Modelling and Performance Study of Large Scale Zigbee Based Green House Monitoring and Control Network

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Abstract

Zigbee wireless sensor networks, known as IEEE 802.15.4 standard, have become quite popular in recent years due to its low power consumption, long battery life and security management. Academic and networking industries have taken interest in Zigbee (IEEE 802.15.4) due to its capability for multiple applications. In this thesis, we have studied Zigbee wireless sensor networks in geographically distributed greenhouses, which are a vital component in agriculture industry today. However due to the complexity and scattered nature of the proposed large scaled network, we only simulate the scenarios in an industry standard and powerful simulator called OPNET to achieve the perfect design and high percentage success. We investigate the performance parameters such as throughput, end-to-end delay, packet loss, traffic sent and traffic received depending on the network topology under various layouts and node conditions based on specific features and recommendations of the IEEE 802.15.4/ZigBee standards.

Since the network delay is the most important characteristic, we investigate this parameter first. We find that the delay increases as the number of greenhouses increases e.g. the delay for 20-greenhouse (GH) scenario is higher than 50- GH scenario. This is contrary to generally perceived understanding however our initial delay was also greater for 50- GH scenario but later due to many un-joined nodes, the delay fell suddenly. The next parameter we investigate is MAC throughput which is seen as increasing when there is communication between maximum nodes. The 20- GHs scenario is shows maximum MAC throughput whereas the scenario with 50- GHs stays way below 20- GHs. We also observe that the number of packets drops significantly in case of 50- GHs. This is attributed to the possibly of the routers dropping the joining or relay requests from end devices while they are too busy in processing requests from other end devices. We can conclude from the above that if the setup is as big as 50 GHs, we can't rely on single coordinator setup as it is too far for the nodes to hop all the way.

On the other hand, the traffic sent in scenario with 20- GH reaches the IEEE 802.15.4 industry specification of 250 kbps showing that the data is being sent at maximum possible rates in this scenario. So, real life implementation of this setup is possible for small number of GHs like 20-

GHs. The scenario with 20- GHs and nodes spaced at 20 m has shown favorable results for all the parameters such as throughput, delay and traffic even for a single coordinator.

Though our simulations worked and have been able to get reasonable results there are many challenges that need be met to improve the outcome of this as well as any other study involving simulation of the geographically dispersed very large scale Zigbee-based wireless sensor networks. Another challenge in this design is that the simulation of 50- GH with nodes close to 1000 takes large amount of time execute. Nonetheless, based on the findings from this work, it will be helpful to design the GH/nodes layout of the implementation in OPNET.

The most important achievement of the work is that we have been able to develop a simulation model for the geographically dispersed very large scale Zigbee-based wireless sensor network representing networked greenhouses. Considering the results of throughput, end-to-end delay, packet loss, traffic sent and traffic received it looks the network can support optimally a 20- GH setup for remote monitoring and control application.

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CHAPTER 1
INTRODUCTION

1.1 Introduction

Greenhouses are essential in modern agricultural production [1]. Greenhouses provide a stable and moderate environment in which off-season plants can survive, regardless of excessive temperatures. Conventional greenhouse monitoring and control systems have their obvious advantages; such as controlling temperature, humidity, light intensity and carbon dioxide content. However, these advantages only work on a small scale. Zigbee based greenhouse monitoring systems (IEEE 802.15.4 standard) solve current problems such as complicated installation and electrical wirings, extreme maintenance costs, poor tension and mobility [2]. Cost, lack of space, power consumption, low data rate and compliancy are the main reasons why conventional greenhouse monitoring, and fieldbus or distributed control systems are not conducive to agricultural production on a larger scale. Wireless Sensor Networks provide a diminution of interference and allow for an uninterrupted flow of sensed data [3]. Achieving high density and high frequency monitoring is reliant upon lower power consumption, smaller volume and wireless sensor nodes [4]. A ZigBee based greenhouse environmental monitoring system is the most sensible solution to these various problems because there are less complications combined with an overall higher production at a lower cost.

To prevent WSNs from being activated in a haphazard manner with an extensive amount of tiny nodes, one must implement precise simulations. These simulations enable us to validate and evaluate the performance of sensor networks within particular environments. The OPNET Modeler provides us with the tools necessary for wide ranges of research. This includes model design, simulation, data collection, and data analysis [5]. The OPNET Modeler allows us the support conducive to analyzing a model's entire composition through distinct and specific event simulations. A Graphical User Interface (GUI) supports the scenario configurations and the network model developments. The simulation results in the form of different graphical presentations which will tell us the exact success rate for a proposed design.

Various strategies have been proposed by researchers to connect sensors to an IP-based network for internet access [6]. IP-based networks not only provide the flexibility and comfort associated with real-time remote access, but it also allows for ad hoc networking, auto configuration and security [7]. We deploy sensor nodes in our area of concern. The whole network is managed by the gateway and it also collects and transmits the sensed data to the backend server through a communication network. Users can browse this information anytime and anywhere in the world if they have internet. Different services such as Internet (wired or wireless) and Global System for Mobile Communications (GSM) can be integrated within the Communication network. Wireless sensor nodes have less processing capability due to their shortage of power; however, this works out as an advantage. In order for the data to be accessible via various devices, the end user should make an arrangement for a 'home server' onsite. Web services have the concept that a group of application programming interfaces (APIs) should be attainable virtually anywhere as long as that particular application has suitable access. It is constructed in such a way as to integrate applications by using open standards, protocols and languages which are broadly accepted via the internet [8]. Web services make it easier to operate systems on a larger scale. They also enhance our ability to improve programs and integrate with enterprise systems [9]. Different WSNs through the internet are being accessed by the web services-based framework [10].

1.2 Motivation

As WSNs are becoming popular day by day, new modifications and ideas in hardware and software design have to be verified for proof of correctness. But it is not possible to test each new implementation because of time and costs. Therefore simulation environments are used to test certain scenarios in advance. This provides additional debugging, monitoring and controlling features, which helps to observe interactions of nodes that would otherwise be impossible in a live-system. But the simulator should provide correct and accurate results as to draw a conclusion on how the entire system could operate practically in the field.

At the moment, there are many simulation environments used for WSNs but their reliability and accuracy are still in question and very little research is conducted in this area. OPNET is one of those simulation networking environments these days used to simulate big networks. That's why it motivated us to choose OPNET to simulate our work to understand the reliability and accuracy of this particular product and to find out whether after simulation, the real life implementation in design and results will be a complete success or not. To the best of our knowledge, this is one of those works conducted in recent times, that has actually allowed us to study the performance of large scale Zigbee wireless sensor networks in OPNET simulation software.

1.3 Statement of the problem

Production of plants in unfavorable climate is made possible by greenhouses irrespective of the geographic location and time of the year. As well as sheltering and protecting them from harsh weather conditions, a greenhouse protects the plants from insects and diseases. Since plants grow under optimum conditions, the quality, growth and productivity of the plants is increased provided there is a good management quality and scheme. Constant monitoring and control of factors like temperature, humidity, light intensity and Carbon dioxide will produce maximum crop yield. But this does not give the growers a complete picture of the operation of the greenhouse system. Zigbee-based nodes can be used to connect the climate related data, processed locally and communicate to a central monitoring station for decision making and sending appropriate control signals to the Zigbee nodes for controlling the environment.

There are also some other issues which need to be looked at. At first it was a problem to set up a single sensor in a designated area of the greenhouse because of the fear of installation of large number of wires and cables to connect number of sensors. This problem can be solved using a Zigbee-based Wireless Sensor Network (WSN). Zigbee nodes need to be deployed in the field to collect and process the data. But network designers would need to decide about the optimum number of nodes which need to be deployed and supported by the network. A number of nodes can be deployed to get the job done but that does not make the process economical and technically reliable at all. Therefore our main objective in this thesis is to find out the optimum number of

Zigbee nodes needed in a WSN covering large number of greenhouses to minimize cost and make the design process optimal. To achieve the perfect design, the best approach would be to develop a simulation model to simulate the scenarios based on number of nodes and geographical locations using a simulator for e.g OPNET to achieve high percentage success. This the problem is to develop appropriate simulation models to study the performance of large scale geographically dispersed Zigbee WSNs based on specific features and recommendations of the IEEE 802.15.4/ZigBee standards so that the conditions of the greenhouses can be monitored and controlled at anytime from anywhere. Results of the simulation model should provide the required information for the practical implementation of such networks for optimum performance.

