocation of GTS in the CFP within the SD [25], [43]. Fig.(2.3) shows the superframe structure of the IEEE 802.15.4 MAC sublayer protocol.

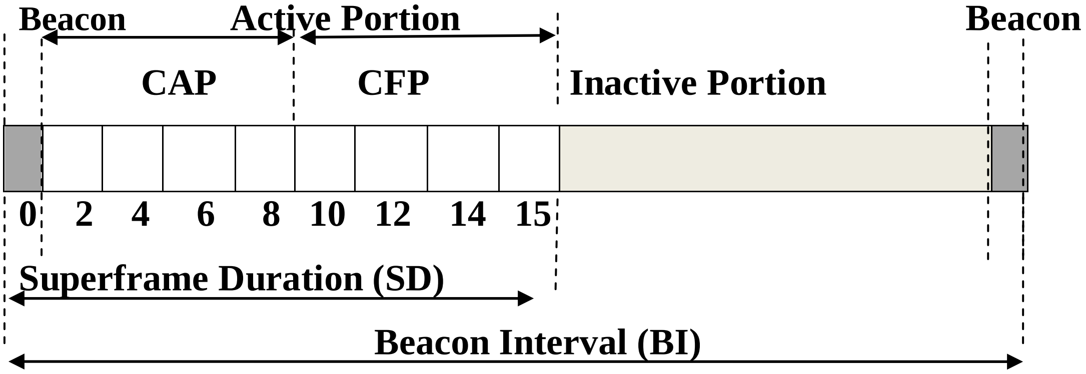


Fig. 2.3: Superframe structure of IEEE 802.15.4 [24].

IEEE 802.15.4 has some drawbacks, which are low communication, low reliability, no protection against interferences, and fading that makes it unsuitable for applications having stringent requirements in terms of latency, reliability, scalability, and operations in harsh environments [22].To overcome the limitations of the IEEE 802.15.4, IEEE802.15.4e MAC protocol has been created by the IEEE working group, which is added new enhancements for an existing IEEE 802.15.4 MAC protocol, in order to address the emerging needs of embedded industrial applications. The next sections offer more explanation of an amendment protocol.

2.1.4 IEEE802.15.4e MAC Protocol

The IEEE 802.15.4e amendment is published in 2012 by the Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) [44] for enhancing the limitations of the IEEE 802.15.4-2011 protocol [22] to support industrial markets [45]. These communication protocols are defined as the superframe structure, and the nodes use the CSMA/CA as a channel access mechanism. IEEE 802.15.4e standard protocol is composed of six different types of time slots that are TxDataRxAck, which is a timeslot used by sensor nodes for sending data and receiving an acknowledgment (ACK) that indicating successful reception. TxData which is resembled the previous has no response, which is used during the data packets when it is broadcast. RxDataTxAck is a timeslot for receiving data frame by node and then transfers back an ACK when the node receives some data frame, and sends back an ACK, to indicate successful reception. RxData is the same as RxDataTxAck without an ACK. Idle is the timeslot used when a node is listening for data, but it no receives data. Sleep is the timeslot during the radio of the node stays off [44].

2.1.4.1IEEE 802.15.4e Functionalities

The IEEE 802.15.4e [40] has been proposed to add functionalities enhancement for the legacy IEEE 802.15.4 standard, in order to accommodate the requirements of emerging IoT applications, especially in the industrial domain. The various improvements provided by IEEE 802.15.4e are:

Multichannel Access: One of the main drawbacks of the IEEE 802.15.4 protocol was the lack of multichannel access. Multichannel access is used for minimizing performance degradation due to the interference that occurs in the network. The IEEE 802.15.4 only supports a single channel for the network communication, restricting the capability to satisfy numerous nodes without contention, and therefore deteriorating its network performance, overall delay, and throughput. IEEE 802.15.4e overcomes these limitations by supporting multichannel operation for some of its MAC modes such as DSME and TSCH.

Information Elements (IE): Information Elements is introduced to support the various MAC modes such as the Information Element for a DSME, which specified the number of superframes in a multi-superframe, number of Channels, and time synchronization specification. The IE of TSCH carries information related to the timeslot length, timeslot ID, or channel hopping sequence [46].

Low Latency and Low Energy: The IEEE 802.15.4e protocol provides supports for low latency network communications, more suitable for industrial control applications. IEEE 802.15.4e allows devices to operate at a very low duty cycle and also provides deterministic latency, which is the main requirement for time-critical applications. To accommodate low energy requirements, the non-beacon-enabled MAC behaviors such as AMCA and the transmissions in the CAP period of the beacon-enabled MAC behaviors such as DSME are supported by low energy mechanisms. The amendment specifies two Low Energy mechanisms based on the latency requirements of the applications: Coordinated Sampled Listening (CSL) is usually used for applications with very low latency requirements. In CSL-enabled receiving devices, the channels are periodically sampled for incoming transmissions at low duty cycles. The receiving and the transmitting devices coordinate with each other to reduce the overall transmitting overhead; Receiver Initiated Transmissions (RIT) mechanisms are used for latency tolerant applications. The RIT mode supports applications that run on low duty cycles and low traffic load [47].

Multi-purpose Frames: The frame formats of all the MAC behaviors in IEEE 802.15.4e are based on peculiar features of each MAC behavior and its targeted application. The DSME MAC mode such as supports applications where determinism and scalability are fundamental. The MAC frame format of DSME thus supports guaranteed timeslots with multi-channel capability. It also can provide features such as Group Acknowledgment to reduce the overall delay for several GTS-based transmissions. The LLDN MAC behavior supports applications that require very high reliability. The frame format of LLDN provides provisions for retransmission of frames using separate uplink timeslots and Group Acknowledgment (G-ACK) to acknowledge several frames using a single ACK frame, thus maintaining low latency and high reliability in a network [40].

MAC Performance Metrics**:** The IEEE 802.15.4e protocol supports upper layers on the network performance through MAC performance metrics. These metrics provide information on the quality of the channel, which helps the network layer to make effective decisions for routing, consequently reducing the overall power consumption and latency of the network. The information provides by the IEEE 802.15.4e includes the number of transmitted frames that required one or more retries before acknowledgment, the number of transmitted frames that did not result in an acknowledgment after a duration of macMaxFrameRetries, the number of transmitted frames which are acknowledged properly within the initial data frame transmission; and the number of received frames that are discarded due to security concerns [48].

Fast Association: In the original IEEE 802.15.4 protocol, the association procedure includes a significant delay, due to the device must wait till the end of the MAC response before requesting the association data from the Coordinator. To address this limitation, an IEEE 802.15.4e introduces a Fast Association mechanism, under which the device requests for association from the PAN Coordinator. If the channels are available, the coordinator allocates a short address to the device. It also sends an association response which contains the assigned short address and status indicator for a successful Fast Association [49].

Enhanced Beacons: Enhanced Beacon (EB) provides greater flexibility and it is used to provide application-specific beacon content to the DSME and TSCH MAC modes. EB carries information on whether TSCH, DSME, and Low Energy (LE) are enabled and information about the respective channel hopping sequences.

2.1.4.2The IEEE 802.15.4e standard Modes

The IEEE 802.15.4e standard provides MAC sublayer modes based on the domain of application as illustrated in fig (2.4). It's only the MAC sublayer protocol [50]. These modes can be classified into two categories are critical real-time MAC modes that are the Time Slotted Channel Hopping (TSCH), which provides a predictable delay, energy efficiency, communication reliability, and high network capacity. TSCH provides both dedicated and shared links [51], Low Latency Deterministic Network (LLDN), which uses Time Division Multiple Access (TDMA) to provide timing guarantees [50], high reliability, and low latency. And Deterministic and Synchronous Multi-channel Extension (DSME) for deterministic latency and scalability requirements. And non-real-time MAC modes such as the Radio Frequency Identification (RFID Blink) used for items and people identification, location, tracking, and also the Asynchronous Multi-

Channel Adaptation (AMCA) for monitoring infrastructure networks [52]. DSME and TSCH were recently incorporated into the revised version of an IEEE 802.15.4 - 2015, which was released in the mid of 2016 [50].

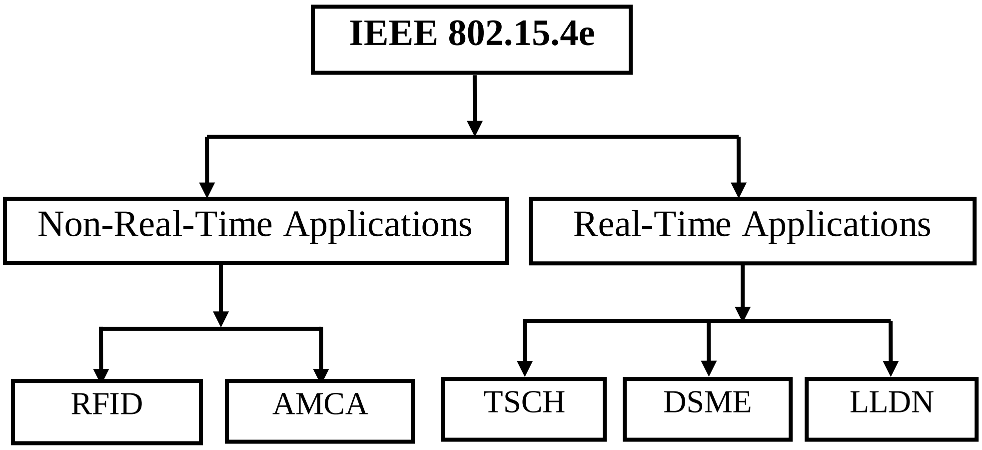


Fig. 2.4: IEEE 802.15.4e MAC Modes.

2.1.4.2.1 The RFID Mode

RFID [20] is an emerging technology that is used for location, tracking items, and people identification. RFID integration with wireless sensor networks has been used in global commercial markets like Walmart [21] for tagging and identifying products. In the Blink mode of a RFID-based IEEE 802.15.4e protocol, transmitters communicate with the receivers using their 64- bit address and optional payload data. The Blink mode in RFID allows the device to communicate its ID, an Extended Unique Identifier - EUI-64 source address, and additional payload data to devices with which they communicate. Devices can connect without any prior association or acknowledgment. The Blink frame can be used especially for transmitting.

2.1.4.2.2 ACMA MAC Mode

The Asynchronous Multi-Channel Adaptation (AMCA) mode can be enabled for the non-beacon enabled mode of IEEE 802.15.4e networks. In the synchronous multichannel adaptation mechanism, two devices cannot communicate using a common channel. In the case of AMCA, the device selects a MAC Designated Channel based on the channel link quality. In order to switch channels for either listening or transmitting, a channel is requested by the coordinator of ACMA during an active scan. Three other MAC modes are designed for time-critical applications which provide deterministic guarantees and improved robustness. This thesis provides a comprehensive overview of the TSCH, DSME, and LLDN which are considered more critical times and suitable for industrial applications.

2.1.4.2.3 TSCH Mode

TSCH networking is emerging as a new promising technology for the IoT and Industry 4.0 because of its easy deployment, more reliability and flexibility, and short latency, which supports star and mesh network topologies, as well as multi-hop communication. TSCH was developed for processing automation, control, equipment monitoring. Also, it's a candidate technology for Industry 4.0 [53]. The term Industry 4.0 refers to the fourth industrial revolution; with the first three coming are mechanical systems, electricity, and modern computers and the Internet [54].

The TSCH schedule enables each node to know when it is allowed either to transmit its messages or to receive them, and each node enters the sleep mode when it is not involved in a communication. The sleep mode enables the node to save a considerable amount of energy and hence significantly increase its energy autonomy. As a consequence, the energy consumed by a node involved in an end-to-end communication is consumed while transmitting or receiving a message or an acknowledgment. However, due to failure, a node may wait for a message that it will never receive in this slot [53]. The TSCH schedule implements a channel hopping scheme to prevent noise, interference, and enable high reliability, while it employs time synchronization to probe low-power operation. Channel hopping of the TSCH networks is the same slot in the schedule translates into a different frequency at each iteration of the slot frame, in order to enable successive packets exchanged between neighbor nodes, which are communicated at different frequencies. Slot frame is the number of time slots in the superframe structure of the TSCH.

TSCH offers a deterministic scheduling method, where every cell consists of a pair of time slots and channel offset for collision avoidance purposes [55]. Channel offset is set to the corresponding number from 0 to 15. Each channel offset is interpreted into a frequency as an equation (2.3):

$$Freq = \left(ASN + channel\ offset\right)\ mod\ 16 \qquad (2.3)$$

Where Frequency is a lookup table containing the set of affordable channels, channel Offset is the channel offset of the time slot in the schedule, and 16 is the number of available frequencies. The slot frame size should be a prime number to be sure that every frequency is used. Absolute Slot Number (ASN) is a variable which counts the number of timeslots since the network was established [56].

The duration of the slot is defined by the standard to be enough for sending packets and receives its acknowledgment, its equal to 15 ms.

TSCH is dependent on schedule; therefore, nodes must remain time synchronized throughout the network deployment’s lifetime. To this end, nodes periodically exchange Enhanced Beacon (EB) packets. Synchronization does not need explicit EB exchange; data packets may also be utilized to compute clock drifts. Typically, an EB contains the time and channel frequency information, as well as information about the original link and slot frame for new nodes to join the network. Nodes can be joined a TSCH network by receiving an EB frame from the neighboring nodes. As observed in fig. (2.5) which include the node C and the node D, a typical TSCH timeslot template for a transmitter and receiver node, node C transmits its data packets after TxOffset, whiles the receiver D uses a Guard Time to avoid missing the incoming packets by turning its radio ONslightly before the packet arrival. Fig. (2.5) also presents the communication between two nodes based on TSCH, and time is divided into a different part called timeslots that have equal length; large enough to transmit a frame and to receive an acknowledgment. At each timeslot, a node may send or receive a frame, or it may turn its radio OFF for saving energy. Finally, each timeslot is labeled with ASN, a variable which counts the number of timeslots since the network was established [25]. This research introduces a detailed discussion of three basic metrics of the TSCH such as energy consumption, throughput, and latency time.

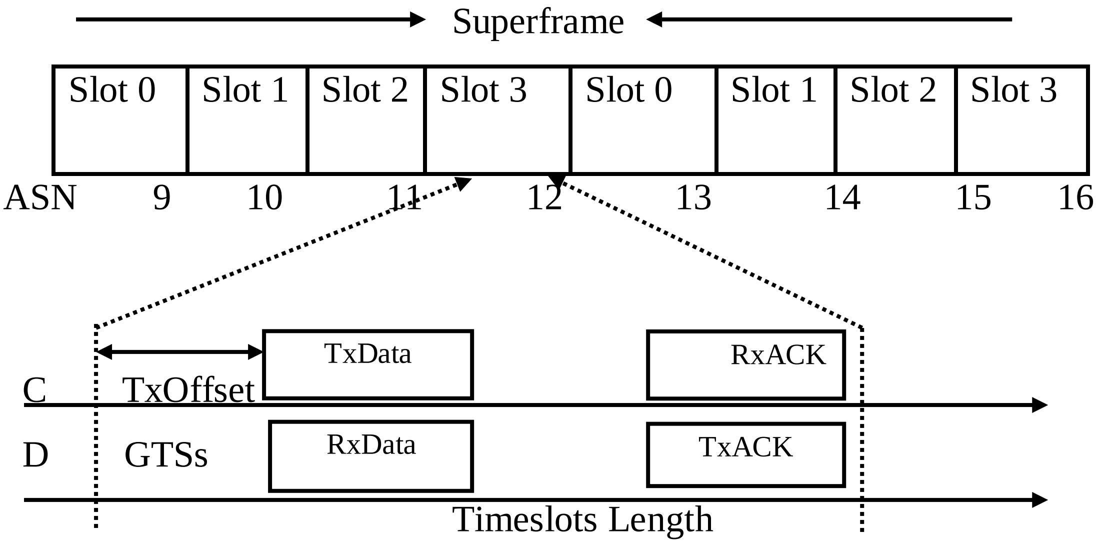


Fig. 2.5: Superframe structure of TSCH [25].

2.1.4.2.3.1 Energy Consumption Model

Significant components of every sensor node are a microcontroller and the radio, which have been more energy consumption. These components have two states, may separate interconnected chips by some digital bus on its aboard, or grouped these chips in a single System-on-Chip. To accurately model the energy consumption in this mode, one must look at a detailed breakdown of the various states; each module enters into each type of slot. Energy consumption by micro-controller and radio change state is a variant [57].

The same analysis holds when computing the energy consumption of the other 6 slot types, and extract QRxDataTxAck, QTxData, QRxData, QIdle, QSleep, and TxDataRxNoAck. This research used an energy model of the different slots according to energy model equations in [51], to determine how much energy is used during each slot frame, and compute the expected battery life of the network. For more information, please go to appendix A.

2.1.4.2.3.2 Throughput

Throughput maximization becomes a crucial issue that can be computed by the following binary integer linear programming (ILP) formulation to be executed by the gateway [56].

2.1.4.2.3.3 Packets Delay

The delay is computed according to the elapsed time between the frame generation from a given node and its reception by the router. The packets delay of TSCH is a fixed value, which is an equal to10ms by the standard. When the Tcycle value is within 10 ms, the network has a nil delay [58].

2.1.4.2.4 DMSE Mode

IEEE 802.15.4e MAC protocol was proposed Deterministic and Synchronous Multi-channel Extension (DSME) mode for WSN standard to provide support industrial environments and healthcare applications [59]. DSME has features, which enhance application solutions of the native IEEE802.15.4. Those features are multi-superframes, CAP reduction, Group Acknowledgment, beacon scheduling, and channel diversity modes [50], [60].

2.1.4.2.4.1 Multi-superframe

The set of superframes called the multi-superframe structure, which defined by the PAN network coordinator of a DSME, as illustrated in fig. (2.4), a superframe in the multi-superframe structure includes a CAP and CFP. In a multi-superframe, a single shared channel is utilized for a successful association, and it is also used for transmitting the EB frames and the frames that send during the CAP. The number of superframes that are accommodated by a multi-superframe is determined by the PAN coordinator based on the number of data packets, which could be transmitted within the time interval and is conveyed to the nodes through an EB [60].

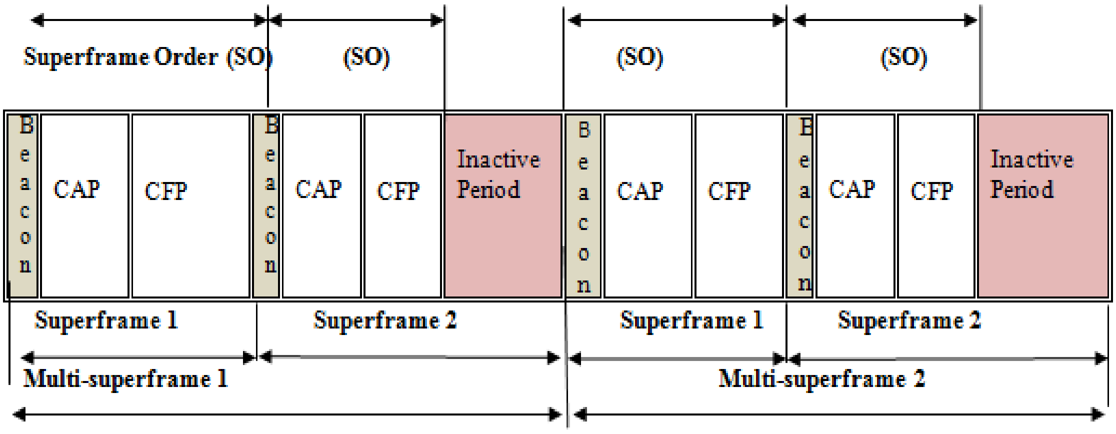


Fig. 2.6 Multi-superframe structure of DSME [50].

The DSME superframe structure defines within three main parameters values are Superframe Duration (SD), Multi-Super frame Duration (MD), and the Beacon Interval (BI). (BI) is the period between two beacons. The Multi-superframe Duration is a new parameter that was developed for DSME. (MD) provides a flexible length of the entire individual superframes within the multi-superframe. These parameters are formulated as the following equations:

$$MD = a\ \text{BaseSuperframeDuration} \times 2^{MO}\ \text{symbols} \quad (2.4)$$

$$\text{for } 0 \le SO \le MO \le BO \le 14.$$

$$BI = a\ \text{BaseSuperframeDuration} \times 2^{BO}\ \text{symbols} \quad (2.5)$$

$$\text{for } 0 \le BO \le 14.$$

$$SD = a\ \text{BaseSuperframeDuration} \times 2^{SO}\ \text{symbols} \quad (2.6)$$

$$\text{for } 0 \le SO \le BO \le 14.$$

Where the (BO) is the MAC Beacon Order that defines the transmission interval of a beacon in a superframe. (MO) is the MAC Multi superframe order that represents the beacon interval of a multi-superframe. A base SD is the minimum duration of a superframe corresponding to the initial order of the superframe, for instance when SO is equal to zero. This duration has a constant value, which is equal to 960 symbols (a symbol represents 4 bits) corresponding to 15.36 ms. Supposed that a bit data rate in the 2.4 GHz frequency band is 250 Kbps. The total number of superframes and multi-super frames in a DSME network can be determined by $2^{(BO-SO).}$As an example, where BO = 3, MO = 3 and SO = 2. In this case, two superframes are combined in a single multi-superframe, as illustrated in fig. (2.5). The DSME GTSs in the available channel appear as grids in the CFP period for those mentioned parameters. The horizontal axis of the grid represents the time, and the vertical axis of the grid represents the frequency. This means that several GTSs should be allocated at the same time but on different frequencies, such as channels [50].

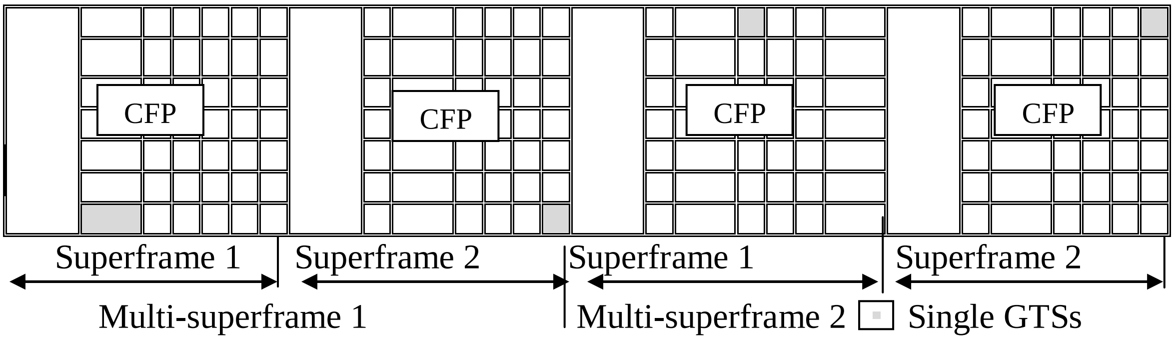


Fig. 2.7: Superframe structure with BO=3, MO=3, and SO=2 [50].

To improve the GTSs functionalities at the CFP, DSME extends the number of the multi superframe for communication, which makes the protocol choose better channels based on link quality and to a higher number of transmissions, and thus the reliability and scalability will be increased. As observed in fig. (2.8), the IEEE 802.15.4 accommodates 4 timeslots for four transmissions, whereas DSME requires only two timeslots. Additionally, it provides more timeslots to be occupied by other nodes in the network. In this case, scalability is increased overall in the network.

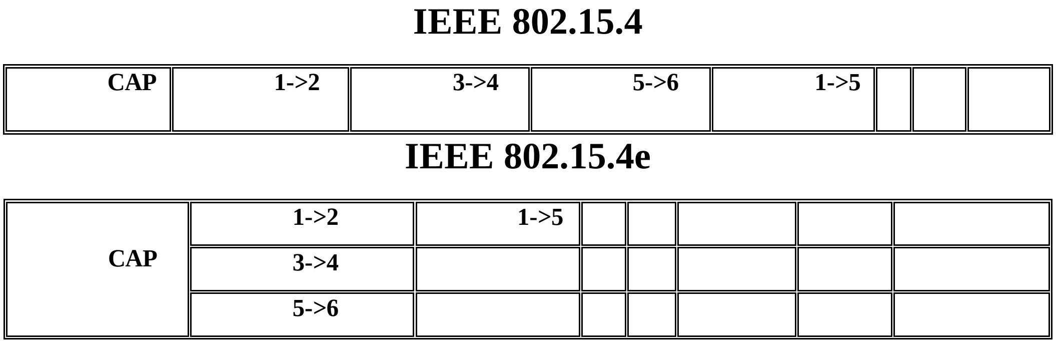


Fig. 2.8: Comparison of DSME GTSs with the legacy GTS [50].

2.1.4.2.4.2 CAP Reduction

The CAP reduction is a technique for minimizing the number of CAP periods in a multi-superframe, by enabling the CAP in the first superframe.

The remaining superframes were presented with a longer CFP. As illustrated in fig. (2.9). The number of DSME GTSs significantly maximizes, which is assigned to the neighboring nodes, while saving energy, and thus, there is no need for a node to stay active during a CAP if no transmissions are expected to occur. CAP reduction is beneficial for highly densest networks with stringent QoS requirements in terms of delay and reliability.

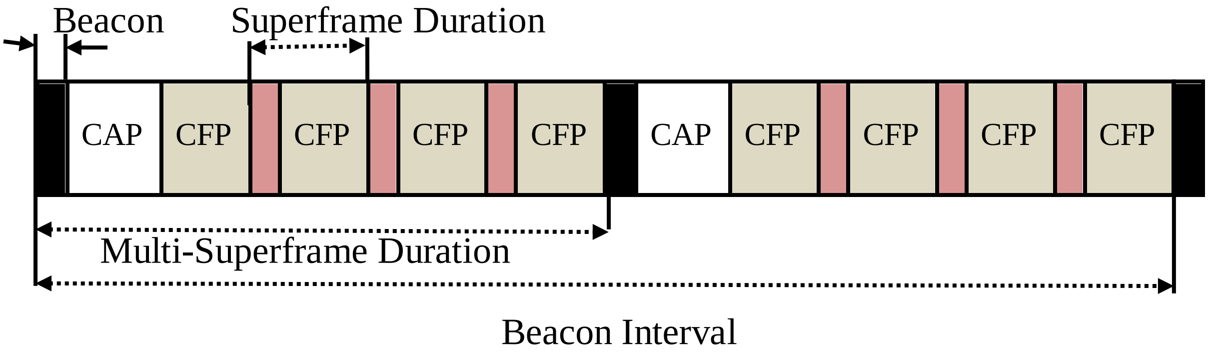


Fig. 2.9: CAP reduction to the technique in DSME [50].

2.1.4.2.4.3 Group Acknowledgment (GACK)

Group Acknowledgment (GACK) is an essential feature of DSME GTS. This technique can provide the capability of sending a single acknowledgment for all guaranteed transmissions via the same multi superframe. The GACK method can improve the performance of the IIoT network by decreasing packets delay and energy consumption through combining several acknowledgments into a single group acknowledgment.

The Coordinator announces the GACK feature using an Enhanced Beacon with a MAC GACK Flag. Fig. (2.8) shows the GACK components. A single GACK is sent by the coordinator to acknowledge every DSME GTSs transmissions in the CFP. GACK information elements (IE) indicate the reception status for the set of GTS data frames that acknowledges and new slot allocations. The GACK element carries the bitmap, which means the state of transmissions in the guaranteed timeslots. GACK Device List is exclusive for DSME, and it shows the devices for which the guaranteed timeslots are allocated in their respective CFP region. The GACK Index field is also DSME exclusive, which specifies the start of every GTS for the allocated nodes according to the GACK device list. Fig. (2.10) shows the basic GACK Elements of the DSME.

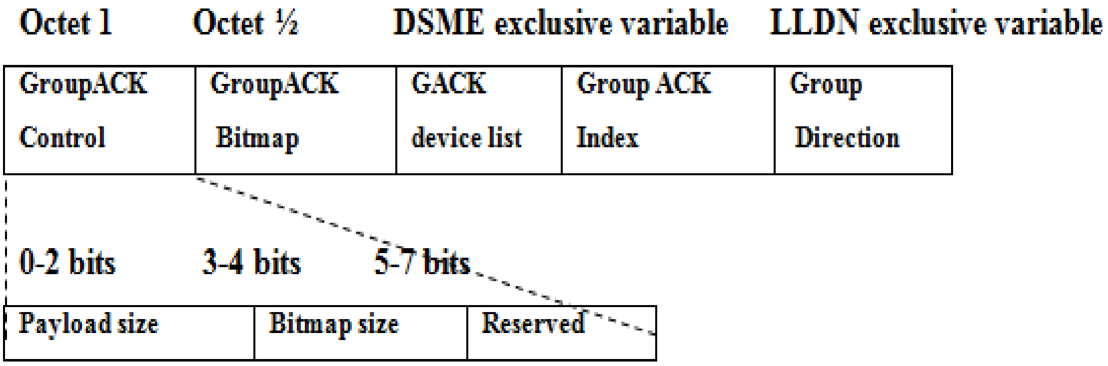


Fig. 2.10: GACK Element of DSME in [50].

Fig. (2.11) considers that the shaded portion in the grid of the first CFP and the second timeslot of the adjacent superframe as the DSME GTSs allocated for retransmission. A single GACK (fourth timeslot of the second superframe) can be given for all these transmissions. GACK saves a lot of energy and time that is spent on individual acknowledgments. In case of a failed transfer, a new DSME GTS will be assigned to carry out that process.

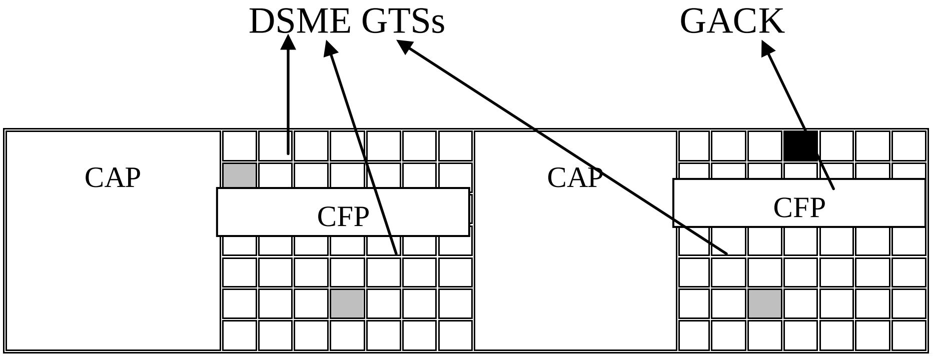


Fig.2.11: Group Acknowledgement in DSME in [40].

2.1.4.2.4 Beacon Scheduling

Beacon Scheduling is a mechanism for avoiding interference and collisions in complex network topologies such as mesh networks. In a DSME network, the devices are time-synchronized using the values of the Timestamp field of the received beacons from the device they are associated with it, thus maintaining global time synchronization in the PAN. When a node wants to join a network, it uses an MLMESCAN. Request primitive to initiate scanning over all the channels that is available in the system. During this scanning process, the joining node searches for all coordinators transmitting Enhanced Beacon frames. The neighboring devices send their beacon schedule information to the new joining device by broadcasting an Enhanced Beacon. The schedule of this beacon is updated as a bitmap sequence. The new joining device searches for a vacant beacon slot, if it is available, it can be used by a node for sending its beacons.

