

# ENSC 427: COMMUNICATION NETWORKS

Simulation of ZigBee Wireless Sensor Networks

Final Report

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## **1. Abstract**

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The ZigBee protocol stack based on IEEE 802.15.4 offers a practical, cost-effective solution for low-cost and low power consumption WPANs. These characteristics make ZigBee networks the ideal candidate for Wireless Sensor Networks in many applications such as Commercial Building and Home Automation, Medical equipment monitoring and Industrial control. Latency and reliability are significant performance measurements in sensor networks; this project focuses on simulating and assessing a Wireless Sensor Network implementing the ZigBee protocol using the OPNET 16 network simulation tool.

## 1. Introduction

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The use of Wireless Personal Area Networks has been steadily increasing in recent years. The inconvenience and logistical concerns of laying wires for a communication network lay the ground for a much more appealing technologies incorporating wireless transmission. Removing the constraints of the physical installation of wires, wireless solutions provide diversity and in many applications can reduce cost.

ZigBee is based on the IEEE 802.15.4 standard along with other protocols like Wi-Fi and Bluetooth. ZigBee operates in the industrial, scientific and medical (ISM) radio band, specifically at 2.4 GHz internationally and 868 MHz or 915 MHz in specific parts of the world. ZigBee differs from Wi-Fi and Bluetooth technologies; in that it was mainly developed for low-rate WPAN's (LR-WPAN). Technology defined by the ZigBee specification is intended to be much simpler and less expensive than that of other WPANs. The simplicity and cost of ZigBee networks makes them a great candidate for wireless control and monitoring applications.

The ZigBee protocol can support over 64,000 nodes and can operate in three network topologies: Star, Tree and Mesh. The large amount of supported nodes is another appealing characteristic, specifically in industrial applications.

## 2. Project Scope

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The primary goal of this project is to investigate and evaluate the ZigBee protocol using OPNET simulation tool. Specifically, this project will analyse ZigBee wireless sensor networks (WSN) in both star and mesh topologies. For both topologies, the number of transmitting nodes and the physical size of the network will be altered to understand their effects. The goal is to emulate a WSN, hence, the physical expansion of the network (to mimic industrial applications) and the addition of numerous nodes to imitate various sensors.

## 3. ZigBee Overview

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### 3.1. Zigbee Specifications

Table 1 below highlight some major specifications of the ZigBee protocol.

Table 1: ZigBee specifications

Transmission Band	868, 915 and 2459 MHz
Transmission Range (meters)	~100
Network size (# of nodes)	> 64,000
Throughput (kb/s)	up to 250
Maximum children (# of children)	254

## 3.2. ZigBee Layers

Figure 1 below depicts the four layers of the ZigBee protocol. The ZigBee Alliance provides the specifications for the Application and Network layers whilst the IEEE 802.15.4 standard provides specifications for the bottom two layers: Medium Access Control (MAC) and Physical. MAC and Physical layer specifications are provided by the IEEE 802.15.4 standard to assure coexistence with other wireless protocols such as Bluetooth and Wi-Fi. The following sections will provide a brief overview of each of the four layers, and the ZigBee Device Object.

