Arab American University

Faculty of Graduate Studies

The Impact of Network Topology on Performance of Wireless Sensor Networks based on Zigbee Protocol

By

Wasim Wael Nathif

Supervisor

Dr. Khalid Rabaya'h

This thesis was submitted in partial fulfillment of the requirements for the Master`s degree in Computer Sciences

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This thesis was defended successfully on 12/1/2019 and approved by:

Committee members	Signature
1. Dr. Khalid Rabaya'h	…………………
2. Dr. Adwan Yasin	…………………
3. Dr. Wasel Ghanem	…………………

Declaration

I certify that this thesis submitted for the degree of Master, is the result of my own research, except where otherwise acknowledged, and that this study (or any part of the same) has not been submitted for a higher degree to any other university or institution.

Signed: ………………

Wasim Wael Ali Nathif

Date: 2/2/2019

Dedication

Praise and thanks to God for all the blessing and for the production of knowledge that, for this thesis would not be possible.

To my Dad Dr. Wael Ali Nathif who paved the path before me upon where I stand now, this is for you, for every second that you fight and struggle for us. This thesis is the result, of our promise to you, to follow your steps to be a good man.

To my mom, the lady of dignity, honesty, and generosity, your embrace had been my shelter, I hold on to every word that you taught us and we learn from you. For the sleepless nights that you had been through when caring for me when I was little, this is my payment for everything that you had given to me.

To my dearest wife, which provided me with comfort and happiness with the light of hope and support.

To my Uncle Saeb Ali Nathif and my brothers, sisters and all my friends who never stop supporting me, wishing God will always bless them and give them the desires of their heart.

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Finally, I would like to thank my friends for supporting and helping me throughout this work.

Abstract

Zigbee wireless sensor networks, built on the bases of IEEE 802.15.4 standard, is gaining popularity in latest years due to its interesting features of being low in power consumption, sustaining long battery life and due to its straightforwardness in security management. Academic and industrial circles are showing increased interest in employing Zigbee technology as it can be used in wide range of present and future applications. In this thesis, the intention is to study and analyse the impact of network topologies on performance of wireless sensor networks built based on the Zigbee protocol. In addition, the effect of different WSN elements have been studied and analysed such as the effect of increasing number of Zigbee end devices (ZEDs), the effect of the number of Zigbee coordinators (ZCs) and Zigbee routers (ZRs). Moreover, the effect of nodes mobility has been also studied and analysed.

In the thesis we used the OPNET powerful simulator to build the needed network designs, which represent a real-world scenario. We then investigated the performance metrics of these networks by calculating the end-to-end delay, throughput, MAC load packet and packet delivery ratio as a function of network topology under various layouts and node conditions based on specifications recommended by the IEEE 802.15.4/ZigBee standards.

The overall conclusion out of this work indicates that considering the metrics of end-to-end delay, throughput, MAC load, and packet delivery ratio, adding one or more coordinators to the network will work to significantly improve the overall performance of the WSN and boost the quality of services of these increasingly deployed networks.

Though efforts to design, simulate and analyse the different WSN scenarios have been succeeded and generated results that might have some practical implications to the WSN industries, generalizing the results and implementing their consequences will still require testing them on a larger scale scenario in a more realistic condition.

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Abbreviations

IoT	**Internet of Things**
WSN	**Wireless Sensor Network**
MAC	**Media Access Control**
WLAN	**Wireless Local Area Networks**
TCP	**Transport Control Protocol**
Wi-Fi	**Wireless Fidelity**
PAN	**Personal Area Network**
CSMA/CA	**Carrier Sense Multiple Access with Collision Avoidance**
AES	**advance encryption standard**
DSSS	**Direct sequence spread spectrum**
ACL	**access control list**
APS	**application support sublayer**
ZDO	**Zigbee Device Object**
SSP	**Security Service Provider**
ZC	**Zigbee coordinator**
ZR	**Zigbee Router**
ZED	**Zigbee End Device**
LEACH	**Low energy adaptive clustering hierarchy**
HEED	**hybrid energy efficient distributive protocol**
QoS	**Quality of Service**
IEEE	**Institute of Electrical and Electronics Engineers**
WPAN	**Wireless Personal Area Networks**
SD	**superframe duration**
BI	**beacon interval**
CAD	**controller assisted distributed**
MLB	**Multipath Load Balancing**

Chapter 1

1.1. Introduction

Wireless sensors networks have gained an intensive research interest during the last decade as it is considered a use-case scenario for the upcoming fifth wireless mobile generation (5G). It is also considered as a special type of Internet of Things (IoT). The massive jump in terms of data rate, latency reduction and the increase in number of users supported, makes it possible for WSN to be realized for many applications such as industrial wireless networks and in-vehicle communications [1]. WSN is defined as a network of tinny sensors that are capable of monitoring, sensing and transmitting short packets of data to base stations or gateways as is shown in Figure 1.1. The entire WSN is connected to the Internet backbone through an IP based gateway, and this makes it more flexible for the user to access the collected data or to control the network at any time, and from anywhere on the earth.

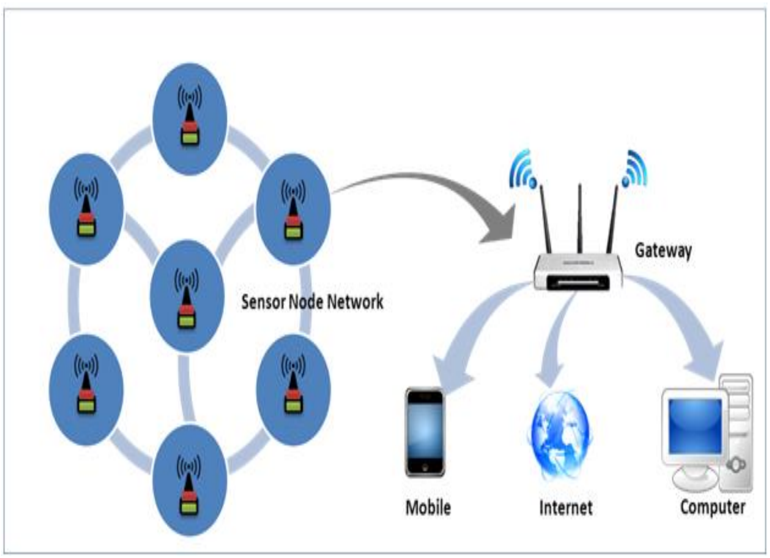


Figure 1.1 Overview of wireless sensor network

The IP based gateway makes it possible to transmit the collected data to another server for further processing. In the WSN sensors are battery powered, thus, energy efficiency is a critical metric for any algorithm related to medium access control (MAC) or the network layer routing protocols.

As is shown in Figure 1.2, IoT/WSN is currently on the top of Gartner's hype cycle for 2015, as an emerging technology and the estimation is that WSN/IoT could be realized within 5-10 years and will be driven by the capabilities of 5G [2]. Furthermore, WSN could be integrated with other emerging technologies such as Big Data and deep learning. This is how WSN will be integrated in the automated solutions for many problems in the field of failure prediction, manufacturing process self-optimization and for healthcare applications, among other potential applications.

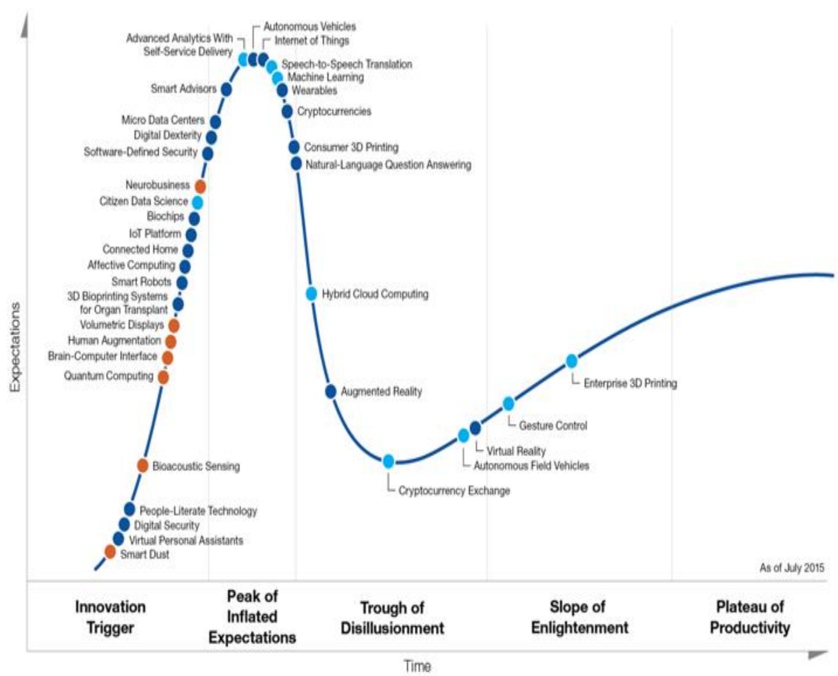


Figure 1.2 Gartner's Hype Cycle for Emerging Technologies, 2015 [2]

As for any other system, WSN should be designed in a way such that the behavior of the network is controlled and estimated beforehand. To that end, simulations, besides theoretical analysis, is used an efficient tool to design, build and analyze WSN. Among other simulators, OPNET Modeler [3] has a wide range of capabilities needed for simulating and analyzing wired and wireless networks including WSNs. OPNET Modeler can also provide access to many routing and MAC protocols which enable the researcher to integrate these protocols, study and analyze them for a proper network design. Such a simulator makes it possible for researchers to study and investigate many aspects of WSN including routing protocols and network topologies before proceeding towards Real-time systems. Besides, OPNET Modeler is a user-friendly simulation environment equipped with a Graphical User Interface (GUI), which allows the user easily to adapt the network scenarios and have the possibility to change the network parameters.

1.2. Problem Statement

The IEEE 802.15.4 / ZigBee standard has been proposed by the Zigbee Alliance as a candidate for WSN. This protocol has the necessary features that suit some applications like WSN, where the nodes are battery powered.

As for any wireless network, many of the network parameters such as end-to-end delay, network lifetime and energy consumptions are affected by the topology formation. Up to the author's knowledge, the effect of the network topology on the performance of WSN based on IEEE 802.15.5 is still an open question and needs a further investigation. Additionally, there has been a lack of information that are related to scenarios specific studies such as the scenario where two gateways are deployed to avoid the bottleneck problem, and so on. These issues will be thoroughly studied and analyzed throughout this thesis.

1.3. Background

Any kind of wireless connectivity nowadays requires a direct connection to the Internet. However, for some applications, the data could be processed at a local network stage before being sent out to the Internet. In the case of WSN, it may not be required for the network to be connected to the internet at all, instead, the acquired data could be displayed locally on a smartphone or a PC. For some other applications, such as industrial WSN or WSN deployed for environmental protection, the data acquired by the sensors must be transferred to a remote location and this task should be accomplished by connecting the WSN to the Internet through one or several gateways. The network topology, i.e., the way the sensors nodes are deployed and connected through point-to-point connection to each other, will have a significant influence on the overall network performance such as the overall throughput and the network lifetime. The topology of WSN is driven by the application for which WSN is used. For example, a star topology could be used for a simple personal area network, whereas a mesh topology may be used for WSN for home monitoring applications [4].

For some applications, the sensors within WSN can be isolated from each other, while for other real-world applications such as industrial WSN and IoT, the sensors should be integrated and deployed in a specific topology. The architecture of any wired/wireless topology can be classified as a flat or as a hierarchical architecture [5]. In the flat topology (also referred as peer-to-peer topology) all the nodes in the network have the same communication and computational capabilities. In hierarchical network topology, the sensors and the nodes are classified according to their capabilities, for example, a node with lower capability capture the required data and transmit the these data to another node that may have more computational capabilities. This kind of nodes (with more capabilities) usually referred as the cluster heads.

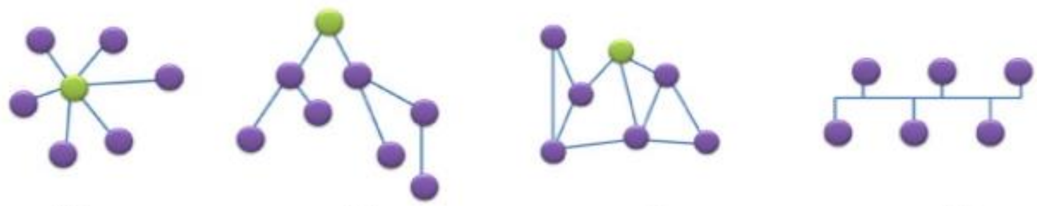


Figure 1.3: Graphical representation of (a) star, (b) tree, (c) mesh and (d) bus topologies

In this thesis, we aim at studying different network topologies, mainly the star, mesh and tree topologies and compare their efficiencies in term of various metrics in combination with specific routing protocols. Figure 1.3 shows the most common forms of network topologies. Line, star and bus topology are common topologies for wired sensor networks. In the case of WSN, star, tree and mesh are the most common topologies, and will be analyzed by this thesis.

1.4. Research Objectives

The performance of WSN based on IEEE 802.15.4 will be studied and analyzed in this thesis. More specifically, the effect of different network topologies, mainly, tree, mesh and star will be studied and evaluated in terms of network metrics such as the throughput, end-to-end delay. Additionally, the effect of different WSN elements will be studied and analyzed such as the effect of increasing number of Zigbee end devices (ZEDs), the effect of the number of Zigbee coordinators (ZCs) and Zigbee routers (ZRs). Moreover, the effect of nodes mobility will be studied and analyzed.

1.5. Thesis Contributions

The main contributions of this study can be summarized as following:

- Analyze the performance of WSN based on the IEEE 802.15.4 protocol. The performance analysis will be carried out by simulations using the OPNET simulator where different network topologies will be considered.
- Propose a modification to the traditional WSN architecture where only one coordinator is used. Hence, the performance of WSN will be studied and analyzed in the case of two coordinators, Studying the effect of the nodes mobility and impact of the number of nodes to see how that will impact the overall performance. The aim of this modification is to solve the bottleneck problem.
- Come up with a list of recommendations regarding which network topology to use, when the different network metrics, i.e. throughput, end-to-end delay, or power consumption is given the priority.

1.6. Organization of the Thesis

The following chapters will exhibit how the above-mentioned contributions will be realized. An overview of the IEEE 802.15.4/ ZigBee protocol applied to WSN will be described in Chapter 2, where the detailed structure of the IEEE 802.15.4 will be detailed. In chapter 3, a literature review on the impact of the network topology on the performance of WSN will be presented. Chapter 4 will detail the simulation environment, and the various WSN scenarios simulated and analyzed using OPNET simulator. The simulation results will be analyzed, discussed, and presented in chapter 5. Conclusions and recommendations for future work will be presented in chapter 6.

Chapter 2

An overview of Zigbee Protocol for Wireless Sensor Networks

2.1. Introduction

In this chapter, we present the main concepts and theories based on which wireless sensor networks (WSN) are built. Firstly, the main fields of applications of WSN will be described. Secondly, an overview of sensor networks design, architecture, and Topologies that will be considered by this thesis will be detailed. This part concludes with a brief description of the major challenges facing these technologies. Throughout the remaining parts of the chapter describes the protocol stacks used by Zigbee Technology.

2.2. Description of Wireless Sensor Networks (WSN)

2.2.1. Wireless networks vs. wireless sensor networks

A wireless network is defined as a network of devices such as computers or mobile phones, or any other device that uses wireless channels as its communication medium. In such a network, devices can either communicate directly to each other or via a base station as is the case in cellular mobile network and in wireless local area networks (WLAN), see figure 2.1 for illustration.

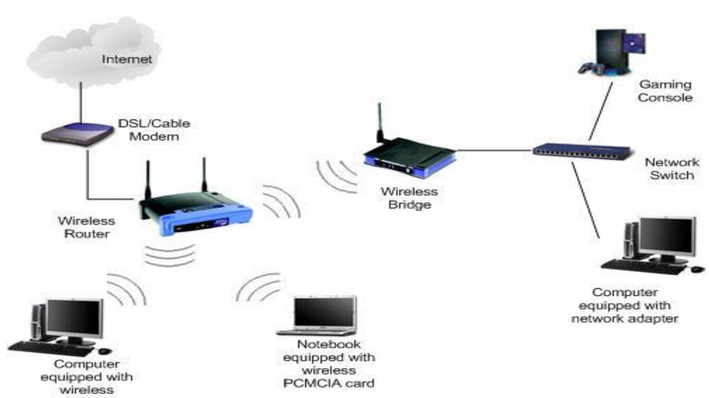


Figure 2.1: An example of WLAN

The protocol that defines the WLAN parameters as is defined by the physical or the MAC layer is the TCP/IP protocol which is derived from the Open Systems Interconnection protocol (OSI).

WSN is considered as an application specific of wireless network. In WSN, spatially distributed tinny sensors are deployed in a spot to monitor a specific phenomenon such as temperature, humidity, light, sound, movement, etc. Usually, each node in WSN consists of a specific sensor, a processing unit, RAM, and RF transmitter, see figure 2.2. Each node in WSN transmits its measurements to a central base station where further processing is applied to the received measurements [6]. Figure 2.3 illustrates an example of WSN where the sensors communicate with each other's and their measurements are sent over to a sink node.