1.4 Methodology

The research methodology consists of designing a Zigbee wireless sensor network in a greenhouse using OPNET modeler. It might be a network of networks and the whole network should be connected with a central monitoring station for e.g. a PC with a gateway so that the data can be accessed and monitored anywhere as long as there is an Internet connection.

We have to develop large scale geographically dispersed Zigbee WSNs to solve the above problem. In this regard, we intend to take the following steps:

a) Study the literature to find the current state of approaches to solve such problems.
b) Identify practical scenerios, setup parameters and design goals
c) Develop the probable simulation scenarios representing practicable situations.
d) Develop the simulation models for each scenario and choose a simulator best suited for the work, in this case the OPNET.
e) Run and execute the scenarios, obtain and analyse the results of simulations.
f) Considering optimal parameter values predict the network size and parameters that satisfies the performance requirements.

We are thinking of simulating seven scenarios altogether in which the first scenario will consist of a single greenhouse with a total of 20 nodes with each sensor placed after 20m; the second scenario will consist of a single greenhouses with a total of 20 nodes with each sensor placed after 10m; the third scenario again will consist of a single greenhouse with 20 nodes but increased power level; the fourth scenario will consist of 20 greenhouses with 378 nodes; the fifth scenario will consist of 20 greenhouses with a total of 378 nodes and the destination traffic is set to random and the sixth scenario will consist of 50 greenhouses with 946 nodes.

We are expecting higher end-to-end delay, throughput and more loss of packets for higher number of greenhouses with higher nodes. This is because we are expecting higher traffic as we increase the number of greenhouses and nodes.

1.5 Thesis Outline

The remainder of this Thesis is structured as follows. Chapter 2 provides an overview of the essential aspects of the IEEE 802.15.4 and ZigBee protocols in the context of this Thesis.

Chapter 3 explains thoroughly about the Zigbee based wireless sensor network in greenhouses. First it gives an overview about wireless sensor networks and then concentrates on Zigbee based wireless sensor network used in greenhouses.

Chapter 4 provides the literature review section on greenhouse monitoring and control networks. The literature reviewed in this section outlines the possible methods, techniques and technologies used in Zigbee protocol in the OPNET simulation software.

Chapter 5 provides an overview of the OPNET simulation software. This section tells us about the structure, limitations and advantages of OPNET modeler specifying why we used it instead of other simulators.

Chapter 6 presents the model development and simulation of the Zigbee based greenhouse monitoring and control network. It explains how the model was made and presents different scenarios of greenhouses for our thesis. Every scenario is different from the other and this section will provide more inside information about the scenarios.

Chapter 7 presents an experimental analysis of the results we get from the simulation. We compare each and every scenario with each other and looking at the graphs, we analyze the results.

The Thesis concludes with Chapter 8, which summarizes the presented contributions and identifies topics for future research.

CHAPTER 2

AN OVERVIEW OF ZIGBEE TECHNOLOGIES FOR WIRELESS SENSOR NETOWRKS

2.1 Wireless Sensor Networks

A wireless sensor network (WSN) is a communication network which monitors physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants with the help of equally distributed independent devices using sensors at different locations and in some cases control of other devices [11] [12]. A vast amount of nodes extends the coverage of the monitoring area [13]. After the sensors have sensed data, the nodes execute in-network calculations and convey messages via a base station when a specific event takes place [14]. A WSN has numerous advantages in comparison to traditional wired networks such as flexibility, cost and security [15].

WSNs are comprised of sensor nodes which are actually small or large nodes. Necessary data is transmitted and routed from one node to another which will result in efficient use of power and resources [16].The ability to deploy large number of these nodes that assemble and configure themselves is the main strength of WSN [17]. Among several networking topologies, WSN favours mesh the most. In a mesh network, a single network of nodes can cover limitless area with the power to route data across different paths as long as there is sufficient density [18].

WSN protocols offer low power radio transceivers, small form factor and extreme scalability [19]. In WSN, the physical radio layer defines the operating frequency, modulation scheme, and hardware interface of the radio to the system. Protocols offering these properties make WSN ideal [18] [19]. ZigBee (a set of specifications built around the IEEE 802.15.4 wireless protocol) is a general support for WSNs.

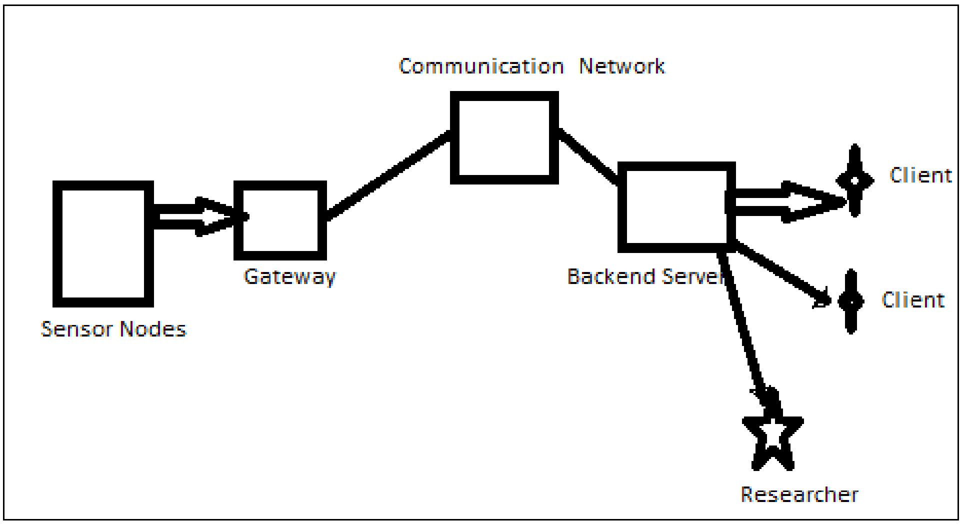


Figure 1: Overview of Wireless Sensor Network

The principle of a Wireless Sensor Network is simple with the number of sensor nodes being usually large. In case of a deployed wireless sensor network, concurring transmissions are possible due to the minimal communication range in nodes. All communication must be passed on in multiple hops to reach the remote sink node due to limited transmitter range and is divided by a significant distance from the initial source node. Messages are routed easily as routes are also static when all nodes are stationary. When monitoring is taking place, all sensed data from one or several source nodes is sent intermittently to a single or multiple sinks. Reduction of traffic and power consumption is achieved by data aggregation. Extensive amounts of transmitted data are not needed to monitor applications. When a source node sends a transmission comprised of sensed information, it must navigate through the network towards the best sink node by hopping from node to node. Routing protocols manages this hopping procedure.

2.1.1 IEEE 802.11

IEEE 802.11, also known as Wi-Fi, is a standard designed for wireless local area networking. It aims to carry out relatively high bandwidth and data transfer since it is used to replace wired LAN [20]. It has a typical transmission range of 30 meters indoors and 90 meters in line-of-sight. But it can go beyond this range depending on transmit power. Depending on the protocol version the data rate can vary between 1 Mbps to 150 Mbps [21]. This standard offers high power consumption with very high data rates. Because of this high power requirement, researchers avoid using this standard [22] [23].

2.1.2 IEEE 802.15.1

IEEE 802.15.1, also known as Bluetooth, is a standard which requires much lower power requirement than IEEE 802.11. This is a personal area network (PAN) standard which actually transfers data from a computer to other devices such as keyboard, mouse or cell phones [24]. It supports tree network topology and can support up to seven remote nodes corresponding with just one base-station.