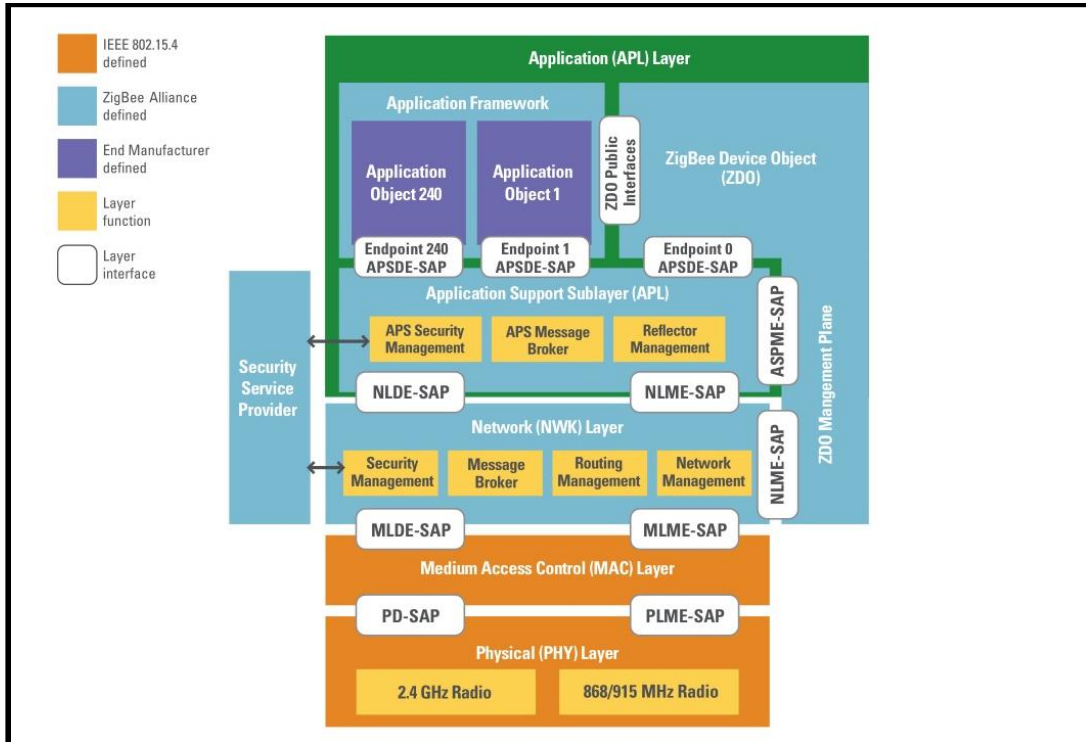


Figure 1: ZigBee protocol layers

### 3.2.1 Application Layer

The application layer is the highest-level layer defined by the ZigBee specification. This layer contains applications running on the ZigBee network and thus provides the effective interface to the user. A single node can support 240 applications, where application number 0 is reserved for the ZigBee Device Object. Applications on this layer can provide services such as building automation, temperature control, industrial control and wireless sensor monitoring.

## 3.2.2 ZigBee Device Object

The ZigBee device object represents the ZigBee node type of the device; defining the nodes role on the network. It is resident on all ZigBee nodes and provides generic ZigBee device functions. Since the ZigBee Device object is present on all devices, it is a useful and interoperable way of managing and gathering system properties.

## 3.2.3 Network Layer

As depicted in figure 1 the network layer is responsible for network management and addressing, message routing, route discovery as well as security features. The ZigBee Alliance defines this layer.

## 3.2.4. Medium Access Control Layer

The MAC layer determines source and destination addressing of frames and is extracted from the IEEE 802.15.4 standard. To provide reliable data transfer, this layer provides multiple access control in the form of Carrier Sense Multiple Access and Collision Avoidance (CSMA/CA).

## 3.2.5. Physical Layer

The physical layer is provided by the IEEE 802.15.4 standard. The physical layer is ultimately responsible for providing the data transmission service. This layer manages the physical RF transceiver; it performs channel selection as well as energy and signal management routines. As well, this layer exchanges data with the MAC layer above it. The physical transmission of radio waves occurs in different frequency bands which are mentioned in table 1. To avoid radio interference in order to support coexistence with other wireless technologies, the physical layer allows for channel selection.

## 3.3. ZigBee Hardware

ZigBee networks can be comprised of three components. The three components are ZigBee coordinators, routers and end devices. Each device is responsible for specific roles within the network. Figure 2 shows the OPNET model for each ZigBee component.



Figure 2: OPNET ZigBee models

### 3.3.1. Coordinator

For every ZigBee network there must be one and only one coordinator. The coordinators responsibilities include initializing the network, selecting the transmission channel and permitting other ZigBee nodes to connect to its network. A ZigBee coordinator can also route traffic within a network.

### 3.3.2 Router

A ZigBee router is responsible for message routing within a network. Not all networks require a router because traffic can travel directly from an end device to a coordinator or even from end device to another end device by using routing features of a coordinator. A routing device can also act as an end device; however, its routing capabilities would be inactive. A router can have child nodes connected to it depending on the network topology implemented.

### 3.3.3. End device

ZigBee end devices connect to routers or coordinators in a network but cannot have other devices connect to the ZigBee network by piggybacking of its connection. End devices are the end points of a ZigBee network and contain limited functionality to talk to parent nodes (coordinator or a router). Since they do not have routing responsibilities and can enter low-power sleep modes during periods of inactivity, ZigBee end devices have substantial battery lives. Due to its limited functionality, end devices impose limited memory footprints and can therefore be less expensive to manufacture than a router or a coordinator.

## 3.4. Network Topology

ZigBee networks support operating in Star, Tree, and Mesh topologies. Depending on the application of the ZigBee network, topology selection can drastically affect the behaviour of the network. For this reason, proper topology selection is very important.



### 3.4.1. Star Topology

The star topology is the simplest of the three and is depicted in figure 3. Its simplicity is very attractive but also presents certain drawbacks. Since the coordinator is at the center of the star all incoming data from end devices destined for other end devices must pass through this node. As well, the coordinator can be the destination of outgoing traffic from end devices, for example, in a wireless sensor network where sensor traffic is sent to the coordinator for logging and/or processing.

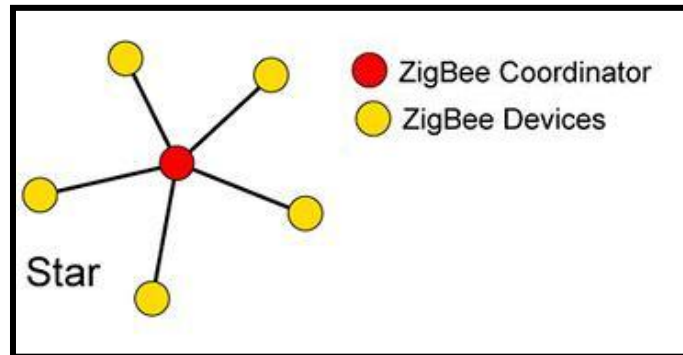


Figure 3: Star topology

### 3.4.2. Mesh Topology

A mesh topology offers multiple paths for messages within the network; this lends itself to greater flexibility than other topologies. If a particular router fails, the network can reconstruct an alternative path through other routers in the network. Figure 4 depicts a ZigBee network implementing mesh topology.