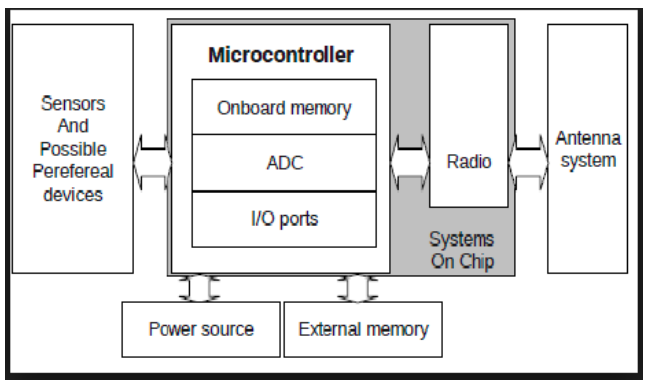


Figure 2.2: typical WSN node

The sink nodes process the received data and send it through the IP network to a central processing unit or server for further processing. Since sensors are battery powered, it is very critical to consider energy efficiency when designing a WSN. One of the issues that plays a role in determining power consumption is network topology since transmitting data through wireless RF is the source which consumes much of the network power.

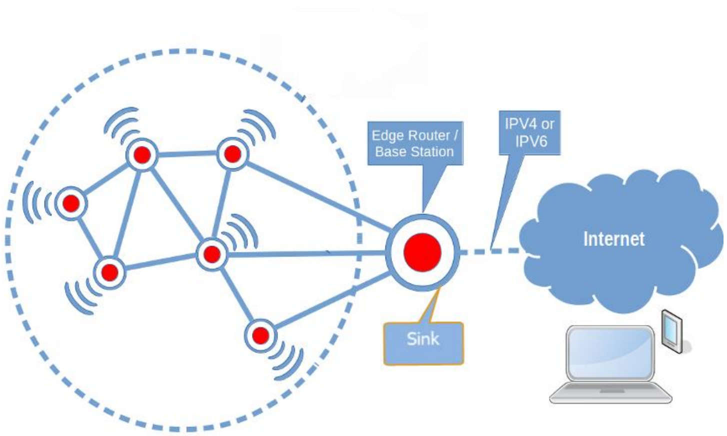


Figure 2.3: An example of WSN

2.2.2. IEEE 802.11 vs. IEEE 802.15.1

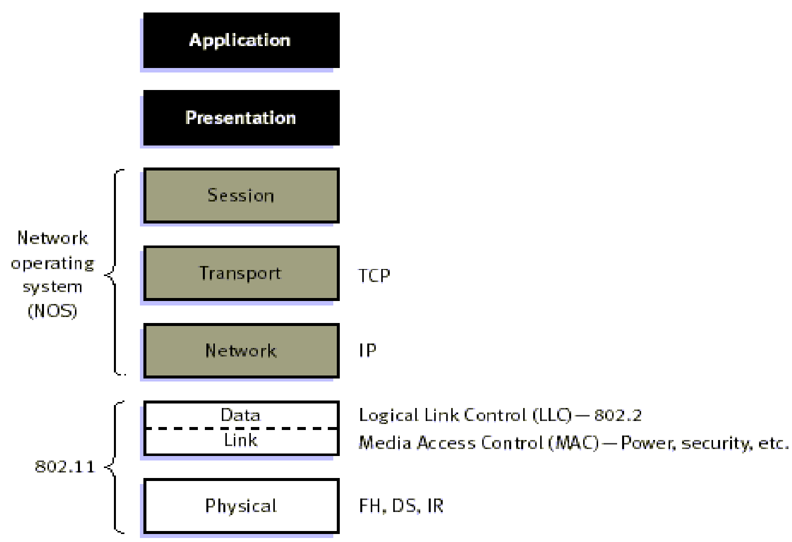


Figure 2.4: 802.11/OSI reference model

The IEEE 802.11 is the official standard for the networks that are supported by the WIFI protocol. This standard is designed with reference to the OSI protocol as is shown in figure 2.4.

Several advanced technologies such as orthogonal frequency division multiple access (OFDMA) and quadrature amplitude modulation (QAM) have been employed in the IEEE 802.11 / WIFI standard, to enable WiFi based networks to support the transmission of high data rates via a wireless channel [7]. According to the protocol specs, WIFI data rate ranges between 2 Mbps for early versions to 1.73 Gbps for up-to-date versions. It is worth to mention that WIFI enabled devices suffer from relatively high-power consumption making this protocol inapplicable for application scenarios such as WSN, where power consumption is very crucial determinant in that application [8].

Alternative wireless technology that is designed to support personal area networks (PAN) is the Bluetooth technology, as defined by the IEEE 802.15.1 protocol. The IEEE 802.15.1 is the official standard for Bluetooth based networks. Compared to WIFI, Bluetooth does not require high power since the transmission range is rather short and works up to 10 meters. Carrier sense multiple access (CSMA) is the MAC technique used in Bluetooth. The number of Bluetooth devices that can communicate with a single base station is limited to seven devices. Bluetooth can provide a shared throughput up to 2.1 Mbps within the 2.4 GHz frequency band. The IEEE 802.15.1 is preferred for connecting personal devices such as a keyboard or headphone. However, it is not preferred for WSN where many devices need to communicate with the base station and with transmission range that goes beyond 10 m [9].

2.2.3. Zigbee / IEEE802.15.4 Protocol

To solve the issue of power consumption, communication range and number of communicating nodes, Zigbee protocol was put forward. Zigbee is a wireless technology that is built on the IEEE 802.15.4 standard. This standard is designed to support high level communication in personal areas networks with low RF power, which can be used in home automation, industrial wireless control, and WSN. Zigbee is the most common technology used for cost and energy efficient wireless networks. The Zigbee transmission range lies within a range of 10 – 100 meters. The IEEE 802.15.4 standard defines the physical layer and MAC layer for Zigbee networks, and it operates in the industrial, scientific and medical

(ISM) radio band, of 2.4 GHz [10]. Zigbee can provide up to 250 Kbps of data throughput which is considerably lower than the throughput provided by other technologies such as WIFI or Bluetooth. However, Zigbee is much more cost and energy effective compared to those technologies.

A set of devices or sensors can wirelessly communicate in a Zigbee network with one of several possible topologies. Data packets can be exchanged among nodes and can be routed to a distant base-station via intermediate nodes. Each node in a Zigbee network has MAC address and a network address, while the whole network has its own ID that should be shared by all nodes in the network. An encryption scheme is also provided by the IEEE 802.15.4 where a 128 bits Advance Encryption Standard (AES) is utilized to protect the data packets communicated by the nodes.

All above-mentioned features of the Zigbee technology make it a good candidate for WSN and for many other applications where power and cost efficiency are crucial elements.

2.3. Zigbee Protocol Architecture

Figure 2.5 shows a simplified overview of the Zigbee protocol stack, which is based on the OSI model [11].

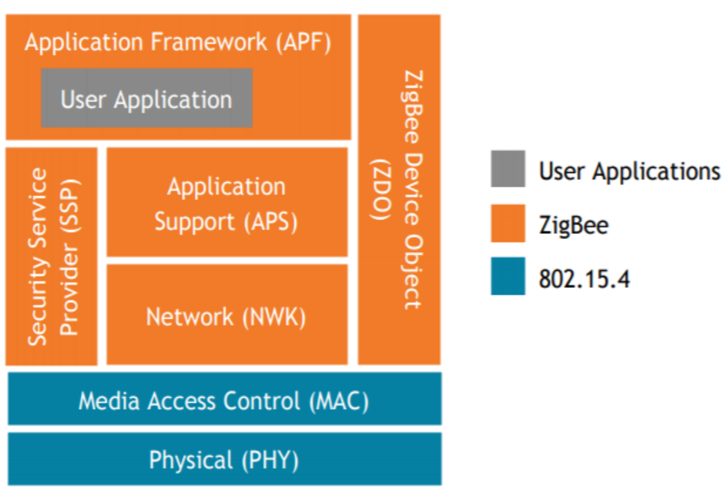


Figure 2.5: Zigbee protocol stack [11]

2.3.1. Zigbee / IEEE 802.15.4 PHY Layer

The physical (PHY) layer in the ZigBee protocol is defined by the IEEE 802.15.4 standard, to be responsible for the physical transmission of data packet over the wireless channel. Modulation and demodulation of the data packets are performed in this layer. Direct sequence spread spectrum (DSSS) modulation scheme is also utilized in this layer. According to the standard version of Zigbee, a maximum throughput of up to 250 Kbps can be provided. The following table gives an overview of the IEEE 802.15.4 frequency bands and their corresponding throughput.

2.3.2 Zigbee / IEEE 802.15.4 MAC Layer

The MAC layer in Zigbee technology is defined by the IEEE 802.15.4 protocol too. The medium access mechanism is CSMA/CA is employed to avoid collisions among transmitted packets from different nodes, where the medium status (occupied / non - occupied) is examined by each node before initiating the transmission process. Additionally, the MAC address for each node is defined and managed by this layer. The network topology based on which the Zigbee network is built, is also defined in this layer. On top of that, the access control list (ACL) is provided by the MAC layer to allow higher layers to support secure communication mechanism.

Table 2.1: overview of the IEEE 802.15.4 frequency bands

PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868/915	868–868.6	300	BPSK	20	20	Binary
	902–928	600	BPSK	40	40	Binary
2450	2400–2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

The IEEE 802.15.4 MAC layer supports two modes of operation, non- beacon enabled and beacon enabled mode. In the beacon enabled mode, each node in the network must transmit a beacon message for the purpose of association and synchronization with other nodes in the network. This synchronization within the entire network makes it possible for each node to send its packet at the beginning of a specified time slot (Slotted CSMA). On the other hand, all nodes within the network are not synchronized in the non – beacon mode, hence, there is no need to transmit a periodic beacon message. In this scenario, the unslotted CSMA/CA is utilized for medium access, where each node can send its packet at any time.

Besides the lack of synchronization among the whole network in the non - beacon mode, the time evolution in the non – beacon mode is continuous, in which an event could occur immediately after the first event end (no need for back - off slot). However, the time evolution in the beacon – mode is discrete where events only occur at the beginning or at the edge of the time slots.

Many research activities have been carried out to study the performance of both operation modes (references are needed here). It can be concluded that the performance of both modes depends primarily on the network parameters such as total number of nodes, network topology, and data packet length.

2.3.3 Zigbee Network Layer

One of the most complex layers in the Zigbee protocol stack is the network layer, which is also defined by the IEEE 802.15.4 standard. This layer has the task of discovering and joining networks based on the network topology defined by the MAC layer in a way such that the network is built according to either mesh, star or tree topology. Supporting different kinds of network topologies is very important feature of the Zigbee technology making it preferred in scenarios when adapting to certain topology is required. Additionally, the network layer is responsible for route discovery through the Zigbee network layout. Routes from source to destination are calculated using specific route discovery algorithms, where these routes are stored in a routing table at each node.

2.3.4 Network Topology

Three different topologies are supported by the Zigbee network layer, these are;

1. Star Topology
2. Tree Topology
3. Mesh Topology

In the following, the features of each topology will be detailed.

- **Star Topology**

One of the simplest network topologies supported by Zigbee is the star topology. In this topology, all nodes are connected to a single coordinator where all the communications should pass through this coordinator as is depicted by Figure 2.6.

Routers may be deployed in this topology as a child node, however, where no routing functionality will be performed, and the router will act as end device in this case. It is worth mentioning that the whole network throughput is controlled by the coordinator, which implies that when the coordinator fails, the whole network will be down. Moreover, the coordinator range will limit the working range of the whole network.

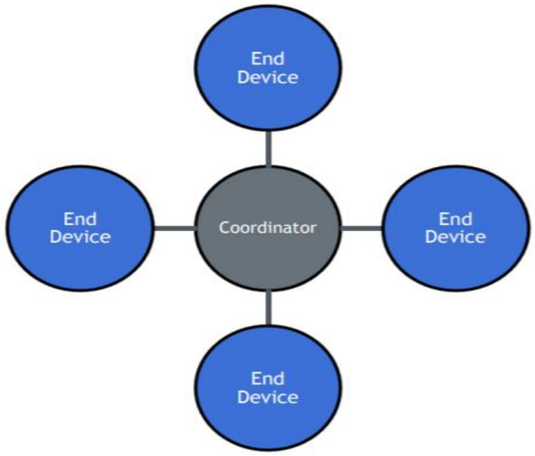


Figure 2.6: Star topology

- **Tree Topology**

In this topology, the coordinator node (or parent node) is the one which initializes the network and forms the root of a tree. End Device is then considered as leaf node (or child node). Intermediate nodes in the tree topology do work only as routers to route packets to the coordinator node.

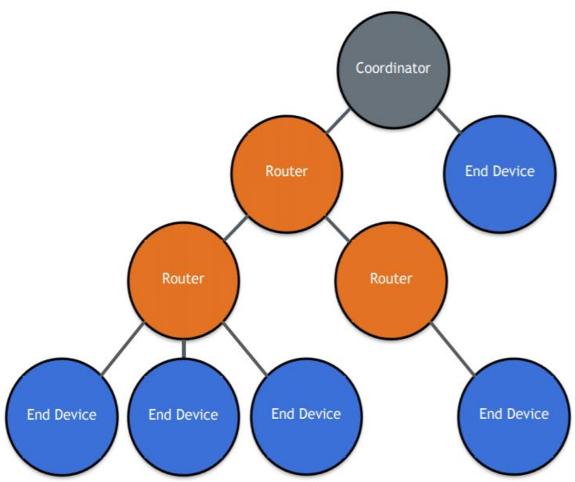


Figure 2.7: Tree topology

However, in the case when no child has joined the network yet, the router could also act as a leaf node. Tree topology can be viewed as two or more connected star networks. Figure 2.7 shows an example layout of tree topology.

A child node can send its message directly and only to its parent node. However, each child node can communicate with another child node by passing the message upward to a common router and then passing it down to the end destination. In the case of a router failure, all the corresponding child nodes will be isolated from the whole network.

- **Mesh Topology**

This topology is counted as the most flexible network topology supported by Zigbee technology. Mesh topology is closer to tree topology than star topology; however, a router in mesh topology can communicate with any other router or coordinator within its transmission range. This implies that various routes could be made available to be used by any pair of source and destination nodes. The Zigbee technology has the functionality of route discovery which allows the network to locate the best possible route from the source to the destination. See figure 2.8 which represents a possible layout for the mesh Zigbee topology.

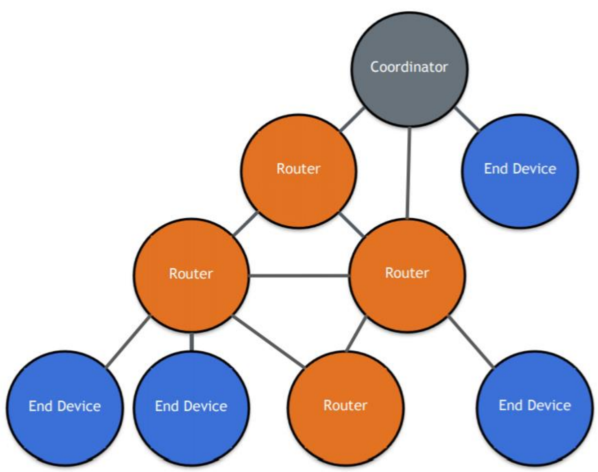


Figure 2.8: Mesh topology

2.3.5 Zigbee Application Support Sublayer

The application support sublayer (APS), is the sublayer located on top of the network layer and acts as an interface to the application framework (APF) layer. The APS sub-layer works to store the IDs of clusters and end devices in the network. Moreover, APS works to filter out packets whose IDs do not match the profile ID. Besides, the APS is responsible for sending out an acknowledgment packet for the transmitting nodes to indicate a successful or failed reception of the sent packet.

The application support layer incorporates three different units that work together to accomplish its functionality and provide quality of service; these units are; Zigbee Device Object, (ZDO), Security Service Provider (SSP), and Application Object (or endpoint).

The Zigbee device object (ZDO), (refer to figure 2.5), is an application sublayer which has the task of Initializing the application, network and the security service (SSP) provided by the Zigbee network. ZDO is essentially needed in any Zigbee supported device that could be deployed in any network such as home automation or smart grids. ZDO is able to access routing tables and IDs for any device within the network. It can further discover neighbouring nodes and manages connectivity with these nodes.

The security mechanism for those layers that require encryption such as the network and the application layers are provided by security service provider (SSP), which is initialized and configured by the ZDO.

Finally, the Application Object (AO) is a software that controls the Zigbee device at the endpoint. It is located at the top of the application layer and is specified by the enabled, manufacturer, and designed to implement the functionality of the device being a light bulb, a light switch, an LED, or an I/O line. Up to 240 applications objects can be supported by a single Zigbee device.