This standard is considerably powerful when one takes into account its short transmission range. The actual number of nodes is limited to seven and when returning from sleep usually takes long time to synchronise to network. This is why IEEE 802.15.1 is not the first choice among researchers. But this standard is very popular among new devices such as mobiles and cameras [24] [25].

2.1.3 Zigbee/IEEE 802.15.4

The IEEE 802.15.4 standard is actually designed to control and monitor the wireless sensing applications. It is the most flexible among all the standards as it supports multiple data rates, transmission frequencies and network topologies. The most useful thing is that the power is minimized because the hardware is purposely devised to put the radio to sleep; thereby, reducing the amount of power needed. Rapid synchronisation is achieved during a node waking up from sleep when compared to IEEE 802.15.1. This characteristic helps to keep the power at a moderate level because the radio can be intermittently turned off [26]. The main features of this standard are numerous. This standard allows for a network that is flexible and inexpensive. It uses minimal power and has a low data rate in a specific, autonomous network among low-cost, fixed, transferable and moving devises. It is made for applications with relaxed throughput requirements which cannot accommodate the power needed to operate heavy protocol stacks.

IEEE 802.15.4 standard operates across several frequencies which are 868 MHz, 902-928 MHz and 2.48-2.5 GHz and offers data rates of 20 Kbps for 868 MHz Band, 40 Kbps for 902 MHz Band and 250 Kbps for 2.4 GHz Band. This standard also offers the use of AES-128 security for encryption of transmitted data [26]. Since the 2.4 GHz Band is a worldwide license-free band it is generally used for all purposes and offers high data rates resulting in a significant reduction of power due to the lower amount of radio transmission time to transfer data when compared to the lower frequency bands [27].

IEEE 802.15.4 is the basis of several WSN specifications such as Zigbee, WirelessHART, 6LoWPAN and MiWi and is globally accepted for wireless sensing applications among researchers. Zigbee is the most favoured and most used specification nowadays [28].

Table 1 specifies important differences between Zigbee, Wi-fi and Bluetooth:

	ZigBee	**Wi-Fi**	**Bluetooth**
Range	10-100 meters	50-100 meters	10 – 100 meters
Networking Topology	Ad-hoc, peer to peer, star, or mesh	Point to hub	Ad-hoc, very small networks
Operating Frequency	868 MHz (Europe) 900-928 MHz (NA), 2.4 GHz (worldwide)	2.4 and 5 GHz	2.4 GHz
Complexity (Device and application impact)	Low	High	High
Power Consumption (Battery option and life)	Very low (low power is a design goal)	High	Medium
Security	128 AES plus application layer security	64 and 128 bit encryption	64 and 128 bit encryption
Typical Applications	Industrial control and monitoring, sensor networks, building automation, home control and automation, toys, games	Wireless LAN connectivity, broadband Internet access	Wireless connectivity between devices such as phones, PDA, laptops, headsets

Table 1: Comparison between Zigbee, Wi-Fi and Bluetooth

2.2 Zigbee based Wireless Sensor Network

Zigbee remote wireless sensor networks offer great flexibility, diversity and potential in many areas of science and engineering. With implementation of ZigBee protocol, now it is possible to transmit variable data from an area of interest at a low power and low cost. Zigbee Wireless sensing and control networks yield precise and effectual Internet Policy Management (IPM), and are perfectly suited to operate in hazardous environments. The advantages of choosing Zigbee WSN are the followings [29]:

a) Unfailingly broadens the manufacturing and process systems and through consistent supervision improves the management of assets.
b) Oversees the supervision of networks thereby improving employee and public safety.
c) Ascertains exact readings from pressure sensors, smoke detectors, meters, gauges, and other safety devices, and discovers problems before they arise.
d) Eliminates the need for manual monitoring thereby reducing unnecessary risk.
e) Other benefits include the dynamic network formation, less expensive, user-friendly, dependable data transfer and short range operation.

2.3 Zigbee Protocol Architecture

IEEE 802.15.4/ Zigbee protocol stack is based on the Open System Interconnect (OSI) model and is divided into four layers. The Zigbee Alliance [83] developed the Zigbee Device Object (ZDO), the application support sublayer (APS), the network layer, and security management. IEEE 802.15.4 is used for the MAC layer and physical layer. Each layer is joined to its adjacent layer using Service Access Points (SAP) which helps to exchange data and commands between layers.

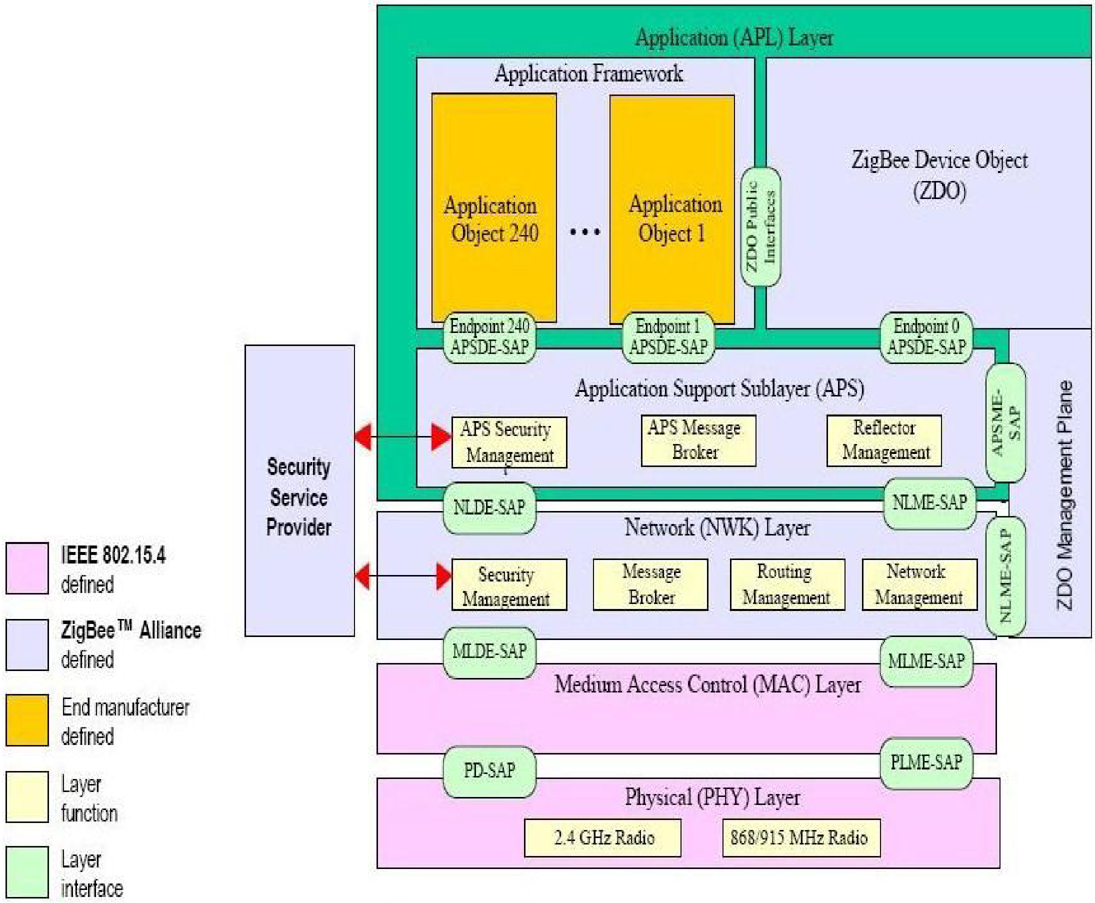


Figure 2: The Zigbee Protocol Stack Architecture [83].