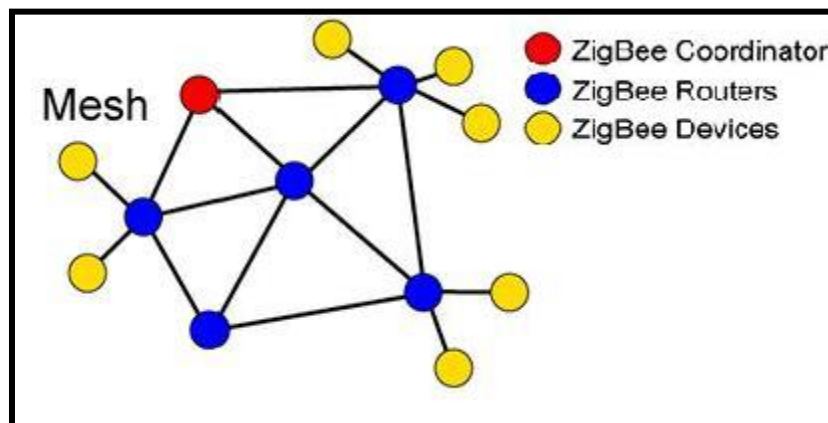


Figure 4: Mesh topology

### 3.4.3. Tree Topology

In a tree network, the coordinator is at the top (root) of the tree. End devices can connect to this root via a direct point to point connection or through a child router of the coordinator. For every child router connected, additional child routers can also be connected, creating different levels of nodes. Message passing within the network works in a hierarchical manner, source nodes must transmit messages to their parents (the node one level higher than the source node) which then relay their messages higher up the tree until it reaches the

coordinator or until it reaches a router that can redirect the message back down the tree to the intended destination. Figure 5 depicts a typical tree topology scenario.

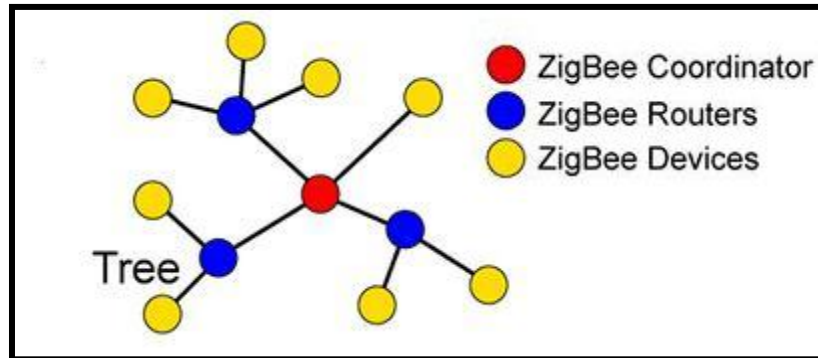


Figure 5: Tree topology

### 4. ZigBee Network Simulation Using OPNET 16

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OPNET 16 is used to simulate a ZigBee network. OPNET contains device models for ZigBee coordinators, routers and end devices. The main focus of the network simulation is to analyse ZigBee network performance in the context of a WSN. WSNs can range in size from a few metres to thousands of meters; for example, agricultural and environmental applications often span large distances while residential building automation applications can be much smaller. As well, some WSNs employ only a handful of end device sensors while others employ hundreds, and sometimes even thousands of end devices.

To compensate for these variations in WSN networks, three scales will be considered: 10mx10m, 100mx100m and 1000mx1000 m. Within each of these scenarios a star and mesh topology will be simulated. Tree networks are omitted from this simulation, due to their relative unreliability I have chosen not to implement this topology as a WSN. In a tree network, if one parent router fails, all communication to children underneath this failed node are lost. As well as varying the scale and topology of the scenario, end devices in each scenario will be increased to better represent real life applications of large WSN's.

#### 4.1. ZigBee Model Properties

To better simulate a WSN, several default parameters of ZigBee models were altered. The altered parameters were transmission power (mW), packet reception power threshold, data rate and transmission bands as described in figure 6.

[-] Physical Layer Parameters	
[-] Data Rate	250000
[-] Packet Reception-Power Thre...	-90
[-] Transmission Bands	(...)
[-] 2450 MHz Band	Enabled
[-] 915 MHz Band	Disabled
[-] 868 MHz Band	Disabled
[-] Transmit Power	0.003

[-] Packet Reception-Power Thre...	-90
------------------------------------	-----

Figure 6: ZigBee model parameters

The transmission power was reduced from 5W to 3mW to reflect typical transmission powers for wireless sensor nodes. Typical packet reception power thresholds for ZigBee devices range from -80 dB to -100 dB, more sensitive devices are more costly; to exemplify ZigBee's low cost characteristics a reception power threshold of -90 dB was selected. The data rate of 250000 bps is not common in WSNs; however, this was selected to explore the worst case scenario. This data rate can reflect an industrial control application where a ZigBee sensor node is continuously monitoring and transmitting a sensor value for a feedback control loop as opposed to intermittent sensor value transmissions. Finally, the transmission band was selected as 2.45 GHz because this band is intended for international use as opposed to 915 MHz and 868 MHz which are limited to certain geographical areas. The transmission band of 2.45 GHz maintains international interoperability of ZigBee hardware.

