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FINAL PROJECT

Evaluation of ZigBee Protocol Network Topologies in Medical Monitoring Environments

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http://www.sfu.ca/~mlew/Group_3_website.html

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Abstract

ZigBee protocol is often used in medical biotelemetry, which is a relatively new concept involving wireless transmission of data from the sensors attached to a patient to a distant monitoring station. There is no standardized topology governing the current networks, therefore, we will compare and evaluate the performance of multiple topologies to determine which is the most suitable in a typical hospital environment. The analysis will be performed in OPNET comparing characteristics such as transmission efficiency and network delay.

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1. Introduction

Medical professionals require reliable monitoring of patient conditions (heart rate, blood saturation, and body temperature) in order to respond in a timely manner should a vital sign drop below an acceptable level. Biotelemetry is a relatively new concept which focuses on acquiring only the necessary vital signs in a portable manner to ensure efficient monitoring of patients. A wireless body network is established across the patient's body in which several sensor nodes acquire and transmit relevant data to medical professionals for analysis. Figure 1 illustrates this concept in which one medical professional is simultaneously observing four patients. This is the typical scenario at Burnaby Hospital where the medical professional to patient ratio is 1:4 [1].

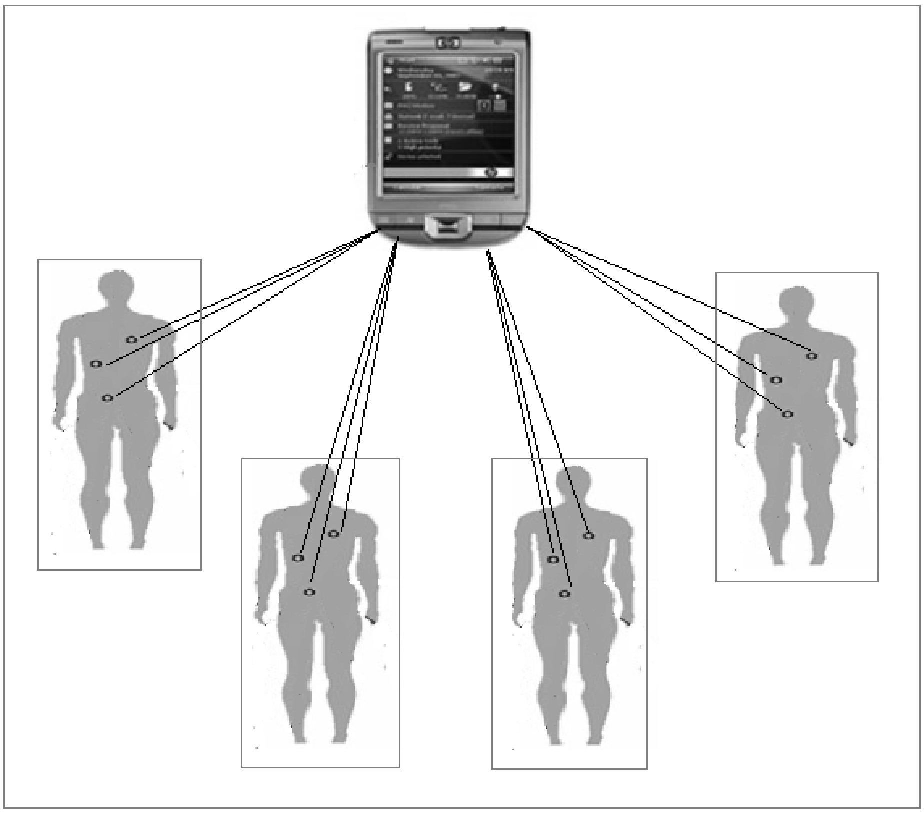

Figure 1: High block diagram of patient monitoring

The fact that each vital sign can be monitored by a device that does not require high power or high data transfer capabilities allows for this method to be accomplished. The respective power and data requirements for the vital signals are shown in Table 1. Although there are numerous other protocols which could successfully achieve the task of biotelemetry, ZigBee protocol compliant devices are ideal to the needs of the medical environment as they are low power, low cost, self-healing, and self-configuring. ZigBee protocol compliant devices are based on the IEEE 802.15.4 physical radio standard which operates at 2.4 GHz at 250 Kbps, while also maintaining a transmission range of 10 m – 1600 m [2].

Table 1 : Power and data requirements for vital signals [3]

APPLICATION	DATA RATE	BANDWIDTH	LATENCY	ACCURACY	RELIABILITY
ECG (12 leads)	12 Kbps	100–1,000 Hz	< 250 ms	12 bits	10^{-10}
Blood saturation	16 bps	0–1 Hz	–	8 bits	10^{-10}
Temperature	120 bps	0–1 Hz	–	8 bits	10^{-10}

Realizing that the ZigBee protocol is the chosen protocol for the medical monitoring environment, our project has been tailored to examine which topology is best suited for this application. The simulations will focus on a hospital environment where a medical professional is responsible for multiple patients, each equipped with three ZigBee monitoring devices attached. We will compare the transmission performance and network delay for the star, tree, and mesh topology to determine which is most favourable.

1.1 ZigBee Architecture and Comparison

With the increasing availability of wireless networks, it is often difficult to isolate a specific type for certain applications. Table 2 compares the ZigBee protocol with numerous other standards in terms of key medical parameters such as coverage, data rates, and power requirements. Realizing these details it is evident that based on the biotelemetry requirements, the ZigBee protocol is the ideal standard.

Table 2: Comparison of Standards

	IMPORTANT PARAMETERS							
STANDARD	COVERAGE	DATA RATES	FREQUENCY	BANDWIDTH REQUIREMENTS	POWER REQUIREMENTS	NETWORKING TOPOLOGY	SECURITY	COMPLEXITY (DEVICE/ APPLICATION)
Wi-Fi	100 m	11 and 54 Mbps	2.4 GHz and 5 GHz	20 MHz	High	Infrastructure (point-hub)	AES block cipher and 32 bit CRC	High
Bluetooth	10 m	1 Mbps	2.4 GHz	1 MHz	Medium	*Ad hoc*, very small network	64 and 128 bit encryption and 16 bit CRC	High
UWB	10 m	100–500 Mbps	3.1–10.6 GHz	≥ 500 MHz	Low	Point-to-point	AES block cipher and 16 bit CRC	Medium
ZigBee	70–100 m	250 Kbps	2.4 GHz	2 MHz	Very low	*Ad hoc*, peer-to-peer, star or mesh	128 AES with application layer security	Low
WiMax	50 m	75 Mbps	2–11 GHz	10 MHz	Low	Infrastructure	AES triple data encryption standard	Low
WiBro	<2 miles	1–75 Mbps	2.3–2.4 GHz	8.75 MHz	Low	Infrastructure mesh	AES with extensible authentication protocol	Low
Wireless USB	10 m	480 Mbps	3.1–10.6 GHz	528 MHz	Low	Point-to-point	AES 128	Low
IR wireless	<10 m with LOS	4 Mbps	16 KHz	2.54 MHz	Low	Point-to-point	Very secure	Low

AES, advanced encryption standard; CRC, cyclic redundancy check; IR, infrared; Kbps, kilobits per second; LOS, line of sight; UWB, ultra-wideband; WiBro, wireless broadband.

The ZigBee architecture consists of four prominent layers. The upper two being the Application Layer and the Network Layer while the bottom two are the Media Access Control Layer and the Physical Layer. Figure 2 provides an overview of the ZigBee protocol layers.