2.1.4.2.4.5 Channel Diversity

One of the most important issues of wireless communications is interference; it occurs due to having heterogeneous radiofrequency devices, this issue can be affecting the reliability of the network. Channel diversity is a mechanism that helps in addressing the interference. The DSME MAC protocol defines two types of channel devices which are channel adaptation and channel hopping.

In channel adaptation, the PAN coordinator is enabled to assignment the DSME guaranteed timeslots either in a single channel or through multiple channels to the peripheral devices. The PAN coordinators can deallocate specific DSME GTSs if the link quality of an allocated DSME GTSs has been degraded. Channel hopping is a methodology by which several devices hop over different channels in a predefined channel order. Channel hopping is a well-established technique that has been used in radio communication systems for decades. In radio systems, many receivers select a channel from a predefined set to receive the required information of the broadcast [51]. In fig. (2.12), the bold cells represent the DSME GTSs in a CFP portion, which has a hopping sequence that follows a channel offset.

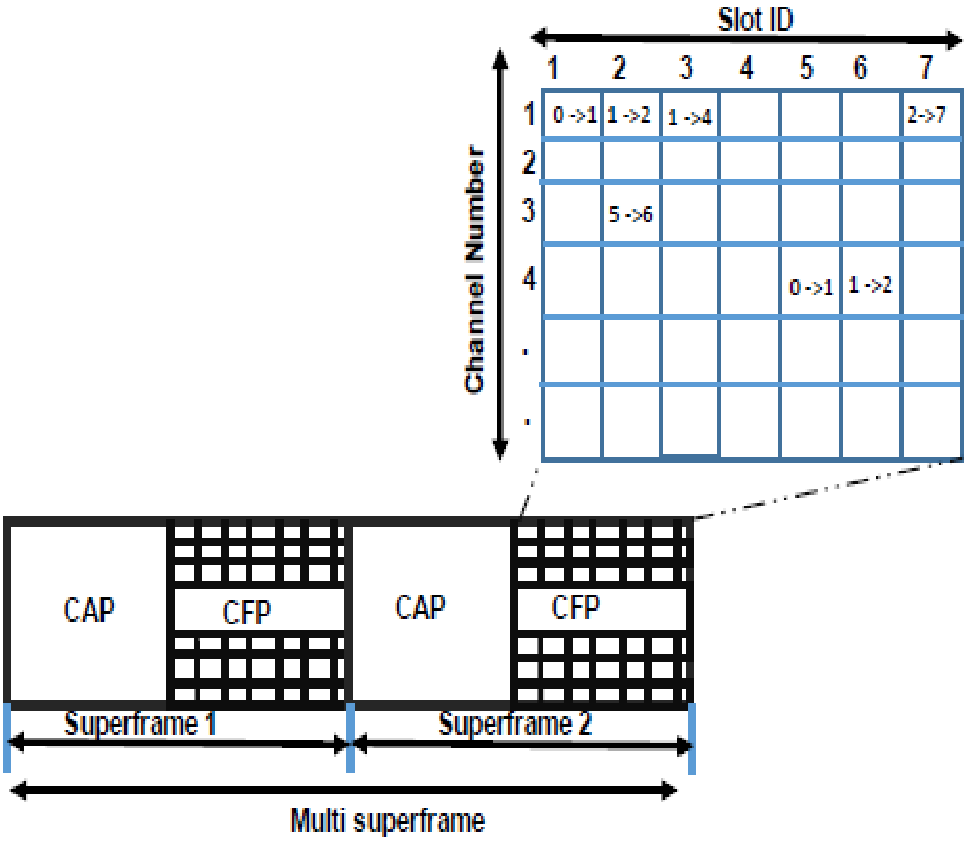


Fig. 2.12: Channel Adaptation in DSME [61].

2.1.4.2.4.6 Performance of DSME Mode

The following sections discuss the theoretical background of the DSME. The terms throughput, packet delay, and energy consumption will be defined, described, and analyzed to explain how to measure them. For more information on how measures the throughput, packets delays, energy consumption, please go to appendix A.

2.1.4.2.4.6.1 Throughput

Normalized performance [21] is the ratio of average time occupied by the successful transmission of the interval between two consecutive transmissions.

2.1.4.2.4.6.2 Energy Consumption

Energy consumption is defined as the ratio of the energy consumed by a node to transmit and receive data successfully. Consider (P_{RX}) and (P_{TX}) are the energy consumption for sending and receiving packets, respectively. Sensor devices are assumed to be in a sleep state during the backoff procedure, which does not consume energy.

2.1.4.2.4.6.3 Packets Delay

The packets delay is defined as the total time required for the information to be generated by the source device and it is to be received at the destination device.

2.1.4.2.5 LLDN Mode

Many industrial applications require deterministic systems for ensuring low delay data aggregation services. IEEE 802.15.4e MAC protocol has been provided the LLDN mode according to the standard, with less than 10 ms delay time for collecting data by a coordinator from 10^{th} devices. To achieve this task, The LLDN depends on two essential features in its structure those are used reduced MAC frame header through eliminating the addresses field in the frame header, keeping only one byte for the frame type, and assigned two bytes for the frame check sequence (FCS). The coordinator can identify the ID of the node through the slot number that the node is being transmitted on. Each node defines a slot in the superframe for which they are the ‘slot owner’, and it does not need to contend the medium before transmission [62].

2.1.4.2.5.1 The LLDN Superframe

Each superframe in the IEEE 802.15.4e LLDN contains a beacon slot, management time slots, and macLLDNnumTimeSlots of equal duration, which is illustrated in fig. (2.11). In the beginning beacon slot of each superframe, the PAN coordinator broadcasts the beacon frame, and the associated nodes start synchronization with the superframe structure. The beacon frame also helps the nodes for re-synchronization, which has gone due to entering the power-saving mode. The time slots in the superframe can be assigned to one or more nodes. However, each slot is assigned to exactly one node and called the slot owner. The slot owner can transmit the data without any explicit addressing in the data frame. When more than one node is associated with one shared slot, namely the shared group time slot [63].

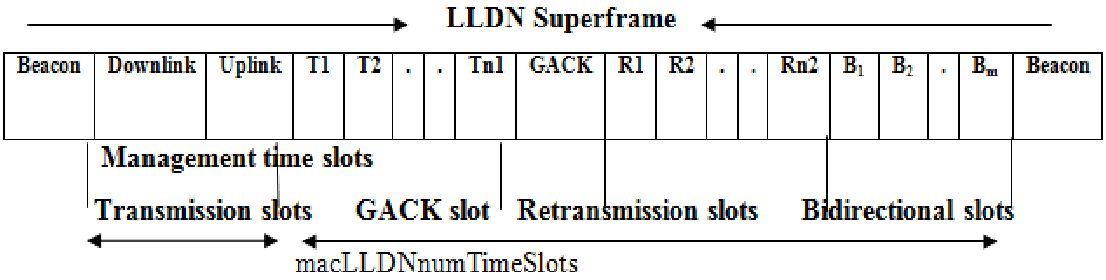


Fig. 2.13: LLDN Superframe Structure with an acknowledgment (GACK) [63].

The nodes in a group shared slot follow the CSMA/CA mechanism with a single eight-bit address inside the data frame to transmit the data to the coordinator. Management time slots are used to send management data in two ways, uplink and downlink [63]. Apart from this, the presence of the bidirectional time slot gives scope for interconnection between the coordinator and nodes. However, the direction of communication is broadcast through the beacon. Fig. (2.13) illustrates one slot is reserved for transmitting a separate GACK by the coordinator, and only the failed nodes use the retransmission slots in the superframe. Note that a node does not know about the number of failed nodes. However, the information received by the GACK contains one bitmap, which indicates the successful and failed transmissions; a node chooses the suitable retransmission slot in the same order as the transmission slot. Based on this information, only the collided nodes attached to one shared slot can find the appropriate retransmission slots and access the channel through CSMA/CA.

2.1.4.2.5.2 Performance of LLDN Mode

This section introduces more knowledge of the essential parameters of the LLDN MAC mode, which are throughput, energy consumption, and packets delay. For more information, please see appendix A.

2.1.4.2.5.2.1 Throughput

Network throughput is defined as the average successful data rate over the communications link. The maximum performance in the network can probe when correctly one node sends the data to the destination. The data communication during the shared slot in the superframe is through the slotted CSMA/CA mechanism.

2.1.4.2.5.2.2 Energy Consumption

The average energy consumption of one node to transmit data successfully in shared slots of the superframe can be analyzed. (T_L) is the time required for sending packets and (T_{CCA}) for each successful channel assessment.

2.1.4.2.5.2.3 Packets Delay

This thesis considers (W_{time}) is the waiting time for a device until the next shared slot becomes available, when the packets are generated outside the allotted shared slot period, (P_{delay}) is propagation delay which is the amount of time needed for one bit of data to transfer to a one-hop destination, and (T_{delay}) indicates to transmission delay that defined as the amount of time required to transmit the total payload concerning the link data rate.

2.2 Literature Review

This research presents a detailed discussion of the methods that have been proposed for achieving high performance based on the MAC sublayer protocols for IIoT systems. Some of the proposed methods have relevant to performance-based energy consumption and others for improving the performance based on the throughput and packets delay. These methods can be divided into three essential categories. Firstly, the general methods proposed for improving the performance of the IIoT networks. Secondly, the proposed methods are related to the superframe structure of the IEEE 802.15.4. Thirdly, the methods also have been proposed based on the structure of the superframe of the IEEE 802.15.4e MAC protocol.

2.2.1 Methods based on IIoT Systems

The work-study of [64] is utilized Ultra Wide Band (UWB) for the IIoT applications, that it makes a driver possible UWB-based 6LoWPAN networks, and opens the way to incorporating UWB in the industrial IoT domain. To do that the DW1000 driver for the Contiki OS is used, the functions of the driver were validated through several experiments.

Performance measurements were performed and compared to a theoretical model.

The latency of data exchange has great impacts on the energy consumption of Industry 4.0, to overcome this challenge, authors were focused on the resource constraint of IoT nodes, and exploit the presence of a few more capable edge nodes that act as distributed local data storing proxies for all IoT devices. Moreover, methods were developed and investigated its performance under real experiments, running TinyOS, and WSN430 as a node platform [65]. A PC-MAC protocol for wireless sensor networks based on IoT proposed in [66], the performance of PC-MAC protocol was investigated under various IoT nodes distributions running the NS2 simulator and then compared with the S-MAC protocol. The experimental result gives the power levels are ranging from 0.05mW to 25mW. The proposed MAC protocol can be achieved higher energy conservation than S-MAC for frames transmission power. To analyze the energy consumption of TSCH enabled platforms for the IIoT, energy consumption of TSCH enabled platforms was measured experimentally based on the TelosB sensors platform. In this experiment, OpenWSN and Contiki OS were investigated under different configurations [67].To estimate the performance of the IEEE 802.15.4e TSCH mode related to delivery rate, latency, and time to association with them, the TSCH was implemented within Contiki OS running on sky mote. Many experiments were performed under the Cooja simulator. The simulator results give the TSCH performs better in delivery and latency than IEEE 802.15.4 [68]. The study in [69] presented and analyzed a modified link scheduling algorithm for IEEE 802.15.4e based solutions to maximize the performance of the IIoT network. To do that, different approaches have been utilized. A novel evidential reasoning method has been overviewed for improving the performance of IEEE 802.15.4. This method investigated its performance under the OPNET simulator. The simulation results presented a better performance in energy consumption and packets delay [70]. The study provided by [71] is adopted architecture for energy-efficient IIoT, which is comprised of a sense entities domain, RESTful service hosted networks, a cloud server, and user applications. Further, energy-efficient mechanisms are proposed in the sense entities domain that conforms to the system architecture. The simulation results showed the advantages of the proposed architecture are more efficient in resource utilization and energy consumption. An optimal energy clustering-based technique was introduced for optimizing energy consumption and decreases the delay in Industrial Wireless Sensor Networks (IWSNs) of IoT systems [72].

2.2.2 Methods based on IEEE 802.15.4

Several studies for MAC protocols were proposed based on IEEE 802.15.4, which mainly focused on the performance based on energy consumption [73], [28], [74]. Superframe Scheduling Algorithm was proposed based on the IEEE 802.15.4 standard for grouping coordinators and improves QoS of the WSN [75]. This algorithm can group the coordinators that have the same features, simultaneously send and receive a beacon frame, and can act in the same period. Work in [73] provides a dynamic CFP allocation for allowing more CFP allocations than IEEE 802.15.4. The CFP allocation is added, and the duration of CFP is variable due to the dynamic CFP allocation. The CAP and CFP are fixed in each superframe, the length of CFP is also variable, but some slots of CAP duration were added to GTSs in the CFP duration. A node-grouping superframe-division MAC protocol based on the IEEE802.15.4 MAC protocol was introduced for maximizing the network performance [28]. The study in [74] gives the Hidden-Node Avoidance Mechanism for WSNs for decreasing energy consumption and delay time. The main idea of this mechanism is to use part of the CAP for the Group Access Period (GAP). As observed, the minimum-superframes duration must be guaranteed for the CAP in each superframe. Also, they have been proposed in [76] a new superframe structure for addressing the limitations of the IEEE 802.15.4. Authors in [77] offered an approach for improving network delay based on the superframe structure that was assumed in the 802.15.4 protocol. In this approach, the PAN coordinator allows the other network nodes to reserve a dedicated time slot to satisfy the bandwidth and latency requirements via a TDMA method. These slots are called guaranteed time slots (GTS). Each node requires at least two GTSs, one for receive acknowledgments, and another for transmitting data. These contiguous time slots form a Contention Free Period (CFP), which is placed at the end of the active period of the superframe. Moreover, this approach is determined the CFP at the beginning of the active portion. All the previous works focus on IEEE 802.15.4 MAC protocol for maximizing performance, while little attention has been devoted, so far, for reducing the CAP period based on the IEEE 802.15.4e MAC protocol.

2.2.3 Methods based on IEEE 802.15.4e

Many studies took place in IEEE 802.15.4e standard protocol for analyzing the performance as real devices or virtually ones. Those studies are basically aimed to improve the performance for throughput, packets delay, and energy consumption. A low-power multi-hop data frame transmission scheme based on the IEEE 802.15.4e MAC protocol was presented in [73] for reducing energy consumption from the transmission frame in the Smart Utility Network (SUN). This scheme can aggregate the frames to address the bottleneck challenges on SUN. Also, a relatively short active period without a CFP is selected to reduce unintended reception during the active period. This scheme can be assisted in reducing energy-based superframes structure. The study that it introduces in [27] is described as the superframe structure based on the IEEE 802.15.4e MAC communication protocol. The superframe consists of only the active period, which is subdivided into CAP and CFP. Nodes in the CAP using slotted CSMA/CA for channel access mechanism to transmit and monitoring periodic data. The CAP is equal to 8-time slots during which the nodes should stay awake. The CFP occupies the remaining seven slots those are known as a Guaranteed Time Slots (GTSs), which are used to transmit time-critical data. The reduction of the number of CAP periods saves energy, and only the first superframe of each multi-superframe uses the CAP. Therefore, it is particularly suitable for factory automation, smart metering, and patient health monitoring. A similar mechanism has been used in the previous works based on the CAP portion in the context of the superframe structure. Table 2.1 shows a summary of the comparisons of the most related works.

Table 2.1 Shows a Summary of The most Related Works.

Papers/ Features	**Paper [73]**	**Paper [27]**
Authors and date of publication.	Fumihide KOJIMA and Hiroshi HARADA , 2014.	Ali Nikoukar, Saleem Raza, Angelina Poole, Mesut Günes, Behnam Dezfouli, 2018
Problem	throughput performance and energy consumption	Energy Consumption
The proposed Technique	An effective and low-energy multi-hop data collection scheme using a superframe division technique with frame aggregation	They have proposed a method for reducing the number of CAP periods.
Methodology	They proposed an effective and low-energy multi-hop data collection scheme using a superframe division technique assuming frame aggregation	The proposed method can reduce the number of CAP periods for saving energy, and only the first superframe of each multi-superframe uses the CAP. The rest of the superframes inside the multi-superframe structure do not make use of the CAP.
Number of Superframes	-	-

Papers/ Features	**Paper [73]**	**Paper [27]**
MAC Protocol	IEEE 802.15.4e MAC protocol.	IEEE 802.15.4e MAC protocol.
Performance Metrics	Throughput and Delay Time.	Energy Consumption
Simulator	-	-
Topology	Star Topology	Star Topology
Hardware platform	-	-
Software platform	-	-
Application	Smart Utility Network (SUN)	Smart Factory Automation
Outcomes	performance can be improved with the largest aggregation size, improve average delay performance by decreasing frame retransmission	Reduce CAP Period
Contribution	Improving frame aggregation	Saving Energy.

This research proposed a new MAC protocol for maximizing the performance of the IIoT networks based on the IEEE 802.15.4e MAC protocol. IEEE 802.15.4e provides a multi-superframe structure. This work attempts to enhance the performance based on three parameters: throughput, packets delay, and energy consumption. The proposed protocol can improve performance by decreasing the CAP size portion.

Chapter Three

Industrial Internet of Things (IIoT)

Chapter Three

Industrial Internet of Things

3.1 Industrial IoT

In this chapter, the essential components of the IIoT will be described in details. Initially, Cyber-Physical Systems, Cyber Manufacturing Systems, and communications technologies of the IIoT concept are explained, followed by a description of the major parts of Industry 4.0. Thereafter, a major background of end-to-end digital integration and hierarchal system within a smart factory will be described explicitly.

3.1.1 Industrial IoT Background

IoT promises an opportunity to build robust industrial systems by the rapid growth of RFID, mobile, wireless, and sensor nodes. IoT introduces solutions to operations for existing industrial systems such as manufacturing systems and transportation systems. An application of the IoT in a smart parking system is used for monitoring the movement and tracking every vehicle in an existing position, and then predicts the future location of the vehicle. Also, IoT has various applications, some of them are transportation, healthcare, smart homes, and industrial environments [78]. The term IIoT is a new concept of the IoT, which is applied in the industrial environments [79]. There is an emerging technology related to IIoT called Industry 4.0. The main difference between IIoT and industry 4.0, IIoT semantically describes a technology movement, while Industry 4.0 is associated with the expected economic impact. Industry 4.0 is generated from IIoT. In all the researches and innovation initiatives, each technology complementary to the other. IIoT is still in its nonage, and platform standards are still in the development or acceptance stage [80].

The efficient systems of industrial fields as smart healthcare, smart grids, and intelligent manufacturing can be classified as Industrial Cyber-Physical Internet of Things [81], which helps to integrate and cooperate with several nodes via networks.

3.1.2 Cyber-Physical Systems (CPS)

Cyber-Physical Systems (CPS) are the systems provided by the networking capabilities through the (IoT) and Internet of Service (IoS), which facilitate remote access, smart services, and big data analytics over the Internet. The initiatives of Germany’s Industries 4.0 and the US Industrial Internet Consortium (IIC) are exploited the (CPS) to provide the modern term of industrial technologies, framework, and guidelines. This is expected to be achieved by convergence of the virtual and physical systems [82]. This desired convergence is expected to assist enterprises and production systems with improving horizontal and vertical integration of the entire value chain. CPS has numerous potential application areas which are smart cities, smart grids, smart healthcare, industrial manufacturing, transportation, retail, public safety, and networking. Depending on the application, CPS includes various components, it can be a simple device, one system, or it can be a system of systems. Based on the CPS, components, application requirements, connectivity, and integration of the value chain and the stakeholders are variant. Hence, different CPS requires different engineering methods and tools [83]. NASA defines CPS as a recent technology of physical resources that exhibit complex patterns of behavior due to highly capable embedded software components [84]. Also, a CPS is characterized by the communication between subsystems that is not necessarily part of mechatronics. In this context, the CPS can be described as a networked system, and usually, the network connotation is implicitly included in the term CPS. On the other hand, CPS comprises embedded computers, communication protocols, and networks that monitor and control physical operations [85].

Fig. (3.1) shows enabling technology for cyber-physical electronics production, the new directions to face current trends, and to meet the requirements of modern smart production, a variety of enabling technologies must be integrated into a production environment. For this, an integrated production system can be promoted to a cyber-physical production system.

These technologies will be examined from a software point of view and complemented by requirements for big data, cloud computing, and distributed intelligence. The technological integration of these enablers into a production environment, adding the need for mobility and human-machine collaboration.

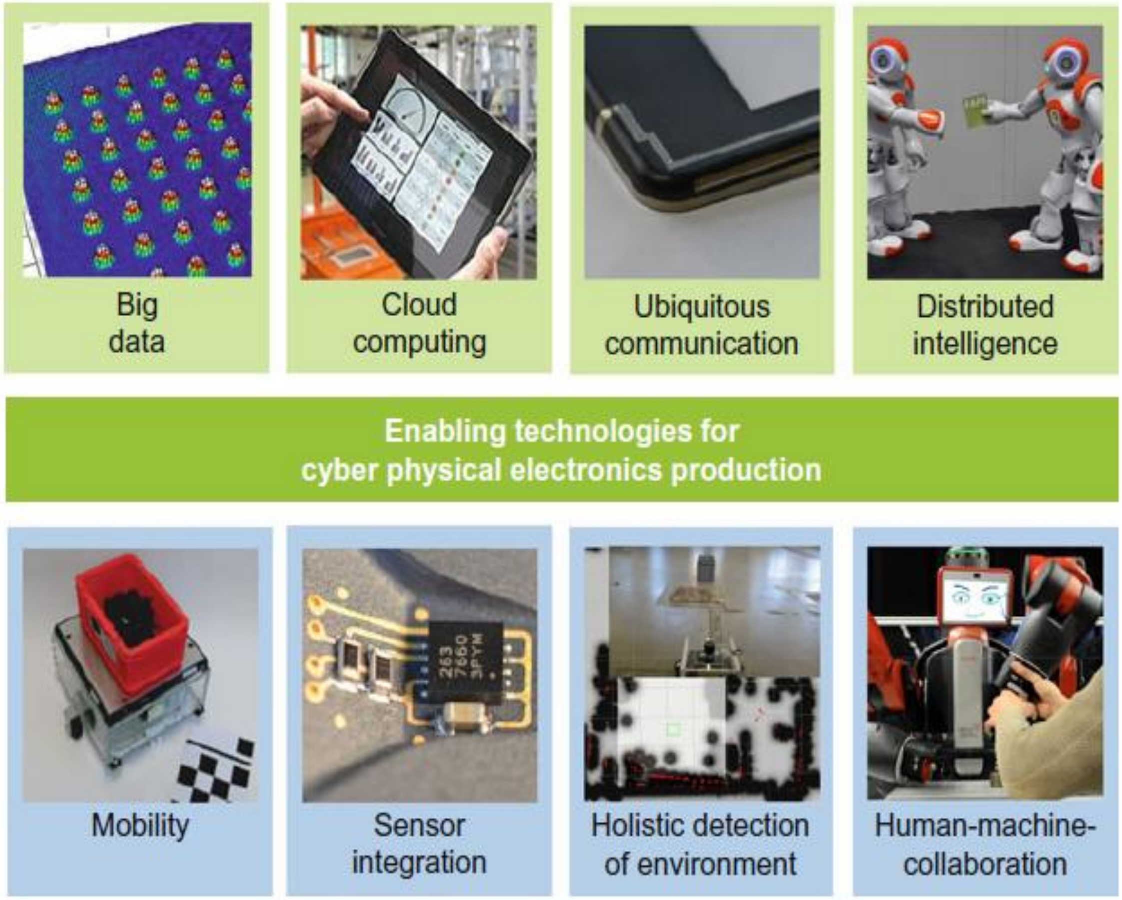


Fig. 3.1: Enabling technologies for cyber-physical production [135].

3.1.3 Cyber Manufacturing Systems (CMS)

Currently, smart manufacturing systems (SMS) have become a very important technology over the world. I 4.0 refers to Industry 4.0, which is focused on the manufacturing industry, it is aimed to bring together information from across distributed production facilities and levels to provide decision-making support throughout the entire process chain holistically and continuously [86]. By aggregating and analyzing data collected from sensors and devices, which enable factories to maximize benefits by improving the efficiency of machines and the throughput of manufacturing processes. CMS is a complex hybrid system, which is composed of different production infrastructures and various applications domains. One of the most critical challenges for adopting CMS is interoperability. The OLE for Process Control Unified Architecture (OPC UA) Foundation has expanded to the original OPC technology that develops, which is not restricted to the Windows operating system. In terms of application areas, OPC UA has been widely implemented in industrial manufacturing to provide communication interfaces for manufacturing execution systems (MES) and enterprise resource planning systems (ERPS). Fig. (3.2) illustrated the interaction among IIoT entities by using standardization communications technologies. This interaction enables the IIoT communications protocols between various components on the Internet. CPS requires open communication technologies in order to allow the integration of modern and current information systems and entities. There are communication protocols that available commercially for deploying in smart factories.

The requirements for communication and data exchange can be described with the four interactions are the transmission of data, retrieval of data, initiation of actions, and monitoring of environmental conditions.

The requirement for standardized semantics allows for interoperable communication and data exchange. The spectrum of transmitted information ranges from machine states via process parameters and routings to formalized knowledge. A standardized information model must be able to represent different information objects and levels and thereby be adaptable and expandable. Fig.(3.2) shows how the IIoT components interact with each other. Therefore, OPC UA provides a semantic information model that can be modified domain-specifically [135].

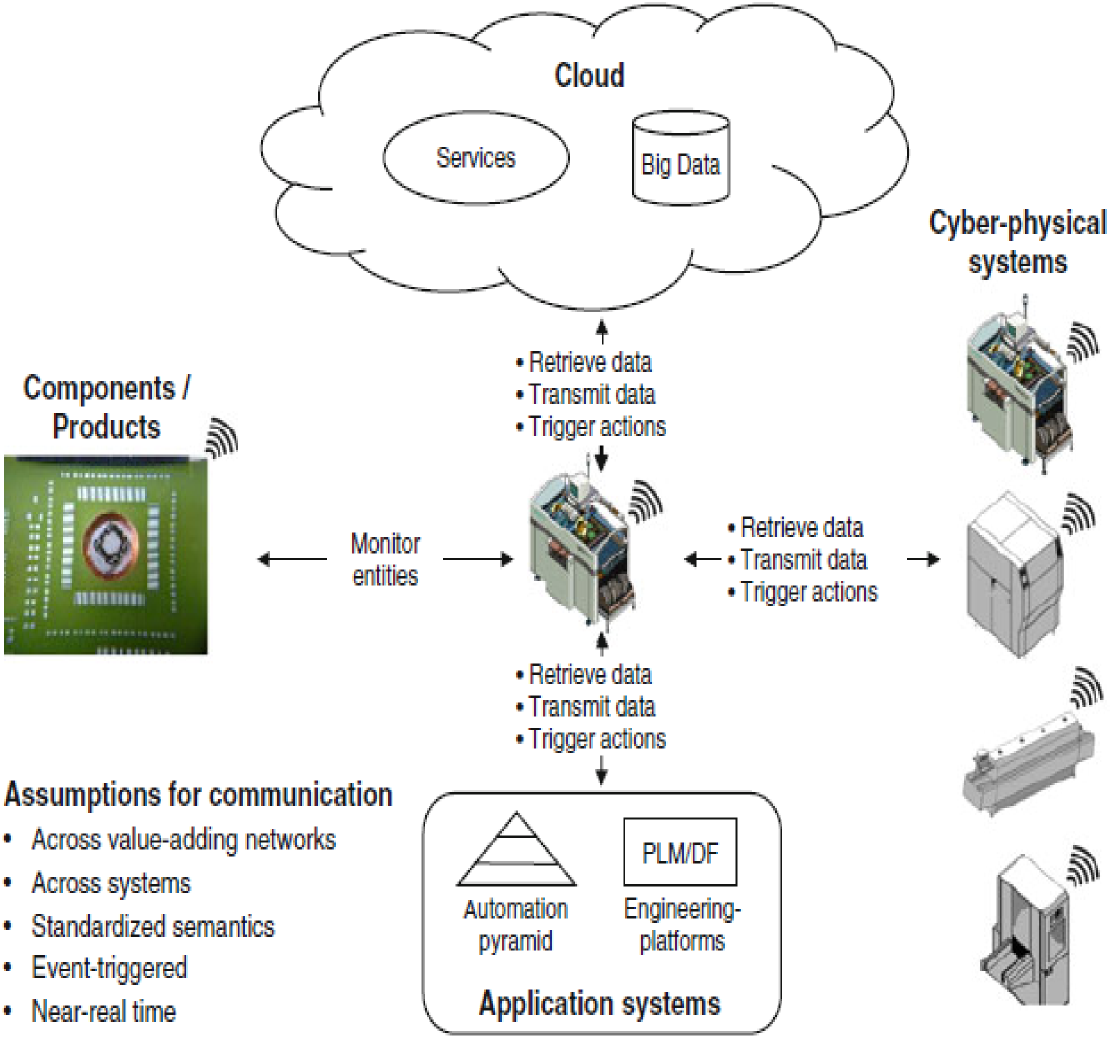


Fig. 3.2: Interaction between entities and systems in IIoT [135].

Manufacturing processes objects are described within OPC UA-defined types, these objects are sensors and actuators. OPC UA offers good scalability for data modeling; it is applied to define large-scale heterogeneous communication infrastructures. In the context of communications implementation, an OPC UA is a typical client-server model and is not limited to any specific data encoding [86].

In the areas of the manufacturing system, the first time to construct the network of objects is back in the 70th of the past century, which is known as Computer-Integrated Manufacturing (CIM). CIM has some challenges that still prevailing so far, which are an integration of managerial, engineering processes, and the realization of flexible and highly autonomous automation. However, in the early 90th the production needs are increased, IT solutions also were increased, so the CIM becomes inefficient and many projects have been failed. In the near past time, can observe that technology and people were not ready to successfully implement these ideas [85]. Also, the data storage units are limited, data transfer rates and interconnection is low, lack of open software tools, and formats for data exchange [85]. There are some functions such a product configuration; workflow, revisions, and authorization are irreplaceable, especially in large enterprises, and it becomes more significant for small businesses.

Product Lifecycle Management (PLM) is aimed at consistent data management over the whole lifecycle. In this case, a smart factory (SF) is usually considered as the cornerstone of PLM, which provides interfaces to different applications during the lifecycle, like production and service. PLM and SF are infrastructures for IIoT. IIoT requires information on the product for communicating and comparing the measured data to the initially specified requirements associated with the product. The main objective of the Digital Factory is to integrate data, models, processes, and software tools [87].

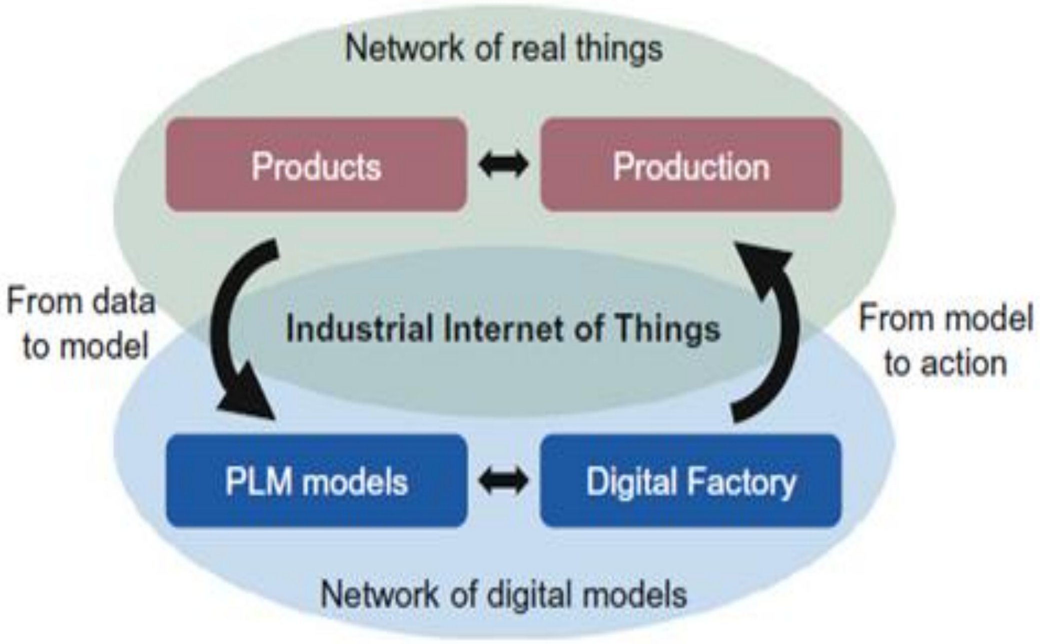


Fig. 3.3: IIoT Network of Real Things [79].