## 4.2. Small scale WSN

This scenario will simulate a 10mx10m area in both star and mesh topologies. In the star topology there will be 10 nodes sending traffic to a ZigBee coordinator at the center of the network and then 50 sensors. The mesh network will also consist of 10 and subsequently 50 nodes sending traffic to the coordinator, of the 10 nodes 2 will be routers (also acting as end devices) and of the 50 nodes 7 will be routers. Figure 7 below depicts the star topology mentioned (with only 4 nodes for visual simplicity) and figure 8 depicts a mesh topology layout (again with limited nodes for visual simplicity).



Figure 7: Star topology in OPNET

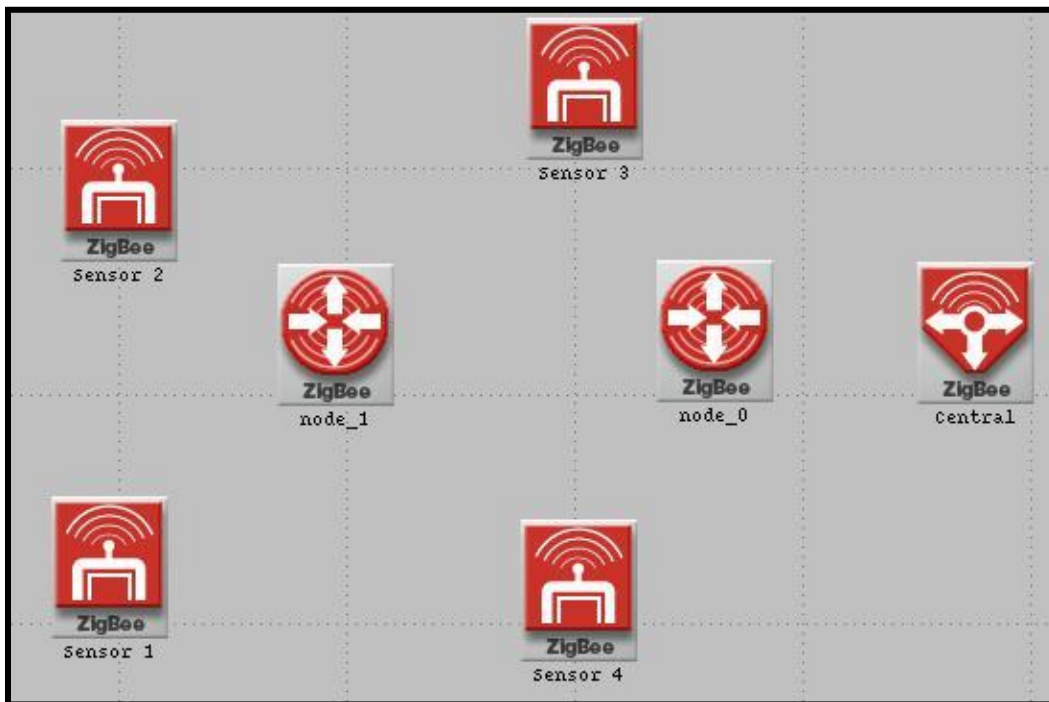


Figure 8: Mesh topology in OPNET

### 4.3. Medium scale WSN

This scenario will inherit the layout of the small scale WSN network mentioned above but on an increased scale of 100mx100m. The number of transmitting nodes and routers remains the same as in the previous scenario.

#### 4.4. Large scale WSN

This scenario is 1000mx1000m large and employs both star and mesh networks. For the star network 10 and 250 transmitting nodes will be simulated. The mesh layout will implement 10, 50 and 250 transmitting nodes with 2,7 and 27 routers respectively.

### 5. Simulation Results

#### 5.1. Small scale WSN

End-to-end delay (ETE) is a global statistic in OPNET, it describes the time it takes for a message to flow from source to destination. Figure 9 details the result of this scenario in relation to time averaged ETE delay of both topologies. We can see the increase in ETE delay as ZigBee nodes are increased from 10 to 50, more importantly we can see a drastic increase in ETE delay between the star and mesh topologies.