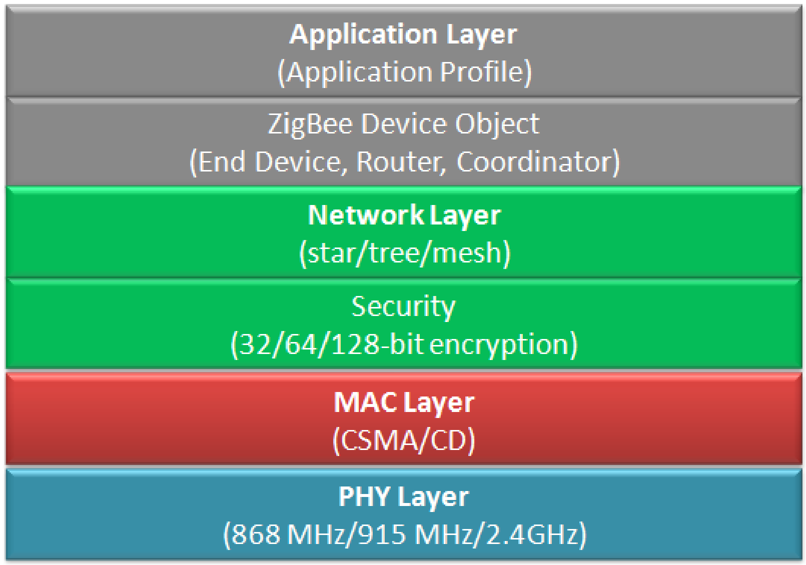

Figure 2: Zigbee architecture layers

1.1.1 Application Layer

The effective interface is provided to the end user in this upper most layer. Application profiles are further defined which force ZigBee manufacturers to comply with certain standards to allow interoperability. The Zigbee Device Object (ZDO) sub-layer establishes local links and determines the role of the devices – End Device, Router, or Coordinator.

The coordinator is responsible for setting up a network. ZigBee networks need to have one coordinator. The router is a ZigBee device that is capable of routing data to other nodes in the network. End devices usually have a sensor function, and in our case, medical sensors [2].

1.1.2 Network Layer

Setting up of networks and determining routes for data transfers are the responsibility of the network layer. Additional tasks of network maintenance are assigned if the device is classified as a Coordinator. The security features are additionally performed in this layer to ensure the transmitted data is encrypted as required.

1.1.3 Media Access Control Layer

Each ZigBee device is provided a unique 64 bit MAC address upon manufacturing. This allows data routing and further implements Collision Detection. The CSMA/CD scheme attempts to ensure efficient transfer of information by sensing the carrier and only transmitting when the medium is free.

1.1.4 Physical Layer

Transmission frequencies are specified in this layer to ensure radio wave interference is avoided. Current standards follow IEEE 802.15.4 which provides three spectrum bands depending on the region of use. Table 3 indicates these respective bands, channels, and operating regions.

Table 3: IEEE 802.15.4 spectrum bands and corresponding regions [2]

Frequency Range (MHz)	Transfer Rate (kbit/s)	Region
868-868.6	20	Europe
902-928	40	North America
2400-2483.5	250	Worldwide

The structure of the PHY protocol data unit is shown below in Figure 3.

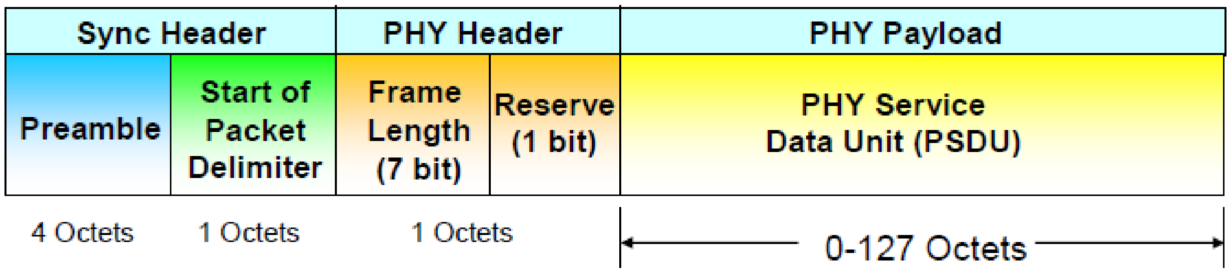

Figure 3: PHY protocol data unit structure [4]

The preamble and delimiter are used for synchronization. The frame length and reserve bit forms the PHY header which determines the size of the PHY payload [4].

1.1.5 ZigBee Model in Opnet

Defining the underlying operation of the ZigBee protocol was beyond the scope of the project but a higher layer understanding was useful in performing the simulations. Figure 4 illustrates the node model of a typical coordinator along with its process model for the mac layer which was provided in the ZigBee library in OPNET.

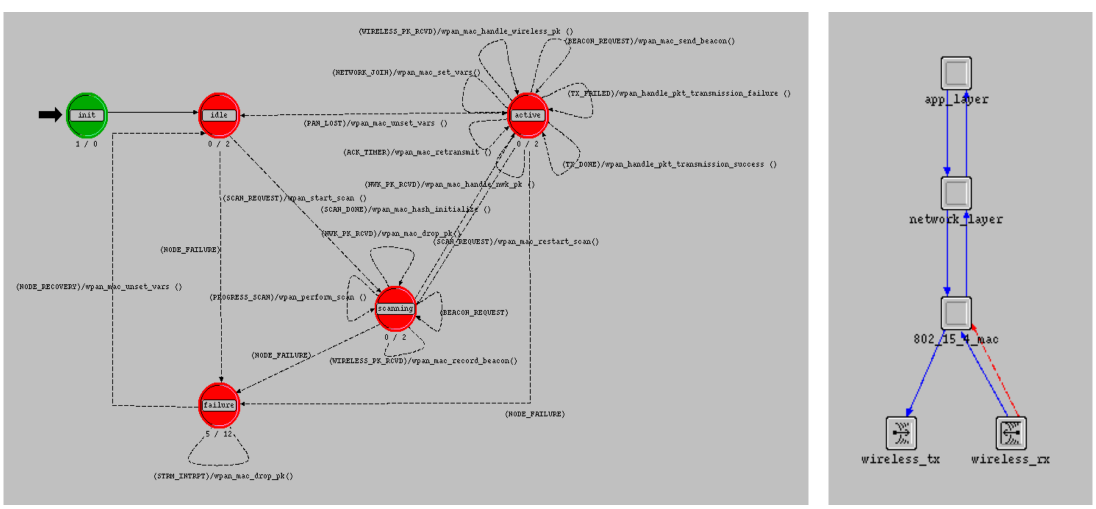

Figure 4: Underlying operation of the Zigbee protocol. MAC process model (Left). Node model (Right)

1.1.6 Operating Modes

There are two operating modes for ZigBee: beacon and non-beacon mode. Beacon mode utilizes slotted CSMA/CD which allows the ZigBee device to turn off for periods of time before it has to turn on for its time slot. The ability for the ZigBee device to turn off in between time slots allows for low power consumption. Non-beacon mode uses unslotted CSMA/CD. The OPNET models provided only had non-beacon mode available.

Since we utilized the non-beacon mode, data transfer is established as shown in Figure 5. Note that we did not use the optional acknowledgement.

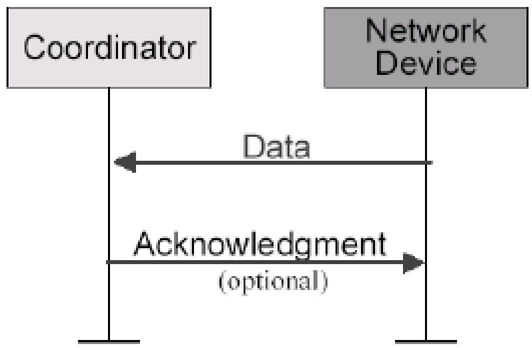

Figure 5: Data connection sequence

2. Simulation Topologies

The focus of this project is to determine which topology for the ZigBee protocol is best suited in the medical monitoring environment. The physical topology of a hospital setting was provided earlier in Figure 1 which illustrated four patients transmitting vital signs data to one receiver who was declared to be a medical professional. Implementation of the ZigBee protocol for this scenario could be constructed with three unique topologies – Star, Tree or Mesh. Figure 6 provides the legend for the objects which are used to graphically indicate the respective topologies.