The ZigBee stack architecture consists of a series of blocks called layers in which every layer delivers a detailed set of services for the layer above. A data entity offers a data transmission service with a management entity providing all other services. An interface to the upper layer is exposed by each service entity through a service access point (SAP), and each SAP provides support to a number of service fundamentals to attain the prescribed functions. IEEE 802.15.4 standard supports the ZigBee stack architecture. The IEEE 802.15.4 standard defines the physical layer (PHY) and the medium access control (MAC) sub-layer based on direct sequence spread spectrum (DSSS) techniques.

The Zigbee protocol architecture is divided into three sections which are:

- IEEE 802.15.4, which consists of the MAC and physical layers.
- Zigbee layers, which consist of the network layer, the Zigbee device object (ZDO), the application sublayer, and security management.
- Manufacturer application: Manufacturers of Zigbee devices can utilize the Zigbee application profile or come up with their own application profile.

2.3.1 IEEE 802.15.4 Physical Layer

The Physical layer (PHY) is the lowest layer of the IEEE 802.15.4/Zigbee protocol stack whose main role is an interaction with wireless channel using a radio transceiver. It executes modulation on outgoing signals and demodulation on incoming signals. This standard manages the physical transmission of radio waves in different unlicensed frequency bands around the world to provide communication between devices within a WPAN. This layer also allows for channel selection to avoid radio interference, as well as data exchange with the layer above (MAC sub-layer) to provide it with service. Therefore it conveys and obtains information from a source. IEEE 802.15.4 compliant radio transceivers function in several frequency bands. The original version of the standard which was published in 2003, defined three bands: 868 MHz band (used in Europe), 915 MHz band (used in North America) and 2.4 GHz band (used worldwide). There is a single channel between 868 and 868.6 MHz, 10 channels between 902 and 928 MHz, and 16 channels between 2.4 and 2.4835 GHz. The data rates are 250 kbps at 2.4 GHz, 40 kbps at 915 MHZ and 20 kbps at 868 MHz. The 2.4 GHz band is most commonly used and it employees the Offset – Quadrate Phase Shift Keying (O-QPSK) modulation with spread spectrum. It has a bit rate of 250 kbps.

Table 2 shows details on how these three frequency bands are used in the IEEE 802.15.4 protocol. It is to be noted that, here 1 symbol = 4 bits.

Frequency (MHz)	Number of channels	Modulation	Chip Rate (Kchip/s)	Bit Rate (Kb/s)	Symbol Rate (Ksymbol/s)	Spreading method
868	1	BPSK	300	20	20	Binary
915	10	BPSK	600	40	40	Binary
2400	16	O-QPSK	2000	250	62.5	16-bit

Table 2: The IEEE 802.15.4 data rates and frequencies of operation

Different types of application use different frequencies. For example, a network should aim for lower propagation loss when it wants to accomplish longer transmission range.

2.3.2 IEEE 802.15.4 Medium Access Control Layer

Medium Access Control (MAC) Layer is located above the physical layer whose main role is to provide fair access to wireless channel by avoiding possible collisions. This layer extracted from the IEEE 802.15.4 standard provides services to the network layer and is part of the Zigbee stack level. The MAC layer addresses data to find out where the frame is going or coming from. Two operating modes are supported by Medium Access layer: Non-Beacon Enabled mode and Beacon Enabled mode. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) medium access mechanism is used by both modes where devices first check the medium state before starting transmission of the message. Finally, the MAC sub-layer can be exploited by higher layers to achieve secure communication by measures such as Access Control List (ACL).

In a Non-Beacon Enabled mode, un-slotted CSMA/CA mechanism is used by MAC in which device could start transmission procedure at any time.

In the Beacon Enabled mode, devices use superframe (Figure 3) structure which is defined by Personal Area Network (PAN) coordinator. The Superframe structure starts with a beacon, special MAC frame, which helps to synchronize all devices participating in a network about time schedule during next superframe. Each superframe (Figure 3) structure is divided into an active and inactive period. Communication between devices is reserved for the active period which is followed by optional inactive period in which all communications between devices are disabled and devices go to low-power sleep until the arrival of the next beacon frame. An active period is divided into 16 slots, which are grouped into Contention Access Period (CAP) and Contention Free Period (CFP). Device which wants to transmit uses slotted CSMA-CA mechanism during CAP but devices don't need to compete for the medium access during CFP because they use guaranteed time slots.

2.3.2.1 Superframe Structure

In the IEEE 802.15.4 MAC protocol, there is an active and a varible inactive period between two consecutive beacons. Frame transmissions are permitted during this active period (or superframe) which is divided into 16 equal time slots. But the nodes in the network may be in the inactive or sleep mode to conserve their energy and the coordinator may not interconnect with its PAN and may enter in a low-power mode during the inactive period.

A superframe structure is used in beacon-enabled mode hemmed in by beacon frames which is sent periodically by the coordinator. Synchronization of the attached devices, identification of the PAN and description of the structure of the superframe are some of the functions of these beacons. MacBeaconOrder (BO) is linked to the beacon interval (BI) at which coordinator shall transmit its beacon frames as follows:

$$BI = aBaseSuperframeDuration * 2^{BO}$$

where 0 ≤ macBeaconOrder (BO) ≤14 and aBaseSuperframe = 960 symbols. A superframe structure is overlooked if BO=15, i.e. non beacon-enabled mode is used.

The active portion has a contention access period (CAP) and contention free period (CFP). By using a slotted CSMA-CA mechanism, devices which want to communicate will compete with each other during the CAP. By using slotted CSMA-CA, all frames excluding the acknowledgment frames shall be transmitted. Alternatively, CFP consists of guaranteed time slots (GTSs), i.e. portions of the superframes entirely committed to particular devices.
The duration of the active portion (SD) is associated with macSuperFrameOrder (SO) as follows:

$$SD = aBaseSuperframeDuration * 2^{SO}$$

where 0 ≤ macSuperFrameOrder (SO) ≤ 14. If SO = 15, the superframe would become inactive after the beacon.

The coordinator will not transmit beacons in case of non beacon-enabled networks and with the exception of the acknowledgment frames, all transmissions shall use unslotted CSMA-CA to access the channel. GTS is not allowed in this mode.

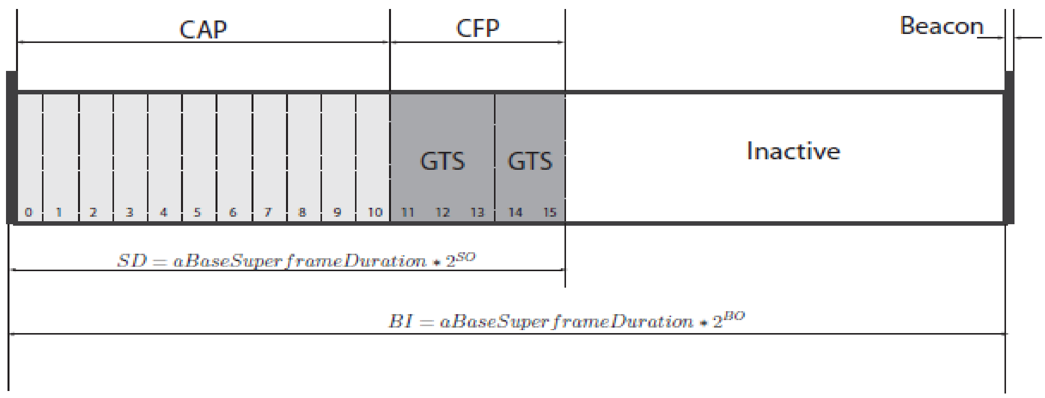


Figure 3: Example of a superframe structure [30]

2.3.2.2 Inter-Frame Spacing (IFS)

The inter-frame spacing (IFS) is an inactive communication period required for assisting the MAC sub-layer to process data received by the physical layer. All transmitted frames are followed by an IFS period to let this happen. The length of the IFS period which is either a long inter-frame spacing (LIFS) or short inter-frame spacing (SIFS) is dependent on the size of the transmitted frame. Selection of the IFS depends on the IEEE 802.15.4 aMaxSIFSFrameSize parameter which defines the maximum allowed frame size to use the SIFS. The CSMA/CA algorithm takes the IFS value into notice for transmissions in the CAP. These concepts are shown in Figure 4.