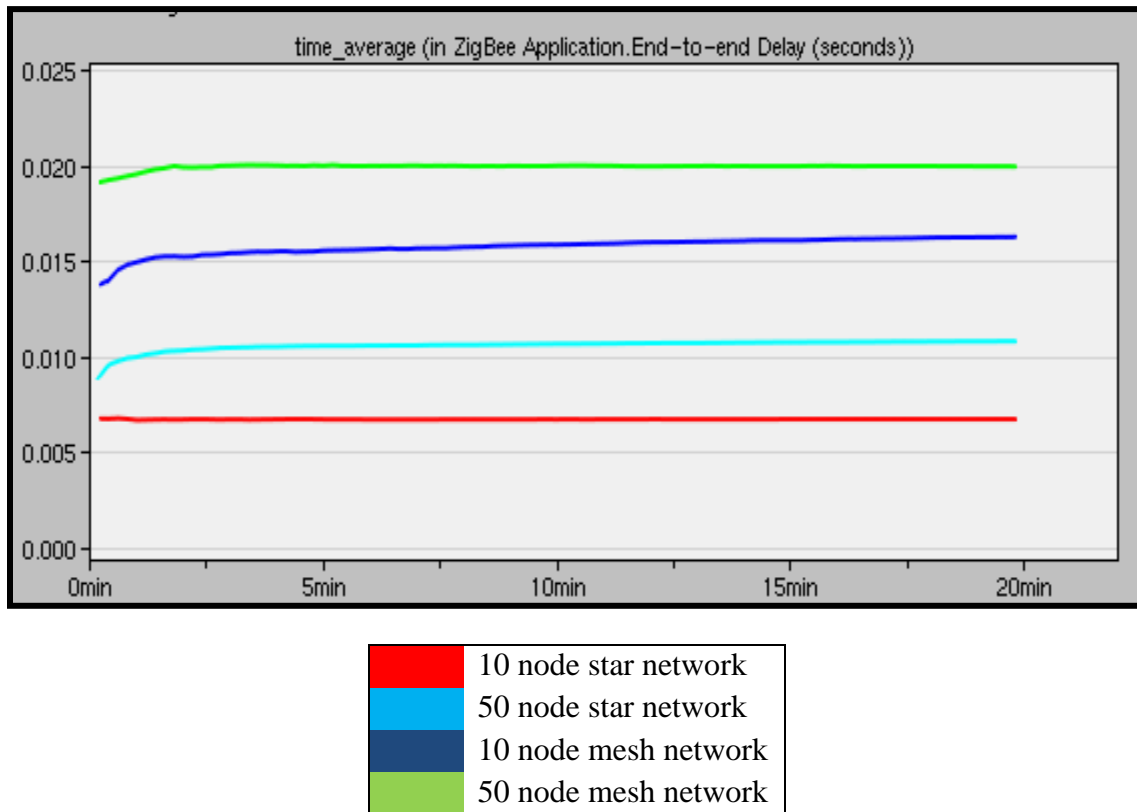


Figure 9: Scenario 1: ETE delay (sec) vs Simulation time (min)

#### 5.2. Medium scale WSN

In this scenario, we see a minimal increase in ETE delay as detailed in figure 10 below. This can be attributed to the transmission range of ZigBee devices, since this scenario is well within the transmission range of ZigBee

devices. Notice that there is an approximately two fold increase in delay when comparing star and mesh networks. This is attributed to the extra hop introduced in mesh networks, for messages to pass from end devices to the coordinator they must first be received by an intermediate device, the ZigBee router. Accordingly, an extra hop is increasing the ETE delay by 100%.