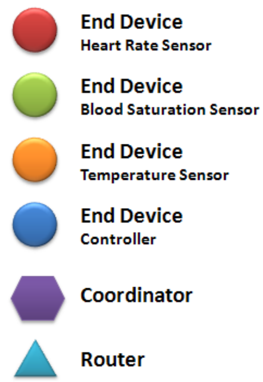

Figure 6: Legend for topology block diagrams

2.1 Star Topology

Minimal devices are required to implement this topology in comparison to the tree and mesh structure. Figure 7 visualizes the end devices on the patients and the end device at the medical professional location. The coordinator is an essential component of the network as it performs the critical function of initializing and maintaining the network. One coordinator can maintain 256 end devices, which is far beyond the requirements in the medical environment. The star topology is a simple network to setup up. However, if the coordinator node fails, the entire network would fail as well. In addition, the range of the star topology is limited.

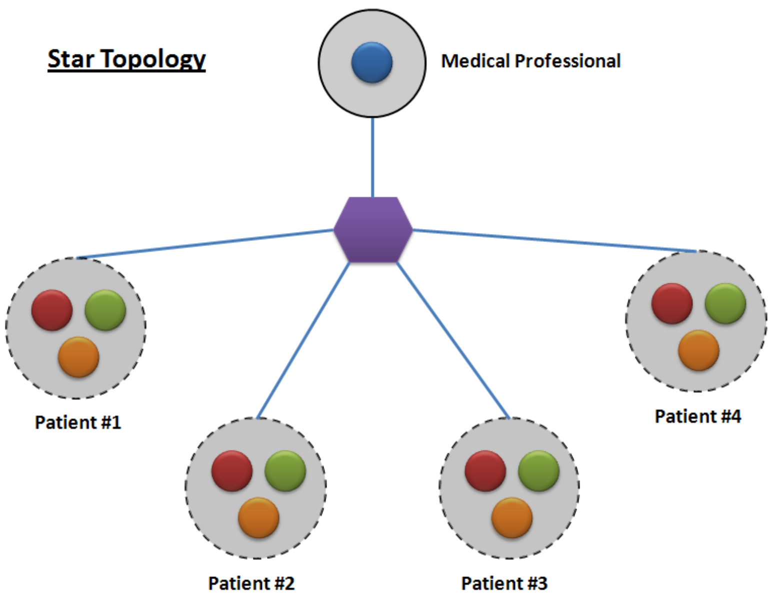

Figure 7: Star topology block diagram

2.2 Tree Topology

As shown in Figure 8, the tree topology mimics the structure of a tree with branches protruding at each level. The routers split each branch into a deeper level which terminates with an end device. In the case with four patients, six routers are employed each catering to a total of 12 end devices. The tree network is hierarchical, in which devices can only send data to their parents. The routers act as parents to the end devices, while the coordinator acts as a parent to the 2 routers as well as the medical professional's end device. An advantage of the tree topology is that the routers extend the range of the network. The disadvantage of the tree topology includes the scenario in which a router fails. Since the router acts as a branch, the corresponding leaves (end devices) of that failed branch will be cut off from communicating with the coordinator. The unfortunate scenario in which a router fails could lead to a critical situation in which data monitoring of two patients will be dropped.

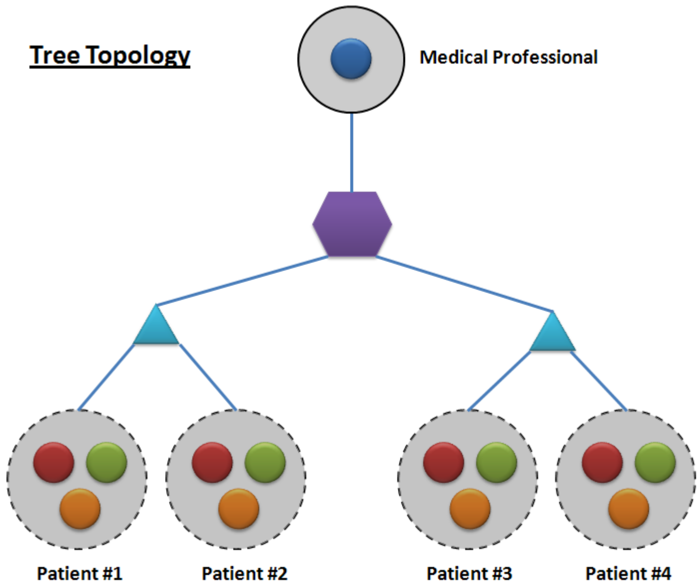

Figure 8: Tree topology block diagram

2.3 Mesh Topology

The mesh topology, as shown in Figure 9, is considered to be the most reliable structure as it employs numerous communication paths. Various routers are engaged to create a mesh network and incorporate redundancy into the network yielding it to be a reliable choice. In case of node failures, the self-healing feature of the ZigBee network is activated which is highly valued especially in the targeted medical environment. The disadvantage of the mesh topology is that it is resource expensive: route discovery is costly, and the routing tables required for this topology are larger than the other topologies [8].

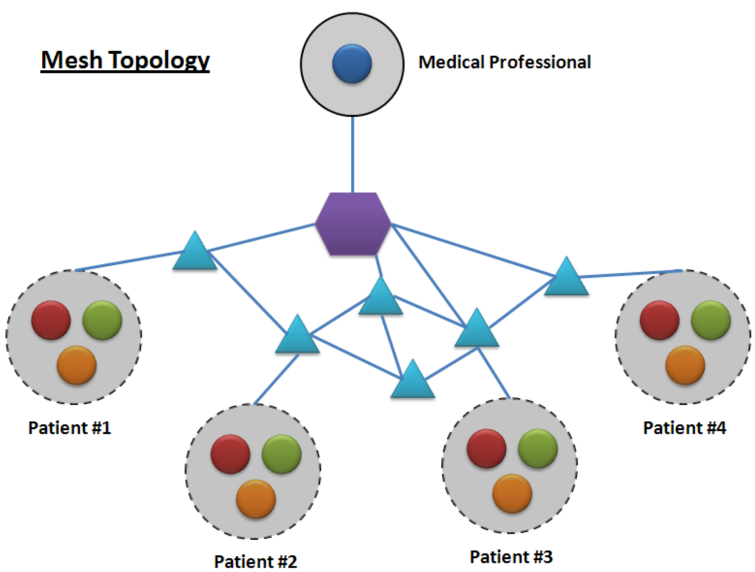

Figure 9: Mesh topology block diagram

3. Simulations

3.1 Basic Simulation

Before proceeding with simulating the chosen topologies, it was advisable to first test the basic structure of the ZigBee network. The medical environment in a typical hospital unit was selected with architecture parameters to be 100m by 100m. A single patient was modeled to demonstrate preliminary results with the simulation time of 1 hour. Figure 10 illustrates the simple topology of three end devices communicating with a single remote end device.