3.1.4 IIoT Opportunities and Challenges

Currently, most studies agree that IIoT and CMS are provided support for Industry 4.0. Industry 4.0 has a tremendous economic impact. For example, a recent survey by Price Waterhouse Coopers (PwC), a consultancy, concludes that the future global cost and efficiency gains by Industry 4.0 will increase annually [88]. Countries with an extensive industry sector as Germany, where the industry has a 30 % share of gross domestic product (GDP) and employs 25 % of the labor force [89] are challenged by digitalization as the successful transformation to IIoT and CMS, which ensures the future economic success of the whole economy. This transformation is especially crucial for the sector of machinery and equipment manufacturing as an enabler for other industry sectors [90]. The change to Industry 4.0 should lead to greater resource efficiency, shorter time-to-market, higher-value products, and new services.

3.1.5 IIoT Applications

Today, the promising potential of the emerging IIoT technologies for connecting smart nodes has a significant role, especially those deployed in smart factories, smart manufacturing systems, and intelligent automation. The most critical benefits of the IIoT that are used for high-resolution production to improve predictability and cost transparency, intelligent production planning that improves the adherence for delivering dates, reduce costs, throughput times, predictive maintenance, automatic fault detection leading to higher overall equipment effectiveness, and a reduction of maintenance costs. Moreover, intelligent process control aiming for zero waste, low tooling costs, minimal resource consumption, short running-in, and production times. Smart products are equipped with a digital identity such as that stored in a barcode or RFID chip, and all information related to the product is stored in some backend-database. Alternatively, the product is equipped with electronics memory and a processor, this data is stored in the database [8].

Human-machine interaction leads to higher labor productivity and improved ergonomics, feedback from production to engineering that optimizes the production systems of the next generation. CPS and IIoT generally have a broad field of applications. As observed in fig. (3.4), the smart factory is one of the most potential applications of an IIoT.

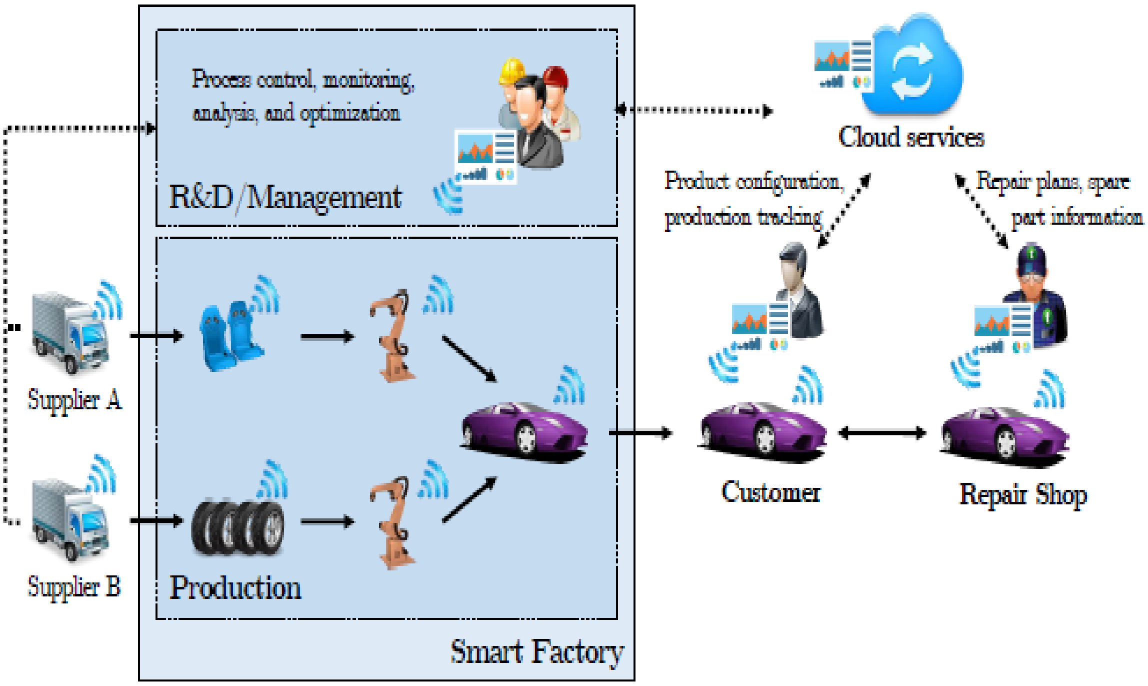


Fig. 3.4: IIoT in Smart Factory [8].

Furthermore, the major challenges of IIoT are the specification of a generally accepted, extensible architectural pattern that supports different kinds of nodes, and other hardware and software systems. On the other aspect, the complexity of the system will be managed and management of the various systems to provide a way to satisfy the information demands, high effort has been made by researchers as well as industrials to introduce several pseudo-standardized [79]. The critical major research initiatives of the IIoT fields that have been developed by German scientists, China, USA, South Korea, and Japan, which are started to implement smart manufacturing technologies, with a focus on safety and under energy constraints.

3.1.6 IIoT Communications Technologies

A few years ago, wired networks are mainly utilized as communication technologies in the network environments, which have many weaknesses that make it difficult to use cables for long-distance and it is not reliable. For these shortcomings, wireless technologies are developed and applied in wide applications throughout the world, like schools, colleges, offices, factories, and industries that are used for exchanging data among devices connected with them [91]. An essential key feature of IIoT communication technology is the ability to provide low power connectivity to a huge number of distributed devices deployed in hall distance. The main goal of IIoT technologies is used to cover a long-range distance with low power consumption and low cost. More technologies that achieving higher data rate, lower latency, and higher reliability are desired. Different types of IIoT communication technologies are studied and classified based on energy wastage, the range of the coverage area, data rate, transmission power, and connectivity among nodes into two categories, which are long-range communications technologies and short-range communications technologies.

3.1.6.1 Long Range Technologies

Low power wide area network technologies are developed to enables low-power, in quantity reach to a +20 dB, which makes the devices connect to the base station in the distance around 10th KM, and long-range connectivity solution for IIoT applications [92]. Popular LPWAN technologies to support long-range communications of the IIoT systems are LoRa [93], DASH7 [94], NB-IoT [95], SigFox [78], LTE-M [96], and Ingenu RPMA [97]. These technologies are enabling to optimize certain parameters based on their characteristics, which make applications developers estimate and choose suitable technology for IIoT deployment.

3.1.6.2 Short Range Technologies

Short-range wireless communication technologies as Bluetooth [64], [98], [92], Wi-Fi [99], [100], [101], and ZigBee [102] are used for communicating device to device. These technologies are suitable for IoT applications but did not adequate for the requirements of IIoT applications, which require long-range communication capabilities of appropriate capacity [103]. There are different categories of wireless communication technologies that are used to exchange data through the IIoT network. These technologies, for example, there are more technologies, which have not been covered in this research. Data requirements, communication range, and power demands are key requirements for selecting better technology.

Many studies have been performed based on the features of short-range communication technologies as data rate, range, packet size, uplink rate, downlink rate, standardization, and their applications in industrial fields. ZigBee outperforms these techniques; it offers better features to industrial automation applications that are low-cost deployment and redeployment, mesh networking to cover the entire industrial plants and factories. Consequently, ZigBee outperforms all of the short-range communication technologies due to having significant support for industrial automation.

3.2 Industry 4.0

The fourth industrial revolution becomes an essential concept in the areas of the manufacturing systems, which drives the change in their environments. Industry 4.0 focuses to use the current technology and optimizing its usage throughout the company to develop a new business model, and to reformulate business processes. However, not only the business is changing significantly, but the change should include also the

Information Technology (IT) and production of Operation Technology (OT) of a company [104].

Industry 4.0 refers to the next stage in the evolution of the organization and control of manufacturing processes. The term Industry 4.0 was originated in 2011 at the Hanover Fair in Germany as a strategy to mitigate the increasing competition from overseas and to differentiate German and European Union industries from other international markets [105], [106], [107]. Also, the German government sought to use intelligent monitoring in production processes to aid decision-making and machine maintenance to reduce costs and increase the competitiveness of German industries [105]. The term is delivered with enthusiasm by the worldwide industry [108] and overlapped in part with other paradigms such as IIoT [109] and with other initiatives made in China, the USA, Japan, and South Korea. Industry 4.0 is directly related to the deployment of smart factories [110], which are conceived to manage more efficiently their resources and to incorporate enough flexibility to adapt up to production needs. Such a necessity for flexibility is associated with the fact that clients are increasingly demanding product customization [111], which has impacts on development and manufacturing at different stages, these stages are design, ordering, development, production, sale, and after-sale.

The primary function of Industry 4.0 is to collect as much information as possible in real-time from all the different parts of the value chain. Moreover, data collection should be as efficient, fast, and flexible as possible, which involves collecting and analyzing data with computerized machines that also help to decrease production costs and to increase quality. For achieving such improvements, IIoT and CPSs allow for collecting, processing, and storing the data obtained from real-world objects [112], by adding intelligence to machines, tools, storage areas, and raw materials of a production chain, it is possible to adapt the factory to be changed, providing flexibility to face industrial and client requirements. Furthermore, such flexibility enables the manufacturing of highly customized products and adapting to the actual demand for avoiding the storage of too much stock.

For achieving all the previous benefits, the Industry 4.0 paradigm proposes the use of different technologies. Some of them have been studied for a long time, but they are still not mature for massive industrial deployment, like Augmented Reality (AR) [112].

3.2.1 Industry 4.0 Issues

Industry 4.0 has different issues for its deployment that are determined as the lack of knowledge about technologies and their opportunities, uncertainty about the benefits of technology investments on products and processes, lack of knowledge about customer demand regarding new products and business models under industry 4.0 vision, limited human and financial resources, difficulties to spot the starting point and milestones of the planning horizon, need for efficient portfolio management for technology investments, requirements for prioritization and scheduling of new product and process projects, allocating the limited resources to the projects and collaborating with reliable partners, and lack of communication-related to the benefits of the Industry 4.0 transformation projects through the organization [113].

The strategies for adopting new technologies by companies into their operations and products should be clear. As the first step, the organization developed a roadmap, which is a sophisticated long-term planning instrument that allows for setting strategic goals and estimating the potential of new technologies, products, and services [112].

3.2.2 Industry 4.0 Technologies

Implementation of Industry 4.0 solutions requires the integration of the following technologies that focused on the ten keys features, which involved in Industry 4.0 are IIoT [114], [115], [116]. CPS [117], [118], [119]. Vertical and horizontal integration systems, [87], horizontal and vertical integration are critical for Industry 4.0 to automate data transmission in smart factories and to communicate with providers and clients. Additive manufacturing (3D printing), the flexibility and customization brought by additive manufacturing are essential in the Industry 4.0 system. Ideally, such characteristics should be provided without raising the price of the product and should not depend on the fact that the manufactured products are identical or different. Moreover, additive manufacturing will make it easier to produce low-volume batches or prototypes, which traditionally have been expensive. Furthermore, decentralized additive manufacturing will reduce delivery times and will enable stock management optimization [120].

Big Data and Data Analytics Companies usually store a lot of data related to industrial and logistic processes and systems, services as sales and after-sales, data traffic as logs of routers and computers [121]. The massive amount of generated data is precious, but they cannot be processed manually, so Big Data techniques become useful for data analytics that helps when processing the information at cloud platforms; it can predict future problems, or the necessity for specific resources [106].

Cybersecurity Connectivity becomes one of the most critical issues of the Industry 4.0 applications, so it is required to protect industrial critical systems and manufacturing lines from cyber-attacks, it has a great impact on the growth remarkably in the last years [121], [122].

In Cloud and edge computing, different enterprises over the world are deploying their applications on the cloud computing systems, which are adopted by Industry 4.0 in it is parts due to has eased the collaboration with other sectors. The traditional cloud-based systems have certain limitations [123], this cloud considers a point of failure, when maintenance, software problems, or attacks occur, and the whole system is blocked. Moreover, it is essential to emphasize that, if the amount of IoT-connected devices keeps on growing at the same rate [120], the number of communications to be handled will increase remarkably and, therefore, the cloud may constitute a bottleneck. Due to these issues, other alternative architectures based on edge computing have been proposed as fog computing [124].

Simulation software, the collected information can be processed to model the behavior of machines, products, and workers of specific industrial processes [125], which presents the actual situation in a real-world factory through visual interfaces, which allows for remote monitoring and supervising operations.

Autonomous robots and vehicles, the next generation of robots that will be used in Industry 4.0 applications include robots [126], industrial robots [127], and Autonomous Ground Vehicles (AGVs) [128], it is interconnected and works collaboratively. Robots help human operators in different tasks; they could be able to perform specific tasks such as searching items or transporting tools on a freeway. Regarding AGVs, they are mainly targeted at logistics and transport in industrial environments, existing AGVs for mining material handling, and are used for automating industrial vehicles [129]. Fig. (4.5) illustrates the main tangible components of the industrial automation systems.

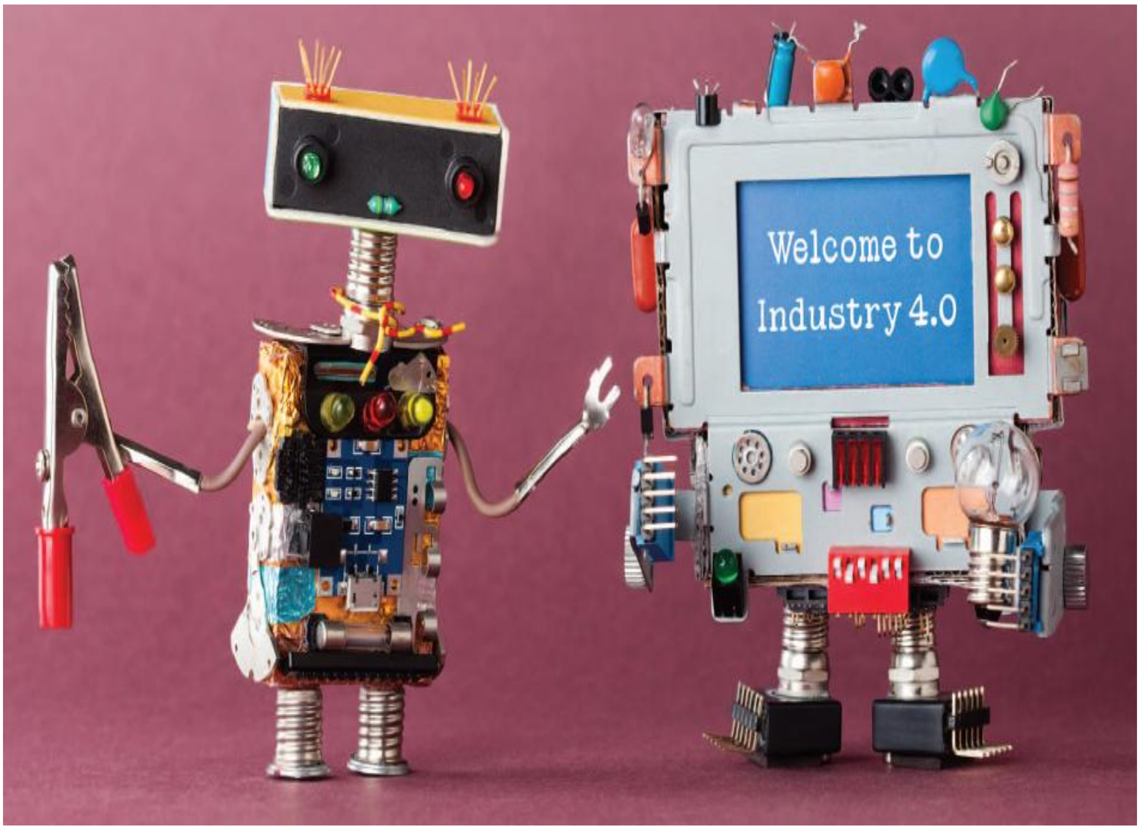


Fig. 3.5: Industrial Automation Systems (118).

Augmented and virtual reality (AR) is a technology that makes use of an electronic device to view directly or indirectly the real-world environment which is combined with virtual elements. In the case of Virtual Reality (VR), both the environment and the items are virtual. AR and VR are proved to be useful in different stages of an industrial process, as a design [130], [131], manufacturing [132], or maintenance [133], [134]. AR technology can help operators to avoid mistakes in assembly tasks and increasing productivity [134], [135], [79], [136]. The illustration in fig. (3.6) puts important theoretical concepts of Industry 4.0, where the smart factory is in the center of Industry 4.0, due to it has several characteristics, which makes things to be communicated through virtual networks.

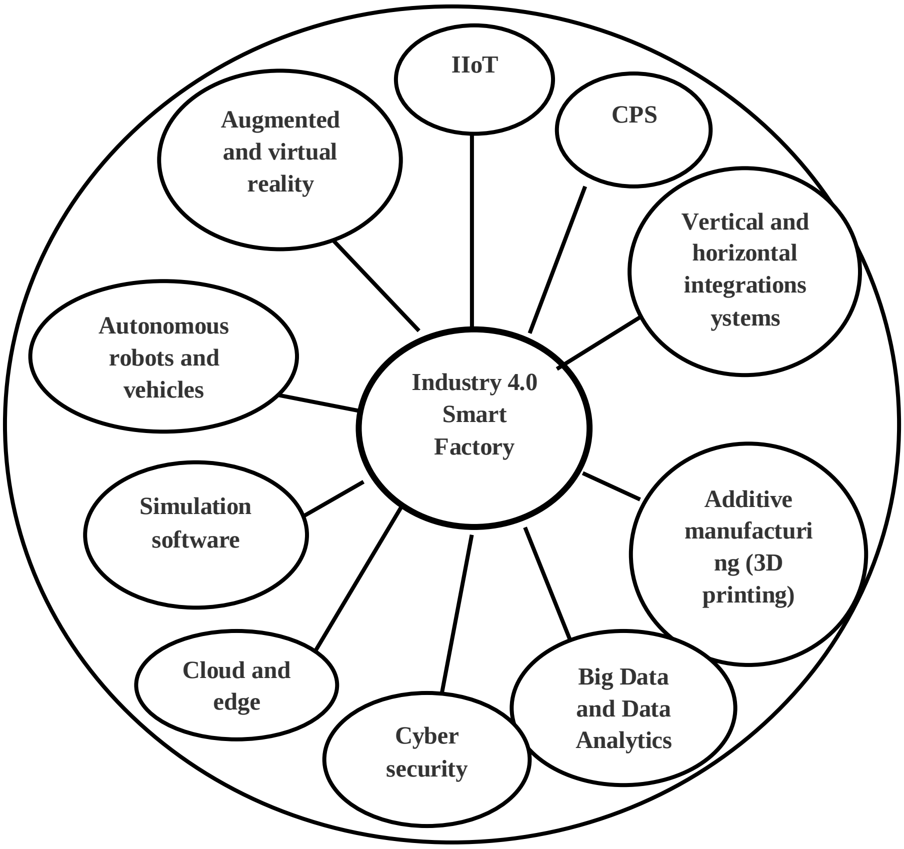


Fig. 3.6: Industry 4.0 Components and Their Related Fields [135].

3.3 Smart Factory

This section discusses two points, the smart factory background, and the intelligent factory architecture system. In the context of Industry 4.0, intelligent manufacturing attracts enormous interest from the government, enterprises, and academic researchers [137]. Therefore, the construction patterns of the smart factory are widely discussed by several researchers. The standards for intelligent factory implementation have not been established yet.

Smart factory can be able to send data and services of industrial through remote monitoring of the machine operation and manufacturing processes in real-time. Wearable and lightweight devices are applied within a smart factory environment for gathering information on the machine operations, products, factory areas, and route it to industrial center service wirelessly.

GSM, 2G, 3G, UTMS, 4G, LTE, and 5G are popular wireless communication technologies for a smart factory. The sensors that installed in the factory to collect real-time machine of moving objects and manufacturing information, the data gathered by the sensors involves temperature, humidity, spatial occupation of factory area, position, and direction, speed of production process, fuel consumption, smoke emission, and noise generation of running machine. These data can be transmitted through both direct connections to the sink node and multi-hop converge cast among mobile systems [138].

In the smart factory, intelligent manufacturing has been gained great attention from the government, enterprises, and academic researchers [112]. Therefore, the construction patterns of the smart factory are widely discussed. According to the architecture of the smart factory [139], [140], [141] includes four tangible layers. This is illustrated in fig. (3.7), the framework of the smart factory contains the following layers, with a focus on critical technologies of every layer:

The physical resources layer consists of intelligent sensors, conveyor equipment, packing products, which need to have support for real-time information acquisition, and communication devices should provide high-speed transmission of heterogeneous information. Besides, the intelligence of underlying equipment should be enhanced to meet the requirements of IIoT [139]. This layer is more consuming energy due to having functionalities of monitoring and collecting data with different types of sensors and actuators, and the energy consumption is formed significant challenges of smart factories so far [142].

The network layer is used to connect layers within the smart factory. According to the distributed control, the connection between controller and actuator is implemented by field bus, Modbus, and EtherCAT. The relationship among equipment achieved by the combination of Ethernet and data distribution services (DDS) is enabled to adopt the network technologies toward self-control and self-organized. The connection between hardware and cloud platform was implemented by the integration of Ethernet and OPC UA, which provided data interaction [140].

The cloud service layer has massive manufacturing data gathered by the first layer; this data can be uploaded to the cloud platform through an industrial wireless network for processing. Predix is a popular cloud platform, which provided data storage and processing resource for data applications. It is depicted as another kind of necessary infrastructure for the smart factory that provides layered services in the form of Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), and Software-as-a-Service (SaaS). Big data analytics support system management, optimization, including supervision, and control [141]. The cloud platform should be able to analyze the semantics of various data. Therefore, ontology is being employed in the modeling of the smart factory, which can provide the abilities of self-organization, self-learning, and self-adaption. Moreover, data analysis could provide a scientific basis for decision-making, while data mining could be used to ensure design optimization and active maintenance [138].

The terminal layer is used to connect end-users equipment like PCs, smartphones, and tablets to the smart factory, which is deployed to support remote monitoring of operation, maintenance, and diagnosis, even remotely through the Internet. Besides, customers can access the orders provided by the cloud timely using the intelligent terminal [141]. Fig. (3.7) is illustrated the important tangible resources of the smart factory.

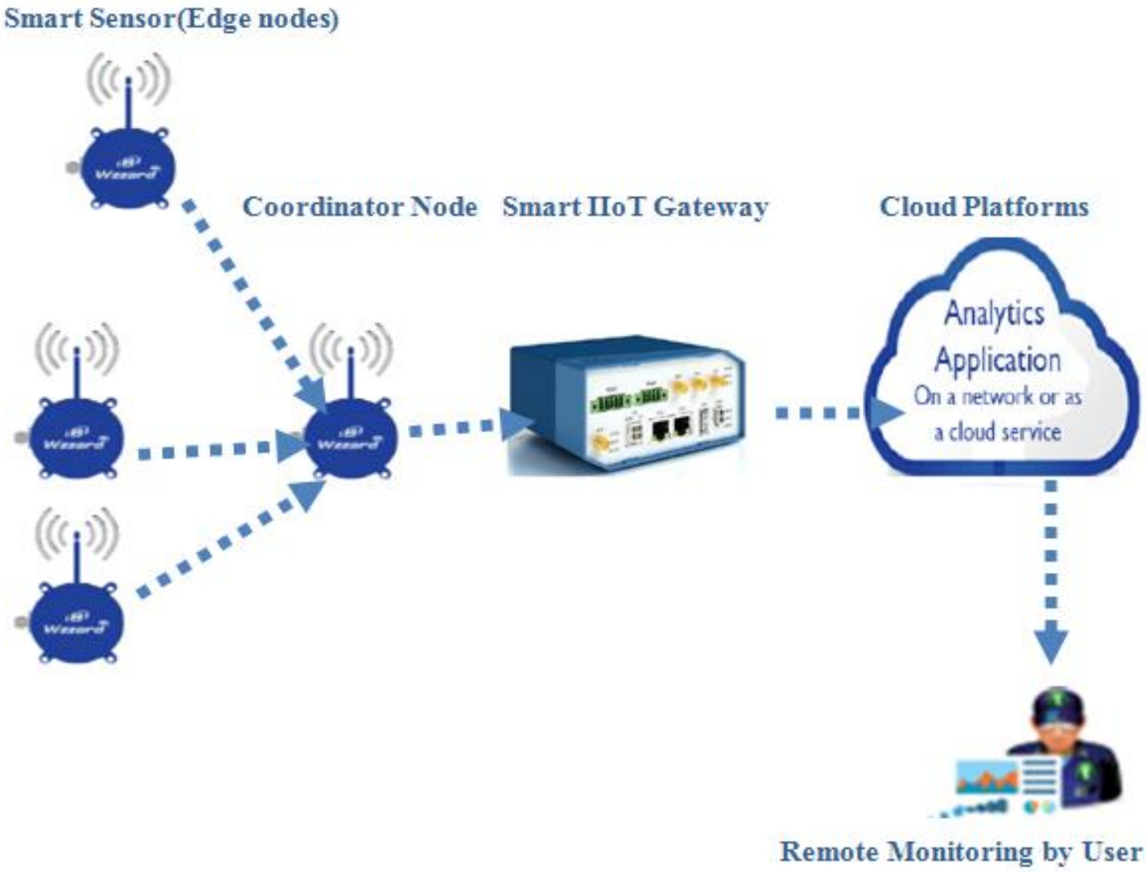


Fig. 3.7: Architecture System for Smart Factory [143].

Chapter Four

Proposed MAC Protocol for Improving Performance of the IIoT

Chapter Four

Proposed MAC Protocol for Improving Performance of the IIoT

This chapter discusses the proposed protocol for improving the IIoT performance-based superframes structure, IIoT network distribution, and how to implement the proposed protocol.

4.1 Proposed CAP Reduction MAC Protocol

IIoT network consists of tiny smart devices called nodes, which are communicated through wireless, with each other to service provided by an important layer known as the MAC sublayer. The MAC sublayer is an essential part of the data link layer (Layer 2) of the open system interconnections (OSI), the OSI is layered networking that does how communications should be done amongst heterogeneous systems. The data link layer includes two sublayers, the Logical Link Control (LLC) and the MAC sublayer, as illustrates in fig. (4.1). The LLC is used for addressing and multiplexing, while the MAC sublayer manages access to the physical network medium, and its fundamental target is to reduce packets collisions in the medium, where this thesis is focused on the MAC sublayer. MAC sublayer is proposed by IoT IEEE 802.15 working group, it is a sublayer of the IoT protocol stack, and it has a responsibility for wireless communications in the IIoT networks. In the MAC sublayer, the nodes need to know if the channel is available or busy by other transmissions before sending frames, this operation can be done by using the CSMA/CA mechanism, CSMA/CA technique is used broadly adopted in different communications technologies. MAC sublayer provides support for emerging wireless communications protocols that are implemented for building robust IIoT networks. The most popular MAC sublayer protocols are IEEE 802.15.4 protocol and IEEE 802.15.4e protocol.

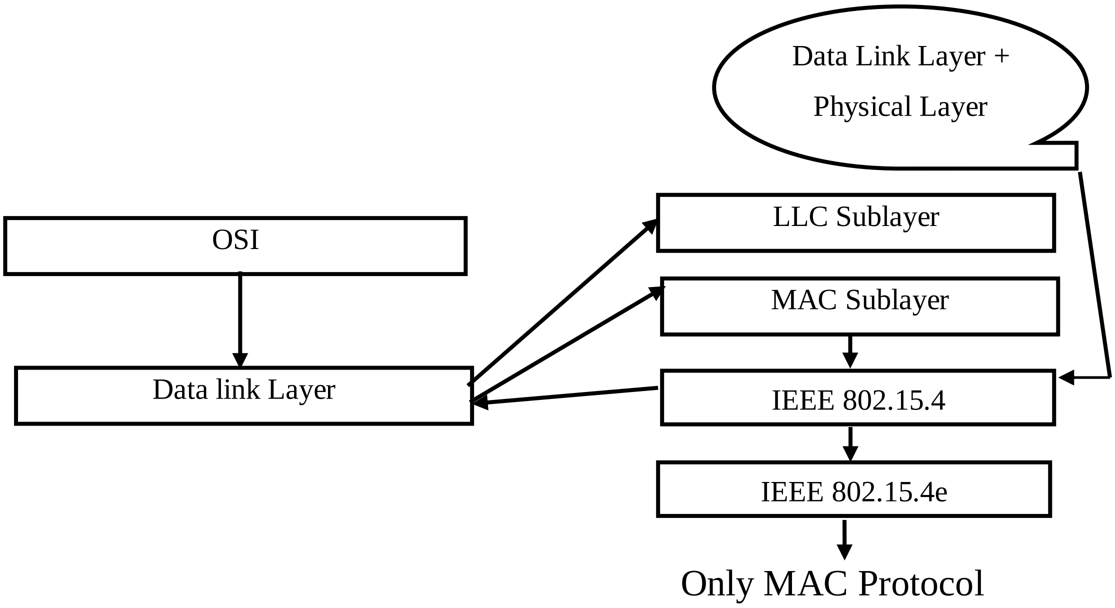


Fig. 4.1: OSI Layers for WSN.

4.1.1 IEEE 802.15.4

IEEE 802.15.4 is developed by the IEEE Working Group for the Physical (PHY) and MAC layer, it was released officially in May 2003 for the wireless communication requirements as low data rate, low cost, low-power, and short-range communication. This protocol is modified to meet the critical requirements of IoT applications. IEEE 802.15.4 suffers from some limitations such as low power, low cost, low data rate, and interference (performance). The structure of the IEEE 802.15.4 is a superframe, which consists of 8-time slots for the CAP period, 7-time slots for the CFP period, and a one-time slot as a beacon. The beacon period is used by the coordinator for broadcasting the beacons in the network, to check all devices associated synchronized with the coordinator.

In the CAP period, nodes are used the CSMA/CA mechanism for connecting to the network, while the nodes are competing for interconnection to the network through CFP. Fig (4.2) shows the structure of the superframe of the IEEE 802.15.4.