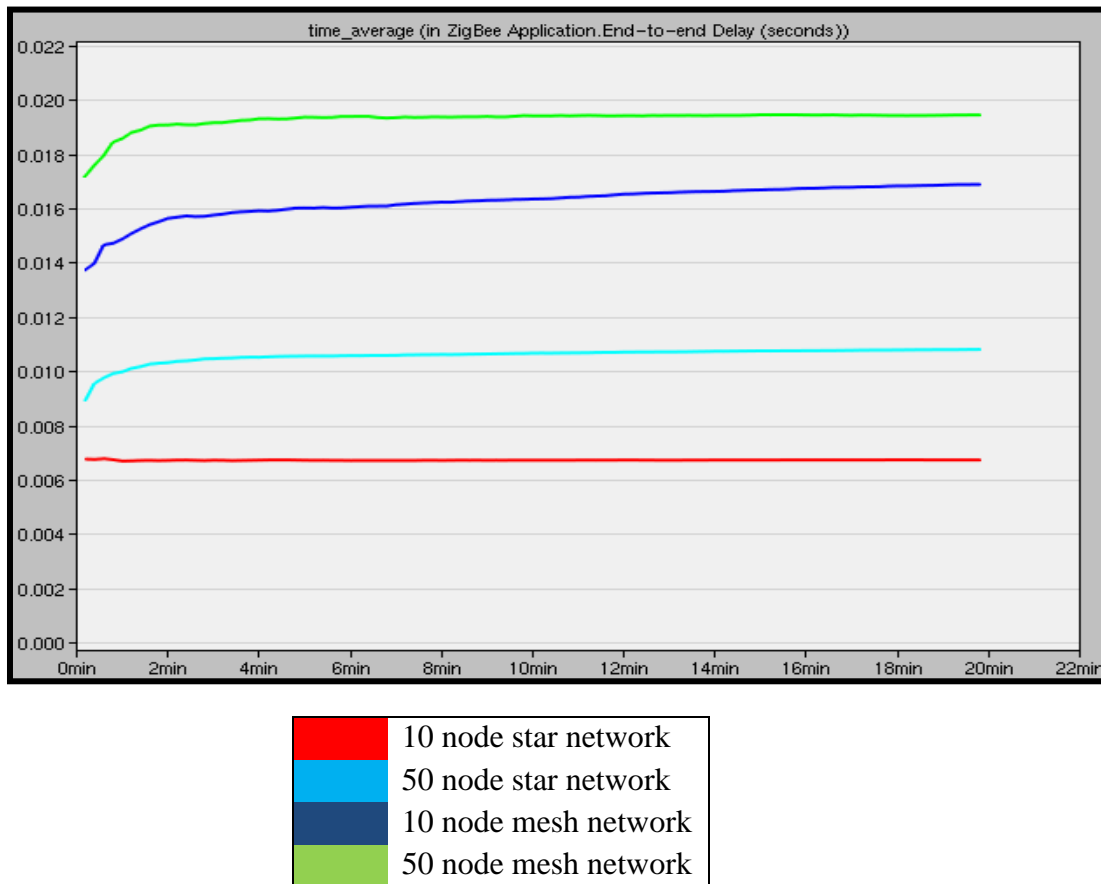


Figure 10: Scenario 2: ETE delay (sec) vs simulation time (min)

### 5.3. Large scale WSN

In this scenario the scale is very large and we expect that some ZigBee nodes will lie outside the transmission range in the star topology. From figure 11 we can see that as we increase the end devices from 10 to 250 for the star topology there is a slight increase in ETE delay. This can be attributed to the increased load on the coordinator due to the immense amount of traffic in the network. For the mesh topology with 10 nodes we observe an expected value of ETE delay around twice that of the star network for 10 nodes; however, as we increase the nodes to 50 and 250 we observe a discrepancy in ETE delay. Instead of ETE delay increasing when 200 nodes are added, it is dropping. This can be attributed to the increase in router density per unit area since the scale of the simulation remains the same and an extra 20 routers are added. When the router density is increased messages originating on the edges of the network can find a more direct route through routers to their destination; the coordinator. When there are only 50 nodes messages must traverse more routers before ending up at their destination.

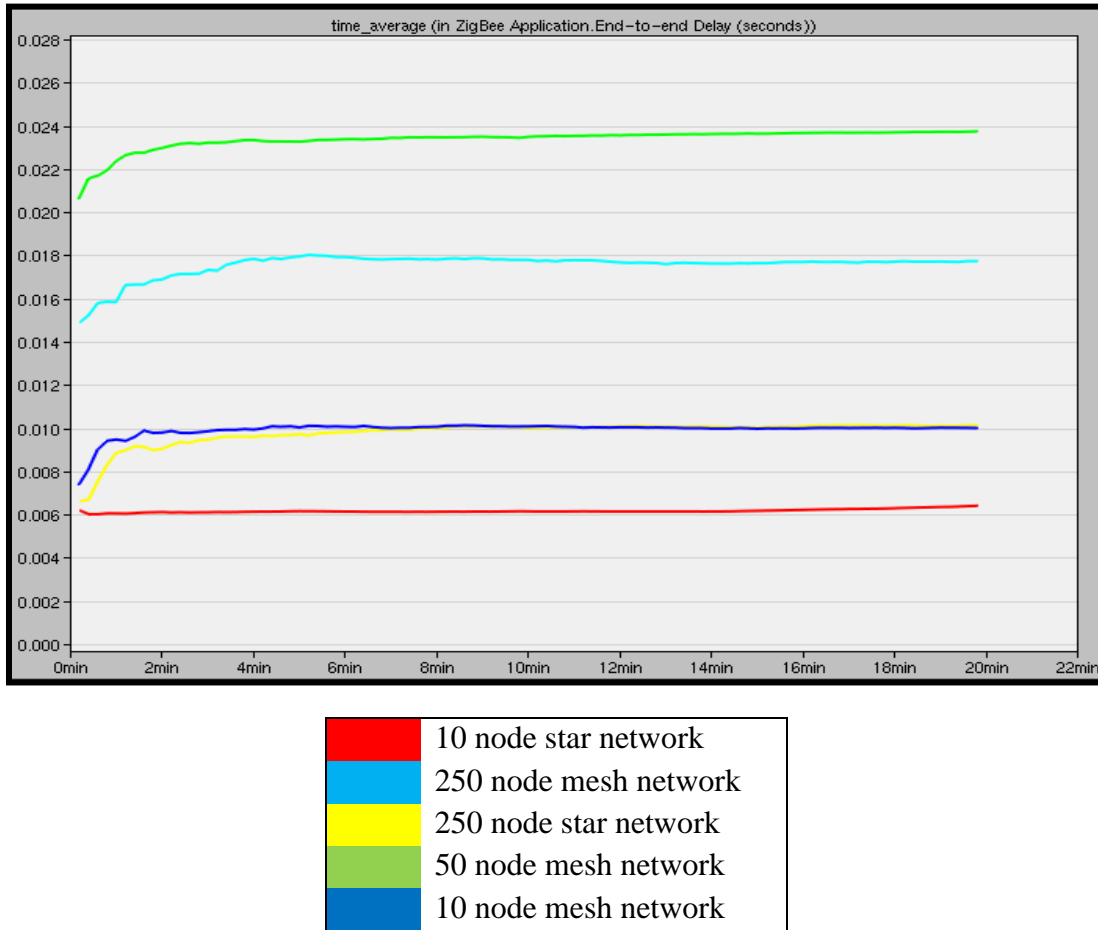


Figure 11: Scenario 3: ETE delay (sec) vs simulation time (min)