2.4 Zigbee Hardware

Zigbee based network should be formed by three elementary objects; Zigbee coordinator, Zigbee router and Zigbee end device. All Zigbee devices are manufactured according to the IEEE 802.15.4 standard for Low Rate Wireless Personal Area Network (WPAN). Below is a description of each element.

Each Zigbee network should have a single coordinator. This node has the task of initializing the entire network, including defining the radio frequency band and the network ID. The coordinator is the node that allows or denies access of other nodes to join the network. Another security and routing services are also performed by the coordinator node.

The Zigbee Router is not necessarily included in all Zigbee topologies. The router node is responsible for forwarding and relaying messages communicated among all nodes. Other nodes can also join the network via a router, in that case it acts as their parent node and the joined nodes are counted as child nodes.

A Zigbee End device is a very simple node in the Zigbee network that can collect, send and receive messages. Usually, the end device is equipped with special sensors or actuators where the recorded measurement is sent through the network to the coordinator. According to the IEEE 802.15.4 standard, the end device is the only device that can sleep, when the messages are buffered at the coordinator or at the router until the end device wakes up again.

Chapter 3

Literature Review on the impact of the network topology of Zigbee networks

3.1 Introduction

Noticeable research efforts have been carried out recently to analyze the performance of wireless sensors network and IoT, by considering different factors that have an impact on the network performance such as the latency and data transmission rate. However, the impact of network topology on the total network performance is still an open research question. Since IoT and WSN could have different deployment scenarios, it worth to study and analyze the effect of the network topology on different performance metrics, of both networks.

Analysing the effect of the network topology is an interesting research topic which had been intensively studied in the case of WLAN and Ad-Hoc networks. However, the effect of such topologies still needs to be investigated considering Zigbee as the network protocol.

An overview of WSN and an energy efficiency comparison study for different network topologies have been studied by [12]. The study concluded that the topology that utilizes the fusion center as a central base-station is the most energy efficient one, particularly, in case of a WSN with a uniform distribution of sensors. However, in the case of randomly distributed sensors, the clustered network topology turned out to be more efficient.

The IEEE 802.15.4 is designed in a way such that it can support low-cost and low power consumption wireless personal area network (PAN). However, this protocol does not provide any constraints on the network topology and it mainly supports star topology (peer-to-peer) and the tree topology. On the other hand, robust multi-hop communication and the more flexible networks are supported by the mesh network topology on the expense of additional complexity. A formation for mesh topology based on the IEEE 802.15.4 protocol has been studied by (Lee et al., 2015). The proposed mesh topology assumes that the entire network nodes operate on a fixed beacon interval (BI) and active super frame duration (SD). Hence, all the nodes share the same super frame structure. The timing diagram of the proposed scheme of [13] is shown in Figure 3.1 In this scheme, the network coordinator collects information like other networks ID and channels, then to join the other network, it selects one of the IDs and broadcast beacon frame ID to the neighbouring network router. The neighbouring network router reply by transmitting an association request which will be replied by an association response and a mesh configuration will be initialized between the two-neighbour networks.

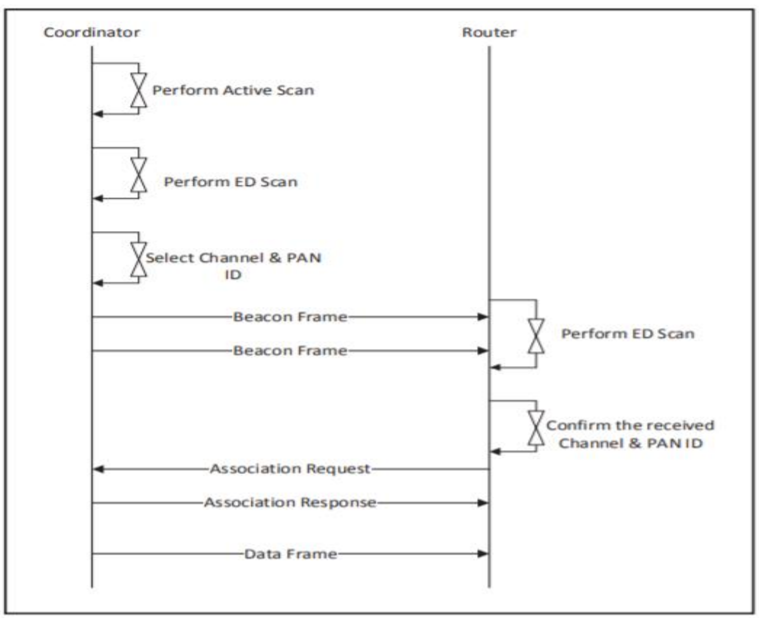


Figure 3.1: Timing diagram of the proposed mesh scheme [13]

It has been shown by (Lee et al., 2015) that their proposed scheme can save up to 16% of the network power consumption compared to the standard IEEE 802.15.4.

A comparison study has been performed by [14] among four different networks topologies; distributed, hierarchical, centralized, and decentralized. In their study, a newly distributed data collection mechanism for network status has been proposed and the impact of this mechanism on the network lifetime has been discussed. It has been concluded that the decentralized topology outperforms other network topologies in term of the network lifetime.

A new topology framework for WSNs that combines three design approaches: clustering, routing, and topology control have been introduced by [15, 16]. An energy efficient zone-based topology and routing protocol have been proposed and tested. Their simulation resulted in an improvement of 28% in energy consumption in relative to their referenced framework.

[17] Have studied the performance of IEEE 802.15.4 based WSN. The performance of three network topologies; star, mesh and tree were calculated and compared to each other's in terms of the overall network throughput. It has been concluded that the mesh topology outperforms other topologies in terms of network throughput for the increased number of sensors. However, when the total number of hops is considered, the tree topology outperforms the others.

[18] Studied the network throughput for application-specific routing protocols and concluded that star and mesh among other network topologies are more flexible and provide more mobility, thus they are suitable for rapid changing applications.

For industrial timely sensitive applications, the deployment of WSN nodes affects the overall network latency and throughput as reported by [19]. In addition, the QoS of the overall network is mainly affected by network reliability and energy consumption, which are determined by number of hops from source to destination [20]. Hence, it is obvious that a good network topology can significantly increase the network throughput and subsequently decrease the end-to-end delay.

[21] Concluded that cluster-tree outperforms mesh and star topology, since it can handle up to 20 % and 45 % more load than mesh and star topologies respectively. However, the cluster – tree topology is better in terms of the end-to-end delay.

Topology control for WSN can be implemented by either power adjustment techniques or by clustering techniques. Low energy adaptive clustering hierarchy (LEACH) scheme as described by [22] is considered as the most popular clustering technique, in which data packets are sent from nodes to the cluster head and then to sink node. This process is achieved through two phases; the setup phase and the steady state phase. In the setup phase, a cluster is formed, and then a cluster head is elected. In the steady state phase, transmission from source to sink takes place through the cluster head. The energy efficiency of such a scheme is very low since the cluster head is responsible for data delivery to the sink node in a single hop. Additionally, similar schemes like hybrid energy efficient distributive protocol (HEED) has been proposed by [23]. In this scheme, the data will be collected by the cluster head and then sent to the sink through other cluster heads in a multi-hop manner. This scheme is more energy efficient since the transmission of the data will be distributed over several cluster heads.

On the other hand, the power adjustment technique proposed by [24] ensures that network lifetime and the energy consumption can be enhanced by having different transmission power levels at the sensor node. In this technique, the transmission power is varied according to the network condition and results in an increased lifetime for the network.

Load balancing plays a vital role in the case of WSN. A controller assisted distributed (CAD) load balancing has been proposed by [25]. In that study shifting the enforcement part from the central controller to PANs was proposed, where each PAN in CAD maintains its load status, whereas the central controller simply maintains node numbers of each PAN.

[26] Have developed a Multipath Load Balancing (MLB) Routing to substitute Zigbee's (Ad-hoc on-demand distance vector) AODV routing protocol. They proposed MLB which consists of two main designs: layer and load balance design. Layer design assigns nodes into different layers based on node distance to IoT gateway. Nodes can have multiple next-hops delivering IoT data. To implement load balance design, all neighbouring layer nodes exchange flow of information containing current load, and this information is used by load balancers to estimate the future load of next-hops. With MLB, nodes can choose the neighbours with the least load as the next-hops and thus can achieve load balance and avoid bottlenecks.

A novel stochastic Zigbee network model has been proposed by [27]. In this study, the widest path process has been utilized for traffic orientation, traffic queuing and for loads minimization. The model has been evaluated by the simulation environment Riverbed and the results show that applying the widest path process will minimize the traffic load at the MAC layer as well as over the whole network. Basically, the widest path process is a technique to discover the best routing path for a certain amount of traffic.

3.2 Knowledge gap

It can be noticed from the literature review that nearly all the studies have considered different network topologies which only have one coordinator for the whole network. However, an intensive study is still required to investigate the performance of the network in the case of two or more coordinators especially for the purpose of load balancing and enhancing the total end-to-end delay. From the theoretical point of view, having two or more network coordinators will result in enhanced performance. Till now and to our knowledge, simulations and analysis of these topologies are still required, and this is the aim of this study.

3.3 Research rational

Technology can serve many diverse industrial and civilian fields. Nowadays, WSN can be employed in scenarios that can make our life safer and easier such as using WSN for controlling our home appliances. Another example where safe WSN is required is the self-driving vehicles where many sensors are deployed and used for many estimation and measurements operations. Such an application requires deep analysis for a proper operation assurance. This is a key motivator for our study.

In addition, the research society will benefit from the result of my study in a way such that they become more aware of the effects of the topology and routing protocols on the performance of WSN.

Chapter 4

Performance Evaluation of Different Network Topologies for WSN

4.1 Introduction to Simulation environment

A bunch of software simulation packages can be used to simulate different kinds of wired and wireless networks. Among other network simulators such as NS-2, NetSim, OMNET++, OPNET stands for Optimized Network Engineering Tools, has been chosen for our thesis for various reasons. OPNET is an extensive and powerful tool with broad range of opportunities to simulate complete heterogeneous networks supported by many protocols [28] OPNET can be set to supply a complete development environment for design, simulation and performance analysis of wired and wireless data networks. Among the reasons to use this simulator is the flexibility with which parameters can be set, and various kinds of networks that can be formed. Additionally, the range of parameters with which the simulation environment can be defined is quite simple and straightforward. The OPNET simulation environment is used to simulate ZigBee-technology based networks by setting up various ZigBee components such as ZigBee coordinator, ZigBee router, and ZigBee end device, where these components can be a fixed or a mobile node [29].

OPNET is developed by OPNET Technologies, Inc. [30]. OPNET is built based on the OPNET Modeler, a fast, distinguished simulation engine operating with a 32-bit/ 64-bit fully parallel simulation kernel available for both Windows and Linux.

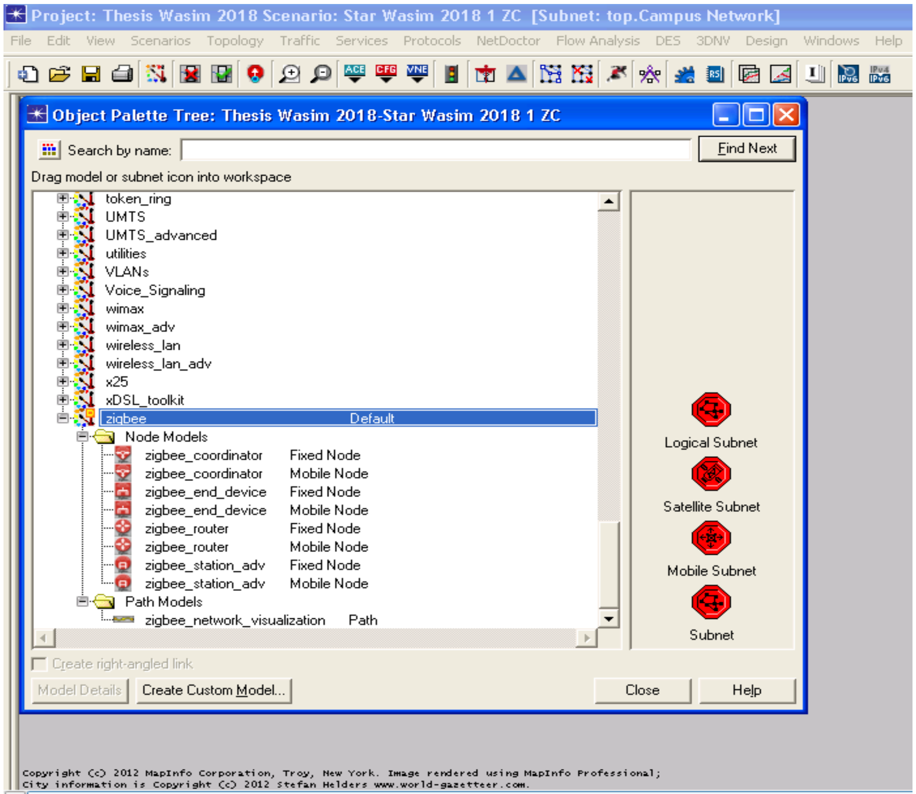


Figure 4.1: OPNET simulation graphical user interface

The OPNET Modeler concentrates on an object-oriented modeling approach and a hierarchical modeling environment with no special routing protocols available for wireless sensor networks. Simulations of wireless networks can be run as a discrete event, hybrid or analytical, encompassing terrain, mobility and path-loss models, see figure 4.1

4.2 The OPNET Simulation Model of IEEE 802.15.4

[31] Developed an open source tool for IEEE 802.15.4 /ZigBee called Open-ZB, which is used by the OPNET simulator. In that environment, the PHY layer has a transmitter and a receiver working at 2.4 GHz frequency with a 2 MHz bandwidth and QPSK modulation. The MAC layer uses slotted CSMA/CA, and generates beacon frames and synchronizes nodes with a PAN Coordinator. The battery module determines used and surplus energy levels. The application layer has a sensory data generator using unrecognized frames and a

MAC command frame generator creating acknowledged frames. The sink module executes statistics of the received frames. The radio model contains the standard OPNET wireless modules emulating the radio channel with elements such as interference, noise, bit error rate (BER), propagation delay etc. Figure 4.2 shows the structure of the IEEE 802.15.4 Simulation Model as described by [32].

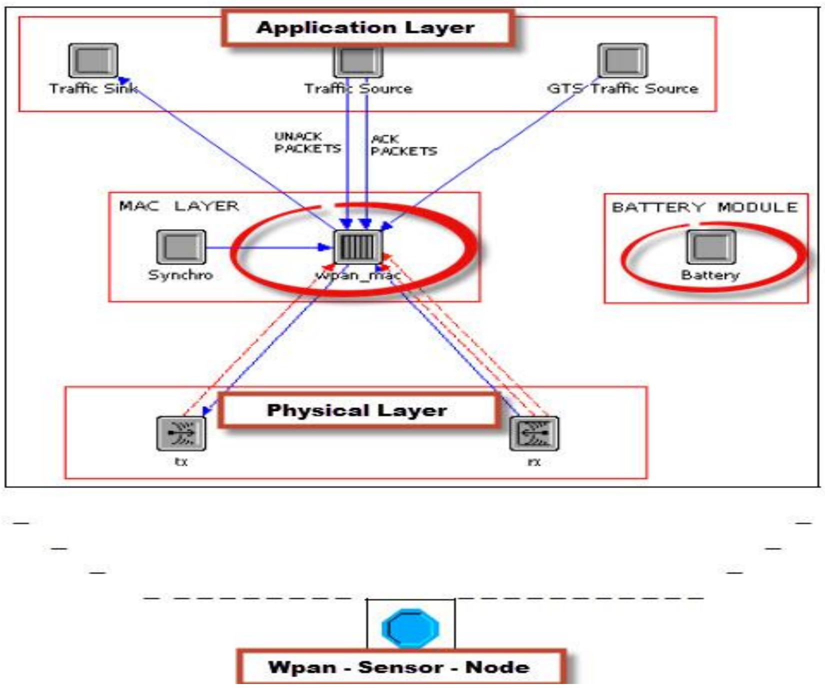


Figure 4.2: The structure of the IEEE 802.15.4 simulation model

4.3 Advantages of OPNET Modeler for Zigbee WSNs

There are certainly some advantages of using OPNET Modeler to simulate Zigbee WSNs. OPNET can provide a wide range of reports and statistics at different layer levels (especially at the MAC layer) for an individual node or for the entire WSN. IEEE 802.15.4/Zigbee networks are battery powered which requires these networks to be low power, low cost, low data rate for the sake of sustaining a long battery life. The Zigbee protocol is an advanced solution that is made to achieve these goals, and to build a reliable, secure and easy to implement in hardware WSN.

4.4 Simulation scenario and parameters

In this section, we report on the efficiency and effectiveness of the proposed network topology throughout series of experiments carried out using the OPNET modeler network simulation. A detailed overview of the implementation parameters of the proposed network topology and the simulation scenarios are provided as well.

It is to be stated that adaptive and performance enhancement for IoT networks is the main target of our analysis of network topologies. This is tested via employing more than one coordinator within the network, to see whether performance can be improved and consequently reduces network bottleneck. Remark that our proposed network topology is contention-based too, which makes the comparison quite fair. The comparison is done via assessing throughput, latency, and reliability metrics for different topologies.