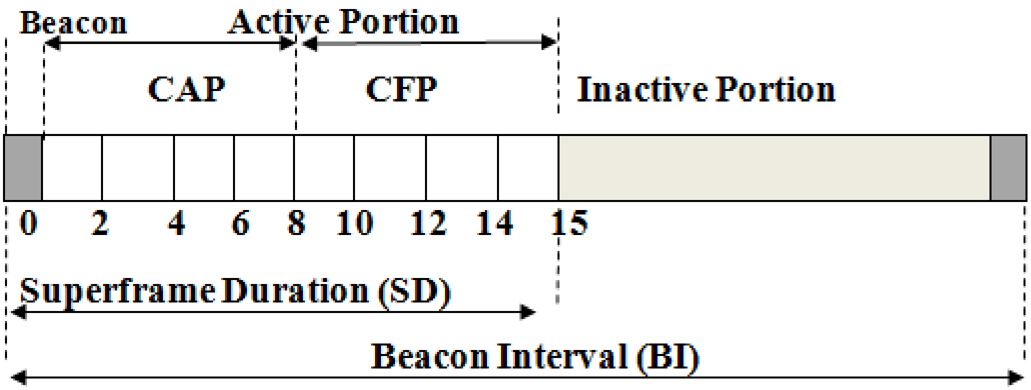


Fig. 4.2: Superframe Structure of IEEE 802.15.4.

4.1.2 The IEEE 802.15.4e

IEEE 802.15.4e amendment is published in 2012 by the Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) for enhancing the limitations of the IEEE 802.15.4 protocol to support industrial markets. It is only a MAC sublayer protocol.

The IEEE 802.15.4e MAC protocol is one of the most popular MAC protocols and very useful for the IIoT network, which is composed of three types (modes), each mode does some functions in wireless communications. These modes are the Time Slot Channel Hopping (TSCH) mode, Deterministic and Synchronous Multi-channel Extension (DSME) mode, and Low latency Deterministic Network (LLDN) mode. This work is focused on the DSME mode due that it can support the multi-superframe. Many research works confirmed that the DSME is significantly successful and very useful for use in industrial, smart healthcare, and smart factories. The structure of the DSME includes a multisuperframe. Multisuperframe includes a set of superframes. Each superframe (SF) = CAP + CFP +

Beacon periods. The CAP + CFP both are fixed to 15-timeslots, where CAP = 8-timeslots, CFP = 7-timeslots, and one-timeslot for a beacon frame. SF is equal to 16 timeslots. Fig. (4.3) is illustrated the main components of the IEEE 802.15.4e.

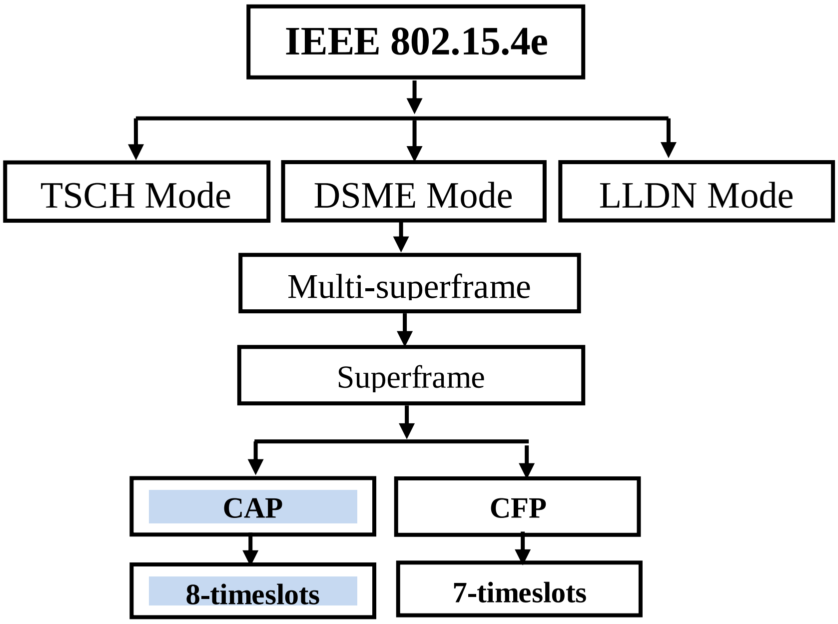


Fig. 4.3: The structure of the IEEE 802.15.4e.

This thesis proposed a new MAC protocol for reducing the CAP size period to maximize the performance of IIoT networks. That performance is composed of three parameters: throughput, the packets delay, and energy consumption.

This work uses the modified method as introduces in [144] for CAP portion reduction. The proposed protocol can reduce the CAP size based on two metrics which are superframe order (SO) and beacon order (BO). Where SO indicates the length of the superframe with the beacon. BO is the cyclic time when the coordinator communicates using a beacon.

SO + BO = 15 timeslots and the one-time slot is a beacon period.

For $0 \leq SO \leq BO \leq 14$.

Every superframe bounded by the beacons periods, and every multi-superframe ended by an inactive period.

Fig. (2.4) illustrates the multi-superframe structure provides by the DSME mode.

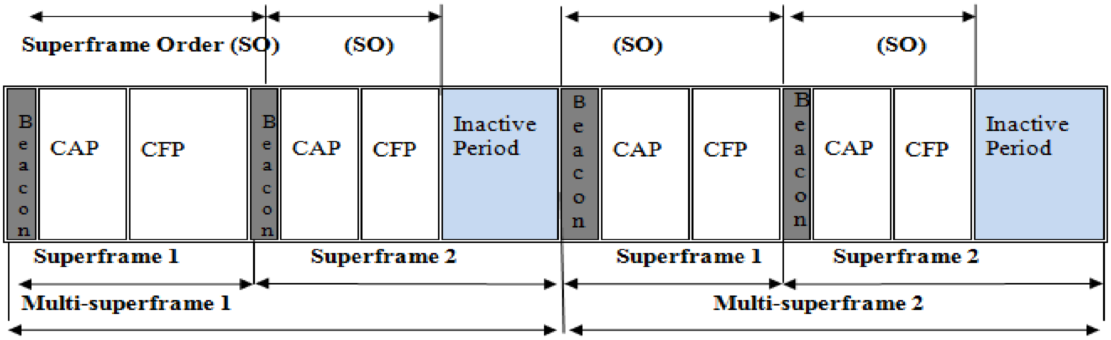


Fig. 4.4: Superframe Structure of DSME.

The proposed protocol can reduce the CAP size period based on the values of the SO. If the value of SO is in the range of 0 to 2, the CAP size is equal to 2 $^{3-0}$, then the time slots = 8, where the time slots are similar to that proposed in IEEE 802.15.4 and IEEE 802.15.4e, which provides one superframe structure. The value of the SO is in the range of 3 to 5. In this case, the CAP length is equal to 2 $^{5-3}$, then the timeslots = 4. The value of the SO is in the range of 6 to 7. In this case, the CAP length is equal to 2 $^{7-6}$, then the timeslots = 2. According to figure (4.5), this thesis is used the DSME which has two superframes; each superframe has 16 timeslots that assigning for the sensors. The proposed protocol reduces the CAP duration by increasing the SO value. If the value of SO is increased, the CAP is decreased. When the CAP was reduced, the number of timeslots are included within the CAP duration is minimized.

This thesis is focused on two main parameters of the superframes: BO and SO, the values of both BO and SO will start from 0 to 14. To obtain an optimal value of the CAP period, this depends on changing the values of SO. As illustrated in fig. (4.5), when the value of SO is set to 5, the number of time slots are being equal to 4-time slots. Based on different experiments that have been conducted an optimal value of both BO and SO realized on the best performance should be tuning to 5. Performance improvement of IIoT networks is directly related to optimal values of BO and SO.

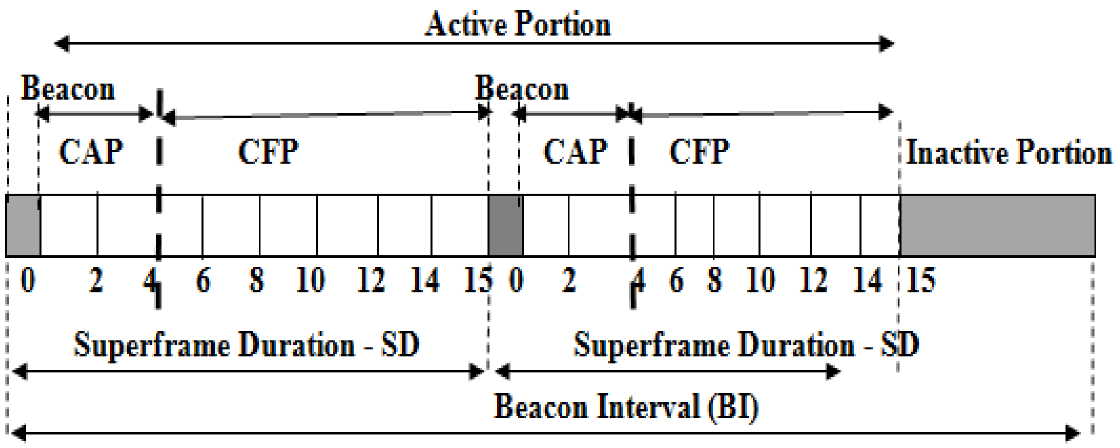


Fig. 4.5: Superframe Structure of the Proposed Protocol.

The following steps for presenting how the proposed protocol can change the values of SO by estimating the averages end-to-end delay of each sensor. These estimations depend on the number of packets received by the specific sensor at that time. Different experiments are explained that the most suitable number of packets after which the checking process that is done by the coordinator is 5 packets [145], and the maximum possible value for checking end-to-end delay is defined in the standard it has a default value equal to 5 [146]. This research used 5 packets as an input parameter to obtain reasonable results compare with the related works, for selecting the better value of SO that relies on the requirements of the IIoT applications.

Step 1: The coordinator will start to assess the total delay each node suffered, so far along with the number of packets received from that node at that moment.

Step 2: The coordinator calculates the nodes' average end-to-end delay according to the SO value which is dynamically changing.

Step 3: The coordinator is checking the process which is done for every 5 packets. According to the results achieved.

Step 4: The coordinator decides if the SO increases. In other words, if the new estimated average delay is checked to be worse than that of the previously calculated one, then the coordinator increases the SO value.

Step 5: if SO is increased, its value does not exceed that of BO value, and if SO reset to the original value and continues an overall process.

Fig. (4.6) illustrates the changing of SO values according to network performance.

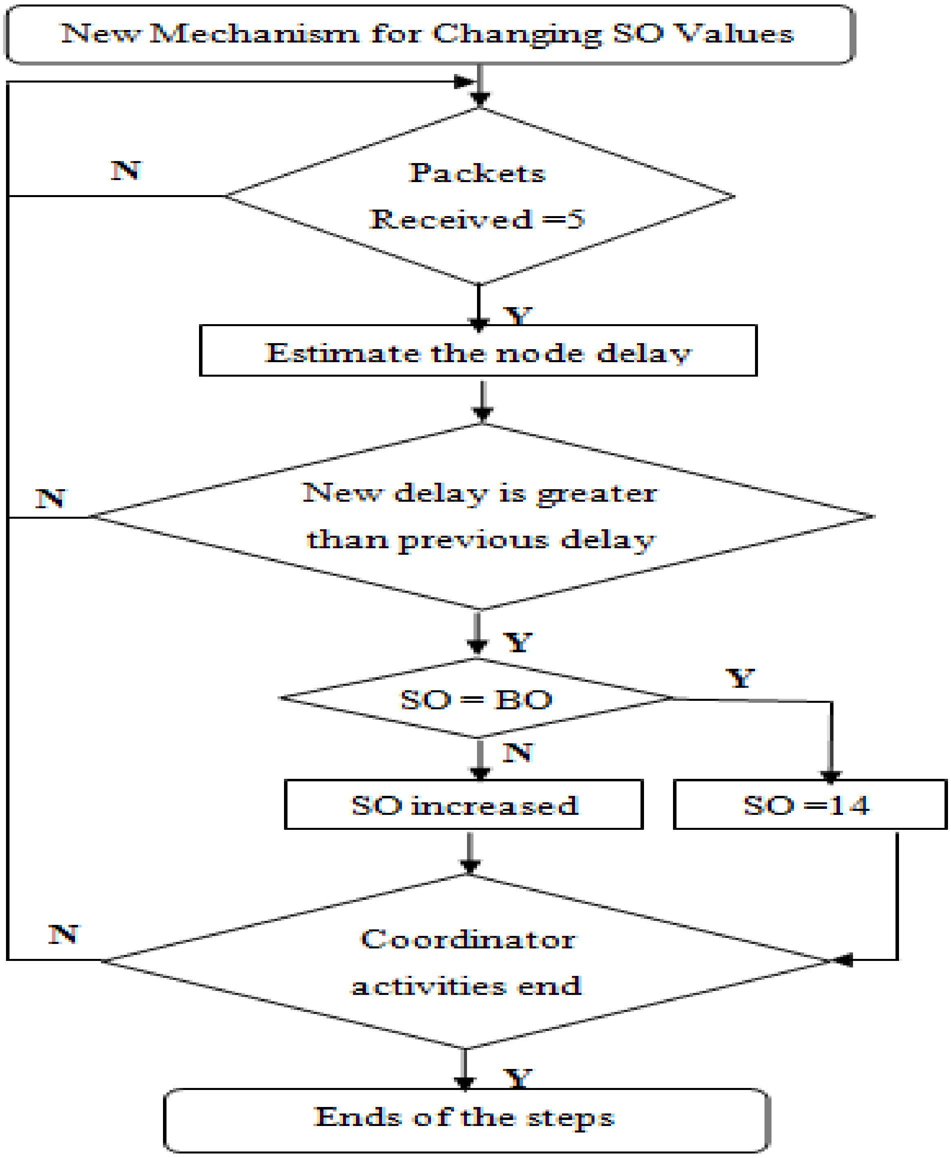


Fig. 4.6: New Mechanism for Changes SO Values.

The proposed protocol gives an optimal distribution of the IIoT nodes and optimal value of the SO, which maximizes the performance measurement to determine throughput, packets delay, energy consumption, and the costs.

4.2 IIoT Network Distribution

The smart sensors in the IIoT network can be represented by an undirected graph G = (V, E), where V represents the set of all sensors nodes, actuators, and gateways in the network. E represents the set of communication links between every two nodes in the IIoT network [147], [148]. These nodes are collecting data from their around environments, then reroute it to a data center called Base Station (BS) or gateway in the network layer of the IIoT architecture systems. The distance between two nodes (i, j) is the minimum number of links between these nodes, which can be formulated as d(i,j) [137] that is illustrated in fig. (4.8), where fig. (4.8) shows the sensor map for Z1 node, and fig. (4.9) shows an implementation for Sky nodes, in which there were eight nodes; seven of which represent as the sensor node and one of them acted as the sink node (this role also applied in different scenarios in this thesis). An optimal distribution algorithm has been developed and deployed in this work, for obtaining the better distribution of the IIoT sensors, these sensors are assigned for the time slots that should cover the same area.

The time slots for smart sensors using CAP have capable to preserve the same performance and functionalities of the IIoT smart sensor with maintaining the optimal distribution to cover the determined area.

An optimal distribution algorithm does a trade-off between performance and network functionalities in order to cover the determined area. One of the most important factors of an optimal distribution is the sensor location, where it needs to calculate the distance between every two nodes and the sensing range for each sensor. That distribution is done according to the following steps as that illustrated in an optimal distribution algorithm for sensors devices. To execute this algorithm, it depends on some parameters are the IIoT sensors should be loaded into the system, the distance (Di) between every two sensors is computed. The sensing range for each sensor is the area that is covered by that sensor radio, if (Di) is greater than the sensing range; this means that there is an area that has not been covered. In this case, the best locations (L_{best}) of the sensors should be calculated, and then are iterated into their new points. Optimal distribution algorithm for the IIoT sensors:

Step 1: Load the IIoT sensors into the system.

Step 2: Calculates the distance (Di) between every two nodes to give suitable locations for the devices.

Step 3: If the distance between every two nodes is greater than the sensing range of that node, go to step 4, else it goes to step 7 then terminates the process.

Step 4: Calculate the best locations (L_{best}) of the sensors.

Step 5: Iterating the sensors into a new location (L_{best}).

Step 6: Conducts an optimal distribution.

Step 7: Extracts the results (Best Location).

Fig. (4.7) shows the steps of an Optimal Distribution Algorithm of the IIoT sensors.

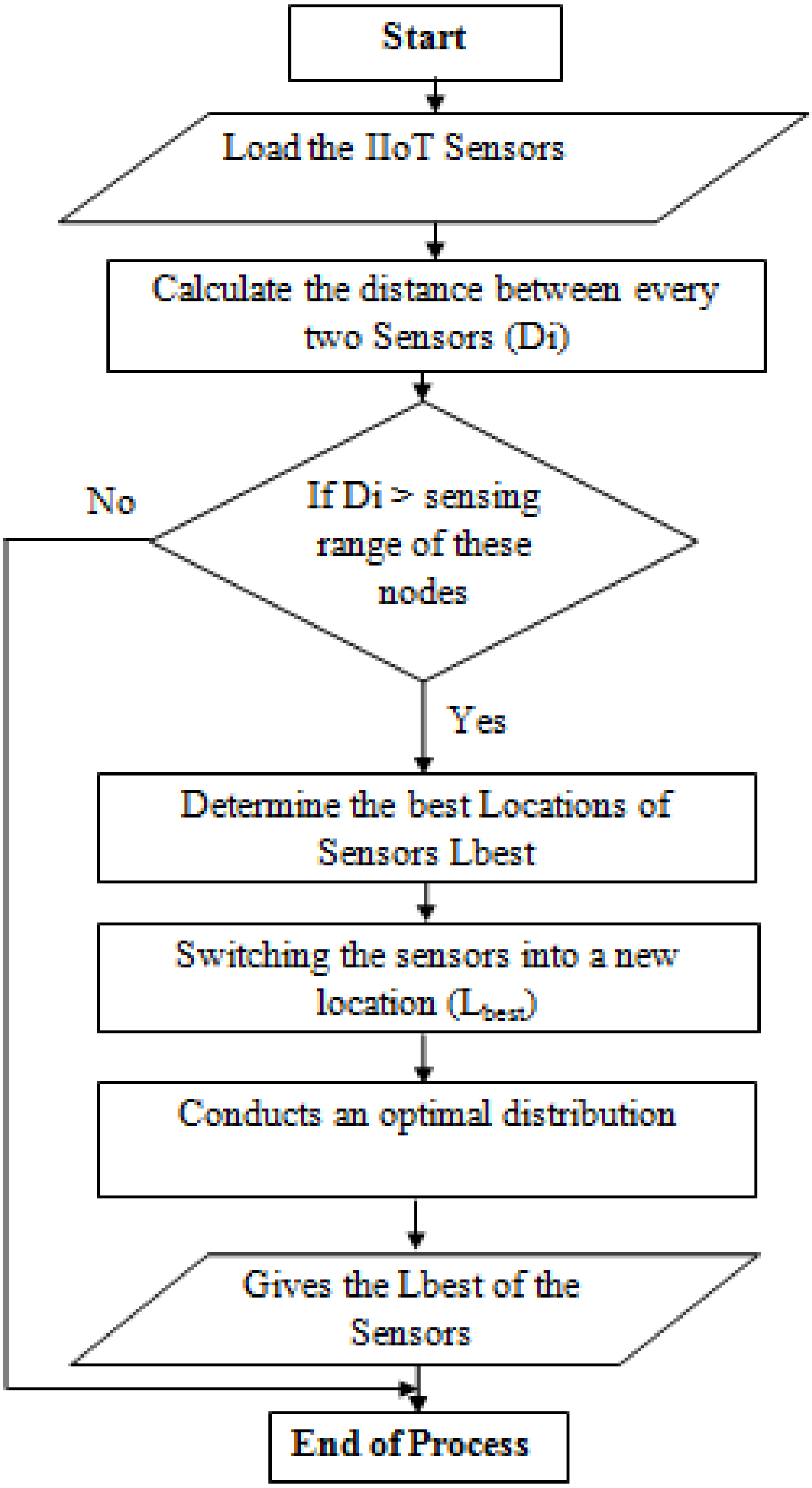


Fig. 4.7: Optimal Distribution Algorithm of the IIoT devices.

Fig. (4.8) illustrated the results of the distribution of the devices after enhanced the IEEE 802.15.4e (for the same area).

Optimal distribution algorithm plays a vital role in the IIoT network based on superframe structure, which depends on the optimal value of contention access period to perform optimal distribution for the sensors; it can be widely applied in different environments of the IIoT networks. To validate the effectiveness of this algorithm, IIoT networks are designed and implemented for testing including the 8 smart sensors under the Cooja simulator, as illustrated in fig. (4.8). The obtained results from this algorithm have been compared with those illustrated in fig. (4.9), which includes 16 sensors.

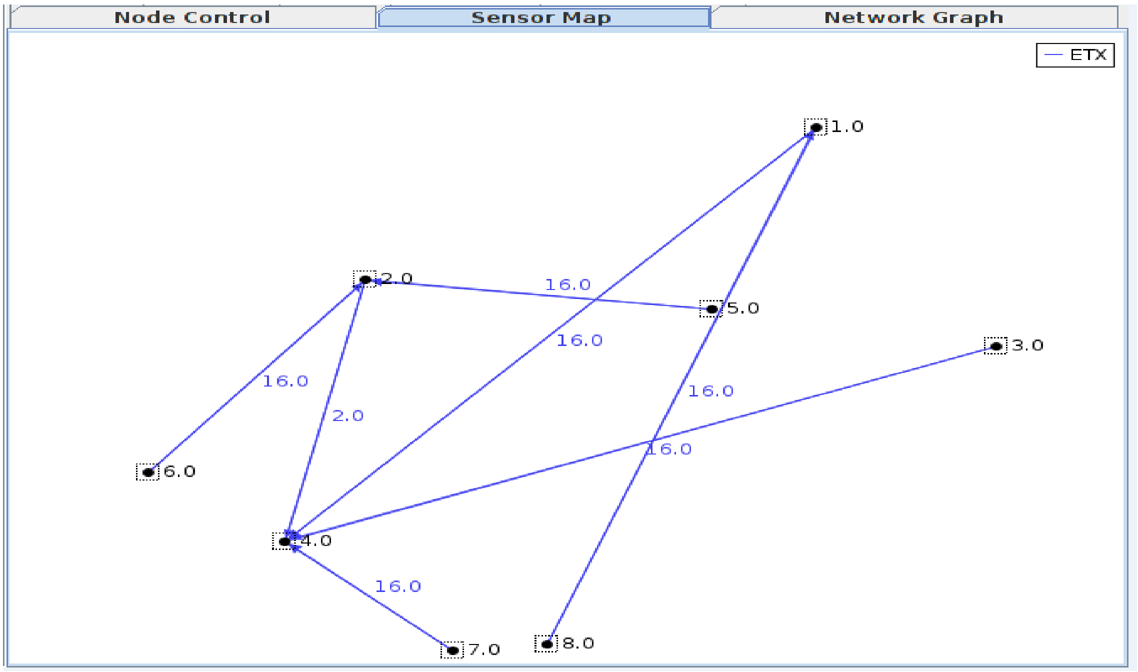


Fig. 4.8: Sensor Map of Z1 after Enhancement.

The IIoT network that illustrated in fig. (4.8) includes eight sensor nodes of the Z1, deployed in a star topology with an optimal distribution, some of them have one hop count such as sensor 1, sensor 2, sensor 3, and sensor 7. And the others have two-hop counts, which are sensor 5, sensor 6, and sensor 8. Seven of them are formed as field nodes, and one sensor is a gateway node (Sensor 4). The gateway node gathers data from their neighboring sensors; it processes these data and provides interfaces to the

IIoT network, which is connected through the wireless network. Smart sensor nodes are set up in industry fields that are combined with sensors and actuators that are used for transmitting process measurements, and control data to accomplish specific applications.

Fig. (4.9) illustrated the results of the distribution of the devices after enhanced the IEEE 802.15.4e (for the same area), which is tested under Sky.

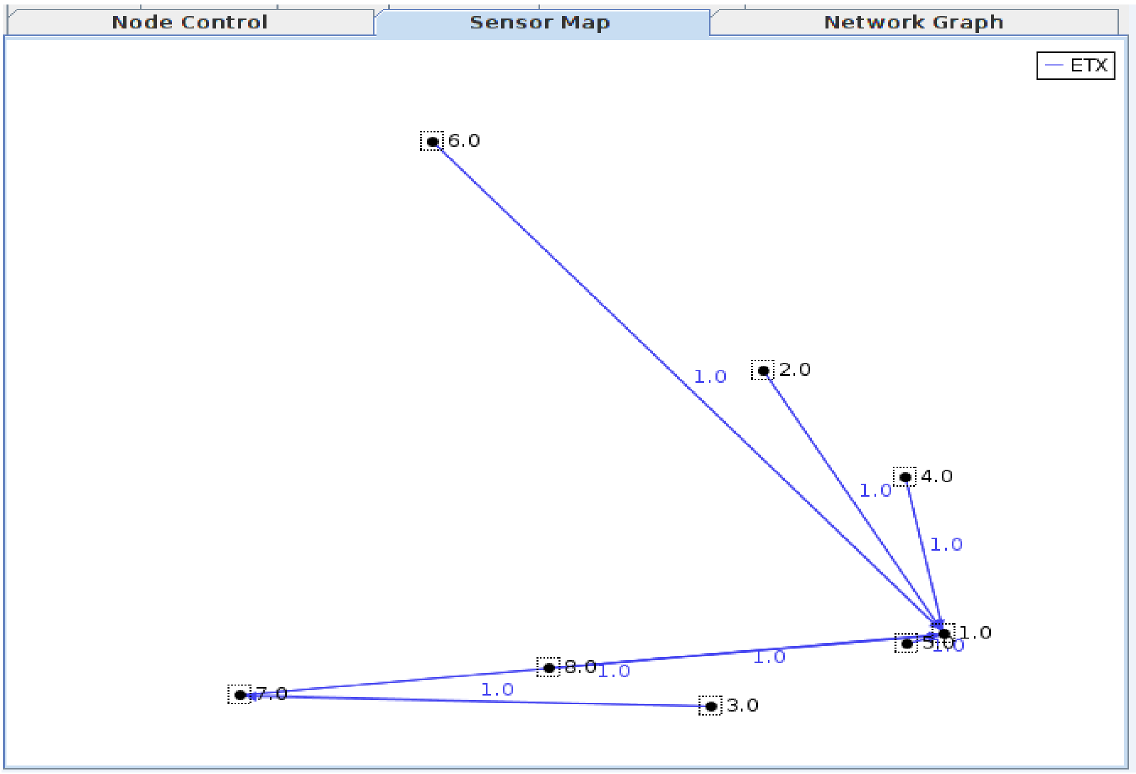


Fig. 4.9: Sensor Map of Sky after Enhancement.

As shown in fig. (4.9), the IIoT network also includes eight nodes of the Sky, it is deployed in a star topology with an optimal distribution, some of them have one hop count as sensor 2, sensors 4, sensor 6, and sensor 8, others have two-hop counts as a sensor 7, which has three hops counts. Seven sensors acted as field nodes, one sensor is a gateway node or base station (Node 1). The gateway node is gathering the center of data from it is neighbor’s sensors, then processes these data, and provides interfaces to the IIoT network, which is connected through the wireless network. Smart sensor nodes are set up in industry fields, which combined with sensors and actuators, are used for transmitting process measurements, and control data to accomplish specific applications.

Figure (4.10) illustrated the results of the distribution of the devices before enhanced the IEEE 802.15.4e protocol that is tested under Z1.

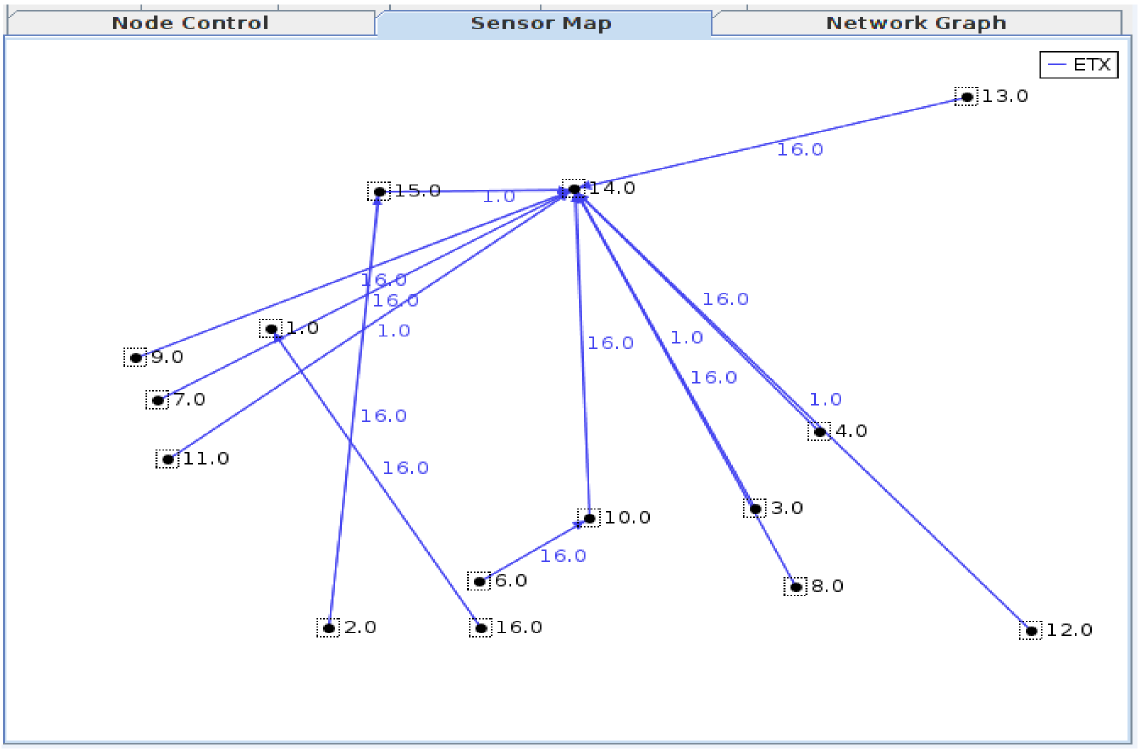


Fig. 4.10: Sensor Map of the Z1.

The IIoT network that illustrated in fig. (4.10) includes 16 sensors nodes of the Z1 mote; it was deployed in a star topology; some of them has one hop count as sensors 1, sensor 3, sensor 4, sensor 5, sensor 7, sensor 8, sensor 9, sensor 10, sensor 11, sensor 12, sensor 13, and sensor 15. Other smart sensors have two-hop counts (sensors 2, sensor 6, and sensor 16). The sensor number twelve acted as field nodes. One sensor is a gateway node (Node 14). The gateway node is deployed for forwarding data to the upper layer, which is an interface to the IIoT network. Fig. (4.11) is illustrated the results of an optimal sensors distribution of the devices before enhancing the IEEE 802.15.4e protocol.