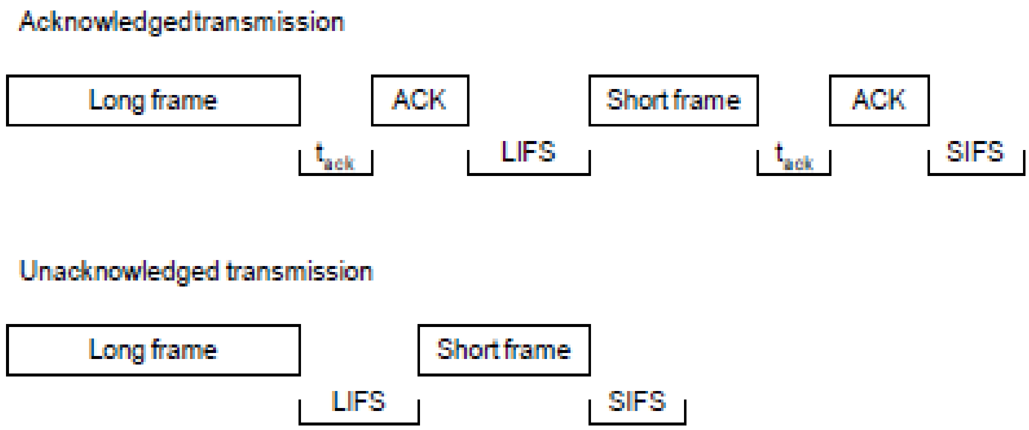


Figure 4: IFS [30]

2.3.2.3 CSMA-CA Mechanism

Contention-based MAC (Medium Access Control) can be either slotted or unslotted CSMA/CA in IEEE 802.15.4 depending on the network operation behaviour which is either beacon-enabled or non beacon-enabled modes respectively.
The CSMA/CA mechanism consists of backoff periods (with the duration of 20 symbols). Three variables are needed mostly for programming medium access:

- *Number of Backoffs* (*NB*) which represent the amount of unsuccessful attempts to obtain the medium ;
- *Contention Window* (*CW*) which represents the amount of backoff periods that need to be clear prior to beginning transmission;

- *Backoff Exponent* (*BE*) which enables the calculation of the amount of wait backoffs before trying to obtain the medium again.

Figure 5 shows a flowchart describing the slotted version of the CSMA/CA mechanism and can be reviewed in five steps:

1. Introduction of the algorithm variables: *NB* equal to 0; *CW* equals to 2 and *BE* is set to the lowest value between 2 and a MAC sub-layer constant (macMinBE);

2. The algorithm anticipates an undefined number of backoff periods before trying to obtain the medium after locating a backoff boundary;

3. Clear Channel Assessment (CCA) to prove if the medium is inactive;

4. The CCA returned an engaged channel, thus *NB* is increased by 1 and the algorithm must begin again in Step 2;

5. The CCA returned an inactive channel, *CW* is decreased by 1 and when it gets to 0, the message is communicated otherwise the algorithm goes back to Step 3.

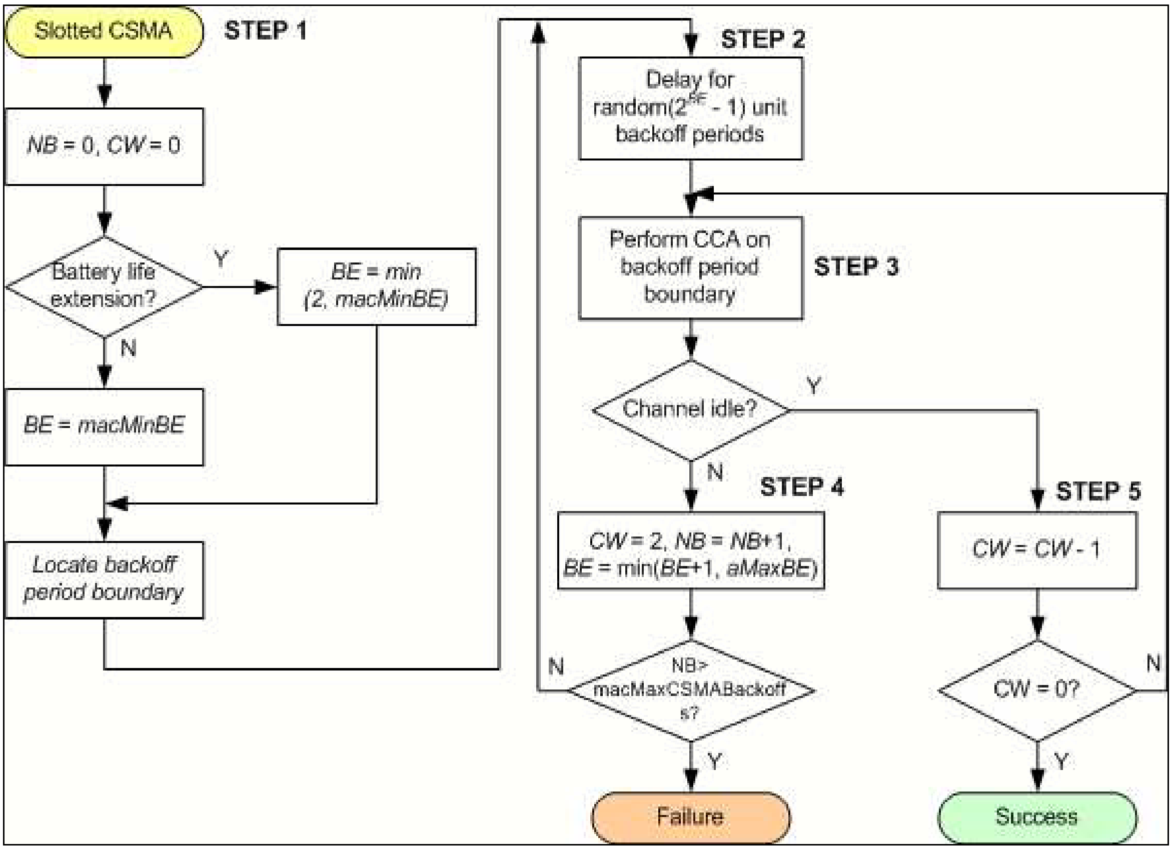


Figure 5: The Slotted CSMA/CA Mechanism [30]

In the slotted CSMA/CA, after the random backoff (step 2), the CSMA/CA should make sure that the remaining operations can be undertaken when the battery life extension is set to 0 and the frame can be transmitted before the end of the CAP. In the CAP, if the amount of backoff periods is more than the remaining then the MAC sub-layer temporarily stops the backoff countdown at the end of the CAP and defers it to the beginning of the following superframe. Similarly if the amount of backoff periods is less or equal than the remainder of backoff periods in the CAP, the MAC sub-layer applies the backoff delay and reconsiders if it should proceed with the frame transmission. If the MAC sub-layer is run ning out of time, it defers until the start of the next superframe and continues with the two CCA evaluations (step 3). The backoff countdown must only take place during the first six full backoff periods after the reception of the beacon when the battery life extension is set to 1, as the frame transmission starts in one of these backoff periods.

The unslotted mode of the CSMA/CA (Figure 6) resembles the slotted version except that the algorithm does not need to rerun here (CW number of times) if the channel is idle. The ACK frames are not reliant upon this mechanism and CW value is not utilized. The random backoff delay begins without alignment to the backoff boundaries after variable initialization since it is not utilized. The CCA is performed after this delay period. In step 3, the channel is monitored for idleness and if it is not active, an instantaneous transmission of a packet is initiated or else the cycle is forced to begin again.