Nine scenarios have been studied and analyzed. In the first three scenarios, the effect of three network topologies is examined (Star, Tree and Mesh) while the network has 1 ZC, 6 ZR and 10 ZEDs and the effect of nodes mobility has been also studied and analysed.

In the second three scenarios, the effect of the three network topologies has been also analyzed in the case of increasing number of ZED (5 to 50 ZEDs) while the network has 1 ZC and 6 ZRs.

In the last three scenarios, the three network topologies have been studied while the network has 2 ZCs, 6 ZRs and the number of ZEDs is varied from 5 to 50.

All scenarios have been compared by means of: end-to-end delay, throughput, and MAC load and packet delivery ratio.

OPNET, which offer two types of user-defined statistics: local and global, in general, see table 4.1.

Table 4.1: Simulation Zigbee parameters overview

parameters	Description
Device Type	End Device,Router,Coordinator
Data Rate	250 kbps
Packet size	Constant (1024) Bits
Transmission Power	0.05 W
Mobile speed	1 m/s
Traffic destination	Coordinator
Mobility type	Random
PAN ID	Auto Assigned
Transmission Bands	2.4 GHz
No. of nodes (overall)	57
No. of coordinator	1 Or 2
No. of routers	6
No. of end devices	5 To 50
Simulation Area Size	650 * 650 M
Simulation time	10000 Sec

Local statistics are ideal for reporting activity that is private to a particular node in the system model, while global statistics are more concerned with reporting quantitative data about the system as a whole. Values measured for end device, router and Coordinator parameter are listed in table 4.1.

The packet arrival rate 250 kbps might be a bit too high for a sensor network, but given the circumstances and environment of the simulation, it worked perfectly for the given scenarios. The CSMA/CA parameters are set to the defaulted values since this satisfies the conditions of our scenarios perfectly.

The performance of the various topologies is strongly affected by the distribution of nodes (whether source, node, or routers). We did our best to keep the same distribution of nodes in all included scenario.

The mobile node speed is 1M/Sec, under the condition that the nodes stay in the transmission/reception range.

In general, the three significant system parameters in the coordinator are the maximum number of children of a router (Cm), the maximum number of child-router of a router (Rm), and the depth of the network (Lm), which is determined by the number of hops from the coordinator to the farthest device.

4.4 Layout of the Scenarios

4.4.1 Scenario One

Star topology with a single coordinator consists of a one Zigbee coordinator, zero routers and 10 end devices with the sensors are placed in the area of 650m* 650m. In each scenario, we studied the impact of topology types on the performance metrics such as an end to end-to-end delay, throughput, MAC Load, and packet delivery ratio.

4.4.2 Scenario Two

Tree topology with a single coordinator consists of a one Zigbee coordinator, 6 routers and 10 end devices with the sensors placed in the area of 650m* 650m from each other

4.4.3 Scenario Three

Mesh topology with a single coordinator consists of a one Zigbee coordinator, 6 routers and 10 end devices with the sensors placed in the area of 650m* 650m from each other.

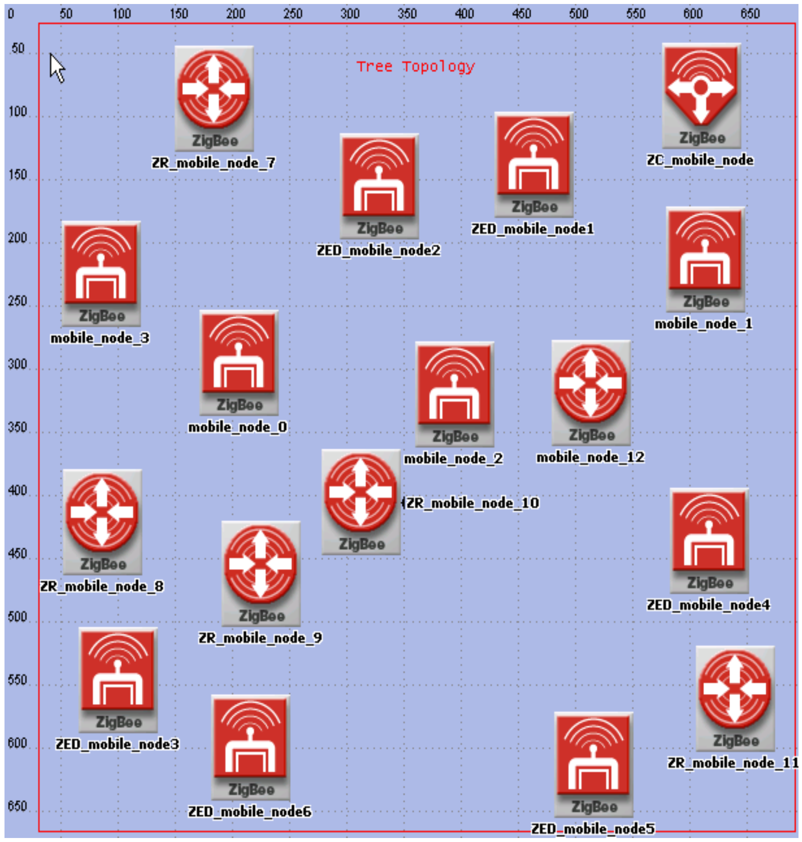


*Figure 4.3: Scenario 1, 2, 3 of Single Coordinator-Star, Tree, Mesh Topology (650m*650m)*

4.4.4 Scenario Four

Star topology with a single coordinator consists of a one Zigbee coordinator, zero routers and variable number of nodes starting from 5 to 50 end devices. In each scenario we studied the impact of adding the number of nodes on the performance metrics such as an end to end delay, throughput, MAC Load and packet delivery ratio. This sensors are placed in the area of 650m* 650m. The maximum area covered by one ZigBee station in specified by OPNET, and as long as the devices are within communication range of one another, they will be able to communicate.

4.4.5 Scenario Five

Tree topology with a single coordinator consists of a one Zigbee coordinator, 6 routers and variable number of nodes starting from 5 to 50 end devices. This sensors are placed in the area of 650m* 650m.

4.4.6 Scenario Six

Mesh topology with a single coordinator consists of a one Zigbee coordinator, 6 routers and variable number of nodes starting from 5 to 50 end devices. This sensors are placed in the area of 650m* 650m.

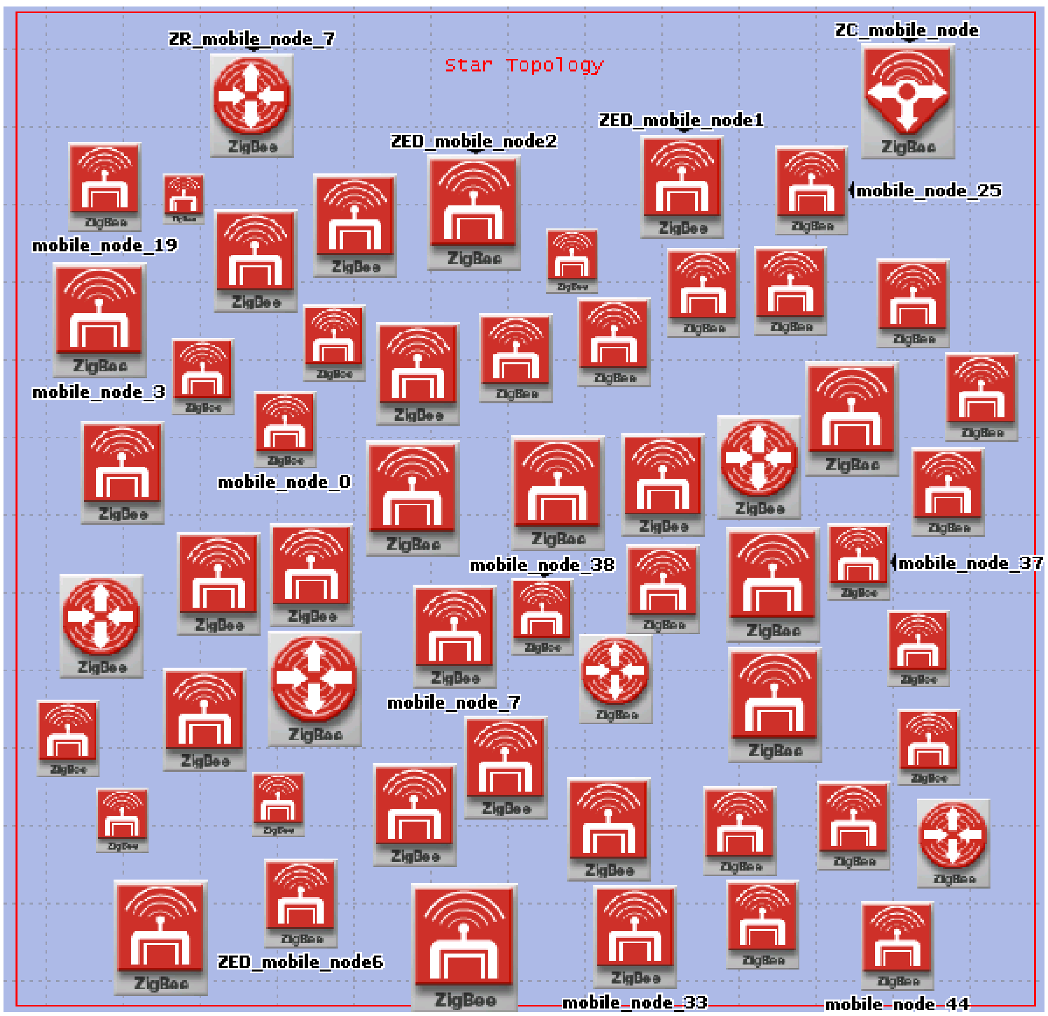


*Figure 4.4: Scenario 4, 5, 6 Function of the number of nodes -Star, Tree, Mesh Topology (650m*650m)*

4.4.7 Scenario Seven

Star topology with a two coordinator consists of a two Zigbee coordinator, zero routers and variable number of nodes starting from 5 to 50 end devices. In each scenario, we studied the impact of adding the number of coordinator on the performance metrics such as an end to end-to-end delay, throughput, MAC Load, and packet delivery ratio. This sensor is placed in the area of 650m* 650m.

4.4.8 Scenario Eight

Tree topology with a two coordinator consists of a two Zigbee coordinator, 6 routers and variable number of nodes starting from 5 to 50 end devices. This sensors are placed in the area of 650m* 650m.

4.4.9 Scenario Nine

Mesh topology with a two coordinator consists of a two Zigbee coordinator, 6 routers and variable number of nodes starting from 5 to 50 end devices. This sensors are placed in the area of 650m* 650m.

But the scenarios could not be connected to internet due to incomplete Zigbee model library in OPNET. To carry out this particular scenario we needed Zigbee gateway to have an internet connection. But this Zigbee gateway is still not available in the Zigbee model library in OPNET and is yet to be implemented in the latest version. To solve this problem, a different alternative was brought into light when we thought of connecting the Zigbee coordinator or router with IEEE 802.11 WLAN, better known as Wi-Fi, which in turn will be connected to an internet cloud in OPNET.

But the job still could not be done since the MAC layers and physical layers of both Wi-Fi and Zigbee Coordinator are completely different and are not compatible with each other. Without Zigbee gateway or Wi-Fi, the scenario could not be completed.

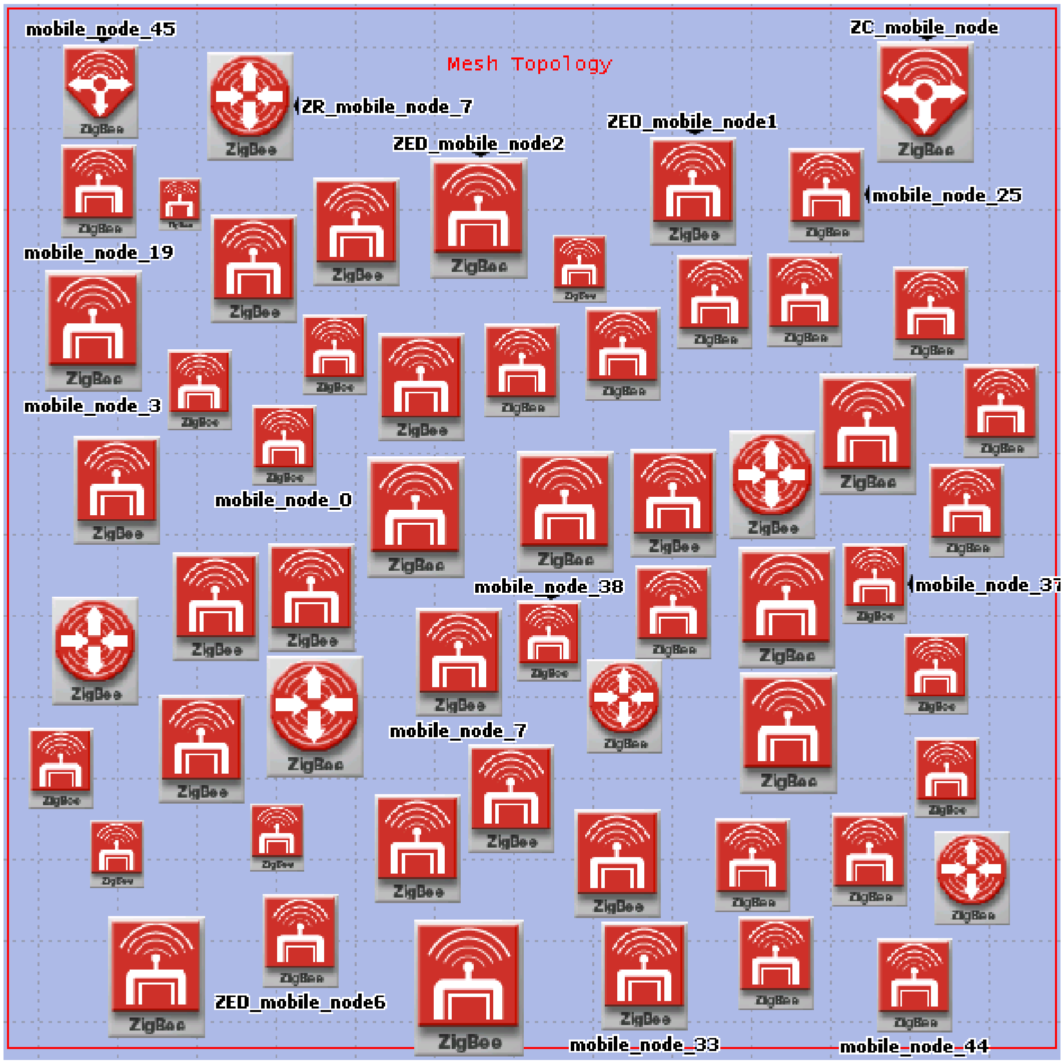


*Figure 4.5: Scenario 7, 8, 7 Function of the number of coordinator -Star, Tree, Mesh Topology (650m*650m)*

Table 4.2: summarizes the parameters used in the nine scenarios

Scenario	Topology	Coordinator	Routers	End Devices
1	Star	1	0	10
2	Tree	1	6	10
3	Mesh	1	6	10
4	Star	1	0	5 To 50
5	Tree	1	6	5 To 50
6	Mesh	1	6	5 To 50
7	Star	2	0	5 To 50
8	Tree	2	6	5 To 50
9	Mesh	2	6	5 To 50

Chapter 5

Simulation Result and Discussion

5.1 Introduction

The results presented in this chapter are obtained through OPNET simulations for the different scenarios proposed earlier in chapter 4. Results of different scenarios are contrasted with each other's and analyzed in terms of end-to-end delay, throughput, Packet delivery ratio, and MAC load for the sake of measuring the QoS of these Zigbee based WSNs. Results of different scenarios will be analyzed based on their recorded metrics for each layer in the TCP/IP protocol.

5.2 The impact of network topology on the performance of the WSN

In this section it is intended to detail the impact of the network topology on the performance of the WSNs, in cases of fixed and mobile nodes. The network performance will be examined through estimating the end-to-end delay of the network, the MAC throughput, and MAC load, in addition to the packet delivery ratio (PDR) which measures the ratio between received packets to the total sent packets in each cases. Tree, star and mesh topologies were included in the study. The simulated configuration encompasses of 10 end nodes, 6 router and 1 coordinator, and it has been decided to use this configuration to study the impact of topology and only topology on the WSN performance. The simulation results are described in the subsections listed below.

- **Impact of network topology on the end-to-end delay**

End-to-end delay is the total time needed between the creation and reception of an application packet. Figure 5.1 shows the results of the end-to-end delay for the 6 considered scenarios described above. As is exhibited by Figure 5.1 the experienced delay is indeed a function of the used topology, and of whether the included nodes are fixed or mobile within the specified rage.