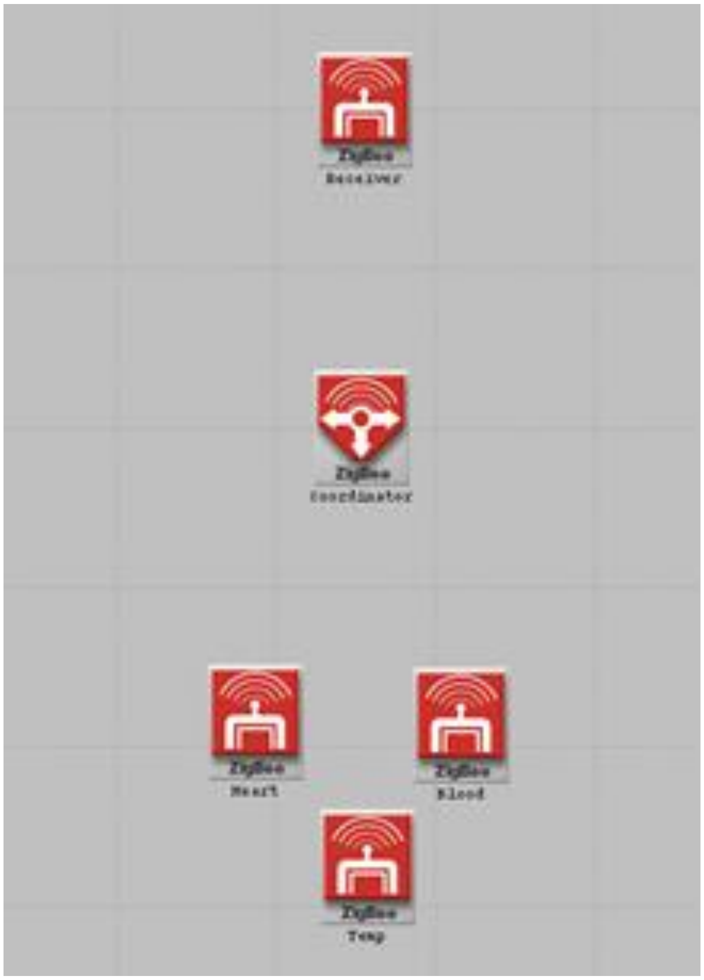

Figure 10: Basic simulation scenario

The heart sensor, the blood sensor, and the temperature sensor are configured to send one packet per second in a star topology. Figure 11 indicates successful transmission of a single packet from each sensor to the doctor end device for a total of three received packets per second.

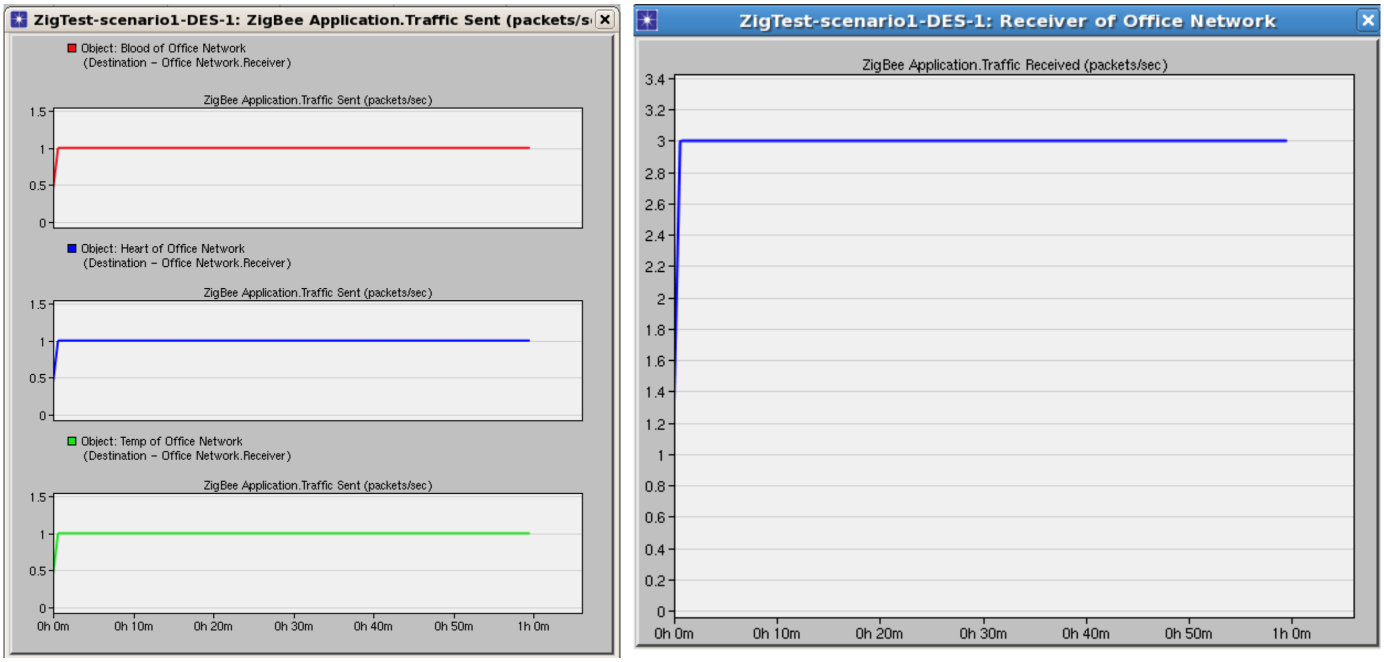

Figure 11: Transmission from each sensor at 1 packet/sec (Left). Total received packet rate at doctor at 3 packets/sec (Right)

Following this, a more thorough simulation was created in which each sensor was modified to send data at their required rates. The heart sensor was set to send at 12 Kbps, blood saturation sensor at 16 bps, and the temperature sensor at 120 bps. Figure 12 confirms receipt of these data packets at the doctor end device with the total received bit rate of 12136 bits/sec.

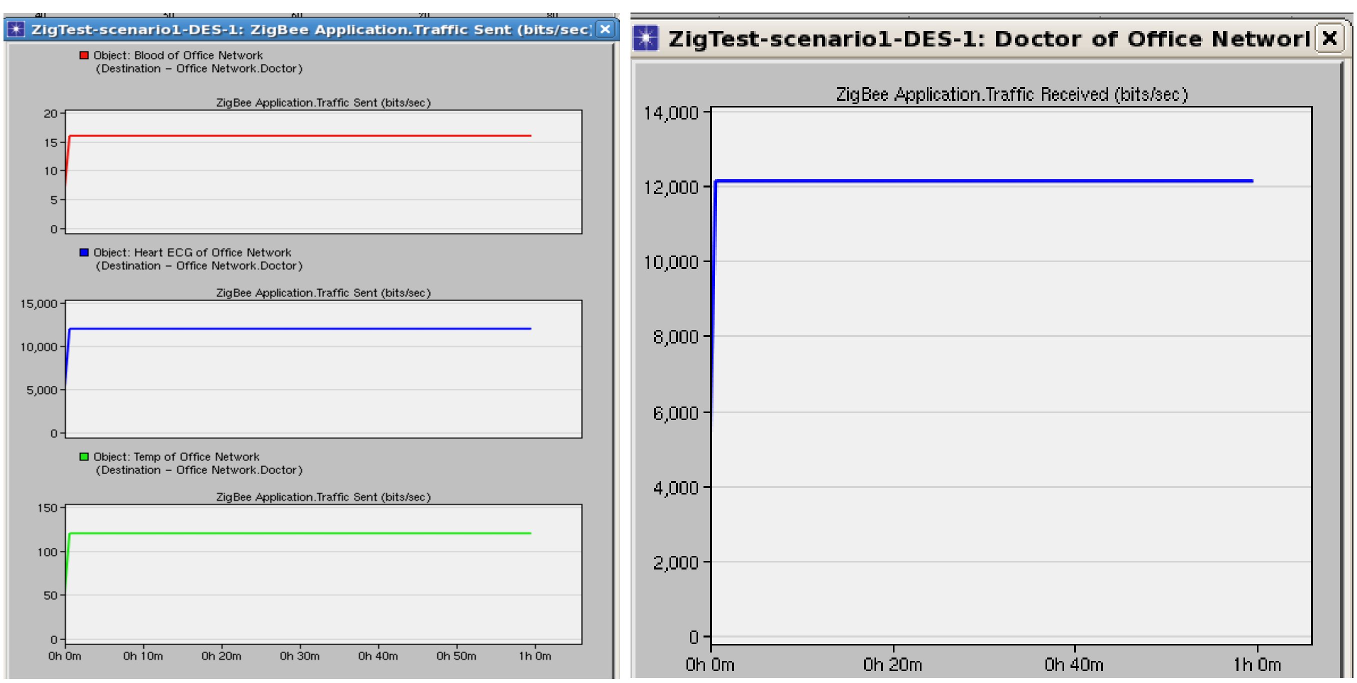

Figure 12: Sensor data transmission rate (Left). Total received rate (Right)

3.2 Complete Simulation

Three different network topologies were simulated to determine which structure is most suitable for the medical environment for patient monitoring. Three vital sensors configured for four patients resulted in a total of twelve sensor end devices which transmitted data to the doctor end device. The primary results which were collected included received data and data dropped. The efficiency of the topologies in terms of data sent and received was most critical in evaluating their operation. In a medical environment it is crucial that all collected data is carefully analyzed before decisions are made. Therefore, in order to ensure this process is upheld by the physicians, they must be provided with all of the acquired data. Simulations performed for the three topologies provided varying results of which mesh was seen to be the most efficient. Figure 13, Figure 14, and Figure 15 depict the structure of the nodes of the three topologies: Star, Tree, and Mesh, respectively.