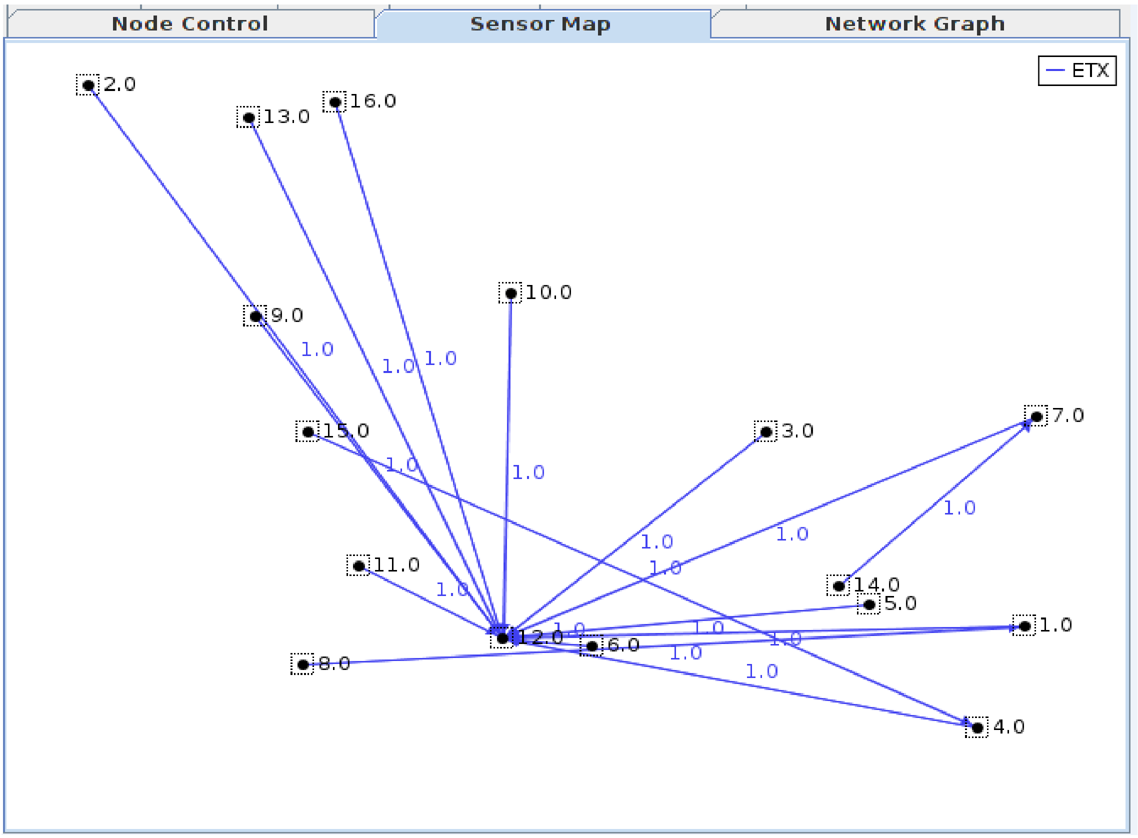


Fig. 4.11: Sensor Map the Sky.

The architecture system of the IIoT network that illustrated in fig. (4.11) composed of 16 sensor nodes of the Sky motes; which are deployed in a star topology, this topology has three hop counts, one hop count, two-hop counts, and three hop counts. One hop count as in sensor 1, sensor 2, sensor 3, sensor 4, sensor 5, sensor 6, sensor 7, sensor 9, sensor 10, sensor 11, sensor 12, sensor 13, and sensor 16. Two hop counts as in sensors 8, sensor 14, and sensor 15. Fifteen sensors of them acted as field nodes and one sensor is a gateway node or the base station (Sensor 12). The gateway node used for gathering data from its neighboring sensors then processes this data and provides interfaces to the IIoT network, which is connected through the wireless network. Smart sensor nodes are set up in industry fields that are connected with sensors and actuators, it used for transmitting process measurements, and control data to accomplish specific applications.

4.3 Performance Evaluation

The performed evaluation process was dividing into two subsections. The first section is introduced the simulation tools and the second section discusses the experiment's measurements. In this thesis, all experiments are conducted by using two smart sensors: Sky sensors and Z1 sensors. So, these sensors are chosen based on the physical dimensions such as the radio communication, an operating system supported by the sensor, microcontroller, the memory type, and suitability for IIoT deployment, to achieve the requirements of the IIoT applications, for more information, please go to appendix F and appendix G. The actual experimental results of the simulation over Zolertia Z1 and Tmote Sky sensors and the performance improvements of the proposed protocol are shown in chapter five. Table (4.1) shows the significant parameters, which utilized in the Cooja simulator.

Table 4.1: Important Simulation Parameters

Parameter	**Value**
OS	Contiki OS 2.7
Microcontroller	MSP430
Transceiver	CC2420
Execution Time	30 Minutes
IP Address	IP v6
Topology	Star
Simulation Area	100m2
Number of Superframes	Two Superframes
Sensor node platform	Z1 and Sky Motes
SO value	5
Simulation Time	30 Minutes

4.3.1 Simulation Tools

This work evaluates the performance of the IIoT network based on different experiments, which are conducted on computing (Desktop) under Windows 10 Service Pack 3 operating system (64 bits), processor core i3, RAM 4 GB running over VMware 12 player, Ubuntu 16.04 Linux, in order to perform that, 8 nodes used for the scenario (A) and 16 nodes also used for scenario (B), which is deployed in a star topology. Z1 and Sky are used primarily based on radio chipsets, CC2420 micro-controller, and IPv6. To evaluate the node performance, the Cooja simulator is running under the Contiki OS. These sensors were randomly deployed in the area of $100m^2$. Hint, the scenario (A) is a proposed protocol, and scenario B is IEEE 802.15.4e standard. For more knowledge around the Cooja simulator go to appendices (A and B).

4.3.2 Simulation Measurements

The performance of the CAP reduction MAC Protocol for reducing energy has been tested, which depends on many different parameters are throughput, packets delay, and energy consumption. In this section, the simulation measurements can specify the performance according to the measurement of the throughput, packets delay, and energy preservations that are achieved by the proposed protocol.

4.3.2.1 Throughput

The throughput of the IIoT system that is measured with experimental evaluation and two scenarios can be modeled in this experiment under a specific duration time, which is represented by Table (4.3).

4.3.2.2 Packets Delay

Table (4.3) illustrates the various values for the packets delay of the IIoT nodes in two simulation scenarios (in NanoSecond).

4.3.2.3 Energy Consumption

For measuring the energy consumption used by the industrial devices in the network is necessary adaptations to the Contiki OS. Energy consumption is measured in two scenarios. The scenario (A) for the average of the energy consumption can be calculated for Z1 and Sky nodes and the scenario B is included in Table (4.3), which consists of Z1 and Sky motes. The total energy E_T consumption was computed by equation (4.1).

$$E_T = P_{CPU} + P_{LPM} + R_X + T_X \qquad (4.1)$$

Where the PCPU refers to the energy computation by the node. Low Power Mode (LPM) power refers to the energy used when the sensor in an idle state. RX is the listening energy required when the sensor is ready to receive the data packets from its neighbor nodes. TX is a transmit energy, which refers to the energy needed by the sensor to send the data packets to its neighboring nodes. In the scenario (A), the average energy consumption of the values of Tx, Rx, LPM, and CPU of each sensor node, including the sink node has been reduced. The proposed protocol is implemented by using the Cooja simulator to simulate the real testbeds of the network through different windows after determined the main parameters such as area, type of the sensor, the value of the SO, and execution time.

Table 4.2: Average Energy Consumption for Each Node.

Nodes/ Parameters	**Z1**		**Sky**	
No. of Nodes	After	Before	After	Before
Tx Power	0.168	0.437	0.064	0.156
Rx Power	0.473	1.133	0.410	0.602
LPM power	0.162	0.159	0.153	0.151
CPU Power	0.046	0.135	0.361	0.364
Avg. Energy Consumption	**0.849**	**1.864**	**0.987**	**1.306**

The measurements of the results are illustrated in the following table by using two different sensors are Z1 and Sky nodes. The duration time for all experiments is kept to 30 minutes. The measurement results of this work before and after enhancing the IEEE 802.15.4e protocol are shown in the following table.

Table 4.3: shows the measurement results before and after enhancing the IEEE 802.15.4e protocol.

MAC Protocols/ Parameters	**Status**	**Node Type**	**No. of Time Slots**	**Throughput**	**Packet Delay Time**	**Energy Consumption**
IEEE 802.15.4e	Scenario B Before	Z1	16	30 Packets	15196 NanoSecond	1.864
		Sky	16	161 packets	12013 NanoSecond	1.306
Enhanced IEEE 802.15.4e	Scenario A After	Z1	8	49 Packets	10094 NanoSecond	0.849
		Sky	8	202 Packets	2880 NanoSecond	0.987

As observed that, after implementing the proposed protocol, the results measured are given high throughput, few execution periods, finally, the performance has been improved, and also sensors are reduced. Accordingly, the costs of the system have been reduced. The proposed protocol gives an optimal distribution of the IIoT nodes and optimal value of the SO, which maximizes the performance measures that determined throughput, packets delay, energy consumption, and the costs.

Chapter Five

Results & Discussion

Chapter Five

Results & Discussion

Performance of the proposed protocol is evaluated along with that the IEEE 802.15.4e MAC protocol. To validate this protocol, a Cooja simulator is used; Cooja is a network simulator that enables cycle-accurate simulations of sensor nodes that run Contiki OS. From various examines noticed that the proposed protocol gives an optimal performance when the value of the SO is setting up to 5.

In this chapter, the simulation results of the empirical study will be analyzed to be able to explain the feasibility of the proposed methods, and the key technology of smart objects will be discussed. The measurements of the time slots state durations are analyzed then explain how the duration values are affected on the performance. Finally, the throughput, packets delay, and energy consumption by each device (Z1, Sky) states are presented in a detailed discussion. Simulation parameters are determined and measured as the same as those presented in Table (4.3). The next sections will discuss the simulation results of the proposed techniques.

5.1 Simulation Results & Discussion

The measurements of throughput, packets delay of the IIoT network, and energy consumption in two scenarios (A, B) are illustrated well in fig. (5.1a, 5.1b, 5.1c, and 5.1d), fig. (5.2a, 5.2b, 5.2c, and 5.2d), and fig. (5.3a, 5.3b, 5.3c, and 5.3d).

5.1.1 Throughput

The measurements of performance in this work are presented in the following figures. In these experiments, the throughput is measured according to scenario (A) and scenario (B), and the duration time is kept at

30 minutes. Four independent tests are done using two different types of sensor nodes. Fig. (5.1a, 5.1b, 5.1c, and 5.1d) which are depicted the variation of the throughput for different packets that are received by the sink node. Performance evaluation of the proposed protocol is verified that the throughput of scenario (A) is increased significantly when compared to the scenario (B), due to sensors have zero loss packets and more time to send packets in the current active period when SO is increased, and then the CAP is decreased, which will also maximize the throughput.

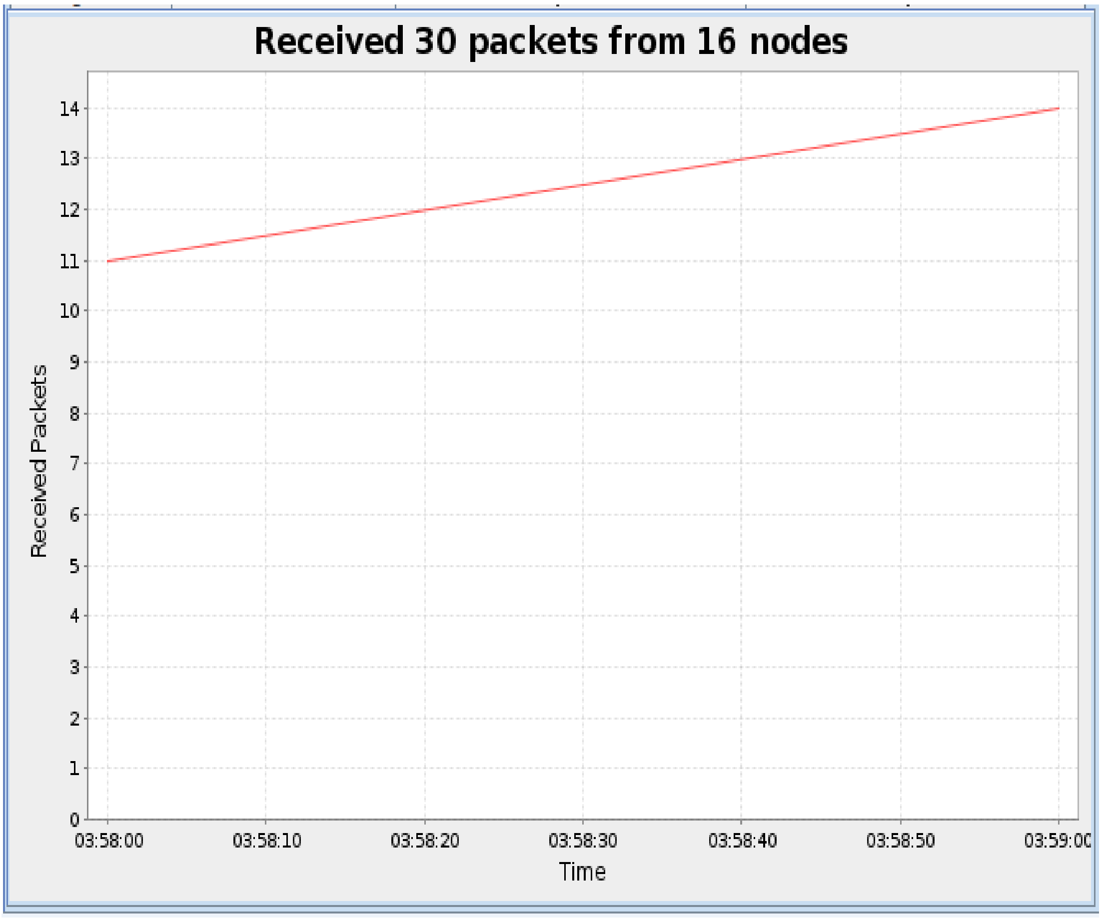


Fig. 5.1a: Throughput of Z1 (Before the MAC Protocol Enhanced).

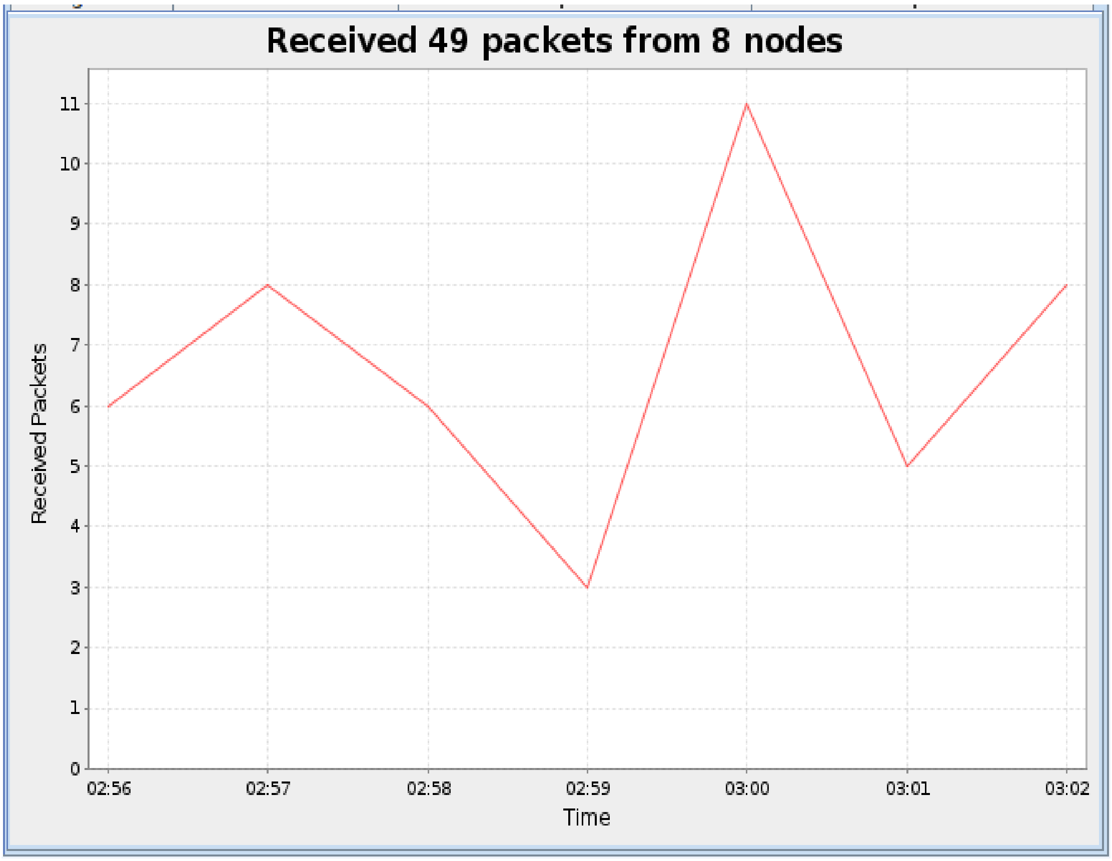


Fig. 5.1b: Throughput of Z1 (After the MAC Protocol Enhanced).

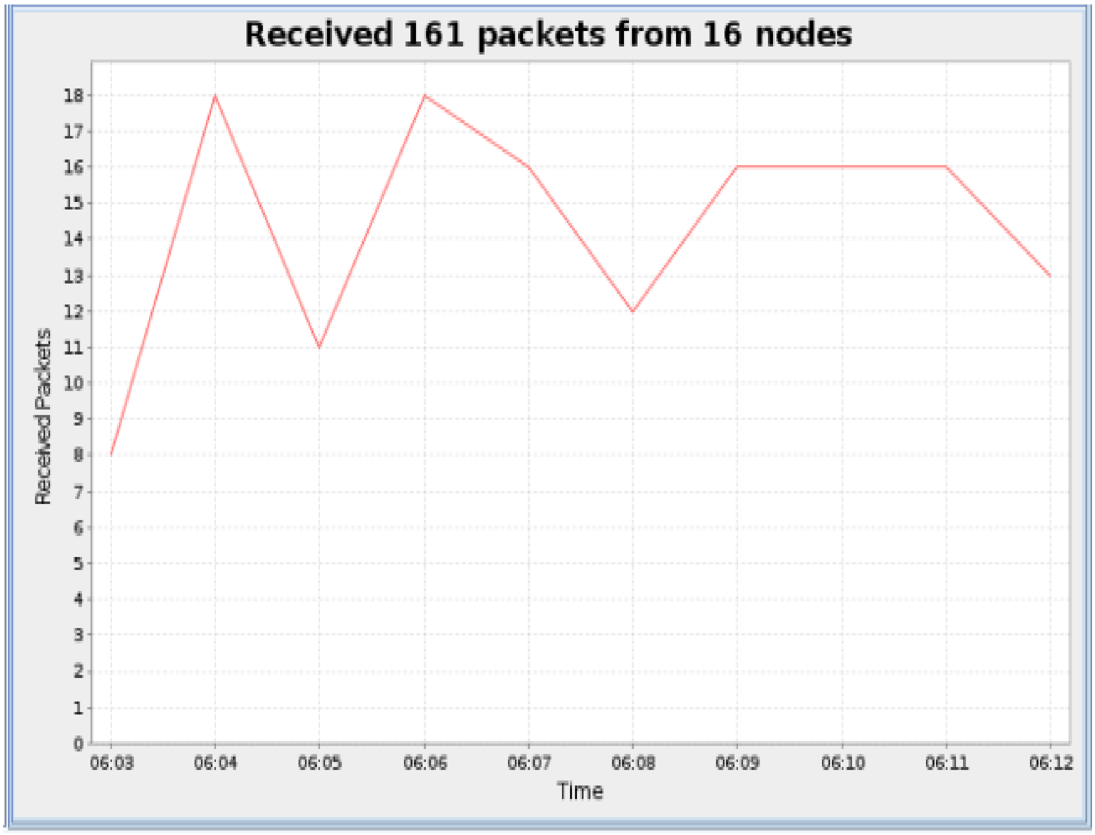


Fig. 5.1c: Throughput of Sky (Before the MAC Protocol Enhanced).

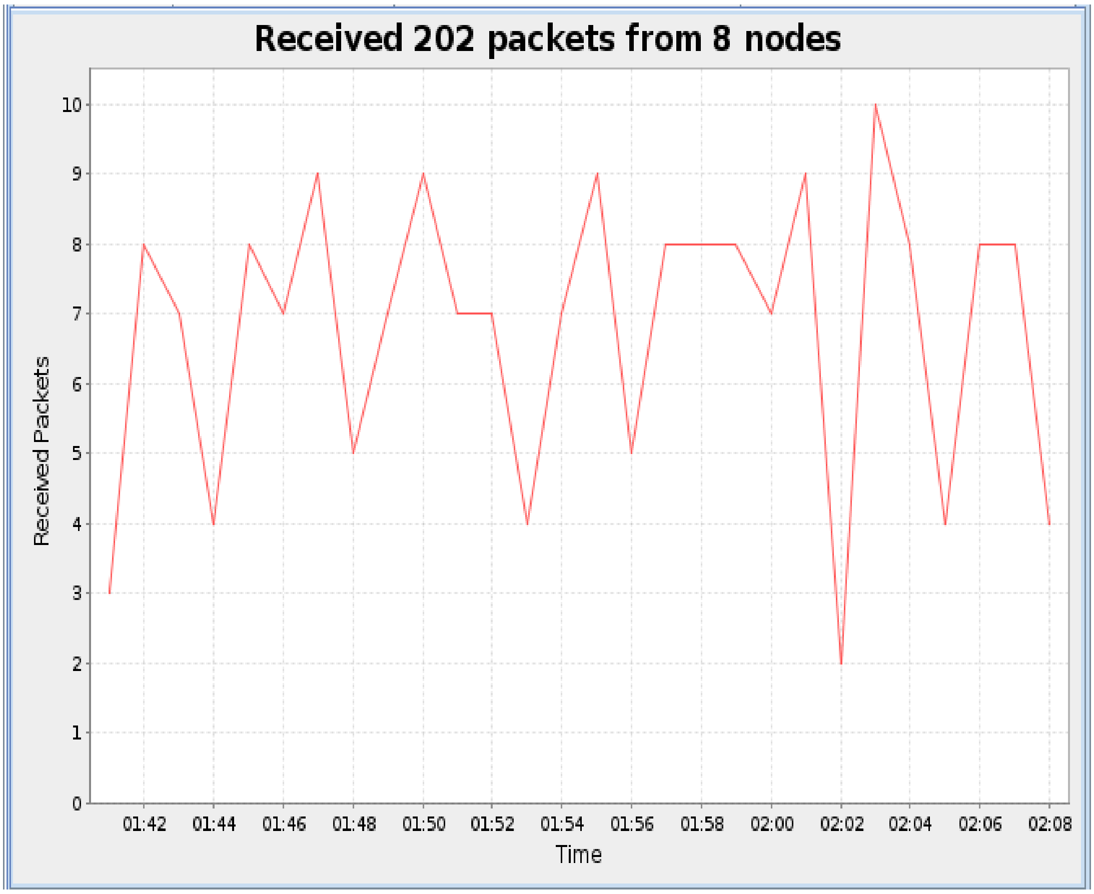


Fig. 5.1d: Throughput of Sky (After the MAC Protocol Enhanced).

5.1.2 Packets Delay

Fig. (5.2a, 5.2b, 5.2c, and 5.2d) show the packets delay results of the IEEE802.15.4e MAC protocol before enhanced (Scenario B) as compared to the proposed protocol (Scenario A). The results of the proposed protocol in the scenario (A) can be compared to the results of an IEEE802.15.4e (scenario B), can observe that the delay is reduced when the proposed protocol is applied in the system because the optimal value of the CAP plays important role in minimizes the number of time slots. So, there will be reduced the number of hop-counts, which gives more time for nodes to send their frames in the current superframe.

This protocol is obtained an optimal packets delay time, which is equal to 10094 Nanosecond. However, all experiments showed that the delays are approaching to zero seconds, as illustrated in the following figures.

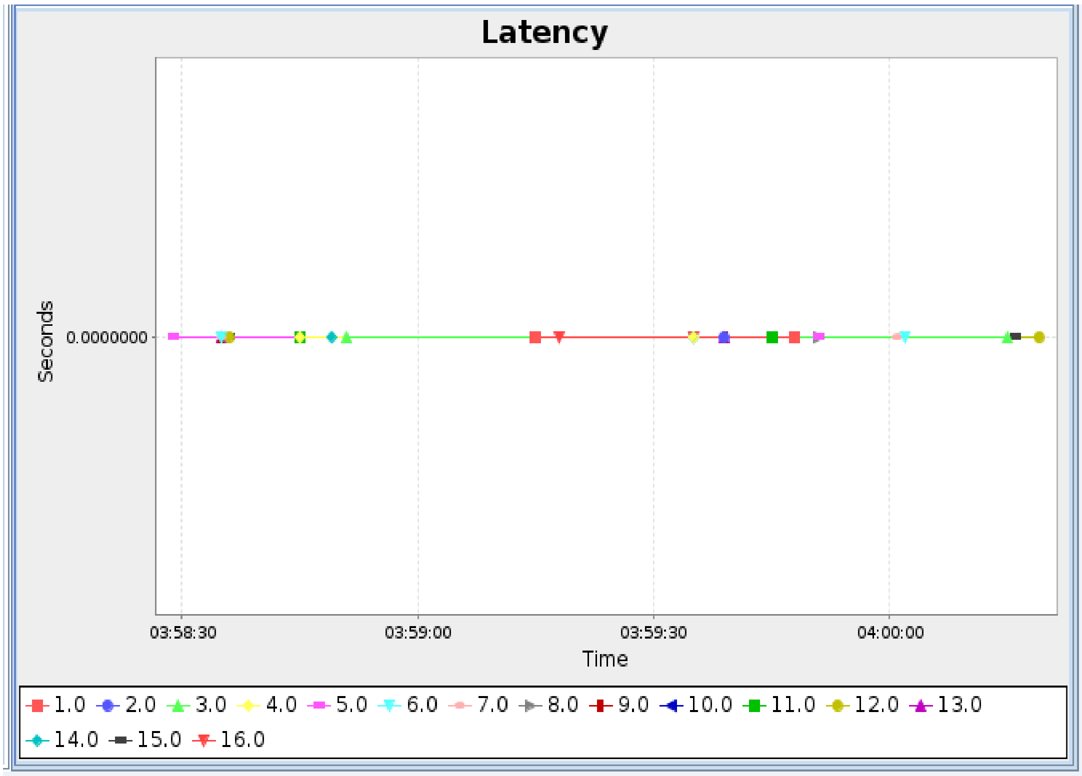


Fig. 5.2a: Packets Delay of Z1 (Before the MAC Protocol Enhanced).

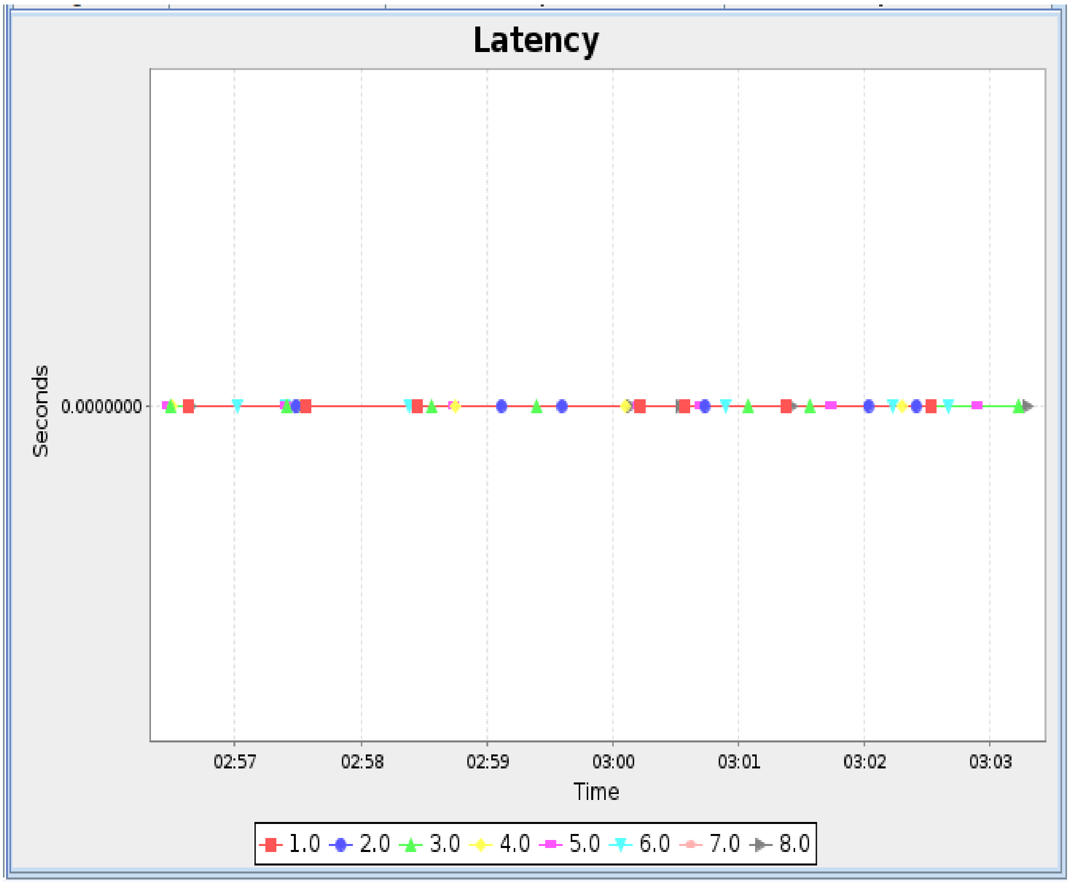


Fig. 5.2b: Packets Delay of Z1 (After the MAC Protocol Enhanced).

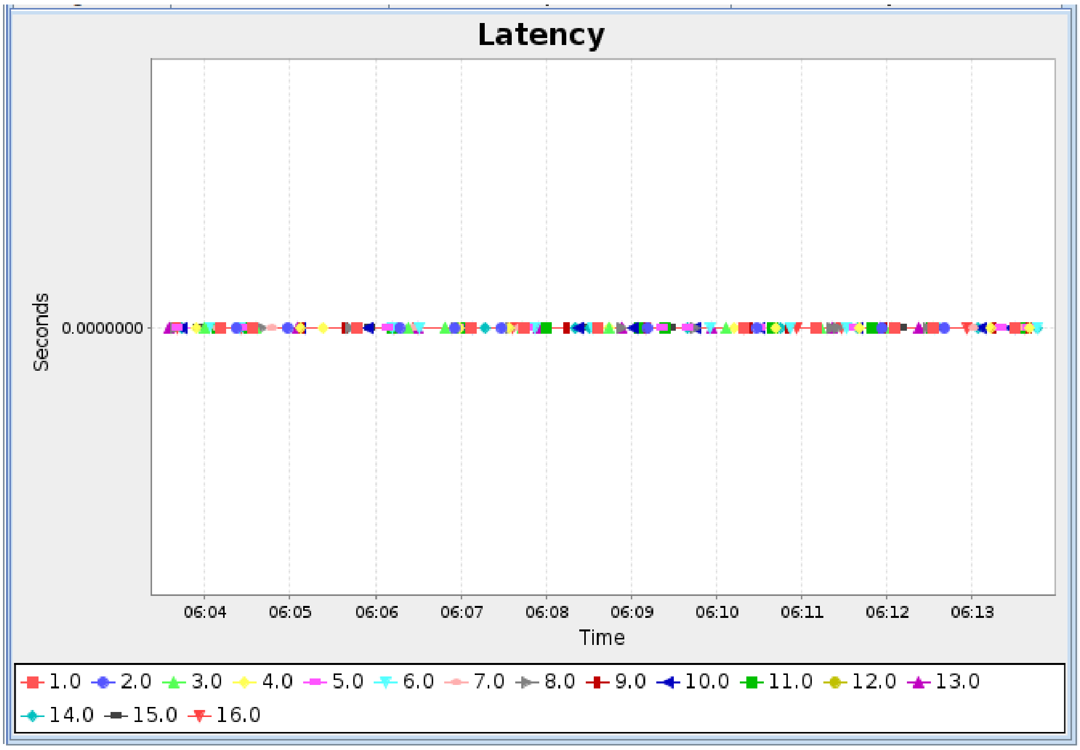


Fig. 5.2c: Packets Delay of Sky (Before the MAC Protocol Enhanced).