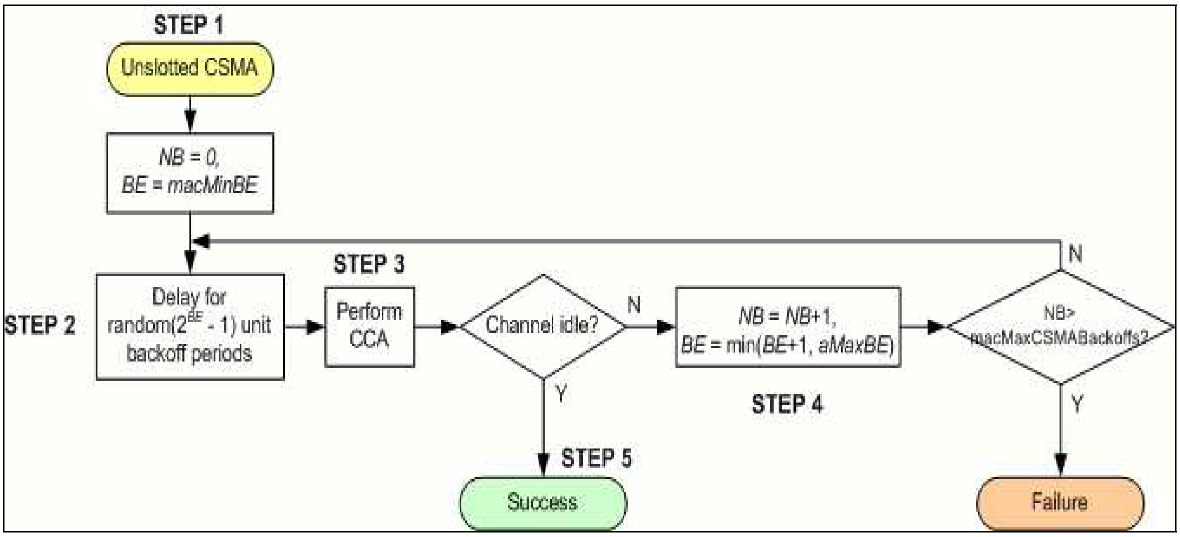


Figure 6: The Un-slotted CSMA/CA mechanism [30]

2.3.2.4 GTS allocation and management

The IEEE 802.15.4 standard allows for granted time slots inside the superframe. A node requests the PAN coordinator for one or more of these contention free periods (CFP), and the PAN coordinator can assign contention free periods to that node upon the availability of the resources.

2.3.3 Zigbee Network Layer

The network layer is established in between the MAC layer and application support sublayer. Zigbee Alliance develops Network Layer whose main role is to provide multihop transmission between devices, which cannot communicate directly. A feature of Zigbee known as self-healing mechanism is acquired through this layer. This layer provides network management, routing management, network message broker, and network security management.

2.3.3.1 Network Topology

The three topologies supported by the Zigbee Network Layer are:

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

Star Topology

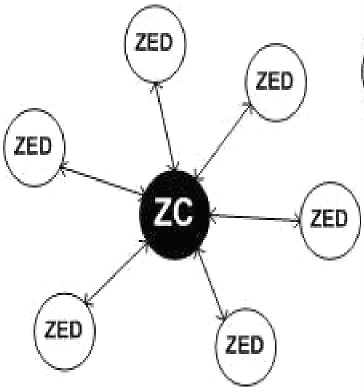
Star topology is the simplest Zigbee topology, consisting of the one PAN Coordinator and the arbitrary number of the End devices, which are located in its radio range. There is no need for any routing mechanism since end devices communicate only with PAN coordinator. In this type of topology, a coordinator is surrounded by a group of either end devices or routers. Even though the router is connected to the coordinator, their message relaying functions are not used. This topology is attractive because of its simplicity and at the same time has some key advantages. The entire network is functionless when the coordinator stops functioning because all traffic must travel through the center of the star.

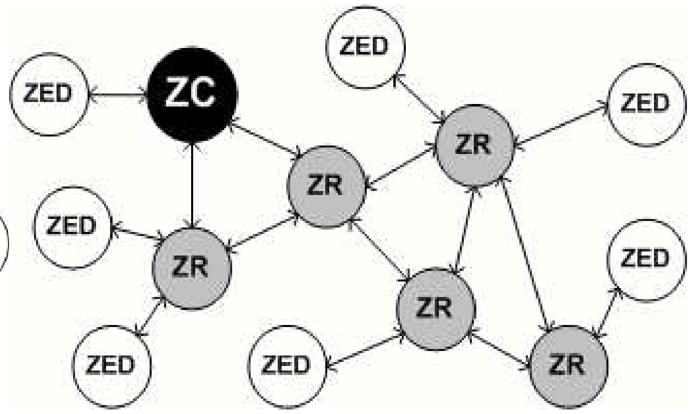
Cluster Tree Topology

In the cluster tree topology, PAN coordinator initializes the network and represents the top (root) of the tree. Coordinator and routers acting as parent devices accept association requests from other devices from the network known as child devices. For every router connected, more child nodes can connect to the router. End device can only act as a child because of its limited capabilities since it does not possess the ability to relay messages. This topology is better known as hierarchical topology because messages which are intended for the child can only be routed through its parent. This topology allows for varying levels of nodes with the coordinator being at the highest level. When messages have to be transmitted to other nodes within the same network, the source node must relay the message to its parent which is the node higher up by one level of the source node, and the message is perpetually relayed further up in the tree until it can be transferred back down to the destination node. A message is only capable of taking one path and that's why this topology could be considered fallible. All communication within the network will break down if the router fails to relay the pertinent messages to its respective children.

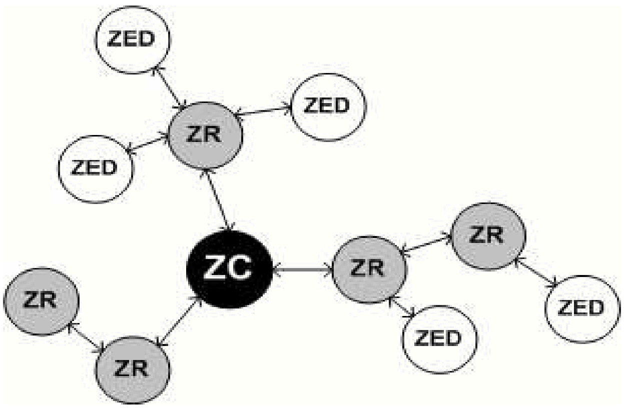
Mesh Topology

A mesh topology is the most flexible topology among the tree because a message can employ numerous paths from source to destination. If a particular router collapses, then Zigbee's self healing mechanism i.e. route discovery will help the network to find an alternative route. In the mesh topology devices can communicate with every other device within its radio range. Compared to cluster-tree topology, mesh topology is more reliable because routes are discovered and maintained dynamically in contrast of the static routes which are created during initialization of the cluster-tree network.





a) Star topology b) Mesh topology



c) Cluster-tree topology

Figure 7: ZigBee Network Topologies: a) Star Topology b) Mesh topology c) Cluster-tree topology [31]

2.3.4 Zigbee Application Support Sublayer

Applications running on the Zigbee network are contained here. The applications to monitor temperature, humidity, or any other desirable atmospheric parameters can be placed on this layer. This layer makes the device useful to the user. A single node can run more than one application. Applications are referenced with a number ranging from 1-240 which means that there is a maximum of 240 applications on a Zigbee device. Application number 0 is reserved for a unique application that exists on all Zigbee devices. Another application number, 255, is also reserved and is used to broadcast a message to all applications on a node. Data is transmitted through The Application Support Sublayer to the application objects via simple terms: request, confirm, and response. There are three additional terms that the APS uses to define a structured communication: a profile, cluster, or endpoint.