To explore the effectiveness of mesh networking in increasing transmission range in this scenario we must also look at goodput, the amount of useful information received by the coordinator. In order to do this, we first look at the goodput of the coordinator in the star topology when there are 250 nodes. Figure 12 depicts the goodput at the coordinator as well as traffic sent by one of the 250 transmitting nodes.

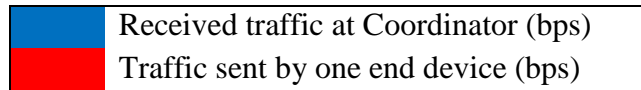
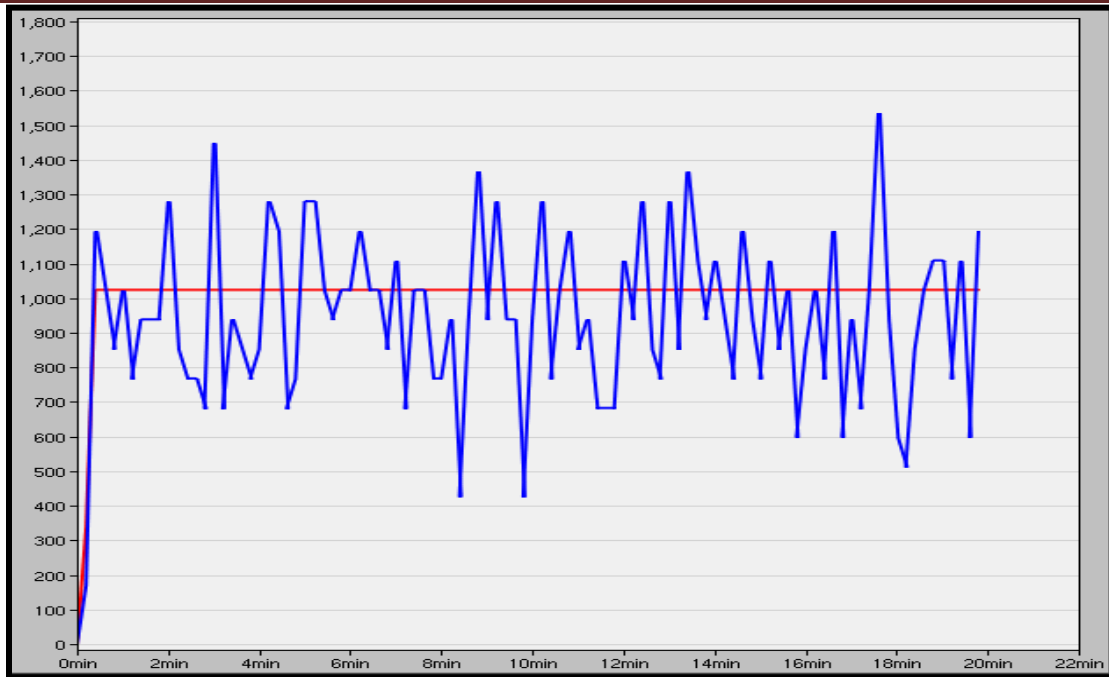


Figure 12: Scenario 3: Data rate (bps) vs simulation time (min)

We can see that although each of 250 nodes is transmitting approximately 1100 bits/sec, the coordinator is receiving anywhere from 500 bits/sec to 1500 bits/sec. Ideally we would expect the coordinator to receive all the traffic destined for it but clearly many nodes are too far away. We can confirm that routers in the mesh topology are effectively increasing the range of outlying nodes by looking at figure 13.