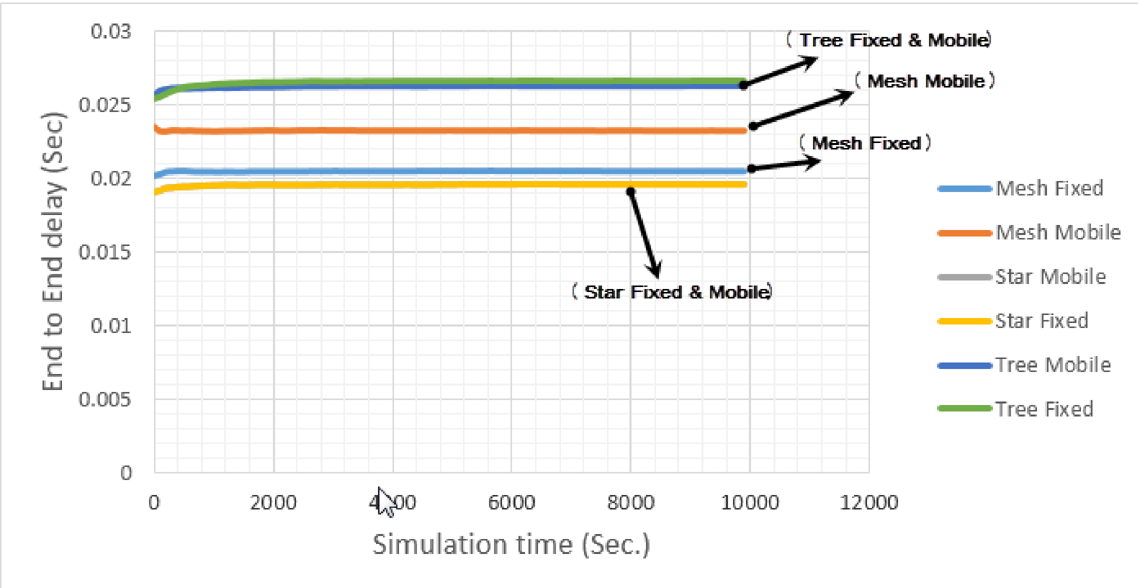


Figure 5.1 end to end delay of all simulated scenarios, (single coordinator Star, Tree, and Mesh with fixed nodes) and (single coordinator Star, Tree, and Mesh with mobile nodes), as a function of the simulation time.

To have a clearer picture of how WSN topology and the nodes status being fixed or mobile, the average delay of each scenario is calculated and listed in table 5.1. Table 5.1 shows that tree topology does experience highest delay among other topologies, for both fixed and mobile nodes' scenarios. Star topology is the least delay and there is no difference between fixed and mobile. And mesh topology in case mobile is higher than the fixed and ranging around 21-23 msec.

Table 5.1: Average delay experience as a function of topology for fixed and mobile nodes

Topology	Delay for fixed nodes (MS)	Delay for mobile nodes (MS)	Percentage change for mobile nodes
Star	19	19	0.0%

Mesh	21	23	9.0%
Tree	26	26	0.0%

End-to-End Delay for Star topology is the least for both fixed and mobile nodes. This can be explained by the fact that star routing is directly communicating with the basis of the network, where the nodes can communicate directly with the coordinator and the lack of additional alternative routes to reach the destination.

However, for the mesh and tree topologies process is higher delay due to the communicating through the multi routers and hops of the network.

- **Impact of network topology on MAC throughput**

Network (MAC) throughput is defined as the number of bits/sec successfully acquired by the receiver in reference to the transmitted packets. MAC throughput considers the total number of bits forwarded by 802.15.4 MAC layer in all nodes of the WSN. Figure 5.2 shows the recorded results of the throughput metric, for the 6 scenarios (single coordinator Star, Tree, and Mesh with fixed nodes) and (single coordinator Star, Tree, and Mesh with mobile nodes). The results recorded by the simulator for these scenarios are summarized in table 5.2 The average throughput, tree topology recorded higher throughput than mesh and tree for both fixed and mobile nodes. The reason for this is because Tree topology is communicating on the basis of the PAN coordinators and ZR which are more efficient as compared to the end devices.

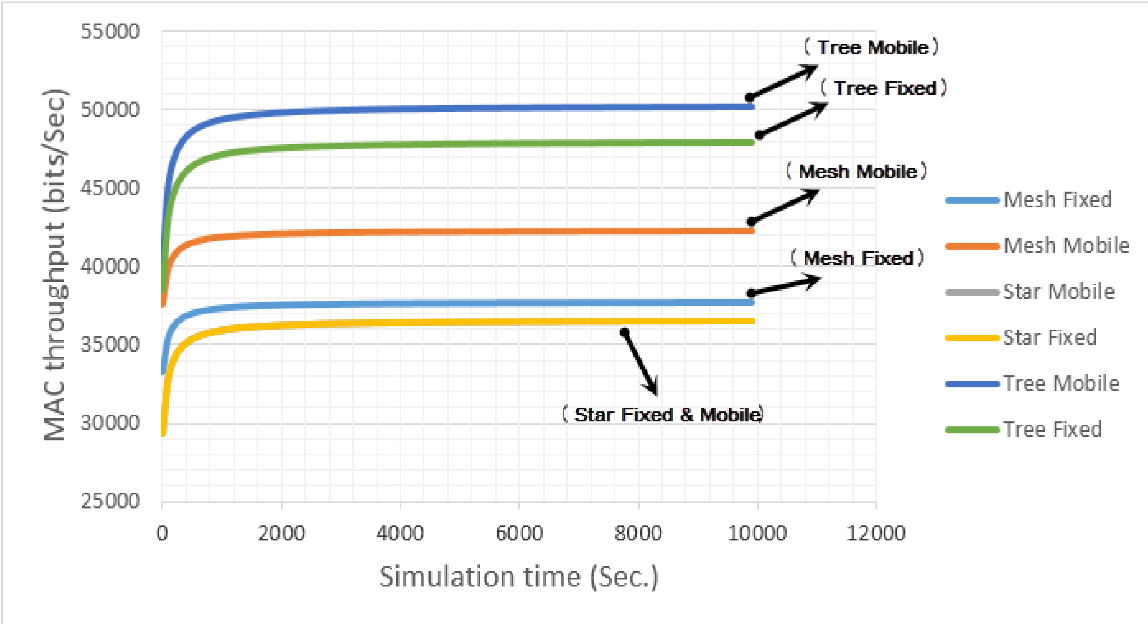


Figure 5.2 MAC throughput of all simulated scenarios, (single coordinator Star, Tree, and Mesh with fixed nodes) and (single coordinator Star, Tree, and Mesh with mobile nodes), as a function of the simulation time.

As is shown by figure 5.2 and summarized by table 5.2, the highest throughput was recorded by the tree topology for both fixed and mobile nodes, with significantly large difference when contrasted with star and mesh topologies. Star topology recorded the same throughput for both fixed and mobile nodes with the value of 36 (Kbits/Sec).

However, in the case mesh and tree of mobile nodes the throughput is higher in all types of topologies.

Table 5.2: average MAC throughput experience as a function of topology for fixed and mobile nodes

Topology	MAC throughput for fixed nodes (bits/sec)	MAC throughput for mobile nodes (bits/sec)	Percentage change for mobile nodes
Star	36000	36000	0.0%
Mesh	37000	42000	12.0%
Tree	47500	51000	7.0%

- **Impact of topology on MAC Load**

MAC Load represents the total load (in bits/sec) submitted to 802.15.4 MAC layer of the coordinator by higher layers of all nodes of the network.

As is shown by figure 5.3 and summarized by table 5.3, the tree topology has the highest recorded MAC load among all topologies, and tree topology in case mobile is higher than the fixed and ranging around 47500-51000 (bits/sec).

Star topology recorded the same MAC load for both fixed and mobile nodes with the value of 36000 (bits/Sec). When the nodes in the settings are given the option to move does not influence the MAC Load of the network topology.

While the mesh topology in case mobile is higher than the fixed and ranging around 37000-42000 (bits/sec).

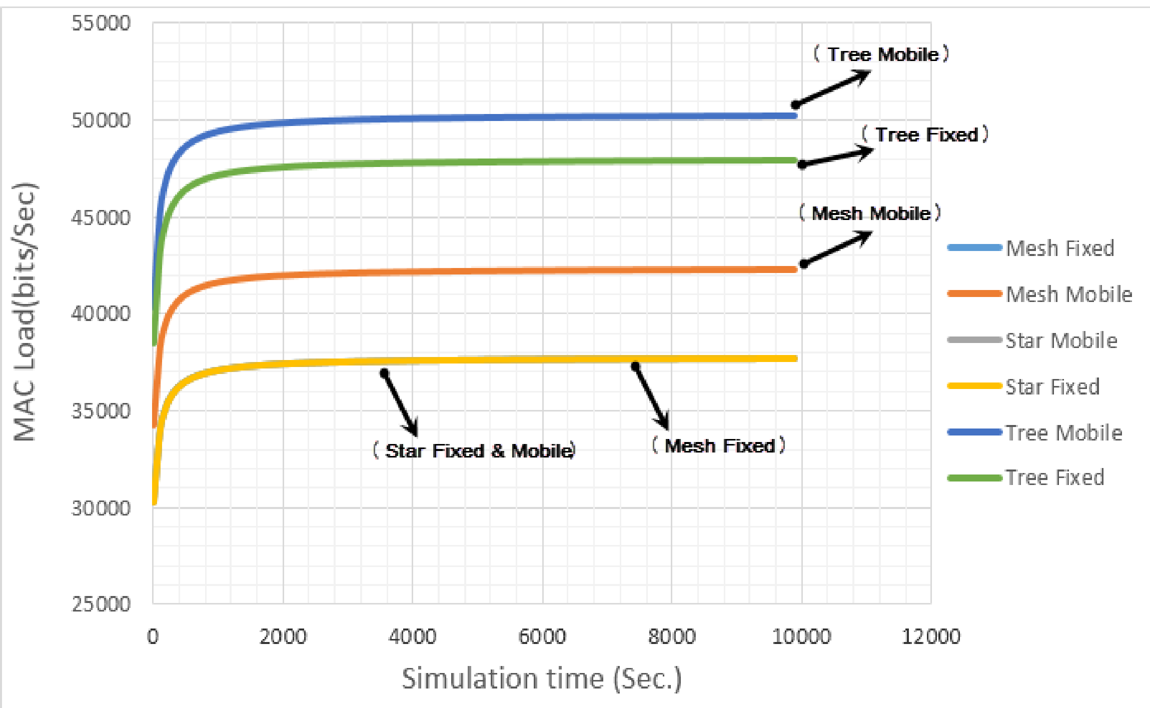


Figure 5.3 MAC load of all simulated scenarios, (single coordinator Star, Tree, and Mesh with fixed nodes) and (single coordinator Star, Tree, and Mesh with mobile nodes), as a function of the simulation time.

The results indicate that as far as the MAC load is concerned, the best possible topology is the star and mesh topologies regardless of the nodes being fixed or mobile.

The MAC load, star topology recorded least values than mesh and tree topologies for both fixed and mobile nodes. The main reason for this difference can be explained by the fact that star routing is directly linked with the coordinator without any routers. Thus has not been cumulate communicated traffic in MAC Load.

Mesh and tree experienced 35% increase in their MAC loads, since ZEDs communicate indirectly with the coordinator through routers, so part of the MAC load is buffered at the routers and part in end devices thus increasing total MAC Load in network.

Table 5.3: average MAC load as a function of topology for fixed and mobile nodes

Topology	MAC load for fixed nodes (bits/sec)	MAC load for mobile nodes (bits/sec)	Percentage change for mobile nodes
Star	37500	37500	0.0%
Mesh	37500	42200	11.0%
Tree	48000	50000	4.0%

- **Impact of topology on Packet delivery Ratio**

Packet delivery is the ratio between the packets successfully received by the coordinator to the total packet sent.

As is shown by figure 5.4, and summarized by table 5.4, packet delivery ratio is higher for mesh and tree topologies when compared to star topology. Star topology recorded the same delivery ratio for both fixed and mobile nodes, and a rate of 94.2 %. However, in case of mesh and tree, the delivery ratio get enhanced to reach 98-99% for both tree and mesh topologies. This implies that mesh and tree are preferred when the packet delivery ratio is the determent factor.

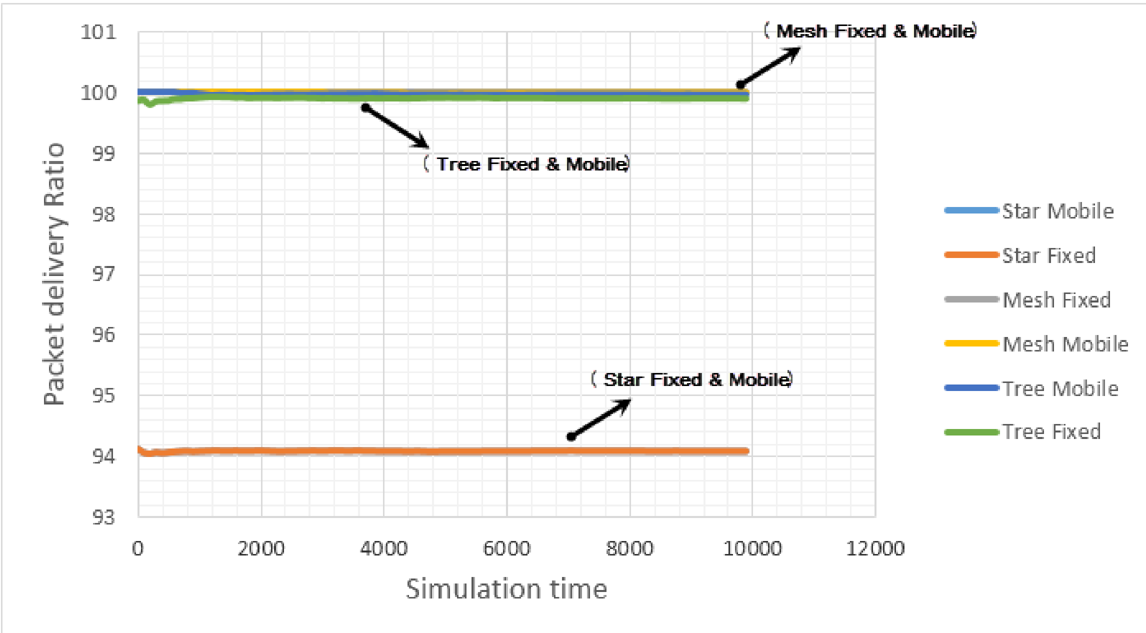


Figure 5.4 Packet delivery ratio of all simulated scenarios, (single coordinator Star, Tree, and Mesh with fixed nodes) and (single coordinator Star, Tree, and Mesh with mobile nodes), as a function of the simulation time.

Table 5.4: average packet delivery ratio as a function of topology for fixed and mobile nodes

Topology	Packet delivery ratio for fixed nodes	Packet delivery ratio for mobile nodes	Percentage change for mobile nodes
Star	94.2	94.2	0.0%
Mesh	99.8	99.8	0.0%
Tree	98.7	98.7	0.0%

The packet delivery ratio. The simulation results show higher results for tree and mesh topologies for both fixed and mobile nodes. This can be explained by the capability of the mesh and tree routing process to find more efficient routes than star topology. This significantly reduces the experienced delay in the transmission for packets originated by end nodes in tree and mesh topologies, and therefore decreases the collision rate, and consequently increases the number of successfully received packets in these topologies in contrast with star topology.

As for the star topology, the higher dropped packets, due there are no alternate routes and hence deceases packet delivery ratio. This is, in general, a significant result especially for applications that require the achievement of the highest possible secured packets, not to use star topologies as their packet delivery ratio is rather low.

5.3 The impact of the number of nodes (ZED) on the performance of WSN

This section is intended to analyse and study the impact of increasing the number of nodes on the performance of the different network topologies; being star, tree or mesh topologies. The simulated scenarios consist of one coordinators, six routers, and variable number of end nodes ranging between 5 and 50. In the following sub-sections we detail the impact of increasing the number of nodes in the WSN on the network performance through studying how the end-to-end delay, MAC throughput, MAC load, and the packet delivery ratio are evolving when the end nodes get increased.

- **End-to-end delay of the WSN in case of the use of one coordinator**

Figure 5.5 exhibits the behaviour of the three topologies in terms of their end-to-end delay as a function of the number of nodes included in the network. Once more the topologies behaved differently when ZED number gets increased. For the star topology, an increasing trend is witnessed, where two regions can be distinguished. Region one is bordered by the number of nodes 40, where moderate increasing slope is defined. However, as of 40 the increase in delay takes a steeper slope, which indicates a drastic increase in the overall delay of the network.