Simulation conditions were set to mimic operation for a complete day of patient monitoring. This allowed the network to stabilize and provide long term, consistent results.

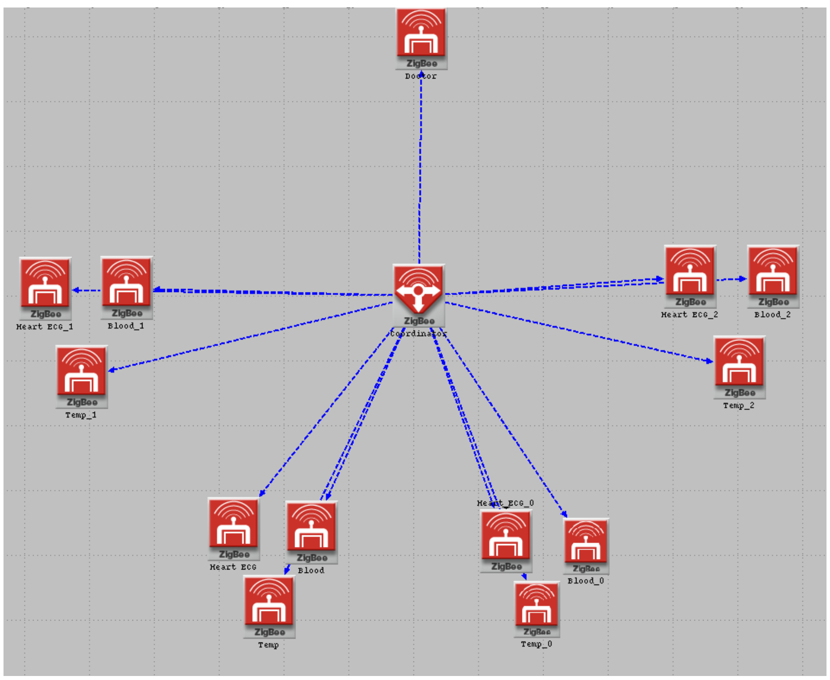

Figure 13: Simulated star topology

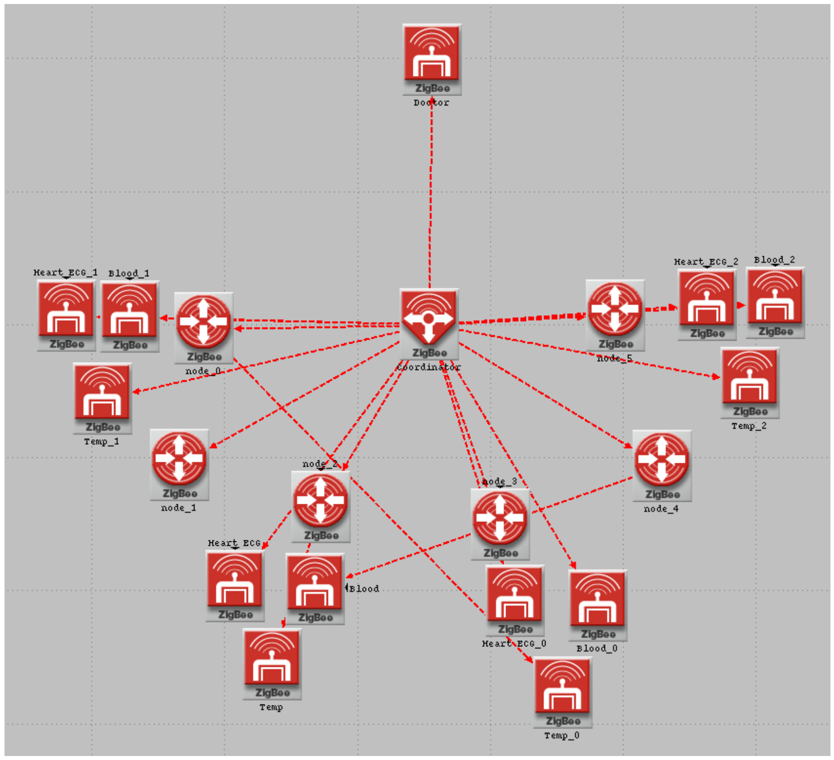

Figure 14: Simulated tree topology

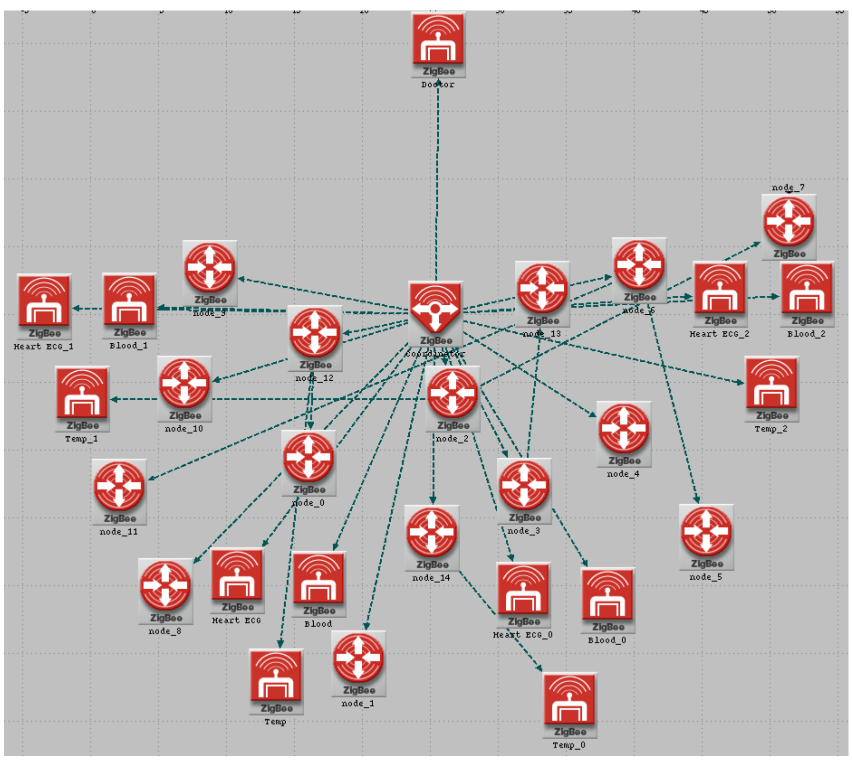

Figure 15: Simulated mesh topology

3.2.1 Stationary Doctor Simulation Results

The comparison graph of the three topologies performance is shown in Figure 16. It is evident that the mesh structure is the most efficient as it has the highest received packet rate and hence the lowest dropped packet. Ideal performance would result in a received bit rate of 48544 bits/sec which is very close to what the mesh network provided.