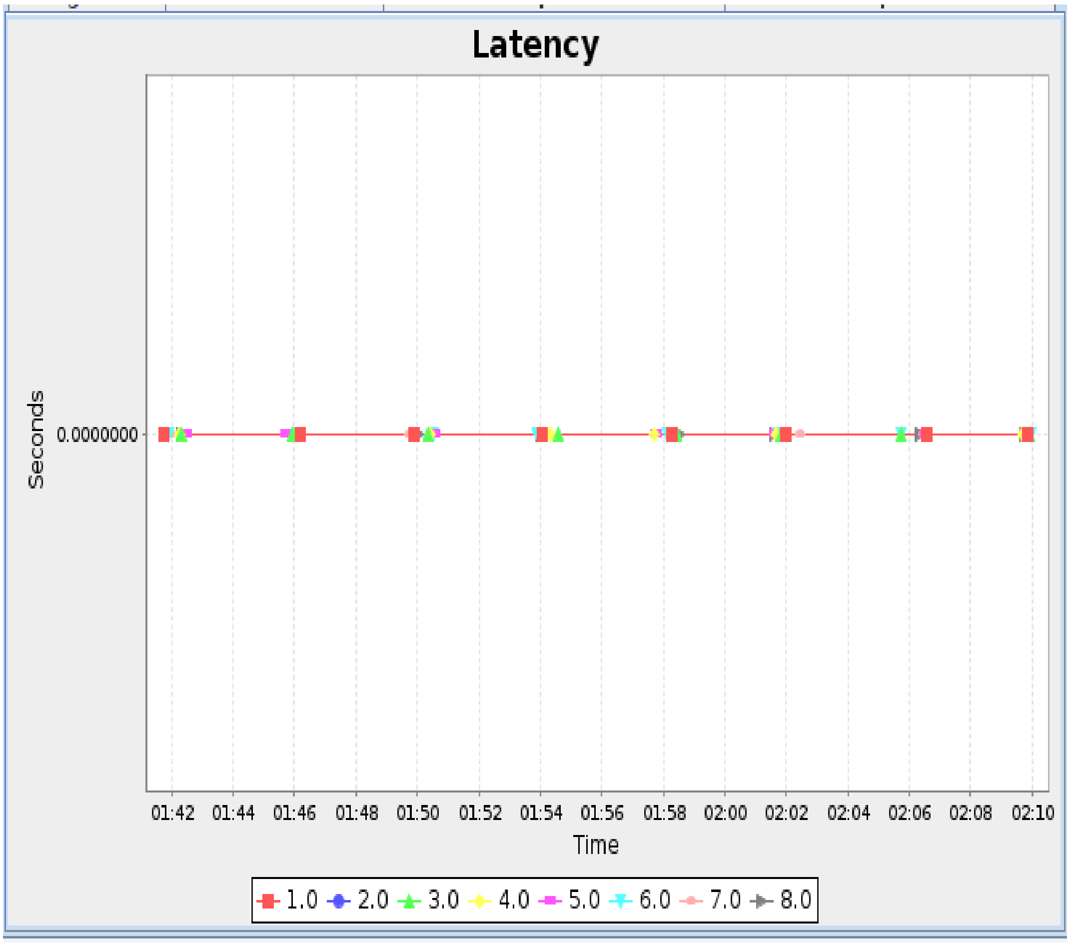


Fig. 5.2d: Packets Delay of Sky (After the MAC Protocol Enhanced).

5.1.3 Energy Consumption

The experimental measurements with the Cooja simulator are based upon four parameters that are the CPU Power, LPM Power, Listening Power, and Transmit Power. The results of the node parameters are provided by fig. (5.3a and 5.3c) (Scenario B) and fig. (5.3b and 5.3d) (Scenario A), respectively. This protocol outperforms the old MAC protocol in terms of packets delay and throughput at all the tests of the CAP period. Thereby, an optimal value of the CAP has decreased the packets loss, retransmission of frames, the number of time slots, and the number of sensors, which enhances the energy consumption.

Based on the tests of these parameters that are shown in fig. (5.3a and 5.3b), there is a significant difference in the values of the total average of energy consumption between scenario (A) and scenario (B), in which the values in the scenario (A) is 0.849 mW and in scenario (B) is 1.864 mW (Z1). In addition to the total average energy consumption with Sky mote in two scenarios are 0.987mW and 1.306 mW, as illustrated in fig. (5.3c and 5.3d).

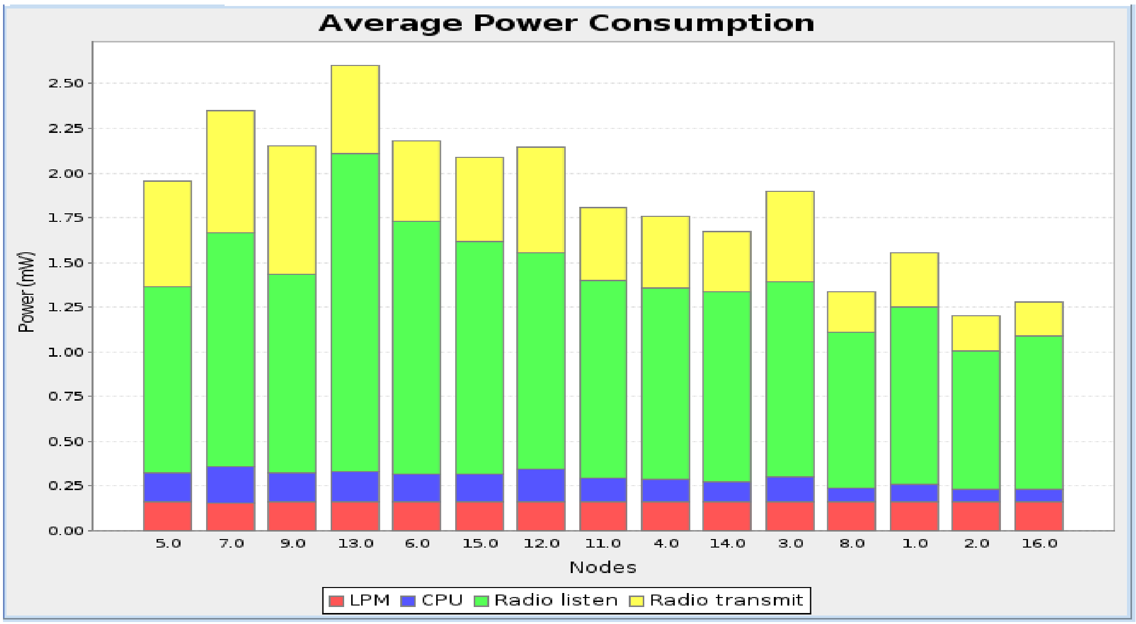


Fig. 5.3a: Energy Consumption of Z1 (Before the MAC Protocol Enhanced).

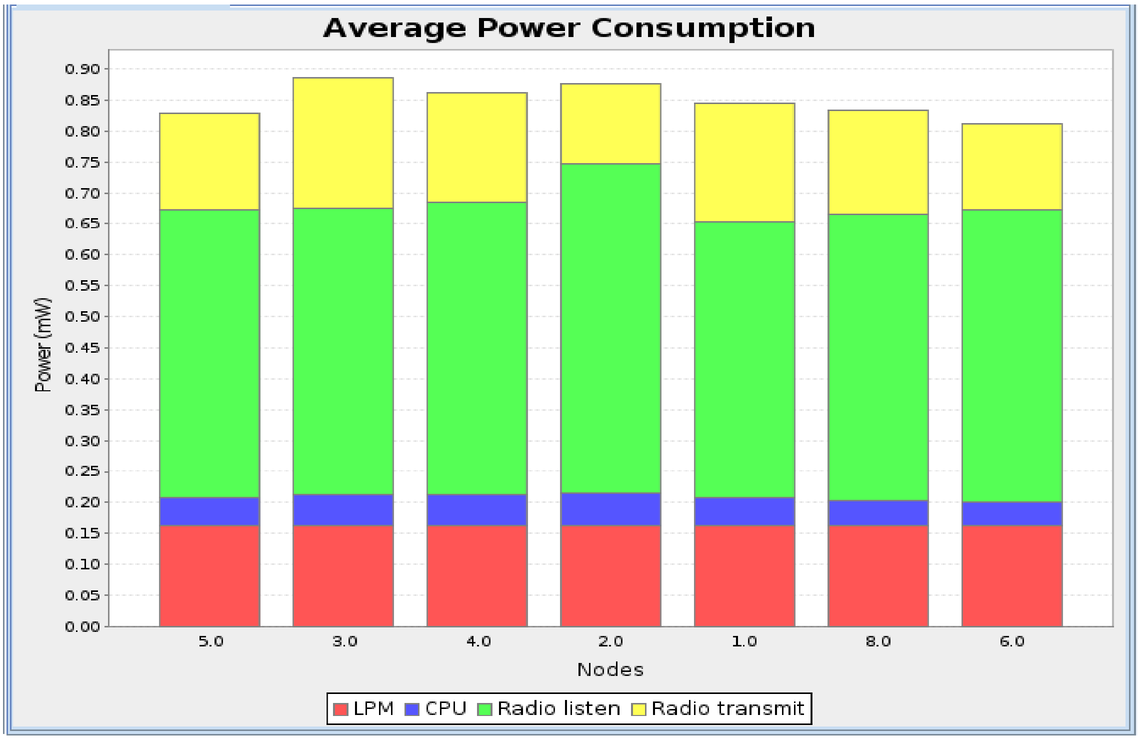


Fig. 5.3b: Energy Consumption of Z1 (After the MAC Protocol Enhanced).

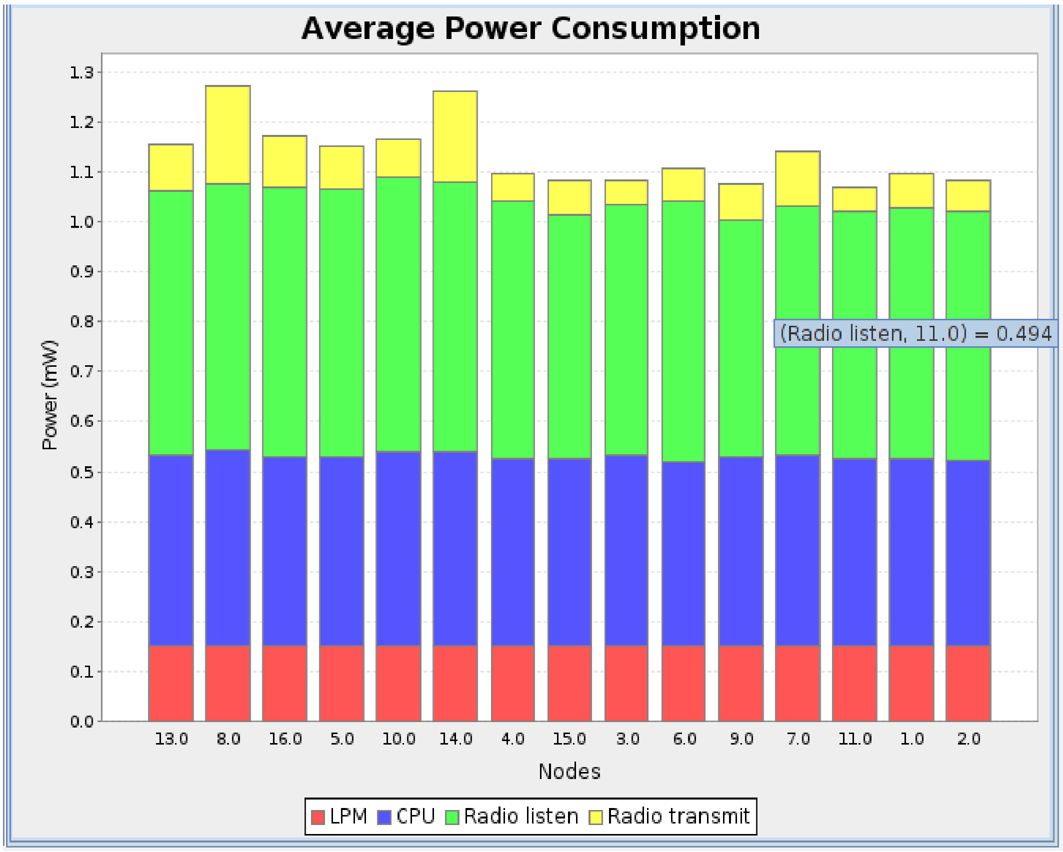


Fig. 5.3c: Energy Consumption of Sky (Before the MAC Protocol Enhanced).

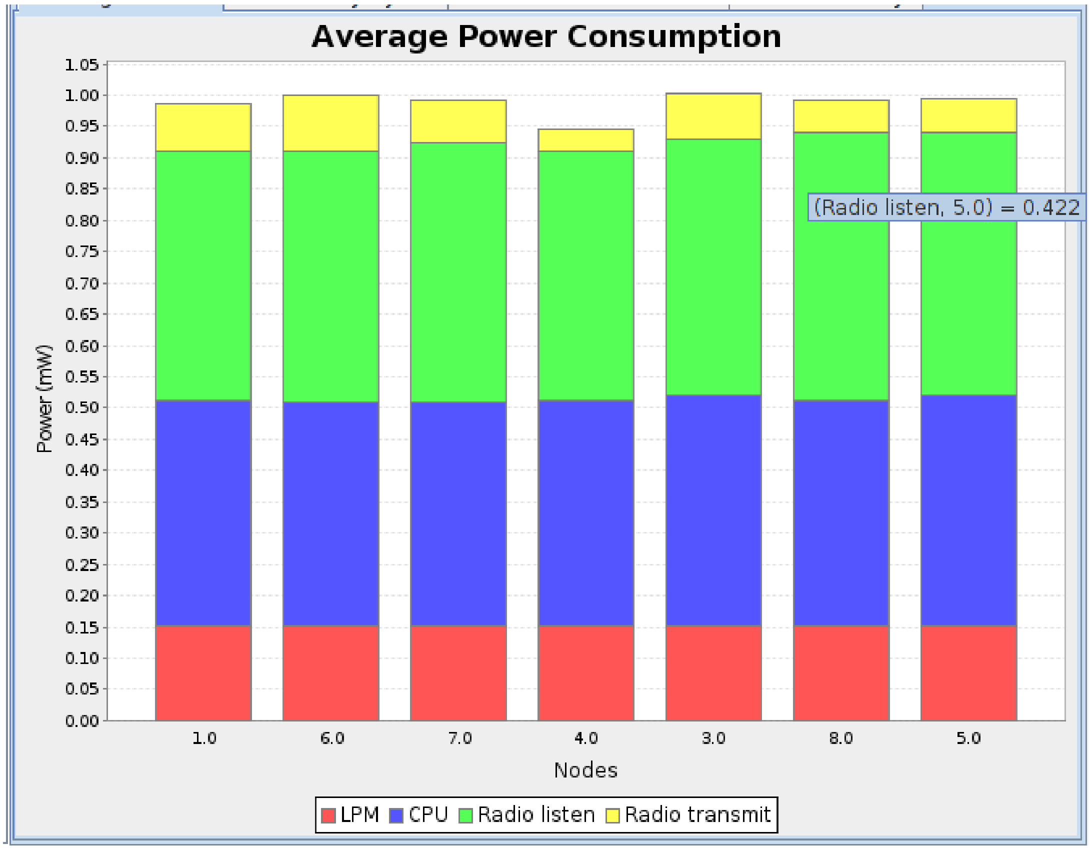


Fig. 5.3d: Energy Consumption of Z1 (After the MAC Protocol Enhanced).

The threshold factor of the acceptable limits for these parameters is not definite and is a trade-off between performance and energy consumption.

As noticed, the testbed is installed based on the Cooja simulator, where the different approaches have been designed, adapted, configured, deployed, and analyzed their performance depends on two scenarios (A, B). Different experiments are conducted, analyzed, and then evaluated the performance of the proposed protocol based on the Z1 and Sky nodes as a popular sensor platform for IIoT applications. The proposed protocol that is applied in scenario (A) has the highest throughput as compared to the scenario (B) as illustrated in fig. (5.1a, 5.1b, 5.1c, and 5.1d) due to the hops count of the network, which increases the packet delay. As shown in Table (4.3), the proposed protocol also obtained fewer packets delay. From the above figures can be observed. The sky is less delay time than that in the Z1 mote (Scenario A). However, in scenario B, the Sky is a higher delay time due to having retransmission and the number of hops. Most of the energy is spent listening, and more fine-tuning of the CPU could further reduce the throughput and decrease the network delay.

Energy consumption for different experiments are measured according to that values in Table (4.3). Various parameters, such as CPU, LPM, Tx, and Rx, are taken into account. The energy consumption by Z1 in the scenario (A) is compared to the energy consumption in the scenario (B). Fig. (5.3b and 5.3d) are illustrated the deployment of the proposed protocol is significantly reduced energy consumption in an industrial network, increases throughput as formed in fig. (5.1b and fig. 5.1d), and decreases network latency (Table 4.3). The results of energy consumption for the Sky sensor are given separately in fig. (5.3c and 5.3d, due to the comparatively significant difference from Z1. From fig. (5.3b and 5.3d), can observe that the Sky mote is more consumed energy in the scenario (B) compared with Z1. For all scenarios (A, B), the CPU and Rx are significantly larger energy consumption.

On the other hand, Z1 is using less energy on the CPU state. The measurements confirm that Z1 achieves the best energy efficiency. R_X scenarios of Z1 use noticeably more power since they have to send ACK messages and receive packets. Regarding scenario (A), as shown in fig. (5.3b and 5.3d). Overall, the energy consumption of Z1 is much higher than that of Sky mote. This can be explained by the high listen to the platform and active CPU energy from the Sky sensor, which required optimizing the behavior of its microcontroller, either in hardware or software platforms. For all, the measurements show slightly higher energy consumption for R_X scenarios, due to higher CPU utilization. On the other aspect, the CPU energy consumption of Sky mote is higher than that of Z1 in the same scenario.

For all three parameters, the performance is maximized due to the number of timeslots is reduced based on the optimal value of the CAP period. Several mechanisms for improving performance are yet to be defined, and many existing techniques are revised in the literature. It is focused on analyzing energy aspects of specific MAC protocol in terms of packet reception, packet loss, idle, and wakeup. The CAP size-reduction MAC protocol has very high chances to widely apply in industrial applications due to having various advantages over many other existing techniques.

Chapter Six
Conclusion & Recommendations

Chapter Six

Conclusion & Recommendations

6.1 Conclusion

As a significant contributing part of IIoT are emerging Cyber-Physical Systems, Industry 4.0, IoT, and cloud service, which makes the factories smarter than the previous generation of embedded systems. To cope with these, IIoT architecture systems have been subjected to extensive work to understand the technology which is still in the early stages and young. Thus, there is an opportunity for tackling their issues, especially the network performance which affects the throughput, packets delay, and energy consumption. Although this thesis is a significant step in the right direction, it is essential to gain enough experience to understand both the adequacy of the IIoT systems applications and their technologies. This thesis is introduced essential issues of the IIoT for the researchers and students whom are interested in this area, especially in Sudan. There is beneficial usage for the IIoT which is implemented for monitoring the operating conditions to predictive maintenance before the failure occurs, which reduces the maintenance costs. One of the most important issues of the IIoT systems is its performance. Technical solutions are derived for addressing the performance issues. The proposed protocol is described in in-depth analysis, which is substantially improved the performance with satisfied the requirements of the IIoT network applications. The performance of the proposed protocol was evaluated under the Cooja simulator-based on two different types of smart sensors running a specific operating system. The proposed protocol is given better results of throughput, packet delay, and significant energy consumption that improved the performance of IIoT systems significantly.

6.2 Recommendations

Future works still need more studies on IIoT technologies to develop robust applications for IIoT. Moreover, future researches should also examine the effects of IIoT on smart factories' environments in terms of production, workers, administrative organization, operational conditions, improve management effectiveness, and the impacts of predictive maintenance on increased profitability. There are some intelligent algorithms ongoing to find practical solutions for IIoT issues. There are open research directions for the IIoT systems are performance based on the IIoT network layer and IIoT application layer, reliability, and Internet connectivity which is considered one of the most critical requirements of the IIoT nodes. Continuous evolution and availability of heterogeneous industry-standard communication protocols at different layers is desirable to provide seamless integration, and connectivity of nodes to form the more reliable IIoT networks. Besides, applications as smart healthcare for remote monitoring patients and industrial automation are very crucial in timely execution, which requires real-time, to meet the hard deadlines to achieve a particular task.

This thesis recommends validating the results by testing these protocols on real experiments and comparing other aspects of the network lifecycle, such as reliability, flexibility, scheduling, node mobility, and synchronization. Also, this work could apply in large-scale networks that could extend to tree or mesh topologies. Furthermore, this work should investigate in more detail the topology characteristics for those nodes that observe to maximize performance and to minimize the energy consumption of IIoT constrained devices. Also, this research plans to run similar tests with the same hardware running different operating systems as OpenWSN, TinyOS, which support the Z1 and Sky node

References

[1] Yasumoto, K., Yamaguchi, H. and Shigeno, H., 2016. Survey of real-time processing technologies of iot data streams. Journal of Information Processing, vol. 24, no.2, pp.195-202.

[2] Mahapatra, C., Sheng, Z. and Leung, V.C., 2016, May. Energy-efficient and distributed data-aware clustering protocol for the Internet-of-Things. In 2016 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE) (pp. 1-5). IEEE.

[3] Jalali, R., El-Khatib, K. and McGregor, C., 2015, February. Smart city architecture for community level services through the internet of things. In 2015 18th International Conference on Intelligence in Next Generation Networks (pp. 108-113). IEEE.

[4] Luo, J., Wu, D., Pan, C. and Zha, J., 2015. Optimal energy strategy for node selection and data relay in WSN-based IoT. Mobile Networks and Applications, vol. 20, no. 2, pp.169-180.

[5] Chang, J.Y., 2015. A distributed cluster computing energy-efficient routing scheme for internet of things systems. Wireless Personal Communications, vol. 82, no. 2, pp.757-776.

[6] Morin, E., Maman, M., Guizzetti, R. and Duda, A., 2017. Comparison of the device lifetime in wireless networks for the internet of things. IEEE Access, 5, pp.7097-7114.

[7] Amadeo, M., Campolo, C., Quevedo, J., Corujo, D., Molinaro, A., Iera, A., Aguiar, R.L. and Vasilakos, A.V., 2016. Information-centric networking for the internet of things: challenges and opportunities. IEEE Network, vol. 30, no. 2, pp.92-100.

[8] Mumtaz, S., Alsohaily, A., Pang, Z., Rayes, A., Tsang, K.F. and Rodriguez, J., 2017. Massive Internet of Things for industrial applications: Addressing wireless IIoT connectivity challenges and

ecosystem fragmentation. IEEE Industrial Electronics Magazine, vol. 11, no. 1, pp.28-33.

[9] Atzori, L., Iera, A. and Morabito, G., 2017. Understanding the Internet of Things: definition, potentials, and societal role of a fast evolving paradigm. Elsevier, Ad Hoc Networks, 56, pp.122-140.

[10] Kolios, P., Ellinas, G., Panayiotou, C. and Polycarpou, M., 2016, December. Energy efficient event-based networking for the Internet of Things. In 2016 IEEE 3rd World Forum on Internet of Things (WF-IoT) (pp. 1-6). IEEE.

[11] Zikria, Y.B., Kim, S.W., Hahm, O., Afzal, M.K. and Aalsalem, M.Y., 2019. Internet of Things (IoT) operating systems management: opportunities, challenges, and solution, Sensors, pp. 1-10..

[12] Zhu, C., Leung, V.C., Shu, L. and Ngai, E.C.H., 2015. Green internet of things for smart world. IEEE access, vol. 3, pp. 2151-2162.

[13] Shrouf, F., Ordieres, J. and Miragliotta, G., 2014, December. Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm. In 2014 IEEE international conference on industrial engineering and engineering management (pp. 697-701). IEEE.

[14] Vasilomanolakis, E., Daubert, J., Luthra, M., Gazis, V., Wiesmaier, A. and Kikiras, P., 2015, September. On the security and privacy of Internet of Things architectures and systems. In 2015 International Workshop on Secure Internet of Things (SIoT) (pp. 49-57). IEEE.

[15] Rio, R., 2015. Optimize Asset Performance with Industrial IoT and Analytics, Dedham, MA 02026 USA, pp. 1 - 6.

[16] Hahm, O., Baccelli, E., Petersen, H. and Tsiftes, N., 2015. Operating systems for low-end devices in the internet of things: a survey. IEEE Internet of Things Journal, 3(5), pp.720-734.

[17] Vasiljević, D. and Gardašević, G., 2016, November. Performance evaluation of OpenWSN operating system on open mote platform for industrial IoT applications. In 2016 International Symposium on Industrial Electronics (INDEL) (pp. 1-6). IEEE.

[18] Althobaiti, A.S. and Abdullah, M., 2015. Medium access control protocols for wireless sensor networks classifications and cross-layering. Procedia Computer Science, Elsevier, vol. 65, pp.4-16.

[19] Aijaz, A. and Aghvami, A.H., 2015. Cognitive machine-to-machine communications for Internet-of-Things: A protocol stack perspective. IEEE Internet of Things Journal, vol. 2, no. 2, pp.103-112.

[20] Chen, J. and Xu, Y., 2010, October. The Study of Superframe duration scheduling with coordinator grouping for Zigbee Cluster-Tree WSNs. In 2010 International Conference on Intelligent System Design and Engineering Application (Vol. 2, pp. 748-752). IEEE.

[21] Sahoo, P.K., Pattanaik, S.R. and Wu, S.L., 2017. A reliable data transmission model for ieee 802.15. 4e enabled wireless sensor network under wifi interference. Sensors, vol. 17, no. 6, pp. 1-18.

[22] IEEE std. 802.15.4e, Part. 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendament 1: MAC sublayer, IEEE Computer Society, 2012, pp. 1-225.

[23] Jeong, W.C. and Lee, J., 2012, June. Performance evaluation of IEEE 802.15. 4e DSME MAC protocol for wireless sensor networks. In 2012 The First IEEE Workshop on Enabling Technologies for Smartphone and Internet of Things (ETSIoT) (pp. 7-12). IEEE.

[24] Rehman, S.U., Berber, S. and Swain, A., 2010, November. Performance analysis of CSMA/CA algorithm for wireless sensor network. In TENCON 2010-2010 IEEE Region 10 Conference (pp. 2012-2017). IEEE.

[25] Choudhury, N., Matam, R., Mukherjee, M. and Shu, L., 2018. Beacon synchronization and duty-cycling in IEEE 802.15. 4 cluster-tree networks: A review. IEEE internet of things journal, vol. 5, no. 3, pp.1765-1788.

[26] Mavromatis, A., Papadopoulos, G.Z., Fafoutis, X., Elsts, A., Oikonomou, G. and Tryfonas, T., 2016, June. Impact of guard time length on IEEE 802.15. 4e TSCH energy consumption. In 2016 13th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON) (pp. 1-3). IEEE.

[27] Capone, S., Brama, R., Ricciato, F., Boggia, G. and Malvasi, A., 2014, April. Modeling and simulation of energy efficient enhancements for IEEE 802.15. 4e DSME. In 2014 Wireless Telecommunications Symposium (pp. 1-6). IEEE.

[28] Nikoukar, A., Raza, S., Poole, A., Güneş, M. and Dezfouli, B., 2018. Low-power wireless for the Internet of Things: Standards and applications. IEEE Access, 6, pp.67893-67926.

[29] Ma, G., Shen, C. and Chen, B., 2011, August. A Node-Grouping Superframe-Division MAC Protocol for Smart Home Based on IEEE802. 15.4 Protocol. In International Conference on Wireless Communications and Applications (pp. 125-136). Springer, Berlin, Heidelberg.

[30] Koubâa, A., Severino, R., Alves, M. and Tovar, E., 2009. Improving quality-of-service in wireless sensor networks by mitigating “hidden-node collisions”. IEEE Transactions on Industrial Informatics, 5(3), pp.299-313.

[31] El Gholami, K., Hou, K.M. and Elkamoun, N., 2012. Enhanced superframe structure of the IEEE802. 15.4 standard for real-time data transmission in star network. International Journal of Computer Applications, 51(15), pp.26-32.

[32] Mahmood, D., Khan, Z.A., Qasim, U., Naru, M.U., Mukhtar, S., Akram, M.I. and Javaid, N., 2014, January. Analyzing and Evaluating Contention Access Period of Slotted CSMA/CA for IEEE802. 15.4. In FNC/MobiSPC (pp. 204-211).

[33] Raposo, D., Rodrigues, A., Sinche, S., Sá Silva, J. and Boavida, F., 2018. Industrial IoT monitoring: Technologies and architecture proposal. Sensors, vol. 18, no. 10, pp. 1-150.

[34] Mytum-Smithson, J., 2005. Wireless sensor networks: An information processing approach. Sensor Review, Elsevier, pp. 1-377.

[35] Ye, W., Heidemann, J. and Estrin, D., 2002, June. An energy-efficient MAC protocol for wireless sensor networks. In Proceedings. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies (Vol. 3, pp. 1567-1576). IEEE.

[36] Doherty, L., Lindsay, W. and Simon, J., 2007, August. Channel-specific wireless sensor network path data. In 2007 16th International Conference on Computer Communications and Networks (pp. 89-94). IEEE.

[37] Heinzelman W. B., Chandrakasan and A. P, Balakrishnan . H., 2002 , An application specific protocol architecture for wireless microsensor networks, IEEE Trans. On Wireless Communications, vol. 1, no. 4, pp. 660–670.

[38] Sagduyu Y. E., and Ephremides A. , Dec. 2004, The problem of medium access control in wireless sensor networks, IEEE Wireless Communications, vol. 11, no. 6, pp. 44–53.

[39] . Singh S, and. Raghavendra C. S , Jul. 1998, PAMAS-power aware multi-access protocol with signaling for ad hoc networks, SIGCOMM Comput. Commun. Rev., vol. 28, no. 3, pp. 5–26.

[40] Harrison Kurunathanx, Ricardo Severinox, Anis Koubaax, Eduardo Tovar, 2018, IEEE 802.15.4e in a Nutshell: Survey and Performance Evaluation, IEEE Communications Surveys & Tutorials, pp. 1-22.

[41] L. Krupka, L. Vojtech and M. Neruda, 2016, The issue of LPWAN technology coexistence in IoT environment, 17th International Conference on Mechatronics - Mechatronika (ME), pp. 1-8.

[42] Josiah E. Balota, Colin Pattinson, Ah-Lian Kor, 2017, Wireless Personal Area Networks: A Survey of LowRate and Low-Power Network Technologies, IEEE, pp. 68-72.

[43] Khalifeh, A.F., AlQudah, M. and Darabkh, K.A., 2017, March. Optimizing the beacon and superframe orders in IEEE 802.15. 4 for real-time notification in wireless sensor networks. In 2017 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET) (pp. 595-598). IEEE.

[44] Daneels, G., Municio, E., Van de Velde, B., Ergeerts, G., Weyn, M., Latré, S. and Famaey, J., 2018. Accurate energy consumption modeling of IEEE 802.15. 4e TSCH using dual-band OpenMote hardware. Journal of Sensors, vol.18, no. 2, journal of sensor, pp. 1-26.