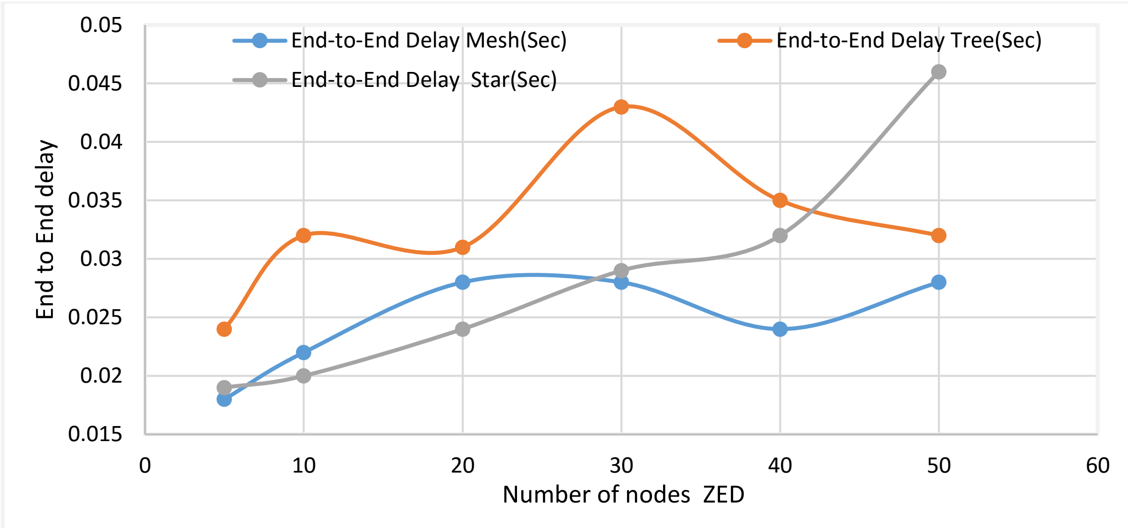


Figure 5.5: WSN end-to-end delay as a function of the number of nodes in case of the use of one coordinator

Mesh topology forms a varying delay trend. An increasing trend is witnessed till about 25 nodes, then it starts to decrease till the node 40, and then it starts to decrease again. The tree topology has shown the worst delay among the others, with a trend that goes up and down. In general, and as the overall delay in concerned, star topology is the best topology for small number of nodes, up till around 30 nodes, and then the mesh topology takes over, to be the network with the best delay.

The first indicator to be discussed is the End-to-End Delay. This indicator is recorded by figure 5.5, which shows that end to end delay substantially varies as the number of nodes gets changed. The general trend is that tree topology has the highest recorded delay for the packets to arrive at the destination, i.e. the coordinator. This is due to the fact that the tree topology has the least options to transfer packets to the destination. Mesh topology recorded a low and less varied delay due to the capability of the mesh topology network to find more efficient routes than tree.

As for the Star topology, the results indicate that the end to end delay is constantly increasing as the number of nodes gets increased. The increase in the number of nodes will generate more packets to be transmitted, and that will create congestion at the coordinator side, and increases the waiting time, i.e. delay for those packets to be processed by the destination. This clearly indicates that star topology is not the best choice for WSN when large number of nodes are involved, especially beyond 40. The simulation has clearly indicated that the best choice for WSN built based on Zigbee protocol is the mesh topology, which minimally impacted by the increase in number of nodes.

- **Throughput of the WSN in case of the use of ONE coordinator.**

It is quite clear from figure 5.4 that the three different topologies witnessed different trends in regards to their throughput. A steady increasing trend is witnessed for the star topology. However, the mesh topology witnessed an increasing trend till the 20 nodes scenario, and then throughput of that topology starts to continuously degrade.

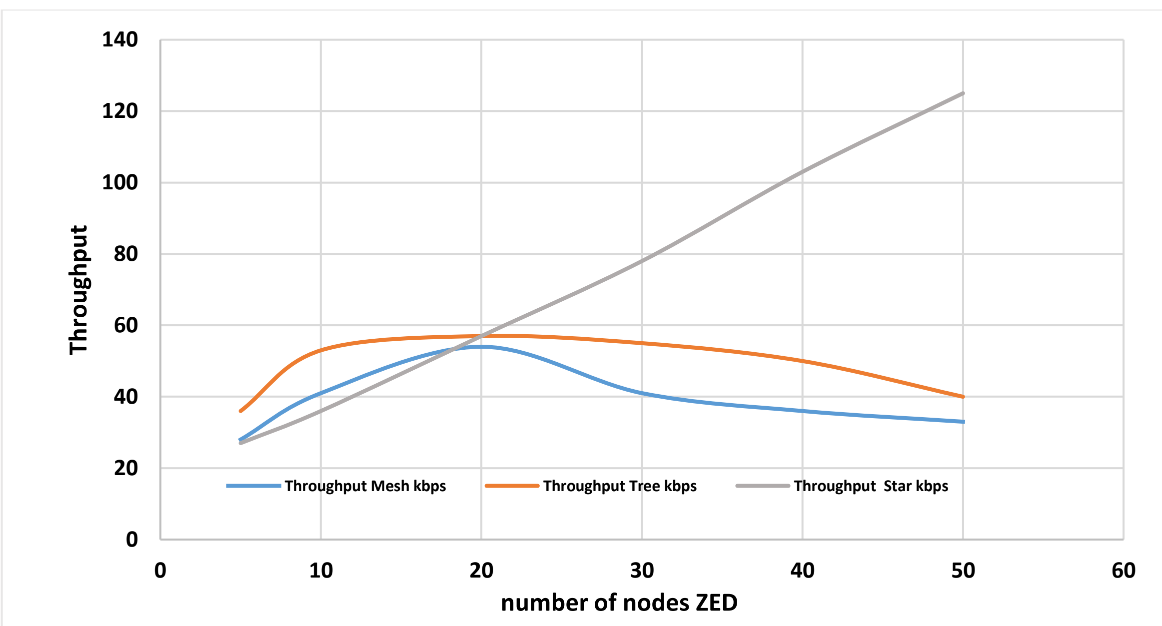


Figure 5.6 WSN throughput as a function of the number of nodes in case of the use of one coordinator.

As for the tree topology, throughput get increased up to 10 nodes, then experienced a flat region in the curve till 30, where it starts to smoothly degrade. In general the tree throughput surpassed that of the mesh topology for all node numbers. In the next chapter an explanation for these witnessed phenomena will be tried.

The second indicator we shall consider is the network throughput. Throughput is the amount of data moved successfully from one place to another in a given time period, and typically measured in bits per second (bps). What counts here in determining the throughput is the time needed for the created packets at the source to be processed and successfully arrive at the destination. The results to be discussed are presented in section 5.3.2 and depicted in figure 5.4. As is shown by the figure 5.4, mesh and tree behaved in the same manner, where the throughput of the two topologies does not substantially changed with the number of nodes introduced in the network. However, the throughput of the star topology shows a linear behaviour in relation to the number of nodes. This can be explained by the fact that there are no collisions experienced by packets generated and transmitted by star topologies. This means that all packets generated by source nodes are fully received by the coordinator. Therefore, throughput which measures number of successfully received packets gets increased by increasing the number of nodes, as they generated more packets. However, the situation is totally different in case of tree and mesh topologies. For these networks more nodes, means more packets, and more collisions, which substantially decreases the number of packets successfully received in unit time by these networks, as the number of nodes gets increased. This practically indicates that star topology is recommended for WSN when large number of nodes, specifically more than 20 nodes. However, below 20 nodes mesh and tree are recommended when throughput is the main determinant factor for the network, with tree having some advantages over both mesh and star.

- **MAC load of the WSN in case of the use of one coordinator**

The MAC load is powerful metric used in WSN network to assess the effectiveness of any network settings. It quantifies how effective is the MAC layer in transmitting what it collects from the upper layers mainly the application layer and transfers that down into the physical layer to be transmitted via the wireless channel.

MAC load should be as small as possible, and having a higher MAC load means that the network configuration is facing problems in transmitting what is supposed to be transmitted. Figure 5.7 demonstrates that the topology which suffers the most in its MAC load when the number of nodes increases is the star topology.

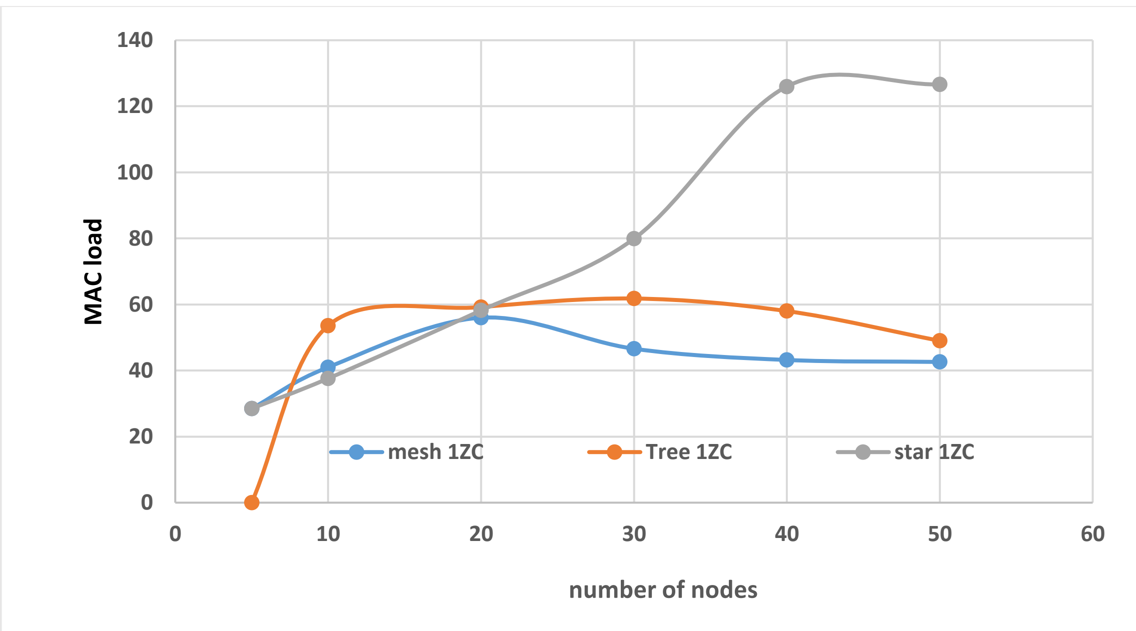


Figure 5.7 WSN MAC load as a function of the number of nodes in case of the use of one coordinator.

In the star topology as the figure 5.7 demonstrates, a drastic increase in MAC load is experienced as the number of nodes is increased.

MAC load quantifies how effective is the MAC layer in transmitting what it collects from the upper layers mainly the application layer and transfers that down into the physical layer to be transmitted via the wireless channel. This discussion is based on the results presented in sub-section 5.3.4 and specifically results depicted by figure 5.7. As is depicted by figure 5.7, the star topology exhibited a continuous increase in its MAC load as the number of source nodes gets increased, while both mesh and tree have lower values for this indicator. Over again, this can be explained by the fact that increasing number of nodes will increase packets arrived at the MAC layer of the coordinator. These packets will be accumulated at the puffer for processing, and this is why we have larger size for the MAC load, than that for tree and mesh. As for tree and mesh, MAC load is distributed among routers in the network which does not lead to an increase in MAC load at the destination coordinator.

AS for practical consideration, and when it comes to MAC load it is preferred to use either tree or mesh especially for number of nodes beyond 20.

- **Packet delivery ratio of the WSN in case of the use of one coordinator**

Packet delivery ratio measures the ratio between the successfully received packets at the sink node (coordinator) with regards to the originally transmitted packets by all network nodes. Figure 5.7 depicts the behaviour of the different network topologies in regards to this metric as a function of number of nodes. In regards to this parameter, the star topology behaves different from that of mesh and tree, which they behave almost the same way. The packet delivery ratio of the star topology gets slightly enhanced as the number of nodes gets increased. However, for both the tree and the mesh topologies the packet delivery ratio witnessed a significant decrease when the number of nodes gets increased. However, as of

20 nodes in the network, tree topology witnessed some degradation in reference to the mesh topology network in regards to the packet delivery ratio parameter.

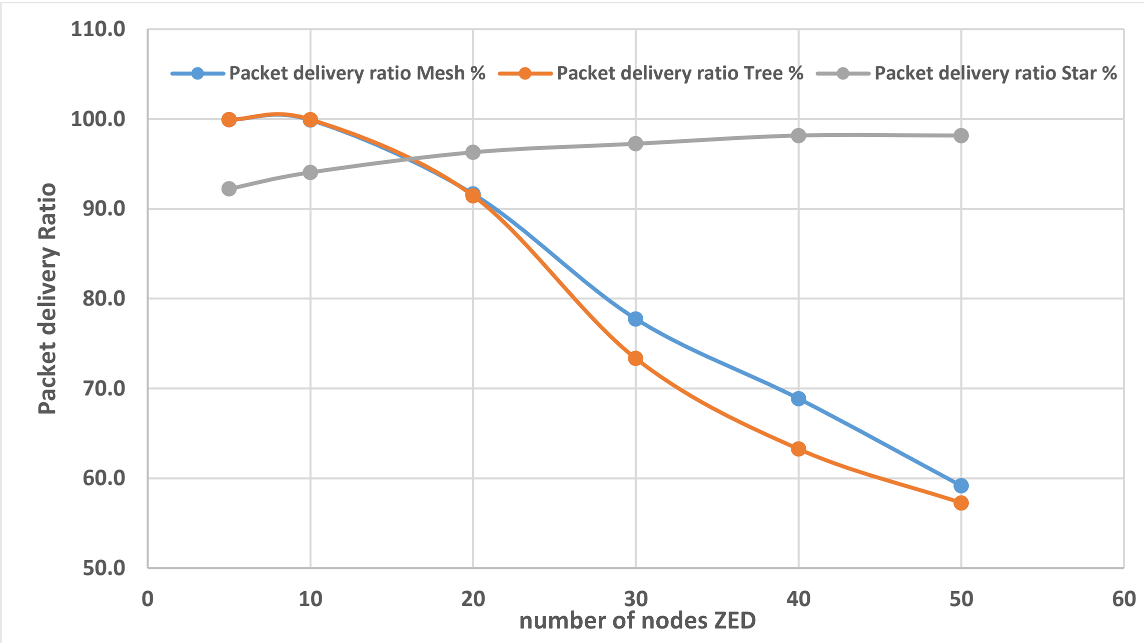


Figure 5.8 WSN packet delivery ratio as a function of the number of nodes in case of the use of one coordinator.

Packet delivery ratio (PDR) measures the ratio between the successfully received packets at the sink node with regards to the originally transmitted packets by all network nodes. Figure 5.6 depicts the behaviour of the different network topologies in regards to this indicator as a function of number of nodes used. Simulated results for PDR show superior trend for mesh and tree over star up to around 15 nodes, when star topology starts to outperform mesh and tree. Star topology keeps above 90% ratio, while tree and mesh dramatically drops from 100% at few nodes to around 60% when 50 nodes are used. This can be readily explained by communication style dictated by the used topology. Recall that the coordinator of the star topology receives generated packets directly from the source nodes, with no delay or packet drop. However, for both mesh and star the generation of more packets by the increased number of nodes will create more and more collisions and dropped packets, which consequently dramatically reduces the PDR for the mesh and tree topologies. Remark that PDR for mesh is better than tree as more optional routes are available for the packets which reduces chances for collisions and dropped packets.

As for practical consideration, and considering only packet delivery ratio, star topology is recommended for use for large number of nodes, preferably for networks containing nodes larger than 15 nodes.

As a summary for this part, we present a table that details the preferred topology when the different indicators are considered in the scenarios. The overall conclusion of this part of the study is that no single topology can give optimal performance for all indicators, and it is up to the network designers to decide which indicator to count for the sake of selecting the most appropriate topology.