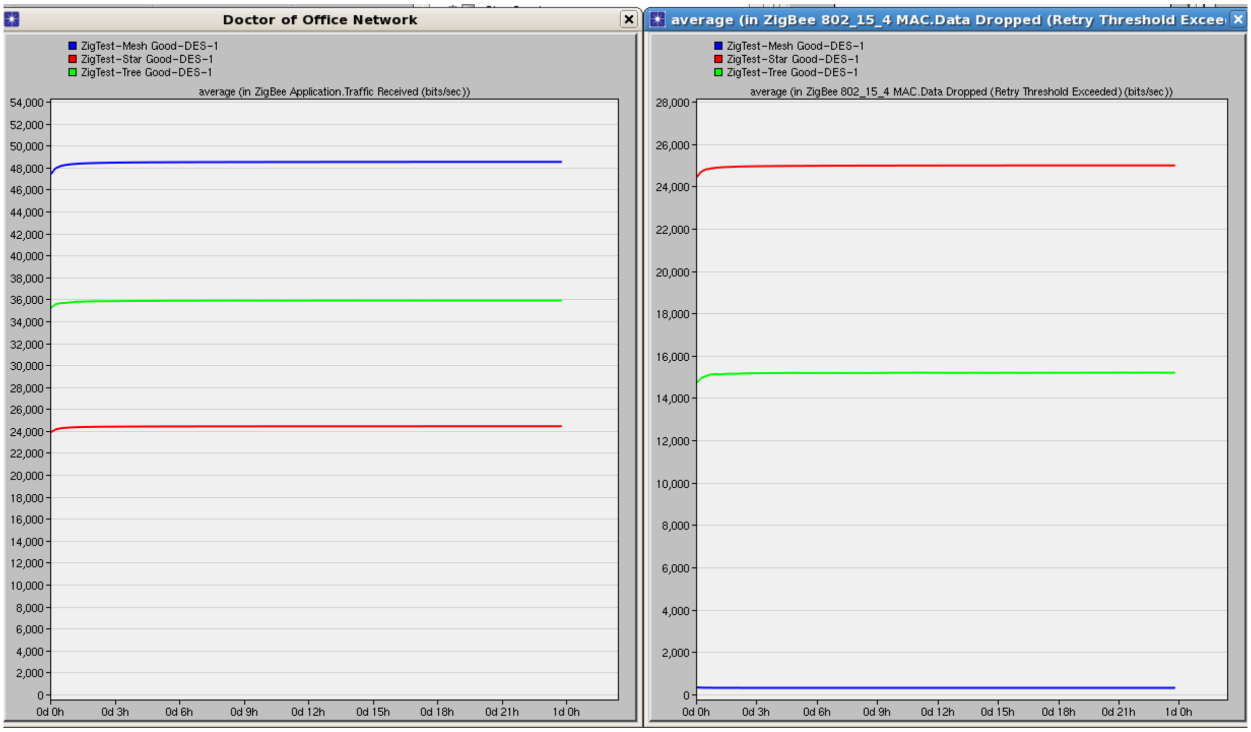

Figure 16: Comparison of transmission efficiency of the tree topologies

Another factor which must be considered to accurately define the most appropriate topology for the medical environment is the delay of the network. Biological data is time-sensitive and thus must be provided to the doctor on a real-time basis.

Figure 17 compares the packet delay of the three topologies. The mesh network resulted in the largest delay but observing the quantitative scale, we conclude that the delay is considered negligible. It is seen that the mesh topology presents an average delay of 21 ms while the other competing tree and star topologies have an average delay of 19 ms and 18 ms, respectively.

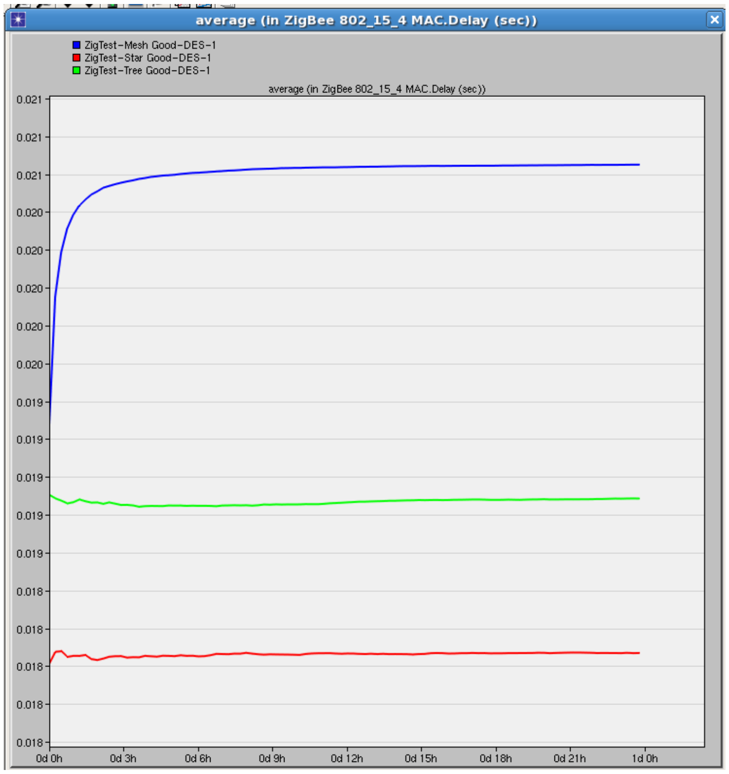

Figure 17: Comparison of packet delay of the three topologies

The reason why the mesh topology has higher network delay is because its route discovery is costly and requires a larger routing table [8].

Therefore, based on the two factors of transmission efficiency and packet delay, the stationary simulation indicates that the mesh topology is the ideal choice for a typical medical monitoring environment.

3.2.2 Mobile Doctor Simulation Results.

However, the doctor is infrequently stationary in a medical environment. Rather they are continually in motion and must be provided with accurate monitoring data from their patients at all times. Expanding upon our previous simulation results of the three topologies, it was now desired to determine whether the ZigBee protocol could also be used in a mobile scenario. We then simulated a mobile doctor by having the physician's end device traverse a triangular trajectory around the hospital ward. The doctor`s end device was provided with a mobile trajectory as shown in Figure 18, and set to move at a velocity of 0.5 m/s. The simulation time was for 4 minutes, which provided the doctor enough time to complete the trajectory. Once again, simulation results that were acquired included data transfer efficiency and network delay.

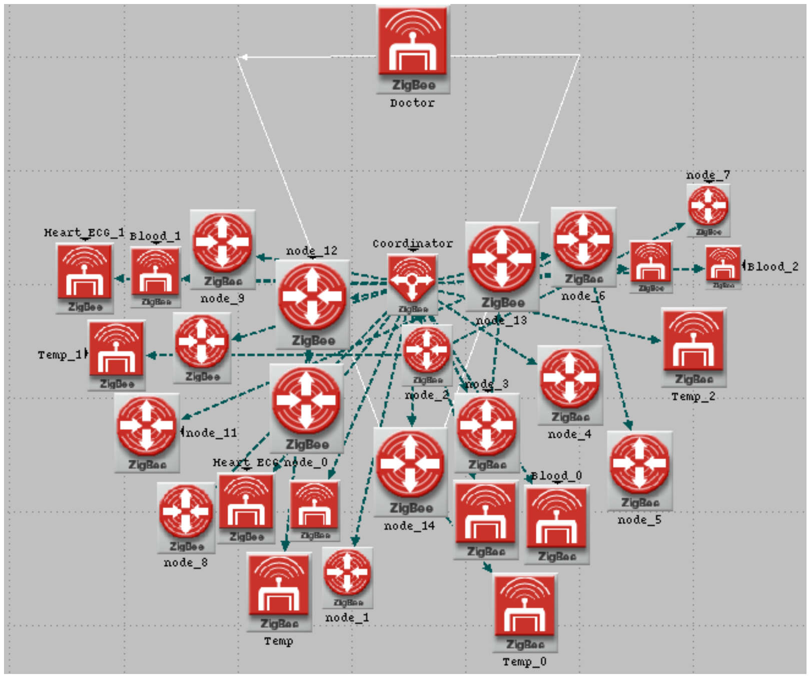

Figure 18: Mobile doctor trajectory in the mesh topology

The triangular trajectory is only shown in the mesh topology; however, the same trajectory was used for star and tree topologies as well. The simulation results are shown below in Figure 19.