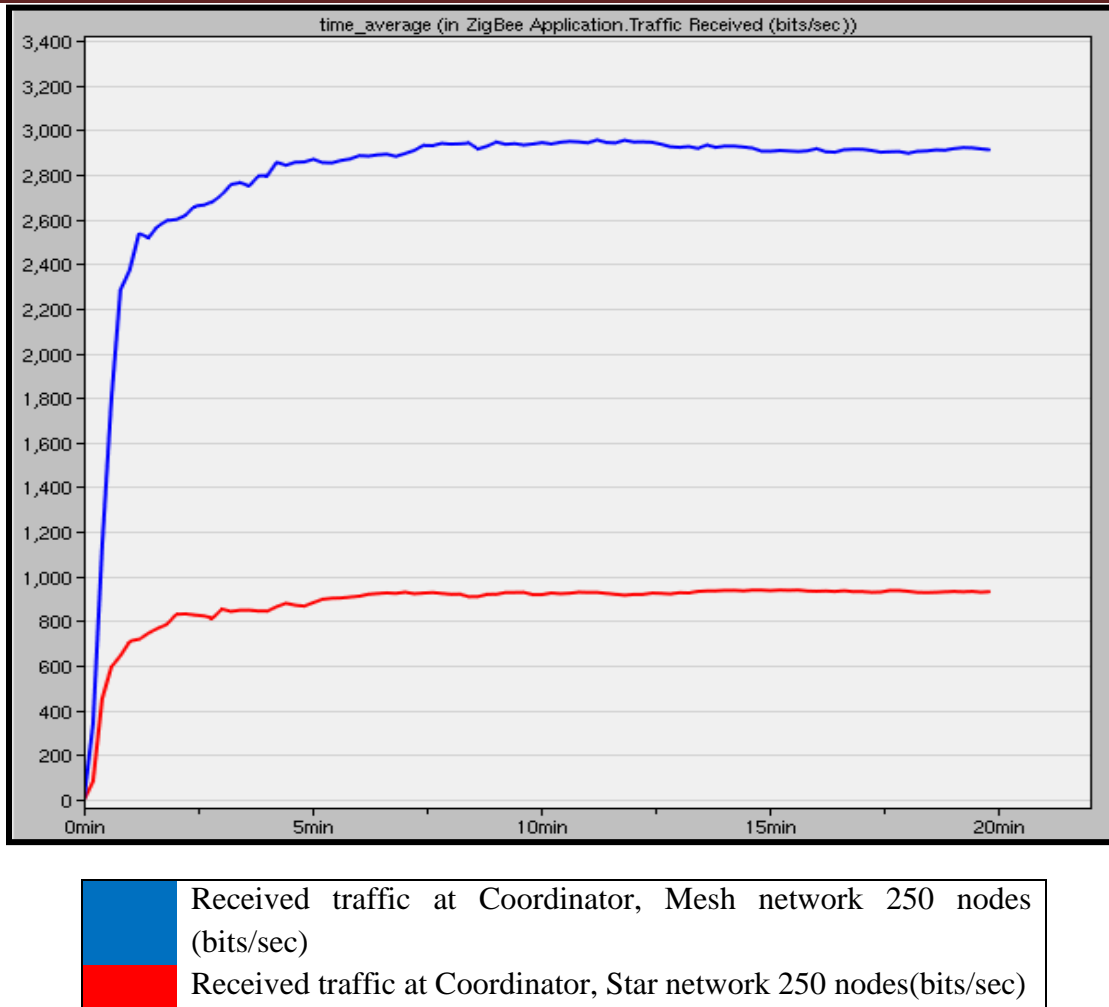


Figure 13: Scenario 3: Data rate (bps) vs simulation time (min)

Figure 13 shows us that by employing a mesh topology the coordinator is receiving approximately 3.5 times more traffic than it did when the star topology is implemented. This effective increase in transmission range is due to the addition of routers in mesh networks, by sending messages to intermediate devices (routers) which then relay messages to other routers until the coordinator is in range, nodes far away from the coordinator can still communicate with the coordinator.

## 6. Discussion and Conclusion

### 6.1. Simulation result conclusion

In this project, WSN's were evaluated in various scenarios to understand how the ZigBee protocol behaves in the application of a WSN. From the simulation results we have observed that for a small sized network the star topology is quite effective, although a mesh network could also be used it would introduce unnecessary cost and complexity to the network. If a mesh network is implemented there would be an unnecessary bottleneck of resources at the router, as well this router would use a considerable amount of energy, circumventing one of the major advantages of the ZigBee protocol: low power consumption. Although there is a bottleneck in a star

network as well (coordinator) we assume that in a WSN this node is not operating via battery power due to its data logging requirements. In the second scenario a medium sized WSN was simulated. Both star and mesh networks performed similarly but the mesh network exhibited larger ETE delays. Depending on the specific application of the WSN in a medium sized network, a star or mesh network can be appropriate. If ETE delay is of utmost importance, for example, in industrial control applications it might be suitable to deploy a star network to reduce ETE delay. Finally, we examined a large ZigBee WSN and concluded that a star topology is not appropriate in this situation. By implementing a mesh topology it is possible to avoid transmission range limitations of ZigBee end devices. This feature is extremely appealing, especially for WSN applications in agricultural and environmental monitoring due to the typically large span of these networks.

### **6.2. Future work**

Some future work that can be implemented is to physically construct a ZigBee network. I am currently working on a Capstone project involving Bluetooth communication to relay sensor data to a central processing unit. In the future I would like to explore implementing a ZigBee network instead of Bluetooth due to unfavorable power consumption characteristics of the Bluetooth protocol. As well, using OPNET in the future I will simulate RF interference to evaluate ZigBee network operation under interference. Ideally I would also like to quantitatively model ZigBee energy consumption in the future.

## 7. References

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