Table 6.1 Preferred topologies when different WSN parameter is taken into consideration

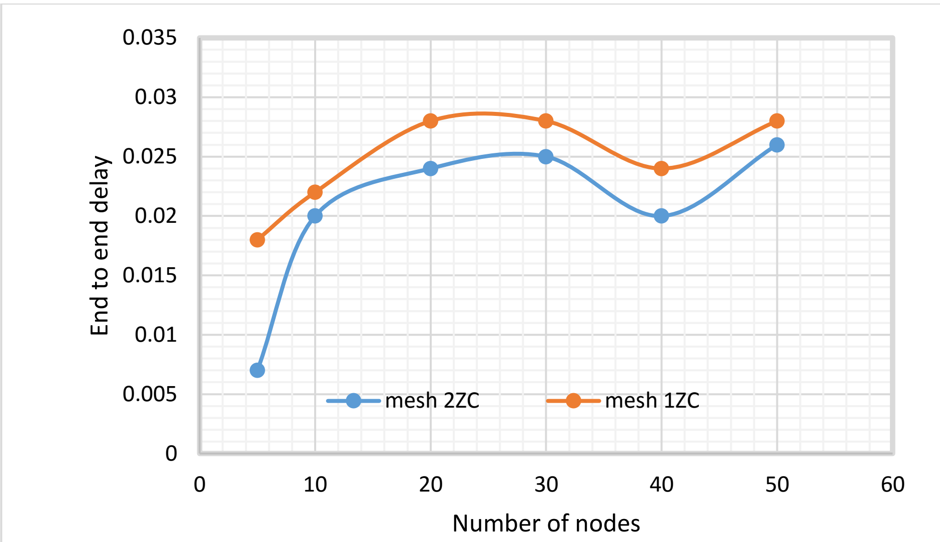
Indicator	Preferred topology with cut-off number of nodes	
End to end delay	Star < 30	Mesh > 30
Throughput	Mesh or Tree < 20	Star > 20
Packet delivery ratio	Mesh or Tree < 15	Star > 15
MAC load	Star < 20	Mesh or Tree > 20

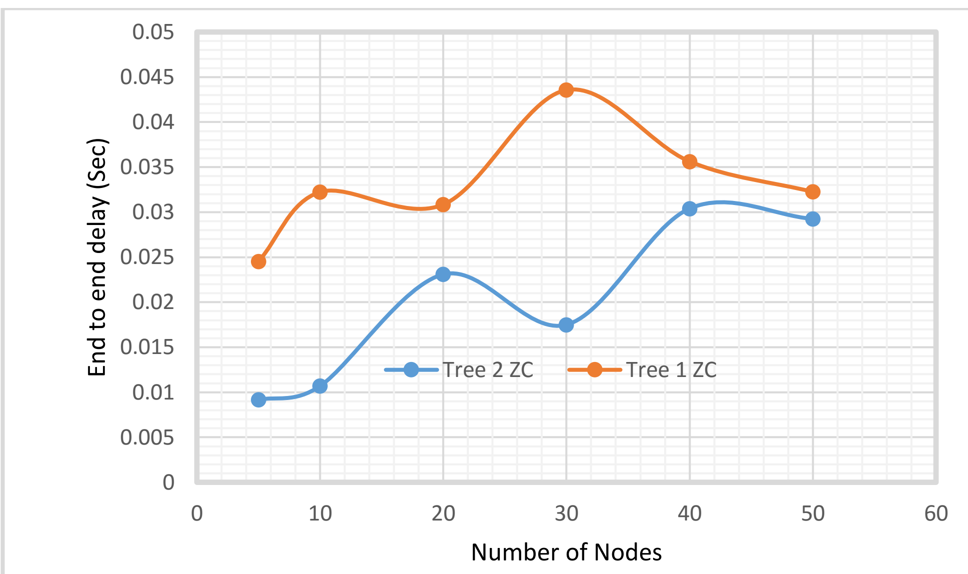
5.4 The impact of number of coordinators on the WSN performance in case of different wireless nodes.

In the previous scenarios only one coordinator has been used to manage the network and to collect the data. In this section the intention is to see the impact of adding one more coordinator.

- **Impact on end-to-end delay**

Figure 5.9 below compares the WNS end-to-end delay for 1 and 2 coordinators for mesh, tree and star topology. A clear significant improvement is witnessed for mesh and tree topologies when one more coordinator is added regardless of the number of nodes is employed. However, the trend fluctuates between 1 and 2 coordinators for the star topology, and there is no clear trend in regards to whether adding one more coordinator will improve end-to-end network delay.





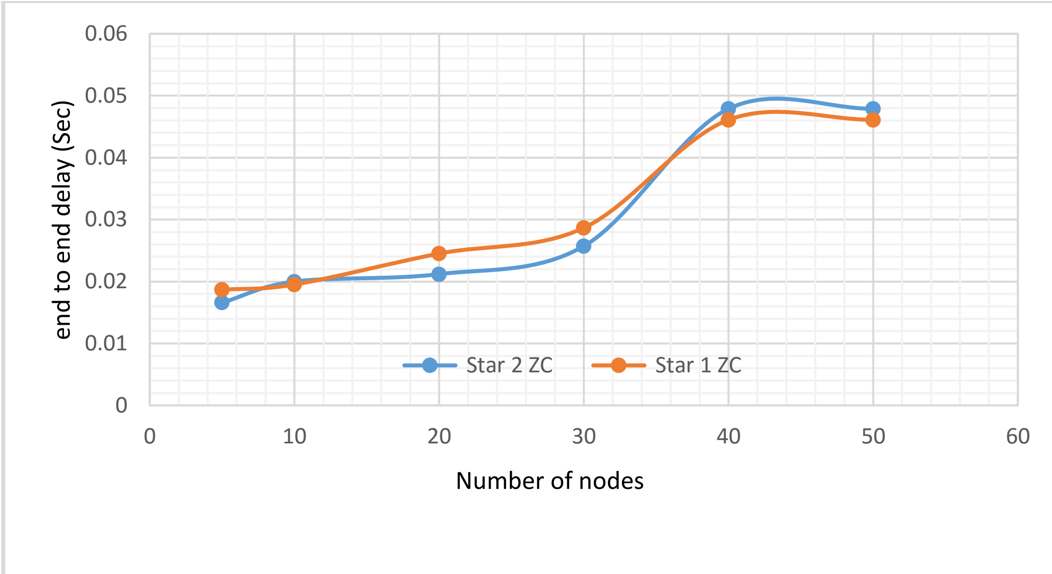


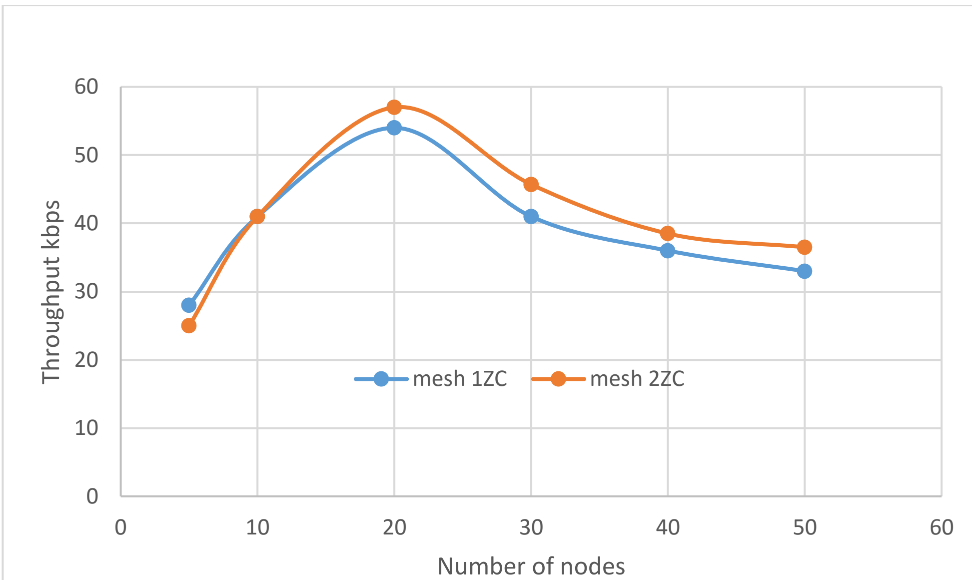
Figure 5.9 end-to-end delay of the mesh, tree and star in case of one and two coordinators as a function of number of node

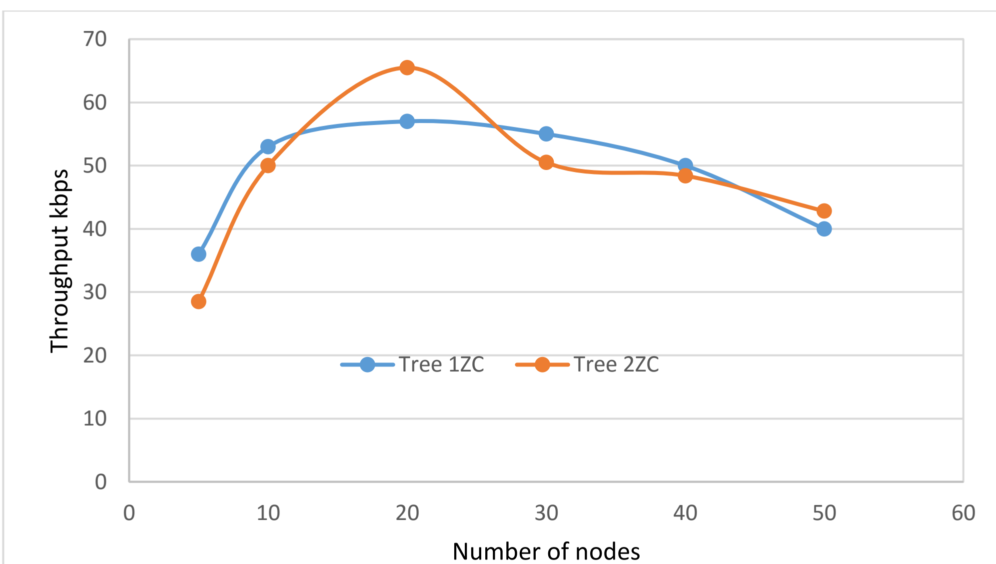
The results to be discussed in this sub-section is that depicted in figure 5.8 a, b, and c. A clear decreasing trend is witnessed for both the mesh and the tree topologies, when two coordinators are added. However, almost the same behavior is witnessed for the star topology when one more coordinator is added. It is quite obvious that adding one more coordinator will take part of the load from the other one, especially if that one is busy, and hence reduces the overall delay regardless on the number of source node used. As for the star topology, the trend is not so obvious, and this is due to the fact that there is a direct link between the source nodes and the coordinators, and that will make insignificant difference on the delay parameter.

- **Impact on throughput**

As is depicted by figure 5.8 shown below, adding one more coordinator has negligible impact on the network throughput for all topologies. Only a slight improvement is witnessed for the mesh topology when one more ZC is added to the configuration. For the tree topology, no clear trend is witnessed and it seems that which case has higher throughput depends on the number of nodes employed.

For the star topology, adding one more coordinator does not have any influence on the throughput before the case which employs 30 nodes. Beyond 30 nodes, 2 coordinator scenarios, starts to surpass that of 1 coordinator.





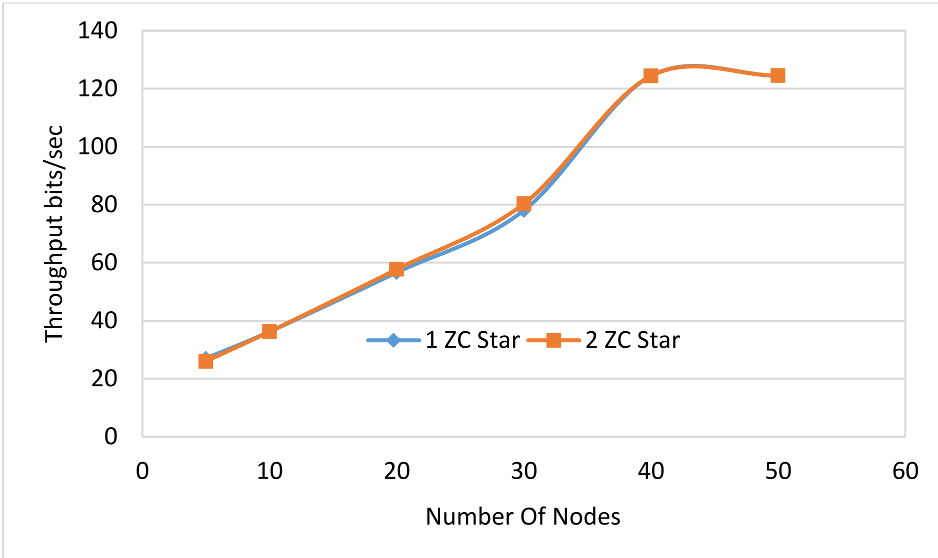


Figure 5.10 throughput of the mesh, tree and star in case of one and two coordinators as a function of number of node

The results to be discussed in this part is that depicted in figure 5.9 a, b, and c, which shows that adding one more coordinator to the network improves the overall throughput of both the mesh and the tree topologies. Yet, no improvement is witnessed when one more coordinator is added to the star topology. In both the mesh and tree slight improvement is witnessed, and this can be explained by the fact that Mesh topology can use more than one path to reach to the destination with regardless of whether we have one or two coordinators. It works only when we have a bottleneck. As for the Star topology, what said for delay can be said for the throughput, since packets generated by source nodes can reach any coordinator at convenience, regardless of number of source nodes.

- **Impact on the MAC load**

The last metric we examined is the impact of adding one more coordinator on the MAC load. Figure 5.9 demonstrates that the MAC load of the mesh topology and the star topology are not affected by the presence of one more coordinator to the network, and their MAC load follows the same trends. However, the tree topology develops a different topology when one more coordinator is added to the network.

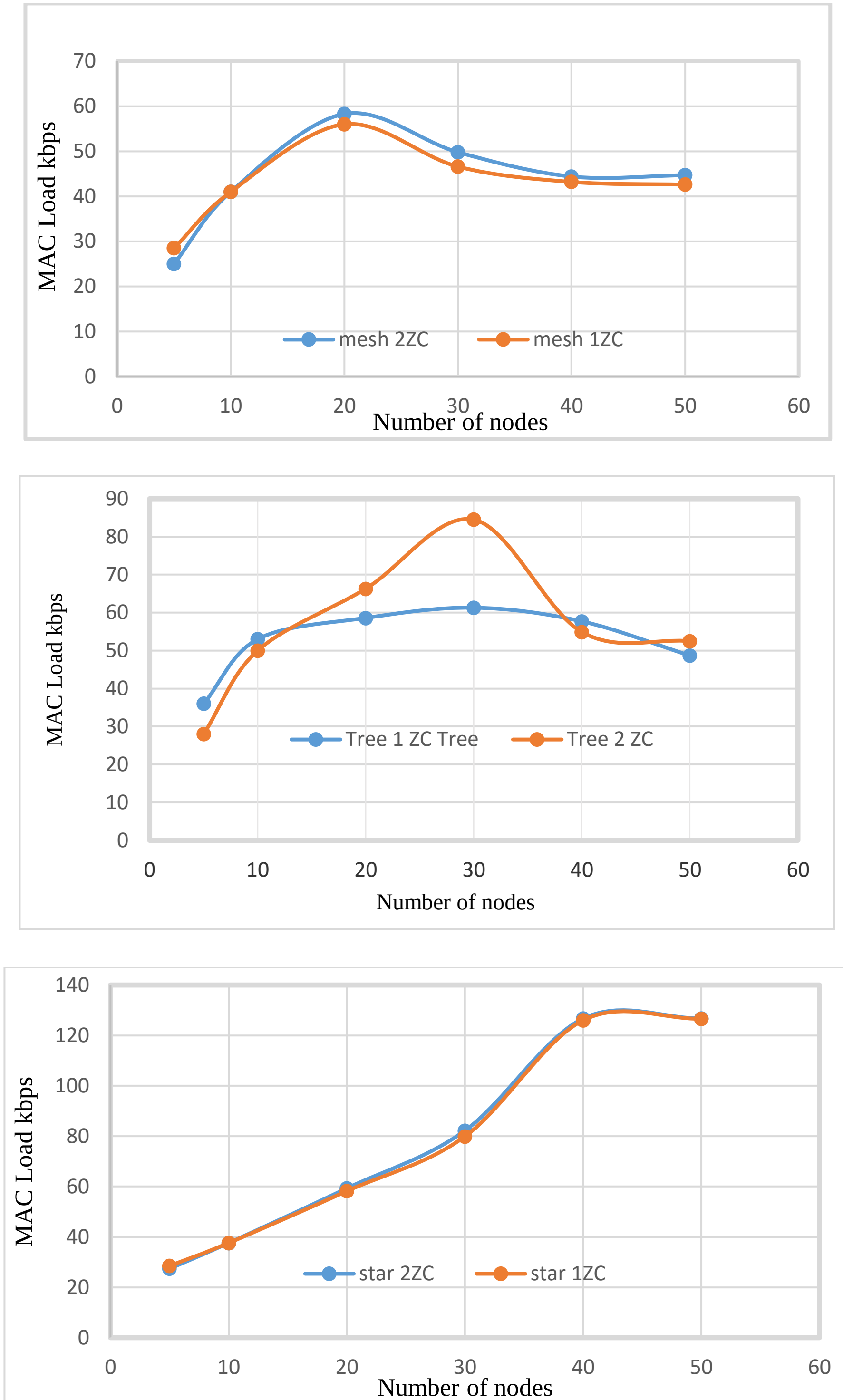


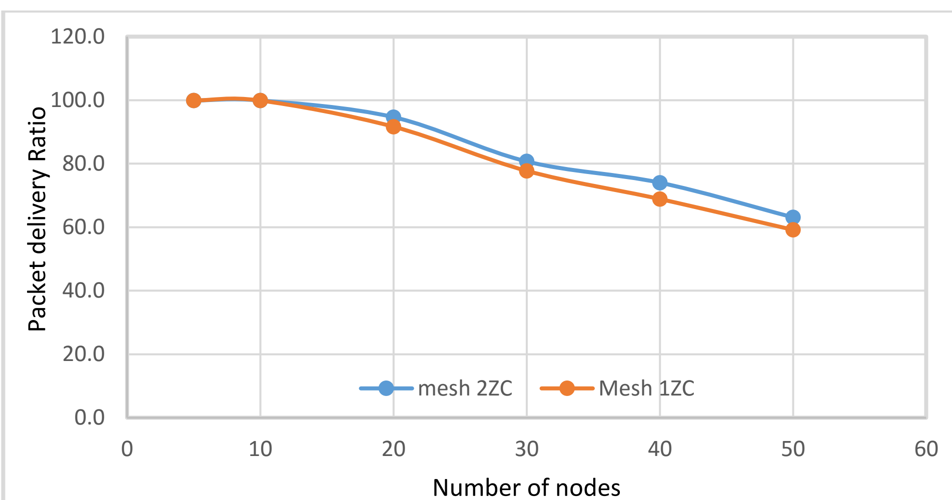
Figure 5.11 WSN packet delivery ratio of the mesh, tree and star in case of one and two coordinators as a function of number of node

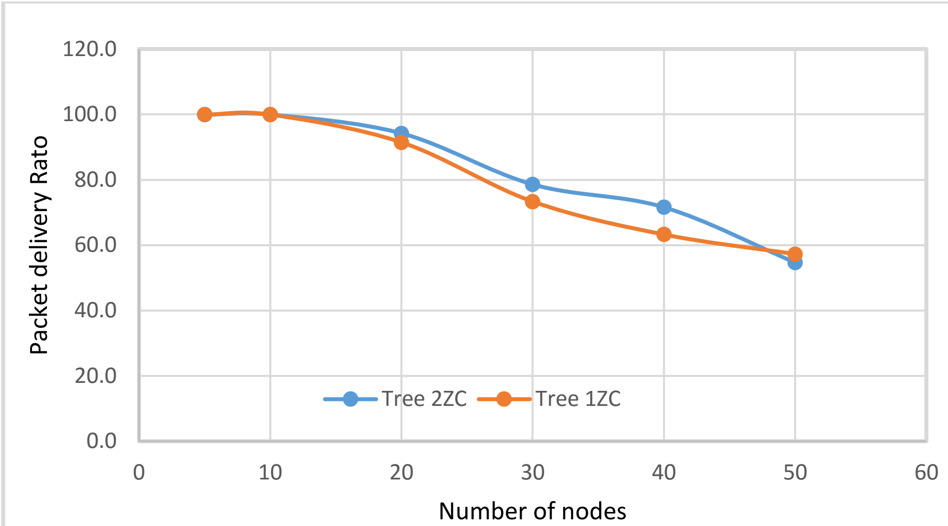
The results to be discussed in this part is that depicted in figure 5.11 a, b, and c. MAC load has the same behavior as the other indicators with slight changes for the case of mesh and tree and the same behavior for star.