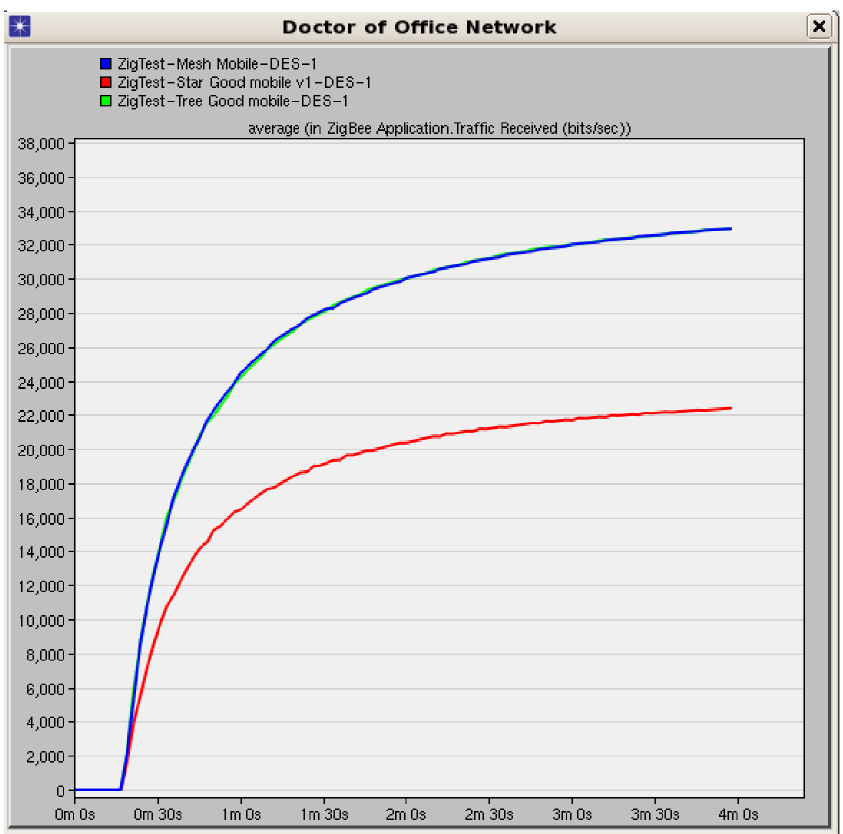

Figure 19: Transmission efficiency of mobile doctor scenario

The tree and mesh topologies had nearly identical transmission efficiencies, while the star topology had the worst transmission efficiency. The similar transmission efficiencies of the tree and mesh topologies may be due to their numerous routers (which the star topology lacks) which allow packets to be routed to the router closest to doctor as the doctor moves through the trajectory. The star topology must have all packets transmitted through the coordinator, which then reroutes the data to the moving doctor. Since all the data must go through the coordinator, there is a higher chance of contention, and the CSMA/CD medium access control may cause an end device to back off too many times until the point where the packet is dropped.

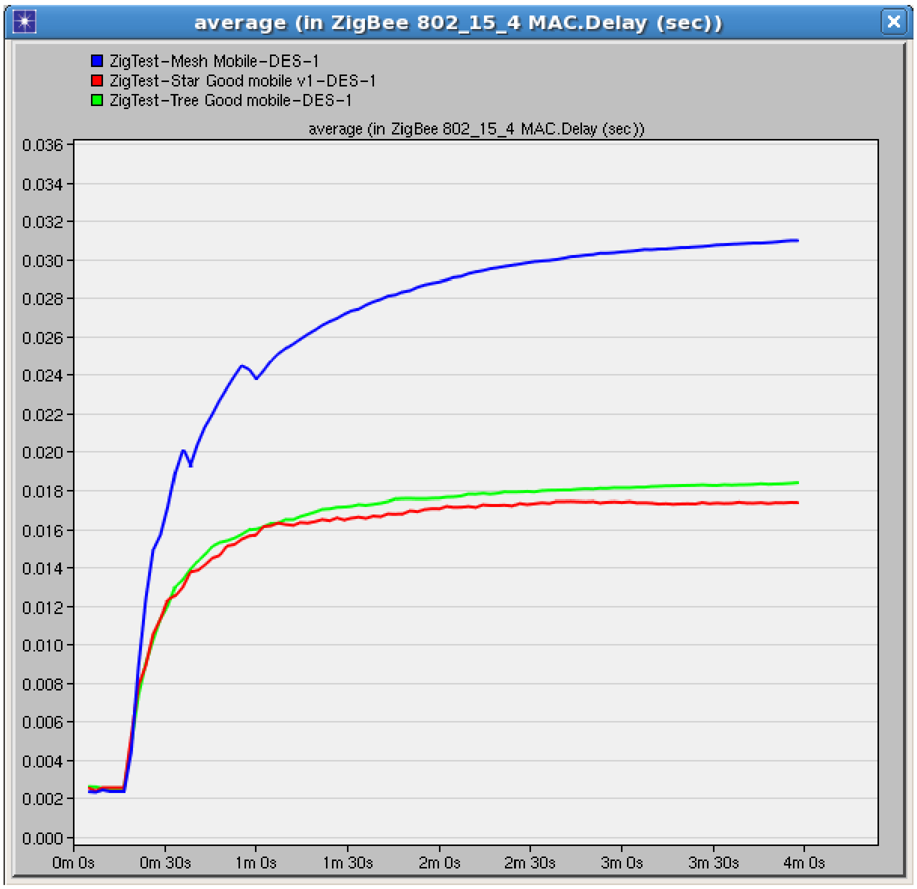

Figure 20: Network delay for the mobile doctor scenario

Not surprisingly, the mesh topology had the highest delay again, while the tree and star topologies had lower delays. Once again the difference observed remains within the millisecond range and is not considered to undermine the efficiency of the mesh topology.

3.2.3 Performance under failure

In a typical monitoring environment, it is vital that the network does not collapse due to small technical difficulties. To assess such factors, one router was disabled in the mesh topology and the tree topology to imitate real time failure. Specifically, we “failed” node 3 (router) in both the tree and mesh topology. The star topology was not tested because removing the coordinator in the star topology would bring down the entire network. Figure 21 (shown below) depicts the mesh topology scenario in which node 3 is “failed”. We have not shown the tree topology scenario because it is essentially the same, except with fewer routers.

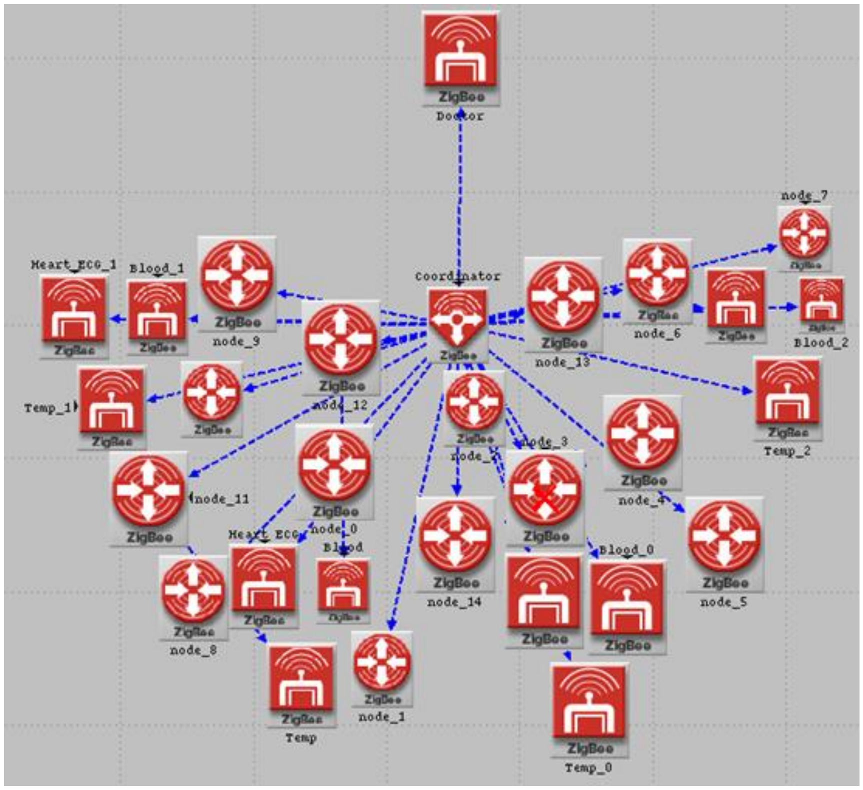

Figure 21: Self-healing mesh topology scenario

The simulation results are shown below in Figure 22.