Zigbee Device Object (ZDO)

There is a special application on every Zigbee device which is known as the Zigbee Device Object or ZDO. This application provides key functions such as defining the type of Zigbee device (end device, router, and coordinator) a particular node is and also initializing and participating in forming a network. Essentially, the ZDO acts as the administrator of application objects, supervising devise management duties.

Application Object (endpoint)

An application object defines input and output to the APS and is synonymous with the term ‘endpoint’ (EP). There are 240 distinctive application objects in every node.

End node

There is a multitude of endpoints in every end node or device. EPs are equipped with an application profile and are also responsible for the communication abilities within multiple or single devices.

2.4 Zigbee Hardware

Zigbee networks contain a mixture of three potential components which are a Zigbee coordinator, a Zigbee router, and a Zigbee end device. Various nodes have different functions within the network layer but all types can have the
same applications.

Zigbee coordinator

Every Zigbee network is permitted only one coordinator. This node initializes the network, selects the appropriate channel, and permits other devices to connect to its network. It is also responsible for routing traffic in a Zigbee network. In a star topology, the coordinator is at the center of the star and all traffic from any end device must travel to this node. End devices can talk to another end device but the message must be routed through the coordinator. The coordinator is at the top of the tree in a tree topology, and it is the root node of the mesh in a mesh network. A Zigbee coordinator also has the capability to provide security services.

Zigbee Router

A router can relay messages in a network and is able to have child nodes connected to it through any router or end device. Router functions only work within a tree or mesh topology since all traffic is routed through the center node (coordinator) in a star topology. Routers can substitute and take place of end devices but the routing functions would be of no use in that case. A router can sleep when inactive if the network supports beaconing but it will periodically wake up to notify its presence to the network.

Zigbee End Device

End devices can be mainly credited for the power saving features of a Zigbee network. They can be sleeping for the majority of the time and expanding battery life of a device since these nodes are not used for routing traffic. These nodes carry enough function to talk to their parent nodes which is either a coordinator or a router. An end device does not possess the ability to have other nodes connect to its network through the end device since it must be connected to the network through either a router or directly to the coordinator.

Zigbee standard uses default distributed address allocation mechanism [32], which is used to allocate unique network addresses to each node , which have been associated to cluster-tree network. It provides a set of the addresses to each potential parent when PAN coordinator establishes a network. Parent then assigns the addresses to its children.

2.5 Available Sensors for Greenhouse monitoring

A Sensor is a type of device helping to detect and evaluate a real-world condition, for instance motion, heat or light and changes it to a corresponding analog or digital representation [33].

Following are some of the sensor technologies available in the market. We drew a table to review the characteristics of each sensor. We can use the result of these comparisons to select our desired sensor technology for the project.

There are four main contact temperature-sensing devices available, divided in three families: thermocouples (self-generating sensors), resistance temperature detectors (RTD) and thermistors (resistive sensors), and temperature-transducing ICs (PN or Semiconductive). These sensors translate the temperature into a reference voltage, resistance or current, which is then measured and processed and a numerical temperature value is computed.

Criteria	Thermocouple	RTD	Thermistor	IC's
Temperature Range	(-233°C – 2316°C)	(-205°C - 649°C)	(-38°C - 260°C)	(-40°C -260°C)
Long-term Stability	Good	Excellent	Poor to Fair	Good
Accuracy	Medium	High	Medium	Medium
Repeatability	Fair	Excellent	Fair to Good	Excellent
Sensitivity	Low	Medium	Very High	High
Response	Medium to Fast	Medium	Medium to Fast	Fast
Linearity	Fair	Good	Poor	Excellent
Self Heating	No	Very Low to Low	High	Medium
Size	Small to Large	Small to Medium	Small to medium	Small
Cost	Expensive	Expensive	Cheap	Relatively cheap
Humidity Sensing Technologies				
Criteria		RHS	TCHS	CHS
Humidity Range		5%-95%	0-100%	5%-95 %
Long-term Stability		Good	Excellent	Good
Accuracy		High	High	High
Repeatability		Fair to Good	Excellent	Excellent
Sensitivity		Medium	High	High
Response		Medium	Medium to Fast	Fast
Linearity		Good	Excellent	Excellent
Size		Small	Small to Medium	Small
Cost		Cheap	Expensive	Relatively cheap
Carbon Dioxide Sensing Technologies				
Criteria		SSE	NDIR	
Long-term Stability		Good	Excellent	
Accuracy		Medium	Medium to High	
Repeatability		Good	Good	
Sensitivity		High	Medium	
Response		Fast	Medium	
Linearity		Good	Good	
Size		Small	Medium to Large	
Cost		Relatively Cheap	Expensive	
Light Sensing Technologies				
Criteria	Photometric	LDR	Pyranometers	Quantum Sensors
Long-term Stability	Good	Good	Good	Excellent
Accuracy	High	Medium	High	High
Repeatability	Good	Good	Good	Excellent
Sensitivity	High	Medium	High	Very High
Response	Fast	Fast	Fast	Fast
Linearity	Excellent	Good	Good	Excellent

Size	**Small**	**Small**	**Small to Medium**	**Small**
Cost	**Expensive**	**Cheap**	**Expensive**	**Expensive**
Soil Moisture Sensing Technologies				
Criteria	**FDR**	**TDR**	**Gypsum Blocks**	**Neutron Probes**
Long-term Stability	**Good**	**Fair**	**Fair**	**Excellent**
Accuracy	**High**	**High**	**Medium**	**High**
Repeatability	**Excellent**	**Excellent**	**Fair**	**Excellent**
Sensitivity	**High**	**High**	**Low**	**High**
Response	**Fast**	**Fast**	**Slow**	**Fast**
Linearity	**Excellent**	**Excellent**	**Fair**	**Good**
Size	**Small**	**Medium**	**Medium**	**Large**
Cost	**Relatively Cheap**	**Expensive**	**Cheap**	**Very Expensive**

Table 3: Sensor Technologies Comparison

Temperature and Humidity Sensor Selection

The temperature of a greenhouse is maintained between Tmax (24°C Day/18°C Night) and Tmin (20°C Day/16°C Night) [34]. We can use this information to select our desired temperature sensing technology for the project. Thermocouple and RTD seems to be best fit for industrial applications after evaluation of temperature sensors and their characteristics. This is because the sensor needs to be kept to a high temperature environment so that we can measure smaller temperature differences with greater efficiency. After comparing thermistor and IC temperature characteristics, we can deduce that IC temperature sensing technology is more suitable than thermistors.

We have three humidity sensing technologies these days on the market with each of them having advantages and limitations. Thermal conductivity humidity sensor has the best overall performance after comparison of each of these technologies. But it is very expensive when we consider price compared to resistive and capacitive sensors. Thus resistive and capacitive humidity sensors are more favored. Considering linearity and repeatability, capacity humidity sensors are far better than resistive type.

Sensirion Inc. recommends one of the best options accessible for temperature and humidity sensing which is SHT75 [35]. It is Sensirion's family of temperature and humidity sensor which measures temperature and humidity to the highest precision [35]. This particular sensor is relatively inexpensive with impeccable continuity and with its minimal size it proves to be rather expedient. For relative humidity sensing, this sensor also has band gap temperature sensor and a capacitive polymer sensing element. A 14bit analog to digital converter and a signal conditioning circuit is effortlessly coupled to both sensors resulting in superior signal quality, free from any disturbances [35]. The only drawback may be the interfacing problem since each sensor needs to be manually programmed separately before using them. Therefore interfacing these sensors could be dull and frustrating at times for some users.

CO_2 Sensor Selection

We have two types of CO_2 sensors on the market these days: Electrochemical and Non-dispersive Infrared (NDIR) CO_2 sensors. Both of them have their advantages and drawbacks. As we compare both sensors, the NDIR CO_2 sensor has more technical advantages due to long-term stability and low power consumption. But electrochemical CO_2 sensors are better than NDIR sensors when it comes to installation cost, accuracy and linearity. We can conclude that the electrochemical sensor is a better option for low cost applications. When compared to other electrochemical CO_2 sensors available, TGS4161 sensors from Figaro Inc. were considered to be the most inexpensive and precise, not to mention the fact that it uses less power. They are perfect for any kind of agriculture applications due to their high resistivity against humidity and temperature.