Impact on packet delivery ratio

The next issue we examined in regards to the impact of adding one more coordinator, is the packet delivery ratio, exhibited in figure 5.10. The packet delivery ratio metric preserved an equivalent trend when one more coordinator is added to the network. However, for the mesh and tree topologies, slight improvement is observed, while the star topology preserved the same trend and values for all node numbers.

The results to be discussed in this part is that depicted in figure 5.10 a, b, and c. As is stated in chapter 5, the packet delivery ratio maintained the trend for the two coordinators as is in one coordinator, with only slight improvement. Yet the PDR behaves exactly the same for star topology in case of one and two coordinators. This can be explained by remarking that adding another coordinator results in fewer collisions and lesser packet drops as there is an alternative paths to reach the destination.





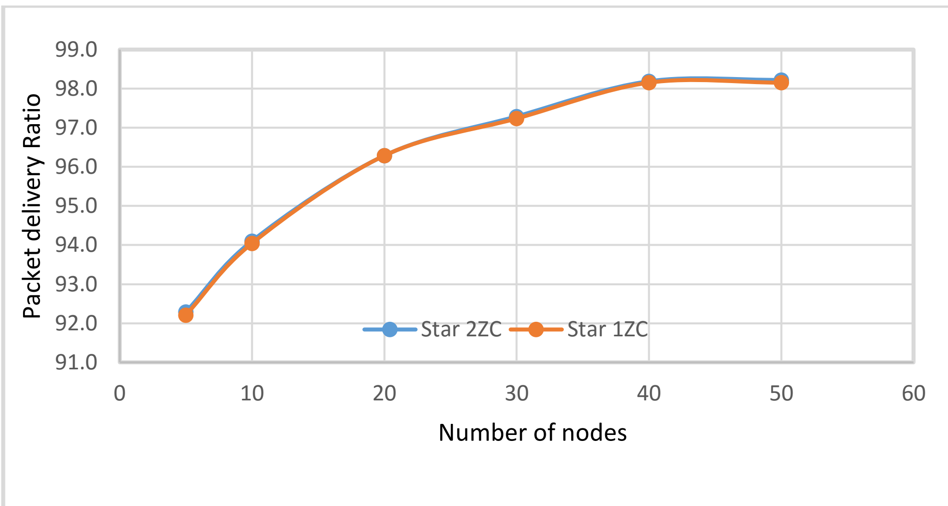


Figure 5.12 WSN packet delivery ratio of the mesh, tree and star in case of one and two coordinators as a function of number of node

Chapter 6

Conclusion and Future Work

This chapter will go through the works done to fulfill the objective explained at the beginning of the thesis, draw conclusions from the findings in the study, and point out future directions based on the present study.

6.1 Conclusions

The main purpose of this thesis was to analyse the impact of network topologies on performance of wireless sensor networks and to examine the possibility of improving the performance of these networks throughout analysing their performance from different perspective. Towards that end, the research efforts were designed around the analysis of the different type of network topologies and study their impact on network performance.

The enhancements introduced by the proposed solutions were assessed using extensive simulation experiments. In the experiments four major network performance metric were tested; end-to-end delay, throughput, MAC Load and packet delivery ratio.

Because the end-to-end delay is the utmost critical feature of a wireless network, we have given this parameter a priority. It turned out that there is no difference in the end-to-end delay between the fixed and the mobile nodes for nodes that are moving at a speed of 1m/sec, regardless of the topology in use.

In relation to end to end delay, it turned out that the end-to-end delay increases in all types of topology as function of the number of nodes. The general trend is that tree topology has the highest recorded delay. Mesh topology recorded a low and less varied delay due to the capability of the mesh topology network to find more efficient routes than tree. As for the

Star topology, the results indicate that the end to end delay is constantly increasing as the number of nodes gets increased. In relation to the impact of adding one more coordinator, it turned out the adding one coordinator decrease the overall delay to certain extent especially for the tree and mesh topologies.

When considering network throughput, it turned out that mesh and tree behaved in the same manner, where the throughput of the two topologies does not substantially changed with the number of nodes introduced in the network. However, the throughput of the star topology shows a linear behaviour in relation to the number of nodes. When adding one more coordinator to the network, it was found that adding one more coordinator to the network improved the overall throughput of both the mesh and the tree topologies. Yet, no improvement is witnessed when one more coordinator is added to the star topology.

When MAC load is considered, it was found that the MAC Load increases in star topology as function of the number of nodes but the mesh and tree will not be affected by the increase in the number of nodes. MAC Load is negligibly impacted in mesh and tree topologies when

To complete the picture about network performance we investigated the packet delivery ratio for the different scenarios. The simulation results demonstrated that the Packet delivery ratio for tree and mesh topologies is higher for both fixed and mobile nodes than star topology.

Packet delivery ratio increases in star topology as function of the number of nodes but the mesh and tree decreases in the packet delivery ratio as function of the number of nodes. Packet delivery ratio gets increased significantly when a second coordinator is added in mesh and tree topologies as function of the number of coordinators in the network but in star topology there is no effect on adding another coordinator.

The general conclusion is that no topology is optimal for all parameters and it is up to network designers to determine the appropriate indicator for selecting the best topology.

6.2 Limitations for the research

The most important limitation in this study was not knowing the optimal number of routers rate required per a couple of end device. And the most important limitations is change in number of nodes.

The performance of the various topologies is strongly affected by the distribution of nodes (whether source, node, or routers). We did our best to keep the same distribution of nodes in all included scenario.

Throughout this project, we have discovered some of the limitations of the ZigBee model in OPNET. It has been broadly popularized that internet connection to a ZigBee network is something which can make monitoring, observation, tracking. Indeed there are applications in health industry building facilities automation which can be only possible if there is an interface between Zigbee network & IP-based internet.

When we tried to implement an Internet connection, we noticed that OPNET doesn't support ZGD (ZigBee Gateway Device) (OPNET versions 17.5).

6.3 Recommendations for further research

The work can be further extended with more simulations. One idea is to study impact adding coordinator on power consumption. Another idea is to consider in add a larger number of coordinators in the network and study their impact from other parameters. As a future work too, we may testing our model in regards to other parameters like transmit rate and data rate and comparing the result with other scenarios, are other good ideas for future research.

Bibliography

[1] Feki, Mohamed Ali, et al. "The internet of things: the next technological revolution." Computer 46.2 (2013): 24-25

[2] Hype cycle for emerging technologies, 2015. Gartner, August. 2015. Available from: http://www.gartner.com/newsroom/id/3114217, May 2018.

[3] OPNET official website, Available: https://www.opnet.com, April 2018.

[4] McGrath M.J., Scanaill C.N. Sensor Network Topologies and Design Considerations. In: Sensor Technologies. (2013).

[5] Al-Karaki JN, Kamal AE. Routing techniques in wireless sensor networks: a survey. IEEE wireless communications. 2004 Dec; 11(6):6-28.

[6] Cheng L, Zhang Y, Lin T, Ye Q. Integration of wireless sensor networks, wireless local area networks and the Internet. In Networking, Sensing and Control, 2004 IEEE International Conference on 2004 Mar 21 (Vol. 1, pp. 462-467). IEEE.

[7] Xu S. Advances in WLAN QoS for 802.11: an Overview. In Personal, Indoor and Mobile Radio Communications, 2003. PIMRC 2003. 14th IEEE Proceedings on 2003 Sep 7 (Vol. 3, pp. 2297-2301). IEEE.

[8] Hiertz GR, Denteneer D, Stibor L, Zang Y, Costa XP, Walke B. The IEEE 802.11 universe. IEEE Communications Magazine. 2010 Jan; 48(1).

[9] Bisdikian C. An overview of the Bluetooth wireless technology. IEEE Communications magazine. 2001 Dec; 39(12):86-94.

[10] Salman N, Rasool I, Kemp AH. Overview of the IEEE 802.15. 4 standards family for low rate wireless personal area networks. In Wireless Communication Systems (ISWCS), 2010 7th International Symposium on 2010 Sep 19 (pp. 701-705). IEEE.

[11] Raut AR, Malik LG. ZigBee Based Industrial Automation Profile for Power Monitoring Systems. International Journal on Computer Science and Engineering. 2011 May;3(5):2028-33.

[12] Kaur G, Garg RM. Energy efficient topologies for wireless sensor networks. International Journal of Distributed and Parallel Systems. 2012 Sep 1;3(5):179.

[13] Lee SR, Back JS, Oh JS, Jeong MA. A mesh topology formation scheme for IEEE 802.15. 4 based wireless sensor networks. InUbiquitous and Future Networks (ICUFN), 2015 Seventh International Conference on 2015 Jul 7 (pp. 150-152). IEEE.

[14] Farhat A, Makhoul A, Guyeux C, Tawil R, Jaber A, Hijazi A. On the topology effects in wireless sensor networks based prognostics and health management. In Computational Science and Engineering (CSE) and IEEE Intl Conference on Embedded and Ubiquitous Computing (EUC) and 15th Intl Symposium on Distributed Computing and Applications for Business Engineering (DCABES), 2016 IEEE Intl Conference on 2016 Aug 24 (pp. 335-342). IEEE.

[15] Karim L, El Salti T, Nasser N, Mahmoud QH. The significant impact of a set of topologies on wireless sensor networks. EURASIP Journal on Wireless Communications and Networking. 2012 Dec 1;2012(1):120

[16] Bisht N, Singh S. Analytical study of different network topologies. International Research Journal of Engineering and Technology (IRJET). 2015 Mar;2(01)

[17] Mounika P. Performance analysis of wireless sensor network topologies for Zigbee using riverbed modeler. In2018 2nd International Conference on Inventive Systems and Control (ICISC) 2018 Jan 19. IEEE.

[18] Soparia J, Bhatt N. A survey on comparative study of wireless sensor network topologies. International Journal of Computer Applications. 2014 Jan 1; 87(1).

[19] Zen K, Habibi D, Rassau A, Ahmad I. Performance evaluation of IEEE 802.15. 4 for mobile sensor networks. InWireless and Optical Communications Networks, 2008. WOCN'08. 5th IFIP International Conference on 2008 May 5 (pp. 1-5). IEEE.

[20] Chaudhary R, Vatta DS. A Tutorial of routing protocols in wireless sensor networks. International Journal of Computer Science and Mobile Computing. 2014 Jun;3(6).

[21] Naseer S, Chaudhry SR. Lr-wpan formation topologies using ieee 802.15. 4. International Journal of Computer Science Issues (IJCSI). 2011 Nov 1; 8(6):39.

[22] Handy MJ, Haase M, Timmermann D. Low energy adaptive clustering hierarchy with deterministic cluster-head selection. In Mobile and Wireless Communications Network, 2002. 4th International Workshop on 2002 (pp. 368-372). IEEE.

[23] Younis O, Fahmy S. HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. IEEE Transactions on mobile computing. 2004 Oct; 3(4):366-79.

[24] Sahoo A, Baronia P. An energy efficient MAC in wireless sensor networks to provide delay guarantee. IEEE.

[25] Huang KL, Tseng CC, Wang JT, Yang TH. A Controller-assisted distributed (CAD) load balancing scheme for zigBee networks. In2011 International Conference on Parallel Processing Workshops 2011 Sep 13 (pp. 1-5). IEEE.

[26] Tseng CH. LBMR: Load-Balanced Multipath Routing for Wireless Data-Intensive Transmission in Real-Time Medical Monitoring. International journal of environmental research and public health. 2016 May 31;13(6):547.

[27] Islam N, Biddut MJ, Swapna AI, Rahman MM. An analytical study to minimize load of ZigBee network based on statistical modeling. In Electrical and Computer Engineering (WIECON-ECE), 2015 IEEE International WIE Conference on 2015 Dec 19 (pp. 139-142). IEEE.

[28] O.P.N.E.T. Technologies, [Inc, Online], Available: https://www.riverbed.com, June 2018.

[29] Krishnamurthi N. Feasibility and performance analysis of sensor modeling in OPNET 2007.

[30] Jurčík P, Koubâa A. The IEEE 802.15. 4 OPNET simulation model: reference guide v2. 0. IPP-HURRAY Technical Report, HURRAY-TR-070509. 2007 May 29.

[31] Cunha, André, et al. "Open-ZB: an open-source implementation of the IEEE 802.15. 4/ZigBee protocol stack on TinyOS." (2007): 1-12.

[32] Jiang H, Wang P, Liu H. Research on OPNET Simulation Model in Wireless Sensor Networks [J]. Computer Engineering. 2007; 4:024.

ويشير الاستنتاج العام لهذا العمل إلى أنه بالنظر إلى مقاييس التأخير من طرف إلى طرف ، وإنتاجية ، وحمل MAC ، ونسبة توصيل الحزم ، فإن إضافة منسق واحد أو أكثر إلى الشبكة سيعمل على تحسين الأداء العام لـ WSN و تعزيز جودة خدمات هذه الشبكات التي يتم نشرها بشكل متزايد.

على الرغم من أن الجهود المبذولة لتصميم سيناريوهات WSN المختلفة ومحاكاتها وتحليلها قد نجحت وحققت نتائج قد تكون لها بعض الآثار العملية على صناعات WSN ، إلا أن تعميم النتائج وتنفيذ نتائجها سيستلزم اختبارها على سيناريو أوسع في واقع أكثر واقعية.

Arabic abstract

ملخص

اكتسبت شبكات زيجبي للاستشعار اللاسلكي المبنية على أسس معيار IEEE 802.15.4 شعبية في السنوات الأخيرة بفضل ميزاتها المثيرة للاهتمام والتي تتمثل في انخفاض استهلاك الطاقة والحفاظ على عمر البطارية الطويل وبسبب إدراكها الواضح في الإدارة الأمنية. تظهر الدوائر الأكاديمية والصناعية اهتمامًا متزايدًا باستخدام تكنولوجيا زيجبي ، حيث يمكن استخدامها في مجموعة كبيرة من التطبيقات الحالية والمستقبلية. في هذه الرسالة ، فإن الهدف هو دراسة وتحليل تأثير طوبولوجيا الشبكة على أداء شبكات الاستشعار اللاسلكية المبنية على بروتوكول زيجبي. بالإضافة إلى ذلك ، تمت دراسة وتحليل تأثير مختلف عناصر WSN مثل تأثير زيادة عدد أجهزة النهاية Zigbee (ZED) وتأثير عدد منسقي Zigbee (ZCs) و Zigbee routers (ZRs). علاوة على ذلك ، تمت دراسة وتحليل تأثير قابلية العقد أيضًا.

في الأطروحة استخدمنا محاكي OPNET لبناء تصميمات الشبكة المطلوبة ، والتي تمثل سيناريو العالم الحقيقي. قمنا بعد ذلك بالتحري عن مقاييس الأداء لهذه الشبكات من خلال حساب التأخير من البداية إلى النهاية ، الإنتاجية ، حزمة تحميل MAC ونسبة توصيل الحزمة كدالة في طوبولوجيا الشبكة تحت مختلف التخطيطات وظروف العقد على أساس المواصفات الموصى بها من قبل IEEE 802.15.4 / معايير ZigBee.