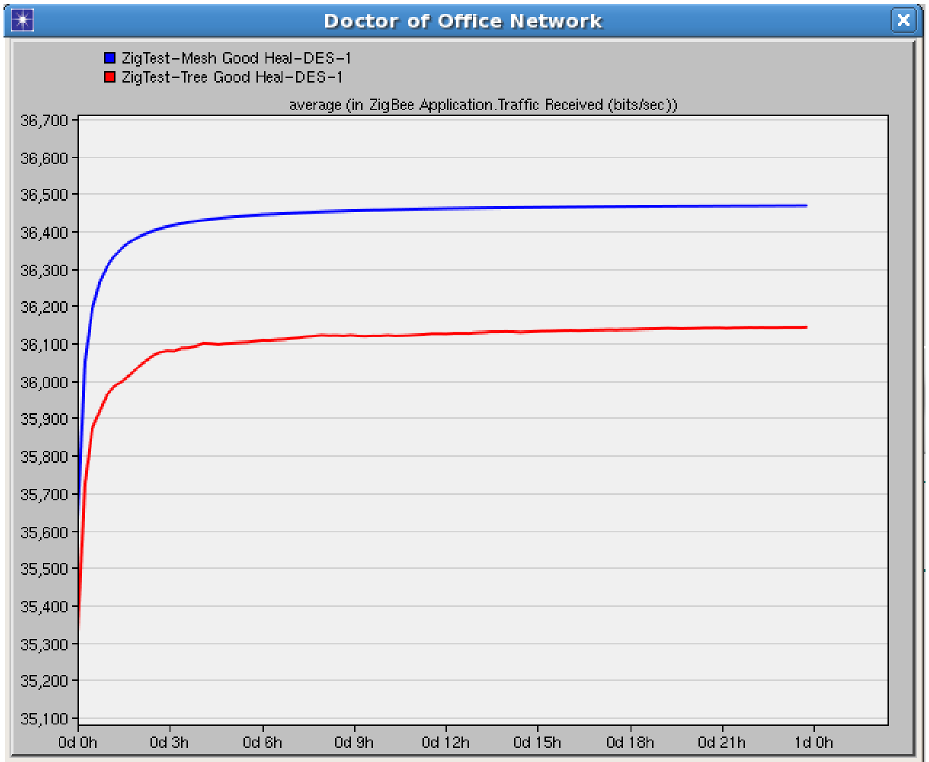

Figure 22: Transmission efficiency of self-healing scenario for tree and mesh topologies

In a tree topology, failure of routers resulted in less successful data being transmitted to the doctor, while the mesh topology data loss was more acceptable. Yet again, it was realized that the mesh topology is most suitable for the medical monitoring environment. The mesh topology has routing capacity, which allows it to route reactively to the situation. Routing capacity indicates that the mesh topology possesses routing tables and route discovery tables [8].

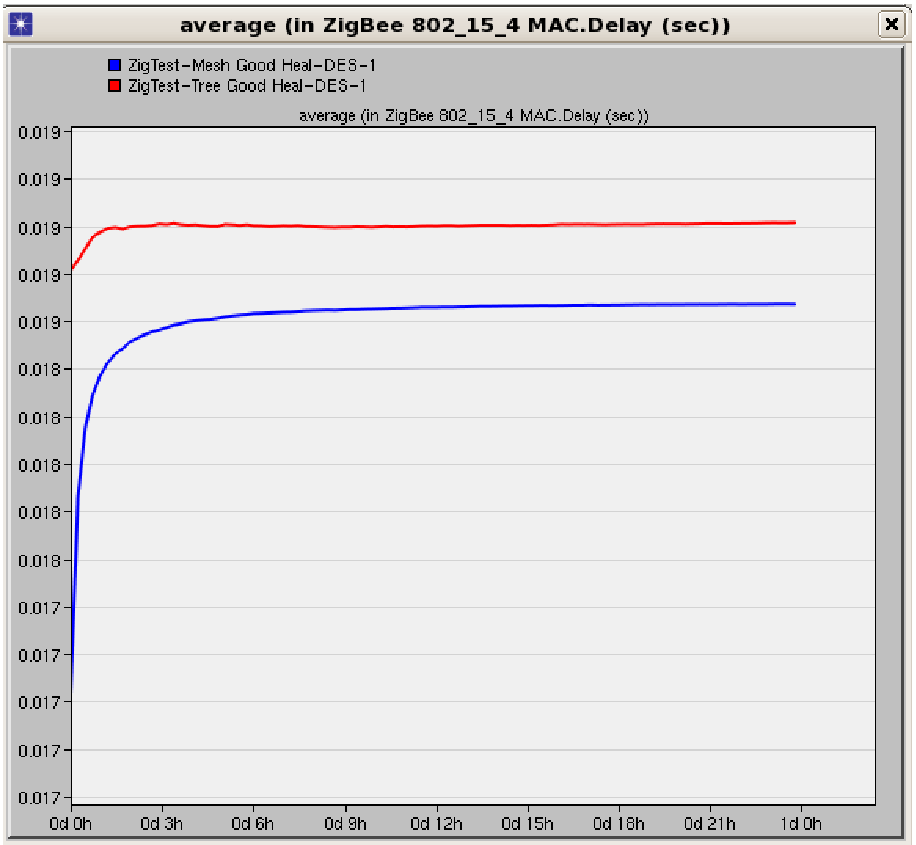

Figure 23: Network delay of self-healing scenario

Although it appears that the tree topology has a higher network delay, the resolution of the average delay (y-axis) indicates that the network delay is approximately 0.019 seconds. The difference between the two is negligible, so we interpret this network delay to be approximately equal. Further, the network delay compares well with the stationary case stimulations in which no routers were failed. Therefore we accept the delay to be tolerable and conclude the self healing feature of the ZigBee protocol to be well implemented.

3.2.4 Study limitations and future work

The ZigBee models we used could not support beacon mode. Adapting the model to support beacon mode would enable the network to run using slotted CSMA/CD, which would allow for increased reliability of data transfer from the patients to the medical professionals as well as lower power consumption. Further comparisons could be made between Bluetooth and Wifi to evaluate the advantages of each and the suitability for the medical environment. Since medical confidentiality must be maintained, future analysis could involve testing the security features of ZigBee models, verifying that data cannot be read by users who should not have access to it. Future work could also focus towards optimizing the minimum number of routers necessary for the mesh topology to be self-healing, but also cost efficient. Simulation of a signal jammer could be done on mesh network to evaluate the self-healing ability of the mesh network.

4. Conclusion

The objective of this project was to determine the ideal communication protocol and its respective topology to be used in the medical monitoring environment. Research provided us with several options capable for this task, of which ZigBee was chosen to be the ideal standard. Its low complexity setup, minimum power operation, and high transfer rates proved to be favourable factors for its selection. Three topologies (star, tree, and mesh) were then explored further and compared to determine the ideal choice. From the simulations performed in OPNET, it was determined that the mesh network topology is best suited for the medical environment due to superior data transmission efficiency (least data dropped) and robust self-healing capabilities. Despite the larger network delays of the mesh structure with delays of ~0.021 seconds (in the stationary scenario) and ~0.031 seconds (in the mobile scenario), it was deemed that critical data was still able to reach the medical professional in a timely manner to ensure active response to a medical emergencies. Therefore, through the consistent top performance observed over the 3 simulation scenarios, the mesh topology of the ZigBee protocol is the ideal choice for medical monitoring environment.

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