[45] Jeong, W.C. and Lee, J., 2012, June. Performance evaluation of IEEE 802.15. 4e DSME MAC protocol for wireless sensor networks. In 2012 The First IEEE Workshop on Enabling Technologies for Smartphone and Internet of Things (ETSIoT) (pp. 7-12). IEEE.

[46] “IEEE standard for low-rate wireless personal area networks (WPANs),” IEEE, Standard 802.15.4, 2015.

[47] KOJIMA, F. (2018). Study on Low-Energy Superframe Performances with Low-Latency Data Forwarding in the Enhanced Smart Utility Networks. 2018 21st International Symposium on

Wireless Personal Multimedia Communications (WPMC), pp. 358-363.

[48] Wun-Cheol Jeong, & Junhee Lee. (2012). Performance evaluation of IEEE 802.15.4e DSME MAC protocol for wireless sensor networks. 2012 The First IEEE Workshop on Enabling Technologies for Smartphone and Internet of Things (ETSIoT), pp. 7-12.

[49] 1Xuecheng Liu, 1,2Xiaoyun Li, 1Shijuan Su, 1Zhenke Fan, 2, 3Gang Wang,2013,Enhanced Fast Association for 802.15.4e-2012 DSME MAC Protocol, Proceedings of the 2nd International Conference on Computer Science and Electronics Engineering (ICCSEE 2013), pp. 1-5.

[50] Kurunathan, H., Severino, R., Koubaa, A. and Tovar, E., 2018. IEEE 802.15. 4e in a nutshell: Survey and performance evaluation. IEEE Communications Surveys & Tutorials, vol. 20, no. 3, pp.1989-2010.

[51] De Guglielmo, D., Al Nahas, B., Duquennoy, S., Voigt, T. and Anastasi, G., 2016. Analysis and experimental evaluation of IEEE 802.15. 4e TSCH CSMA-CA algorithm. IEEE Transactions on Vehicular Technology, vol. 66, no. 2, pp.1573-1588.

[52] Juc, I., Alphand, O., Guizzetti, R., Favre, M. and Duda, A., 2016, April. Energy consumption and performance of IEEE 802.15. 4e TSCH and DSME. In 2016 IEEE Wireless Communications and Networking Conference (pp. 1-7). IEEE.

[53] Minet, P., Khoufi, I. and Laouiti, A., 2017, October. Increasing reliability of a TSCH network for the industry 4.0. In 2017 IEEE 16th International Symposium on Network Computing and Applications (NCA) (pp. 1-10). IEEE.

[54] Mohammad Dastbaz and Peter Cochrane, August 2019, Industry 4.0 and Engineering for a Sustainable Future, Springer, pp. 2.

[55] Karalis, A., Zorbas, D. and Douligeris, C., 2019. Collision-free advertisement scheduling for IEEE 802.15.4-TSCH networks. Sensors, . vol. 19, no. 8, pp. 1-22.

[56] Ojo, M., Giordano, S., Portaluri, G. and Adami, D., 2017, December. Throughput maximization scheduling algorithm in TSCH networks with deadline constraints. In 2017 IEEE Globecom Workshops (GC Wkshps) (pp. 1-6). IEEE.

[57] Vilajosana, X., Wang, Q., Chraim, F., Watteyne, T., Chang, T. and Pister, K.S., 2013. A realistic energy consumption model for TSCH networks. IEEE Sensors Journal, vol. 14, no. 2, pp.482-489.

[58] Dhondge, K., Shorey, R. and Tew, J., 2016, January. Hola: Heuristic and opportunistic link selection algorithm for energy efficiency in industrial internet of things (iiot) systems. In 2016 8th international conference on communication systems and networks (COMSNETS) (pp. 1-6). IEEE.

[59] Choudhury, N., Matam, R., Mukherjee, M. and Lloret, J., 2020. A Performance-to-Cost Analysis of IEEE 802.15. 4 MAC With 802.15. 4e MAC Modes. IEEE Access, 8, pp.41936-41950.

[60] Capone, S., Brama, R., Ricciato, F., Boggia, G. and Malvasi, A., 2014, April. Modeling and simulation of energy efficient enhancements for IEEE 802.15. 4e DSME. In 2014 Wireless Telecommunications Symposium (pp. 1-6). IEEE.

[61] De Guglielmo, D., Brienza, S. and Anastasi, G., 2016. IEEE 802.15. 4e: A survey. Computer Communications, Elsevier, vol. 88, pp.1-24.

[62] Al-Nidawi, Y., Yahya, H. and Kemp, A.H., 2015, December. Impact of mobility on the IoT MAC infrastructure: IEEE 802.15. 4e TSCH and LLDN platform. In 2015 IEEE 2nd World Forum on Internet of Things (WF-IoT) (pp. 478-483). IEEE.

[63] Bitencort, B., Moraes, R., Portugal, P. and Vasques, F., 2016, July. AdapTA: Adaptive timeslot allocation scheme for IEEE 802.15. 4e LLDN mode. In 2016 IEEE 14th International Conference on Industrial Informatics (INDIN) (pp. 304-309). IEEE.

[64] Charlier, M., Quoitin, B., Bette, S. and Eliasson, J., 2016, November. Support for IEEE 802.15. 4 ultra wideband communications in the Contiki operating system. In 2016 Symposium on Communications and Vehicular Technologies (SCVT) (pp. 1-6). IEEE.

[65] Raptis, T.P., Passarella, A. and Conti, M., 2018, May. Maximizing industrial IoT network lifetime under latency constraints through edge data distribution. In 2018 IEEE Industrial Cyber-Physical Systems (ICPS) (pp. 708-713). IEEE.

[66] Hu, J., Ma, Z. and Sun, C., 2011, December. Energy-efficient MAC protocol designed for wireless sensor network for IoT. In 2011 Seventh International Conference on Computational Intelligence and Security (pp. 721-725). IEEE.

[67] Boccadoro, P., Barile, M., Piro, G. and Grieco, L.A., 2016, September. Energy consumption analysis of TSCH-enabled platforms for the Industrial-IoT. In 2016 IEEE 2nd International Forum on Research and Technologies for Society and Industry Leveraging a better tomorrow (RTSI) (pp. 1-5). IEEE.

[68] Alves, R.C. and Margi, C.B., 2016, October. IEEE 802.15. 4e TSCH mode performance analysis. In 2016 IEEE 13th International Conference on Mobile Ad Hoc and Sensor Systems (MASS) (pp. 361-362). IEEE.

[69] Banik, J., Arjona, R., Tacca, M., Razo, M., Fumagalli, A., Vijayasankar, K. and Kandhalu, A., 2017, January. Improving performance in industrial Internet of Things using multi-radio nodes and multiple gateways. In 2017 International Conference on

Computing, Networking and Communications (ICNC) (pp. 604-608). IEEE.

[70] Hung, F.H., Tsang, K.F., Chi, H.R., Chan, H.F. and Wu, C.K., 2016, October. Improve performance for IEEE 802.15. 4 protocol in healthcare environment. In IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society (pp. 6222-6225). IEEE.

[71] Wang, K., Wang, Y., Sun, Y., Guo, S. and Wu, J., 2016. Green industrial Internet of Things architecture: An energy-efficient perspective. IEEE Communications Magazine, vol. 54, no. 12, pp. pp.48-54. IEEE, 2016.

[72] Long, N.B., Choi, H.H. and Kim, D.S., 2016, September. Energy-aware routing scheme in industrial wireless sensor networks for Internet of Things systems. In 2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA) (pp. 1-8). IEEE.

[73] Li, C., Li, J., Zhen, B., Li, H.B. and Kohno, R., 2010. Hybrid unified-slot access protocol for wireless body area networks. International Journal of Wireless Information Networks, 17(3-4), pp.150-161.

[74] Koubâa, A., Severino, R., Alves, M. and Tovar, E., 2009. Improving quality-of-service in wireless sensor networks by mitigating “hidden-node collisions”. IEEE Transactions on Industrial Informatics, vol. 5, no. 3, pp.299-313.

[75] De Guglielmo, D., Al Nahas, B., Duquennoy, S., Voigt, T. and Anastasi, G., 2016. Analysis and experimental evaluation of IEEE 802.15. 4e TSCH CSMA-CA algorithm. IEEE Transactions on Vehicular Technology, vol. 66, no. 2, pp.1573-1588.

[76] Khan, S., Alvi, A.N., Javed, M.A., Roh, B.H. and Ali, J., 2020. An Efficient Superframe Structure with Optimal Bandwidth Utilization

and Reduced Delay for Internet of Things Based Wireless Sensor Networks. Sensors, vol. 20, no. 7, pp. 1-17.

[77] El Gholami, K., Hou, K.M. and Elkamoun, N., 2012. Enhanced superframe structure of the IEEE802. 15.4 standard for real-time data transmission in star network. International Journal of Computer Applications, 51(15), pp.26-32.

[78] Da Xu, L., He, W. and Li, S., 2014. Internet of things in industries: A survey. IEEE Transactions on industrial informatics, 10(4), pp.2233-2243.

[79] Jeschke, S., Brecher, C., Meisen, T., Özdemir, D. and Eschert, T., 2017. Industrial internet of things and cyber manufacturing systems. In Industrial internet of things (pp. 2-3). Springer, Cham.

[80] Ferrari, P., Flammini, A., Sisinni, E., Rinaldi, S., Brandão, D. and Rocha, M.S., 2018. Delay estimation of industrial IoT applications based on messaging protocols. IEEE Transactions on Instrumentation and Measurement, 67(9), pp.2188-2199.

[81] Li, S., Ni, Q., Sun, Y., Min, G. and Al-Rubaye, S., 2018. Energy-efficient resource allocation for industrial cyber-physical IoT systems in 5G era. IEEE Transactions on Industrial Informatics, 14(6), pp.2618-2628.

[82] Lee, J., Bagheri, B. and Kao, H.A., 2015. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. Manufacturing letters, 3, pp.18-23.

[83] Jbair, M., Ahmad, B., Mus' ab H, A. and Harrison, R., 2018, May. Industrial cyber physical systems: A survey for control-engineering tools. In 2018 IEEE Industrial Cyber-Physical Systems (ICPS) (pp. 270-276). IEEE.

[84] Panimozhi, K. and Mahadevan, G., 2016, July. Bandwidth utilization in wireless sensor networks with priority based multi-stack

architecture. In 2016 2nd International Conference on Applied and Theoretical Computing and Communication Technology (iCATccT) (pp. 62-67). IEEE.

[85] Fernández-Caramés, T.M. and Fraga-Lamas, P., 2018. A review on human-centered IoT-connected smart labels for the industry 4.0. IEEE Access, 6, pp.25939-25957.

[86] Luo, Z., Hong, S., Lu, R., Li, Y., Zhang, X., Kim, J., Park, T., Zheng, M. and Liang, W., 2017, September. OPC UA-based smart manufacturing: system architecture, implementation, and execution. In 2017 5th International Conference on Enterprise Systems (ES) (pp. 281-286). IEEE.

[87] Büchi, G., Cugno, M. and Castagnoli, R., 2020. Smart factory performance and Industry 4.0. Technological Forecasting and Social Change, Elsevier, 150, pp. 1-10.

[88] Lu, Y., Richter, P. and Lohan, E.S., 2018, June. Opportunities and Challenges in the Industrial Internet of Things based on 5G Positioning. In 2018 8th International Conference on Localization and GNSS (ICL-GNSS) (pp. 1-6). IEEE.

[89] Petrillo, A., De Felice, F., Cioffi, R. and Zomparelli, F., 2018. Fourth industrial revolution: Current practices, challenges, and opportunities. Digital Transformation in Smart Manufacturing, pp.1-20.

[90] Bartodziej, C.J., 2017. The concept industry 4.0, An Empirical Analysis of Technologies and Applications in Production Logistics In The concept industry 4.0, Springer, Gabler, Wiesbaden, pp. 1-158.

[91] Weyn, M., Ergeerts, G., Wante, L., Vercauteren, C. and Hellinckx, P., 2013. Survey of the DASH7 alliance protocol for 433 MHz wireless sensor communication. International Journal of Distributed Sensor Networks, 9(12), pp.1-9.

[92] Catherine, R.I., 2017. Comparison of wireless techniques applied to environmental sensor monitoring”, SINTEF Digital Acoustics and Communication, accessed 4/4/2018, available online on: https://brage.bibsys.no/xmlui/bitstream/handle.

[93] Hejazi, H., Rajab, H., Cinkler, T. and Lengyel, L., 2018, January. Survey of platforms for massive IoT. In 2018 IEEE International Conference on Future IoT Technologies (Future IoT) (pp. 1-8). IEEE.

[94] Grabia, M., Markowski, T., Mruczkiewicz, J. and Plec, K., 2017, September. Design of a DASH7 low power wireless sensor network for Industry 4.0 applications. In 2017 IEEE International Conference on RFID Technology & Application (RFID-TA) (pp. 254-259). IEEE.

[95] Urbina, M., Astarloa, A., Lazaro, J., Bidarte, U., Villalta, I. and Rodriguez, M., 2017. Cyber-physical production system gateway based on a programmable SoC platform. IEEE Access, 5, pp.20408-20417.

[96] Mahmoud, M.S. and Mohamad, A.A., 2016. A study of efficient power consumption wireless communication techniques/modules for internet of things (IoT) applications, vol. 6, no. 02, pp. 1-12.

[97] Akpakwu, G.A., Silva, B.J., Hancke, G.P. and Abu-Mahfouz, A.M., 2017. A survey on 5G networks for the Internet of Things: Communication technologies and challenges. IEEE access, 6, pp.3619-3647.

[98] Subhan, F., Hasbullah H., Rozyyev A., and Tahir S,B., 2011. Handover in bluetooth networks using signal parameters. Information Technology Journal, vol. 10, no. 5, pp. 965-973.

[99] Pan, G., He, J., Wu, Q., Fang, R., Cao, J. and Liao, D., 2018, May. Automatic stabilization of Zigbee network. In 2018 International Conference on Artificial Intelligence and Big Data (ICAIBD) (pp. 224-227). IEEE.

[100] Liu, Q., Zuo, Y., Luo, G., Wang, H., Huang, and M., Cao, Y., 2016. Receiver-assisted cellular/wifi handover management for efficient multipath multimedia delivery in heterogeneous wireless networks. EURASIP Journal on Wireless Communications and Networking, Springer, vol. 1, pp. 1-13.

[101] Predix.The Platform for the Industrial Internet, 2016 General Electric Company, July 2016, pp. 1-22.

[102] Lee, S.K., Bae, M. and Kim, H., 2017. Future of IoT networks: A survey. Applied Sciences, 7(10), pp.1-25.

[103] Golubeva, T., Zaitsev, Y., Konshin, S. and Duisenbek, I., 2018, July. A study on the Wi-Fi radio signal attenuation in various construction materials (obstacles). In 2018 Tenth International Conference on Ubiquitous and Future Networks (ICUFN) (pp. 718-723). IEEE.

[104] Nowakowski, E., Häusler, M. and Breu, R., 2018, October. Analysis of Enterprise Architecture Tool Support for Industry 4.0 Transformation Planning. In 2018 IEEE 22nd International Enterprise Distributed Object Computing Workshop (EDOCW) (pp. 184-191). IEEE.

[105] Morrar, R., Arman, H. and Mousa, S., 2017. The fourth industrial revolution (Industry 4.0): A social innovation perspective. Technology Innovation Management Review, 7(11), pp.12-20.

[106] Zhao, H. and Hou, J., 2018, December. Design Concerns for Industrial Big Data System in the Smart Factory Domain: From Product Lifecycle View. In 2018 23rd International Conference on

Engineering of Complex Computer Systems (ICECCS) (pp. 217-220). IEEE.

[107] Peralta, G., Iglesias-Urkia, M., Barcelo, M., Gomez, R., Moran, A. and Bilbao, J., 2017, May. Fog computing based efficient IoT scheme for the Industry 4.0. In 2017 IEEE international workshop of electronics, control, measurement, signals and their application to mechatronics (ECMSM) (pp. 1-6). IEEE.

[108] Geissbauer, R., Vedso, J., Schrauf, S., 2016. Industry 4.0: building the digital enterprise, global industry 4.0 survey. PwC, Munich, pp. 1-36.

[109] Darshini, B.D., Paventhan, A., Krishna, H. and Pahuja, N., 2016, January. Enabling real time requirements in industrial IoT through IETF 6TiSCH. In 2016 International Conference on Internet of Things and Applications (IOTA) (pp. 121-124). IEEE.

[110] Um, C., Lee, J. and Jeong, J., 2018, November. Virtualized oneM2M system architecture in smart factory environments. In 2018 28th International Telecommunication Networks and Applications Conference (ITNAC) (pp. 1-6). IEEE.

[111] Kühn, W., 2006. Digital factory: simulation enhancing the product and production engineering process. In: Winter simulation conference, pp 1899–1906.

[112] Wan, J., Yi, M., Li, D.I., Zhang, C., Wang, S. and Zhou, K., 2016. Mobile services for customization manufacturing systems: An example of industry 4.0. IEEE Access, 4, pp.8977-8986.

[113] Ustundag, A. and Cevikcan, E., 2017. Industry 4.0: managing the digital transformation. Springer., pp. 97.

[114] Blanco-Novoa, Ó., Fernández-Caramés, T.M., Fraga-Lamas, P. and Castedo, L., 2017. An electricity price-aware open-source smart socket for the internet of energy. Sensors, 17(3), pp.1–34.

[115] Fernández-Caramés, T.M., 2015. An intelligent power outlet system for the smart home of the Internet of Things. International Journal of Distributed Sensor Networks, 11(11), p.214805.

[116] Suárez-Albela, M., Fraga-Lamas, P., Fernández-Caramés, T.M., Dapena, A. and González-López, M., 2016. Home automation system based on intelligent transducer enablers. Sensors, 16(10), p.1595., pp.1–26.

[117] Harrison, R., Vera, D. and Ahmad, B., 2016. Engineering methods and tools for cyber–physical automation systems. Proceedings of the IEEE, 104(5), pp.973-985.

[118] Wollschlaeger, M., Sauter, T. and Jasperneite, J., 2017. The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0. IEEE industrial electronics magazine, 11(1), pp.17-27.

[119] Klötzer, C., Weißenborn, J. and Pflaum, A., 2017, July. The evolution of cyber-physical systems as a driving force behind digital transformation. In 2017 IEEE 19th Conference on Business Informatics (CBI) (Vol. 2, pp. 5-14). IEEE.

[120] Fernández-Caramés, T.M. and Fraga-Lamas, P., 2018. A Review on the Use of Blockchain for the Internet of Things. Ieee Access, 6, pp.32979-33001.

[121] Ajah, I.A. and Nweke, H.F., 2019. Big data and business analytics: Trends, platforms, success factors and applications. Big Data and Cognitive Computing, 3(2), pp. 1-30.

[122] Hur, C.H., Kim, S.P., Kim, Y.S. and Eom, J.H., 2017, August. Changes of cyber-attacks techniques and patterns after the fourth industrial revolution. In 2017 5th International Conference on Future Internet of Things and Cloud Workshops (FiCloudW) (pp. 69-74). IEEE.

[123] Kshetri, N., 2017. Can Blockchain Strengthen the Internet of Things?, in IT Professional, vol. 19, no. 4, pp. 68-72.

[124] Bonomi, F., Milito, R., Zhu, J. and Addepalli, S., 2012, August. Fog computing and its role in the internet of things. In Proceedings of the first edition of the MCC workshop on Mobile cloud computing (pp. 13-16).

[125] Qi, Q., and Tao, F., 2018, Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison, in IEEE Access, no. 99, Jan.

[126] Nagesh, N., Wells, J., Holland, S., Pearson, T. and Peacock, B., Cobots for the automobile assembly line. in Proceedings of the IEEE International Conference on Robotics and Automation, Detroit, United States, 10-15 May 1999.

[127] Robla-Gómez, S., Becerra, V.M., Llata, J.R., Gonzalez-Sarabia, E., Torre-Ferrero, C. and Perez-Oria, J., 2017. Working together: A review on safe human-robot collaboration in industrial environments. IEEE Access, 5, pp.26754-26773.

[128] Bouguerra, A., Cirillo, M., Dimitrov, D. N., Driankov, D., Karlsson, L., Lilienthal, A. J., Pecora, F., Saarinen J. P., Sherikov, A., Stoyanov, T., Andreasson H., 2015. Autonomous Transport Vehicles: Where We Are and What Is Missing," in IEEE Robotics & Automation Magazine, vol. 22, no. 1, pp. 64-75.

[129] Arutselvan, K. and Vijayakumari, A., 2015. Assistive Autonomous Ground Vehicles in Smart Grid. Procedia Technology, 21, pp.232-239.

[130] Cave, H., 2016. VR in... the factory of the future, in Engineering & Technology, vol. 11, no. 3, pp. 44-47.

[131] Schneider, M., Rambach, J. and Stricker, D., 2017, March. Augmented reality based on edge computing using the example of

remote live support. In 2017 IEEE International Conference on Industrial Technology (ICIT) (pp. 1277-1282). IEEE.

[132] Shin, C., Park, B.H., Jung, G.M. and Hong, S.H., 2014, December. Mobile augmented reality mashup for furture IoT environment. In 2014 IEEE 11th Intl Conf on Ubiquitous Intelligence and Computing and 2014 IEEE 11th Intl Conf on Autonomic and Trusted Computing and 2014 IEEE 14th Intl Conf on Scalable Computing and Communications and Its Associated Workshops (pp. 888-891). IEEE.

[133] He, Q., 2010. Research and application of virtual reality technology in mechanical maintenance, in Proceedings of the International Conference on Advanced Technology of Design and Manufacture, Beijing, China, 23-25.

[134] Loch, F., Quint, F. and Brishtel, I., 2016, September. Comparing video and augmented reality assistance in manual assembly. In 2016 12th International Conference on Intelligent Environments (IE) (pp. 147-150). IEEE.

[135] Carvalho, A.C.P., Carvalho, A.P.P. and Carvalho, N.G.P., 2020. Industry 4.0 Technologies: What Is Your Potential for Environmental Management?. In Industry 4.0-Current Status and Future Trends. IntechOpen. pp. 1-17.

[136] Chen, B., Wan, J., Shu, L., Li, P., Mukherjee, M. and Yin, B., 2017. Smart factory of industry 4.0: Key technologies, application case, and challenges. IEEE Access, 6, pp.6505-6519.

[137] EL HAMDI, S. and ABOUABDELLAH, A., 2020, March. Proposal of a General Framework of Smart Factory. In 2020 International Conference on Electrical and Information Technologies (ICEIT) (pp. 1-6). IEEE.

[138] Qin, Z., Wu, D., Xiao, Z., Fu, B. and Qin, Z., 2018. Modeling and analysis of data aggregation from convergecast in mobile sensor networks for industrial IoT. IEEE Transactions on Industrial Informatics, 14(10), pp.4457-4467.

[139] Chen, B., Wan, J., Shu, L., Li, P., Mukherjee, M. and Yin, B., 2017. Smart factory of industry 4.0: Key technologies, application case, and challenges. IEEE Access, 6, pp.6505-6519.

[140] Wang, S., Wan, J., Li, D. and Zhang, C., 2016. Implementing smart factory of industrie 4.0: an outlook. International journal of distributed sensor networks, 12(1), pp.1-10.

[141] Schuh, G., Pitsch, M., Rudolf, S., Karmann, W. and Sommer, M., 2014. Modular sensor platform for service-oriented cyber-physical systems in the European tool making industry. Procedia Cirp, 17(1), pp.374-379.

[142] Lee, H., Yoo, S. and Kim, Y.W., 2016, January. An energy management framework for smart factory based on context-awareness. In 2016 18th International Conference on Advanced Communication Technology (ICACT) (pp. 685-688). IEEE.

[143] Ruduan Y., and Elfaki S., 2020, Design Algorithm for Improving Propagation (Delay) of Industrial Internet of Things Systems Based on Superframes Structure, International Journal of Computer Science Trends and Technology (IJCST) – Vol. 8, Issue 2, March 2020, pp. 71-81.

[144] Kurunathan, H., Severino, R., Koubâa, A. and Tovar, E., 2019. DynaMO—Dynamic Multisuperframe Tuning for Adaptive IEEE 802.15. 4e DSME Networks. IEEE Access, 7, pp.122522-122535.

[145] Salayma M., Mardini W., Khamayseh Y., and Yasin B. M., (2013) “Optimal Beacon and Superframe Orders in WSNs FUTURE

COMPUTING” , The Fifth International Conference on Future Computational Technologies and Applications, 49-55.

[146] Francois Despaux, 29 Mar 2018, Modeling and evaluation of the end-to-end delay in wireless sensor networks, hal archives-ouvertes, pp. 28.

[147] Dou, R. and Nan, G., 2015. Optimizing sensor network coverage and regional connectivity in industrial IoT systems. IEEE Systems Journal, 11(3), pp.1351-1360.

[148] Hamid, M., Abdullah-Al-Wadud, M. and Chong, I., 2010. A schedule-based multi-channel MAC protocol for wireless sensor networks. Sensors, 10(10), pp.9466-9480.

Appendices

Appendix A: Performance Evaluation of IEEE 802.15.4e Modes

1. TSCH Mode

This section shows how measure the throughput, packets delay, energy consumption.

1.1 Energy Consumption

The charge drawn from a battery during the execution of this slot is the sum of the charge in each of these steps.

$$Q_{TxDataRxAck} = \int_{0}^{TsSlotDuration} I_{TxDataRxAck}(t)\,dt \tag{1}$$

Equations (1) to equation (9) were defined as the energy consumed in a slot frame for every time slot.

$$Q_{FIdle} = \frac{\left(\left(N_{aRxTx} - N_{uRxTx}\right) + N_{aRx} - N_{uRx}\right) X\ Q_{idle}}{PDR} \tag{2}$$

Equation (2) defines the contribution of idle slots to the total charge drawn in the slotted frame. The numbers of slots that are in the idle mode are those that have been configured on the schedule as RxDataTxAck or RxData, but during this time slot has no data is received.

Available slots are known as subscripts, where subscript (*u*) indicates to use slots. Consider the Packet Delivery Ratio (PDR) defined as the number of packets being acknowledged divided by the number of packets being sent by a node. In the following equations, (N) stands for several available slots where the node will be listening for a packet and will send an ACK.

Equation (3) defines the contribution of Sleep slots. As shown in equation (3), the TxDataRxAck slots ($N_{a\ Tx\ Rx}$) that are not used ($N_{u\ Tx\ Rx}$) are in the sleep state. In this case, during a TxDataRxAck slot, the transmitter has no data to send, and the radio is turned OFF.

$$Q_{FSleep} = \left(N_{sleep} + \left(N_{aTxRx} - N_{uTxRx}\right) + N_{aTx} - N_{uTx}\right) x\ Q_{sleep} \tag{3}$$

Equation (4) defines the contribution of N_{uTxRx} TxData Ack, which is used. In that case, two contributions are taken; the first one involves the number of bytes being sent. NBSent which is considered for the maximum packet size as energy consumption measurements have been done with MaxPktSz1 packets.

$$Q_{FTxRx} = \frac{N_{uTxRx} \times \left(\frac{NBSent}{MaxPktSz} \times Q_{Tx} + \left(Q_{TxRx} - Q_{Tx}\right)\right)}{PDR} \tag{4}$$

Probability Delivery Ratio (PDR) expected by the network is considered. Equation (5) describes the energy consumption in the slots that are being in TxData.

$$Q_{FTx} = N_{uTx} \times \left(\frac{NBSent}{MaxPktSz} \times Q_{Tx} \right) PDR \tag{5}$$

Equation (6) computes the contribution of RxData Ack slots. The number of slots that are used is defined as $N_{uRxTx.}$ Also, the number of bytes being sent is considered.

$$Q_{FRxTx} = N_{uRxTx} \times \left(\frac{NBSent}{MaxPktSz} \times Q_{Rx} + \left(Q_{RxTx} - Q_{Rx} \right) \right) \quad (6)$$

Equation (7) computes the contribution of RxData slots.

$$Q_{FRx} = N_{uRx} \times \frac{NBSent}{MaxPktSz} \times Q_{Rx} \qquad (7)$$

Equation (8) defines the total charge drawn during a slot frame and is the sum of participation by the different types of slots.

$$Q_{slotframe} = Q_{FIdle} + Q_{FSleep} + Q_{FTxRx} + Q_{FTx} + Q_{FRxTx} + Q_{FRx} \qquad (8)$$

Lastly, equation (9) defines the battery lifetime of a node, in days, assuming it runs from a 3.6 V power supply.

$$lf = \frac{B_{capacity} \times 3.6}{Q_{slotframe}} \times \frac{length_{slot} \times length_{slotframe}}{3600 \times 24} \qquad (9)$$

1.2 Throughput

The probability that the channel is busy (P_t), there is at least one transmission in the considered timeslot. Since there are several devices on the channel (n), and each device transmits packets with probability (τ). The probability (Pts) is the successful data transmission probability conditioned on the fact that the channel is busy. (Pt) and (Pts) are computed as an equation (10):

$$Pt = 1 - \left(1-\tau\right)^{n}, Pts = \frac{n\tau\left(1-\tau\right)^{n-1}}{1-\left(1-\tau\right)^{n}} \qquad (10)$$

The throughput is defined as the successful transmission of data with the ratio of the channel time. The channel time includes channel free time and channel busy time.

$$S \quad = P_t P_{ts} t_p / \gamma \quad = \; P_t P_{ts} t_{p/} \left(1 - P_t\right) \sigma + \; = P_t P_{ts} t_s + P_t \left(1 - P_{ts}\right) t_c \qquad (11)$$

Where (t_p) is the time duration for the payload of the packets,(t_s) is the time for the successful transmission of one packet and received an acknowledgment (ACK).

$$t_s = t_h + t_p + t_{ack} \qquad (12)$$

In an equation (2.16) is the time for a transmission failure of one packet:

$$2 \quad t_c = t_h + t_p + t_{ack} - to \qquad (13)$$

(t_h) is the time duration that includes physical (PHY) header and MAC header, (t_{ack}), (t_{ack}-to), (T_{ack}) are the time's duration for an (ACK), and transmission as ACK, respectively [55].

1.3 Packets Delay

Packets Delay is calculated as an equation (14):

$$Delay = (ASNRx - ASNTx) * 10ms \qquad (14)$$

2. DSME Mode

Three main parameters: throughput, packets delay, energy consumption are measured based on DSME mode.

2.1 Throughput

(S) is the normalized throughput of a device. The channel is sensed busy if at least one device is transmitting data. (P_{tr}) is the probability that there is at least one transmission. Since there are (M) devices attached to the coordinator and (Φ)is the probability that a tool attempts its first CCA, then:

$$P_{tr} = (1 - (1 - \Phi)^{M})(1 - \alpha)(1 - \beta) \tag{15}$$

Thus, the normalized throughput of a machine is:

$$S = P_{tr} P_S L_D \;/\; \left(1 - P_{tr}\right)\sigma + P_{tr} P_S T_s + P_{tr}\left(1 - P_S\right)T_c \tag{16}$$

Where, (T_s) is the meantime of successful transmission, and (T_c) is the meantime that the channel is occupied because of the collision. (L_D) is the time of payload, and (σ)is the duration of a unit backoff slot. (Ts) and (Tc) are calculated as:

$$\begin{Bmatrix} T_s = 2T_{CCA} + 2\sigma + T_D + \delta + T_{ACK} \\ T_c = 2T_{CCA} + 2\sigma + T_D + \delta_{max} \end{Bmatrix} \tag{17}$$

Where, (T_{CCA}) is the time duration for performing CCA, (T_D) is transmitting data, (T_{ACK}) time duration for receiving an acknowledgment, (δ)is the time for an acknowledgment, (δ_{max}) is the maximum waiting time for an acknowledgment and (σ) period of one backoff slot.

2.2Energy Consumption

The energy consumption due to the turnaround process from the sleeping state to the sensing state is assumed to be (Ptx+Prx /2). Where (TL) is the time duration for transmitting packets, (TA) for receiving an acknowledgment, (TCCA) for each successful CCA, ($T_{ta,}$) is turnaround time, and (δmax) is the maximum time to wait for the reply, respectively. Total energy consumption per device can be expressed as follows.

$$E = \propto TCCAPRX + 2(1-\alpha)\beta TCCAPRX + (1-\alpha)(1-\beta)\left\{(1-PS)Ec + PSEs\right\} / (1-\alpha)(1-\beta)PSTdata \tag{18}$$

Where, (Es) is the energy consumption of successful transmission, and (Ec) is energy consumption due to the collision, Es and Ec can be calculated as an equation (19).

$$\left(\begin{array}{l} Es = 2TCCA\,PRX + 2Tta\left(PRX + Prx\right)/2 + TLPTX + TAPRX \\ Ec = 2TCCA\,PRX + 2Tta\left(PRX + Prx\right)/2 + TLPTX + \delta maxPRX. \end{array}\right) \tag{19}$$

2.3 Packets Delay

Set (Dj) is the delay for successfully transmitted packets at a time (j + 1), and the packets have been failed for (j) times. Then

$$Dj = T_s + jT_c + \sum_{i=0}^{j} D_b \tag{20}$$

Where (D_b) is the delay that the device successfully found the channel idles during maxMacBackoff number of backoff slots. (T_s) is the meantime of successful transmission, and (T_c) is the meantime that the channel is occupied due to the collision. (B_k) is an event that the channel access is successful for (k + 1)t_h times, and the channel access is failed for (kt_h) times. (B) is an event that the channel access is successful within the maxMacBackoff number of backoff. Hence, the expected backoff delay in one transmission attempt is:

$$D_b = \sum_{i=0}^{m} \frac{P^{i}_{backoff}\left(1-P_{backoff}\right)}{1-P^{m+1}_{backoff}} \sum_{k=0}^{i} \frac{W_i - 1}{2} \quad (2.27)$$

If the packet is generated outside its allocated CAP, then it has to be in the wait state until the next allocated CAP comes. Therefore, if the packet arrival follows the Poisson process with packet arrival rate, then

$$waiting\ time = \int_{0}^{BI} \left(BI - x\right)\lambda e^{-\lambda x} dx \qquad (21)$$

Propagation delay is the amount of time it takes for the head of the signal to travel from the sender to the receiver. It can be computed as the ratio between the link length and the propagation speed over the specific medium. (E_j) an event that the packet is transmitted successfully (j + 1) times and the packet has failed for (j) times. (E) is an event that the packet is transmitted successfully within maxFrameRetries. (r) is considering the maxFrameRetries.

$$P_r\left(\frac{E_j}{E}\right) = \frac{\left(1-P_S\right)^{j} P_S}{1-\left(1-P_S\right)^{r-1}} \qquad (22)$$

Therefore, the network delay is:

$$D = \sum_{j=0}^{r} P_r\left({E_j}/{E}\right) D_j + Waiting\ time\ + propagation\ delay \qquad (23)$$

The packet may not be transmitted in the current CAP period if (D is bigger than CAP $_{period}$) and has to wait for the next superframe. Therefore, the total average delay can be computed as an equation (24):

$$Delay = \left\lceil \frac{D}{CAP_{period}} \right\rceil BI + D \bmod CAP_{period} \tag{24}$$

3. LLDN Mode

Three key metrics: throughput, packets delay, energy consumption are measured based on the LLDN mode.

3.1 Throughput

The throughput of the IEEE 802.15.4e LLDN network can be calculated according to an equation (2.32):

$$Throughput = L_{pkt} P_{success} PHY_{rate} \tag{25}$$

Where (L_{pkt}) is the payload duration, ($P_{success}$) refers to the probability of successful packet transmission, and (PHY_{rate}) indicates the physical data rate of IEEE 802.15.4e, respectively.

3.2 Energy Consumption

Average energy consumption for a node can be calculated according to an equation (2.33):

$$Average\ Energy = \alpha T_{CCA} P_{rx} + (1-\alpha) T_S P_{tx} + (1-pb) T_L P_{tx} \tag{26}$$

Where, (P_{rx}) refers to energy consumption for receiving packets, (P_{tx}) is energy consumption for transmitting packets, and (T_S) is the time duration for transmitting the known signal.

3.3 Packets Delay

Therefore, an average transmission delay in the IEEE 802.15.4e network, when the transmission is successful in the (j-th) superframe, can be calculated as:

$$Delay = \sum_{j=1}^{\infty}(1 - Psuccess)j - 1\ Psuccess\,(j - 1)BI + Wtime + Tdelay + Pdelay \quad (27)$$

Where ($P_{success}$) is the successful data transmission probability and (BI) is the beacon interval.

Appendix B

The Graphical User Interface (GUI) for Cooja Simulator

Appendix A discusses an initial setting of the Cooja simulator under the Linux operating system (Ubuntu), and how it uses this simulator to simulate the real testbeds of the network through different windows.

1. Cooja Installation and Start-up

To install the Cooja simulator on windows, firstly set up virtual machine software, then should visit the Contiki website. Secondly, download the Contiki OS. Once the Instant Contiki OS image has been downloaded and unzipped, it can be opened using VMware. Thirdly, to start the simulation software opens a terminal window and enters the following commands, cd Contiki/tools/Cooja command, enters the ant- run command, then press enter.

The Cooja software should now start, as shown in figure (1). Although Cooja is extremely very complex, it has a few simple instructions; very quick data, which are collected by motes as well as giving the ability to observe radio communication and messages gaining by sensors within the network can be able to change their transmissions and interference range.

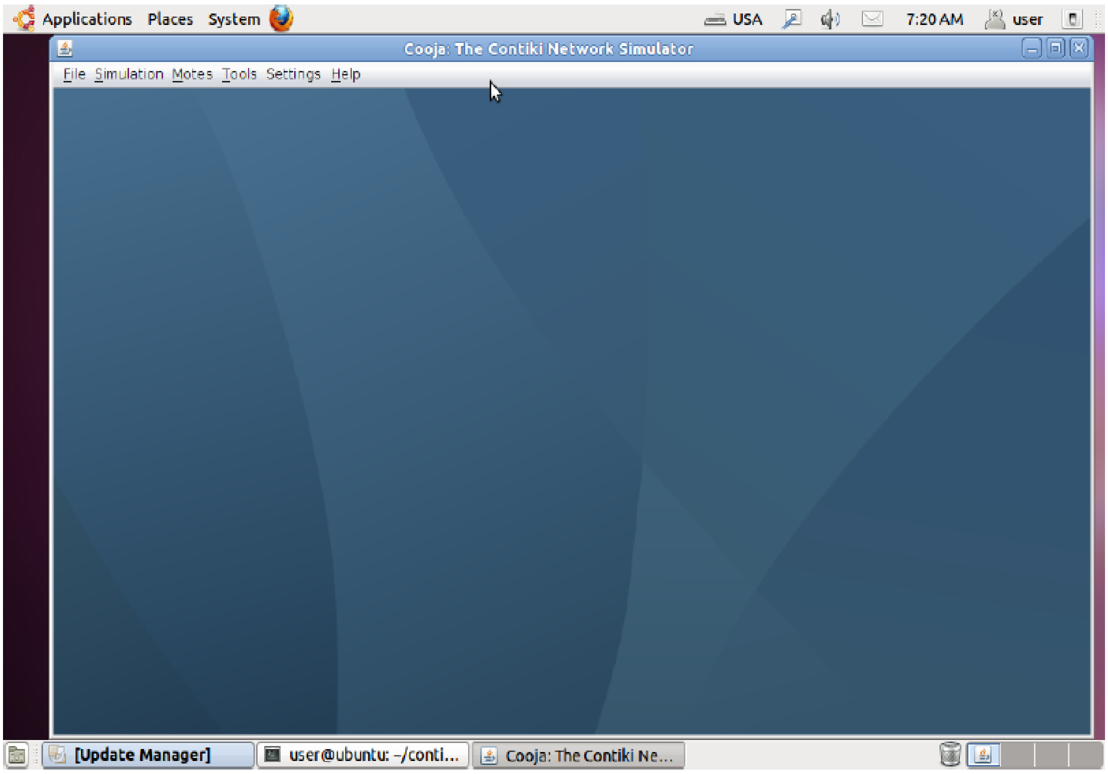
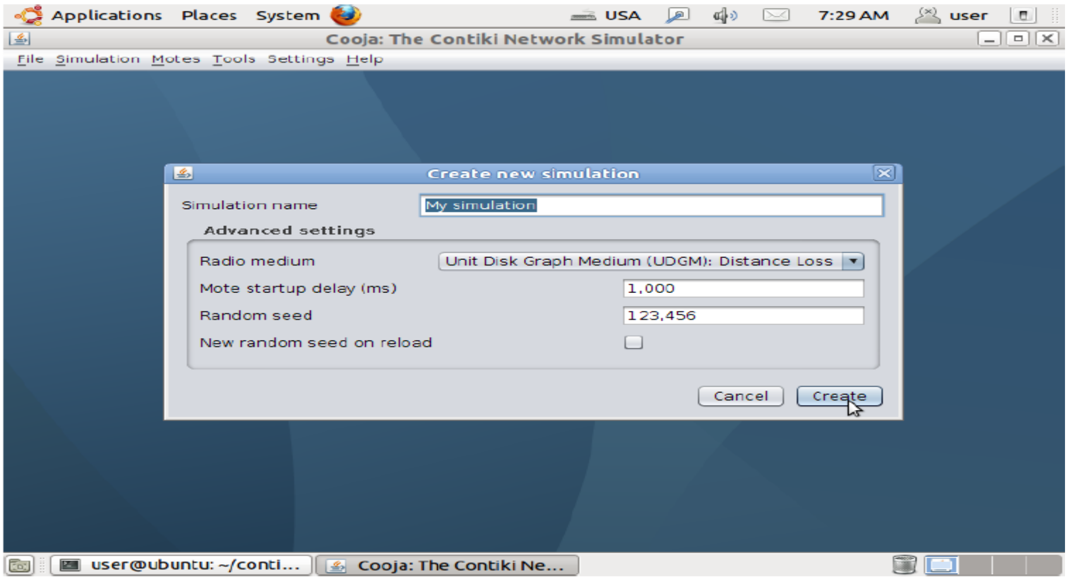


Fig. 1 Initial Cooja Screen

For opening a new network simulation, click the file in the menus bar, and then New Simulation and the screen are shown as illustrated in fig. (2).



Create new simulation

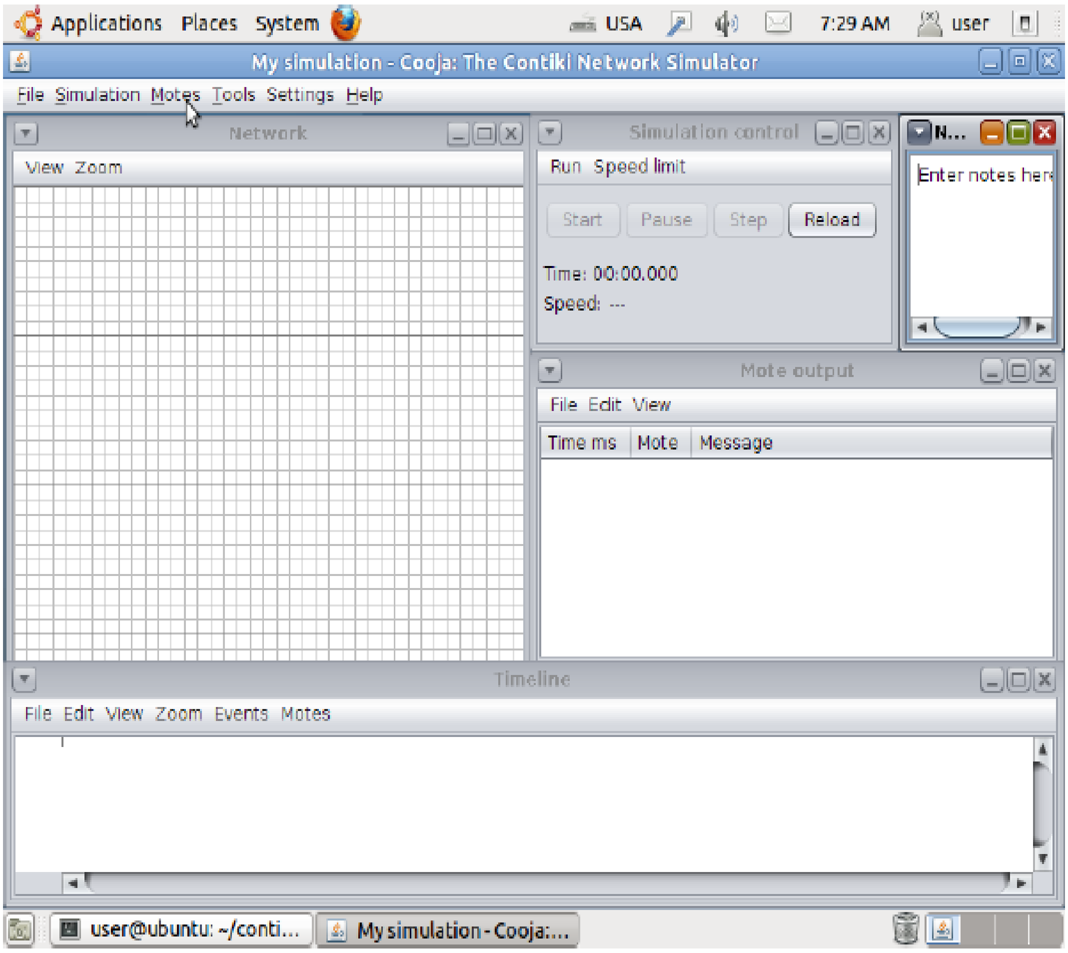
Simulation name: My simulation

Advanced settings

Radio medium: Unit Disk Graph Medium (UDGM): Distance Loss
Mote startup delay (ms): 1,000
Random seed: 123,456
New random seed on reload ☐

Fig. 2: Cooja Create a new simulation

For creating a new simulation can be clicked the create button at the Mote menu. The results as shown in fig. 3.



Time: 00:00.000
Speed: ---

Fig. 3: Initial Cooja Simulation Screen

There are no motes in the network as of yet to be run. These are added by clicking on Motes, Add motes, Create new mote type and then Sky mote or any mote can be closed from the resulting drop-down menu as illustrated in fig. (4). The results screen is displayed in fig. 5.

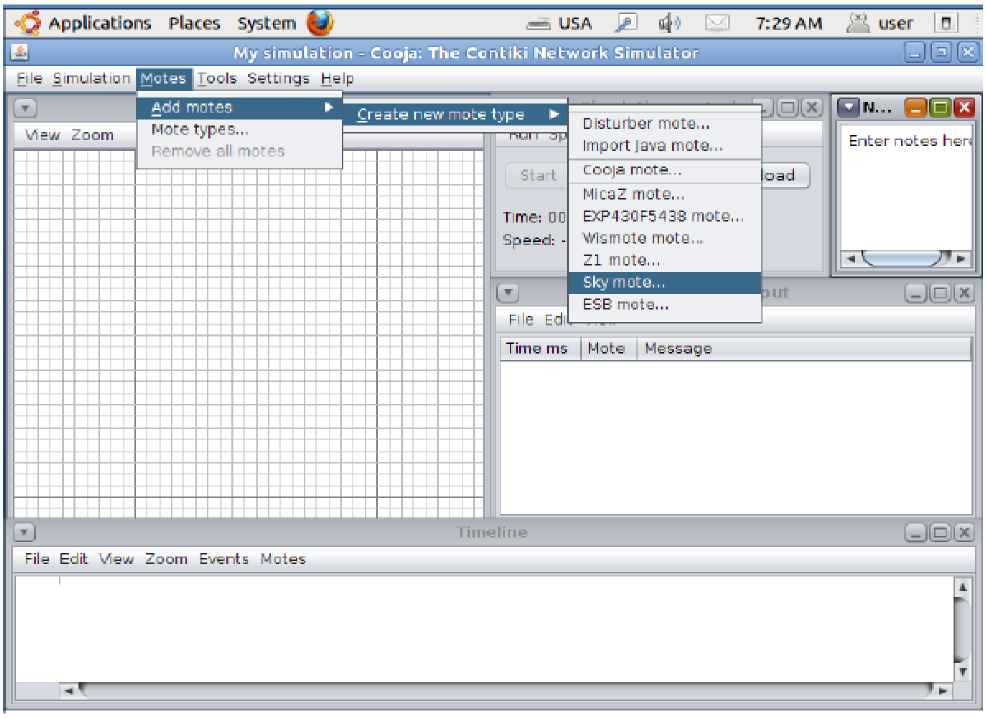


Fig.4: Cooja Add Mote

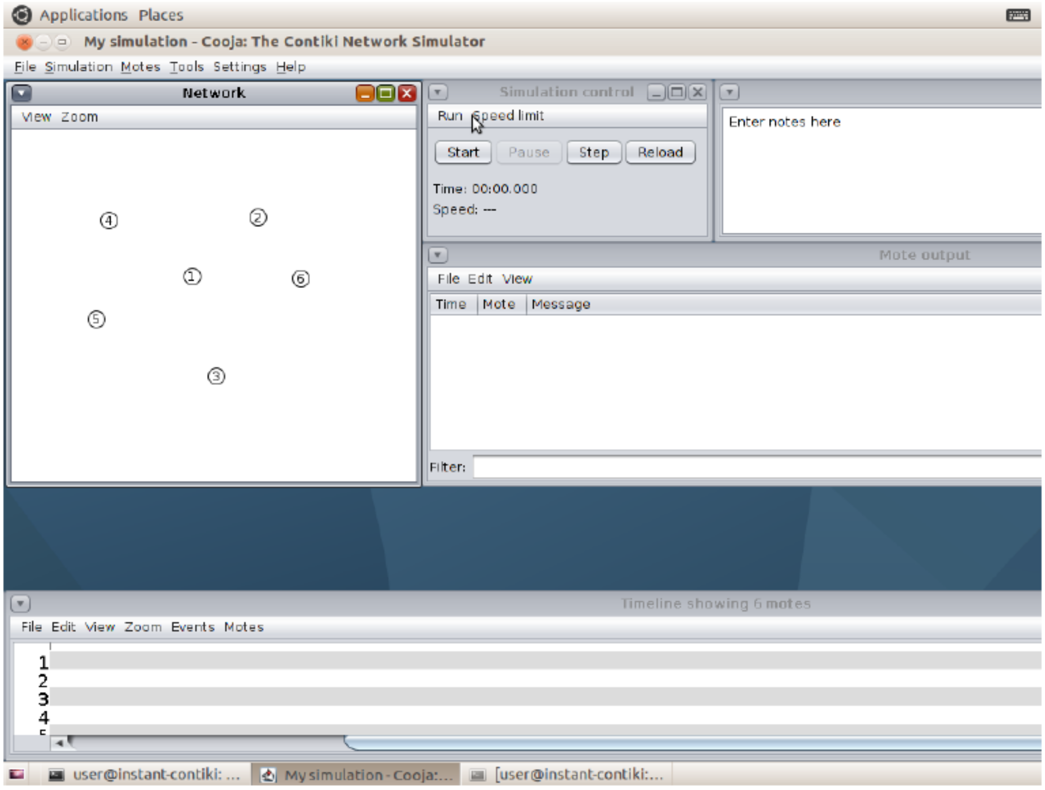


Fig. 5: Cooja Network

The network topology could include a sink node and many sender nodes. All senders transmit to the sink node.

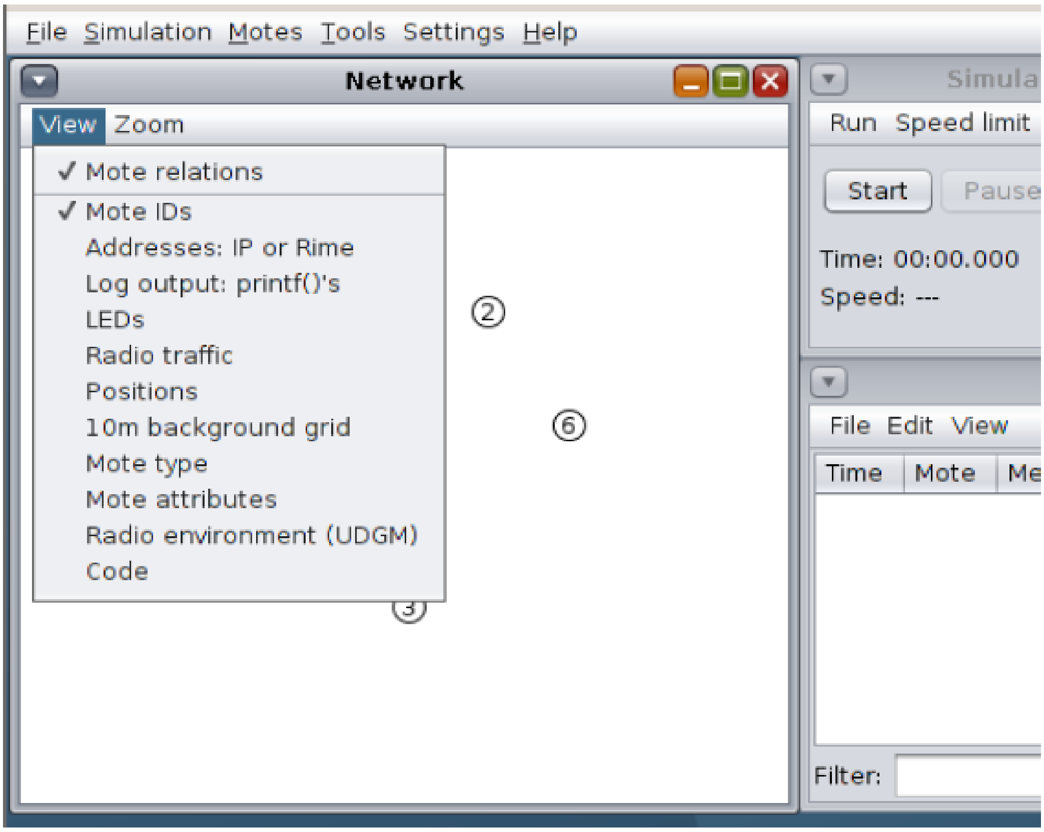


Fig. 6: Cooja View Dropdown.

2. Cooja Simulation View

This section describes important items of the various windows and the purpose of them, as well as the many other display options available before actually running the network test.

The simulation windows are the timeline window as that illustrated at the bottom of fig. (5), which is shown events over some time for communicating nodes at layer two[1].

The Mote Output window can display the node outputs window. The Simulation Control window has four main commands buttons for starting simulation are Start, Paused, Stop, and Reload simulation. The simulation can also be controlled entirely from this window. There are other options in this context that are the network window is showing the design of the

---

[1] Https:// www.contiki.net

network nodes and can be significantly modified to more easily post various factors of the network. The view dropdown menu is presenting several options that are the Mote relations and Mote IDs are showing the numbering of every node. The Addresses or Rime option displays an IP address of each mote (IPv6). Log output: printf()'s' is displayed printf messages from the node code inside the actual view window. LEDs are useful for observing the LED lights on the simulated node. The Radio Traffic option is extremely useful for animating the network once the simulation is running. Using this option will display the exchange of messages among nodes allowing the observation of the selection of parents and how the DODAG is built. Positions display the relative location of each node. The 100m^2 is handy to give a sense of scale to the network layout. Mote type employs a color scheme to show the difference between motes of different types. In this demonstration network, two types of nodes are used – one is the sink node and five nodes are the senders. Mote attributes that allow the use of code to alter the colorizing of nodes as well as other options. Radio environment (UDGM) is presenting the transmission range for each specific node and is useful when deciding upon the optimal position of nodes within a simulated network. Finally, Code displays code as it is being run.

Appendix C

Source Code for Cooja Simulator

This section an overviewed simulation codes for three parameters are throughput, Packet delay, and energy consumption

1. Throughput

```
<script>TIMEOUT(300000, log.log(“Total PRR ” + totalPRR + “\n”));packetsReceived= new Array();packetsSent = new Array();
serverID = 1;
nodeCount = 31;
data_length = 23;
totalPRR = 0;
controlpackets = 0;
for(i = 0; i <= nodeCount; i++) {
packetsReceived[i] = 0;
packetsSent[i] = 0;
}
while(1) {
YIELD();
msgArray = msg.split(‘ ‘);
if(msgArray[0].equals(“DATA”)) {
if(msgArray.length == 9) {
// Received packet
senderID = parseInt(msgArray[8]);
packetsReceived[senderID]++;
log.log(“SenderID ” + senderID + ” PRR ” + packetsReceived[senderID] /
packetsSent[senderID] + “\n”);
totalReceived = totalSent = 0;
for(i = serverID + 1; i <= nodeCount; i++) {
```

```
totalReceived += packetsReceived[i];
totalSent += packetsSent[i];
}
totalPRR = totalReceived / totalSent;
throughput = (totalReceived * data_length * 8) / total_simulation_time;
log.log(“Total PRR ” + totalPRR + ” recv ” + totalReceived + ” sent ” + tot
alSent + ” Throughput ” + throughput + “\n”);
} else if(msgArray.length == 6) {
// Sent packet
packetsSent[id]++;
log.log(” IIIID ” + id + ” packetsSent[id] ” + packetsSent[id] + “\n”);
}
}
}</script>
```

2. Latency

```
 * This file is part of the Contiki operating system.
  * \file
 //  Testing the broadcast layer in Rime
#include "contiki.h"
#include "net/rime/rime.h"
#include "random.h"
#include "dev/button-sensor.h"
#include "dev/leds.h"
#include <stdio.h>
/*-----------------------------------*/
struct latency_structure{ // Structure to save the time when the message
was send
   rtimer_clock_t timestamp;// Time when the message was send
};
```

```
/*---------------------------------------------------------------------------*/
PROCESS(example_broadcast_process, "Broadcast example");
AUTOSTART_PROCESSES(&example_broadcast_process);
/*---------------------------------------------------------------------------*/
//Receive a broadcast with the timestamp and compute the latency
static void
broadcast_recv(struct broadcast_conn *c, const linkaddr_t *from)
{
  struct latency_structure msg;
  rtimer_clock_t latency;
  packetbuf_copyto( &msg ); // Copy the message from the packet buffer to
the structure called msg
#if TIMESYNCH_CONF_ENABLED
  latency = timesynch_time() - msg.timestamp;
#else
  latency = 0;
#endif
  printf("broadcast message received from %d.%d with latency %lu ms\n",
         from->u8[0], from->u8[1], (1000L * latency) /
RTIMER_ARCH_SECOND );
}
static const struct broadcast_callbacks broadcast_call = {broadcast_recv};
static struct broadcast_conn broadcast;
/*---------------------------------------------------------------------------*/
PROCESS_THREAD(example_broadcast_process, ev, data)
{
  struct latency_structure *msg;
  static struct etimer et;
  PROCESS_EXITHANDLER(broadcast_close(&broadcast);)
```

```
  PROCESS_BEGIN();
  broadcast_open(&broadcast, 129, &broadcast_call);
  while(1) {
    /* Delay 2-4 seconds */
    etimer_set(&et, CLOCK_SECOND * 4 + random_rand() %
(CLOCK_SECOND * 4));
    PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&et));
#if TIMESYNCH_CONF_ENABLED
      msg->timestamp = timesynch_time();
#else
      msg->timestamp = 0;
#endif
    // Do not send the normal/original 'hello' message. Instead, send a
message with the timestamp.
   packetbuf_copyfrom(msg,   sizeof(*msg) ); // This message msg includes
the timestamp
    //packetbuf_copyfrom("Hello", 6);
    broadcast_send(&broadcast);
    printf("broadcast message sent\n");
  }
  PROCESS_END(); }
/*---------------------------------------------------------------------------*/
</stdio.h>
```

3. Energy consumption

```
public double getCPUPower()
{
 return (values[TIME_CPU] * POWER_CPU) / (values[TIME_CPU] +
values[TIME_LPM]);
public double getLPMPower()
```

```
{
 return (values[TIME_LPM] * POWER_LPM) / (values[TIME_CPU] +
values[TIME_LPM
}
  public double getListenPower()
 {
return (values[TIME_LISTEN] * POWER_LISTEN) /
(values[TIME_CPU] +  values[TIME_LPM]);
}
 public double getTransmitPower()
{
return (values[TIME_TRANSMIT] * POWER_TRANSMIT) /
(values[TIME_CPU] +  values[TIME_LPM]);
}
  public double getAveragePower()
{
 return (values[TIME_CPU] * POWER_CPU + values[TIME_LPM] *
POWER_LPM  + values[TIME_LISTEN] * POWER_LISTEN +
values[TIME_TRANSMIT] *  POWER_TRANSMIT) /
(values[TIME_CPU] + values[TIME_LPM]);
}
 public long getPowerMeasureTime()
{
 return (1000L * (values[TIME_CPU] + values[TIME_LPM])) /
TICKS_PER_SECOND;
}
```

Appendix D: Published Papers

1. Journal Papers

1. Yousuf Ruduan Hussein[1], and Salah Elfaki Elrofai[2], 2020, Enhancement of the Contention Access Period for Reducing Energy Consumption of Industrial Internet of Things Based on IPv6, SUST Journal of Engineering and Computer Sciences (JECS), Vol. 21, No. 1, 2020, pp. 7-16.

2.Yousuf Ruduan Hussein[1], and Salah Elfaki Elrofai[2], 2020, Design Algorithm for Improving Propagation (Delay) of Industrial Internet of Things Systems Based on Superframes Structure, International Journal of Computer Science Trends and Technology (IJCST) – Vol. 8, Issue 2, March 2020, pp. 71-81.

Appendix E: Contiki OS

Contiki is an open source operating system that runs on tiny low-power microcontrollers and makes it possible to develop applications that make efficient use of the hardware while providing standardized low-power wireless communication for a range of hardware platforms. Contiki is used in numerous commercial and non-commercial systems, such as city sound monitoring, street lights, networked electrical power meters, industrial monitoring, radiation monitoring, construction site monitoring, alarm systems, remote house monitoring[2].

---

[2] http://contiki-os.org

Appendix F: Zolertia Z1 Smart Sensor

Zolertia is an IoT hardware solution for the development of 6lowpan smart applications. Engineers, universities, R+D centers, and companies around the world are already using Zolertia boards to design and create their Internet of Things connected products.

The new industrial revolution where machines collect and interpret data to make decisions and provide technical assistance in order to increase efficiency and provide preventive maintenance. Zolertia module Zoul can be embedded in industrial machines allowing the internet communication necessary to make Industry 4.0 happen[3].

Zolertia Z1 Sensor

---

[3] https://zolertia.io/industry/

Appendix G: Tmote Sky Smart Sensors

Tmote sky is the next generation mote platform for extremely low power high data rates, sensor network applications designed with the dual goal of fault tolerance, and development ease. **Tmote sky buy** offers a robust solution with hardware protected external flash; applications may be wirelessly programmed to the Tmote sky module. In the event of a malfunctioning program, the module loads a protected image from flash[4].

Tmote Sky Sensor

---

[4] https://telosbsensors.wordpress.com