Soil Moisture Sensor and Soil Temperature Sensor Selection

There are four types of soil moisture sensing technologies available on the market known as FDR, TDR, Gypsum Blocks and Neutron probes. It was concluded that Neutron probes were very expensive and bulky. The user needs a license and permission from the government to activate the device due to its nature of operation [36]. Gypsum blocks was found to be the worst option as we compared it to other soil moisture sensing technologies leaving us with FDR and TDR. As we compare FDR and TDR, we find that both technologies are very suitable for this application. FDR sensors are least expensive and have long-term stability; so it might be a better choice.

VG400 Soil moisture sensor and THERM200 soil temperature sensors from Vegetronix Inc. were also there. But when compared to other sensors on the market, these sensors are less expensive and use less power. They are also superior in terms of linearity and stability. One must consider the fact that they were only constructed to compute the temperature and moisture of the soil.

Light Sensor Selection

Light sensing technology is a commonly used sensing technology in modern day industry. Given the fact that there is such a vast selection of light sensors available, one must be careful making his selection.

Plants take in sunlight to stimulate the photosynthesis process. Photo-synthetically Active Radiation or PAR [37] is generally referred to the sunlight in range of 400 to 700 nanometers commonly used by plants. It is essential to keep an eye on PAR to make sure that the plants are acquiring enough light for photosynthesis. There are four types of sensors for this particular purpose: photometric sensors, light dependent sensors, pyranometers and quantum sensors. Pyranometers and quantum sensors are most suitable for measuring sunlight but are very expensive. Thus we need to look for something cheap. We found LDR sensors to be the least expensive when we compared it to photometric sensors. NOPR12 sensors are also a good option since their spectral response is around 380 to 740 nm, which falls under the PAR range. But it is better to use quantum sensors or pyranometers for agricultural applications.

2.6 Simulation using OPNET Modeller

Performing simulations and developing models is always useful before using WSNs in the field. The reason is because WSNs may be used haphazardly with an extensive amount of small nodes. In order to prove that the sensors are working at an optimum level, simulation must occur within specific environments.

The OPNET Modeler environment has the capability to study model design, simulation, data collection, and data analysis [38]. A comprehensive development environment is given by OPNET Modeler which supports the design of communication networks and distributed systems. A thorough analysis can be executed by setting up distinct event simulations. This allows us to determine how a model performs in specific scenarios. The configuration of the scenarios and the development of network models are supported by the Graphical User Interface (GUI). The three hierarchical levels for configuration are:

1. The network level 2. The node level and 3. The process level. The source code is based on C/C++. A variety of built-in functions supports the analysis of simulated data [39]. The various graphical presentations for the simulation outcomes tell us how accurate our proposed design is for a particular greenhouse. The node mobility can be utilized in diverse kinds of nodes i.e. Zigbee coordinator, end device and router nodes.

The OPNET ZigBee model uses four process models which are:

1. Zigbee MAC Model
2. Zigbee Application Model
3. ZigBee Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) Model
4. Zigbee Network Model

ZigBee MAC Model: The Zigbee MAC model incorporates a model of the IEEE 802.15.4 MAC protocol. The model utilizes channel scanning, joining and failure/recovery process of the protocol in the unslotted operation mode.

ZigBee Application Model: The Zigbee Application model represents a low fidelity version of the ZigBee Application Layer as specified in the ZigBee Specification. The process model initiates network joins and formations, generates and receives traffic and generates different simulation reports.

ZigBee Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) Model: This model implements the media access protocol of the MAC layer.

Zigbee Network Model: The Zigbee Network model implements the ZigBee Network Layer as specified in the ZigBee specification. This model is responsible for routing traffic, process network join, formation requests and generating beacons [38].

2.7 Conclusion

This chapter dealt with an overview of Zigbee Technologies for WSNs. First it starts with all the WSNs available in the market and then comes to our main focus i.e. Zigbee/IEEE 802.15.4. It gives us an inside look at the Zigbee protocol architecture which includes its physical layer, medium access control layer, network layer and all the topologies supported by Zigbee and finally application support sublayer. There is also a section on sensors available on the market these days for greenhouse monitoring. The next chapter will focus on Zigbee based Wireless Sensor Network in greenhouse environments.

CHAPTER 3

LITERATURE REVIEW ON ZIGBEE BASED GREEN HOUSE MONITORING AND CONTROL NETWORKS

3.1 Introduction

This chapter discusses about Zigbee based wireless sensor networks, its characteristics, architecture and typical set-up. It also focuses on management, security and internet connections and web technology related to WSNs. By the end of this chapter, the reader will have a clear understanding of Zigbee wireless sensor technologies along with some of the related works done in this field. All the related research papers and journals that provide thought and concept concerning this project are explained for extracting knowledge, developing the concepts, implementing and studying the scenarios.

3.2 Literature Review

Zigbee technology has brought instant development in sensor networks in various applications. Users can sense, compute and communicate with elements to monitor and act accordingly in the direction of events. Data collection, monitoring, surveillance and medical telemetry are some of the typical applications. The most essential applications of Zigbee are sensor and automatic control, for e.g. military application, industrial control, smart buildings and environment monitoring. Greenhouse climate monitoring is also a befitting field endorsed by Zigbee alliance.

In ZigBee specification, high level communication protocols in the form of small, low-power digital radios based on the IEEE 802.15.4 standard for wireless personal area networks (WPANs) is used. ZigBee uses the 802.15.4 standard to classify application profiles to distribute among manufacturers. Zigbee technology allows sensors to be activated extensively in wireless control and monitoring applications where the low power-usage allows longer life with smaller batteries. The mesh networking offers high reliability and a much larger range.

In wireless network communication architecture, no cables are needed to connect from one point to another. Wireless operations help in long range communications which would have been impractical to implement given the extensive amount of wires needed. It can be put into action using radio frequency communication, microwave communication or infrared (IR) short-range communication. The Zigbee operating framework is usually a high-tech network where each node can sense, compute and communicate with each other. They can receive or send messages (full-duplex), and messages can also be transmitted to a gateway using self-configuration and multi-hop routing. Different ways to join and connect each gateway is constantly being applied to enhance the coordination in the communication line. A gateway usually connects the remote network with Internet, satellite or mobile communication network. Sometimes more than one gateway might be implemented for large-scale applications.

A wireless sensor network usually has a gateway and some wireless nodes, routers and coordinators. Gateways and nodes are implanted with a CC2420 RF transceiver which is ZigBee compliant and produced by Chipcon company. The transceiver sends all the collected data between gateways and nodes to be transmitted to a server. Nodes use battery power which is why their power capabilities may be limited because of its small size. A sufficient amount of power is needed for the network to work consistently over a long period of time since the transmission rate is low. Therefore a low-power design is always recommended.

In environment control and monitoring, Wireless Sensor Actor Network's (WSANs) success for climate control depends on the network to synchronize properly between nodes to execute TDMA-like power scheduling policies. The main idea is to divide time into periodic cycles and each cycle into a number of smaller time slots where only a pair of nodes is allowed to communicate. The time slot width can be as low as few tens of milliseconds [40]. Usage of an effective real-time OS on each sensor node is required, which might be hard because of the limited memory and computational resources of the WSAN nodes. However, recent work [41] has brought positive results and it is now one of the most successful research areas in WSNs/WSANs.

A large number of devices having spatial complications running different services are another important issue. The prototyping of measurable, compliant and stalwart software is a significant point in WSANs since the end user does not care about the whereabouts of the control being performed. He cares that the WSAN can self-configure and migrate control authority from one node to another. This additional concept which has many advantages in the control system design has been proposed recently [42].

Here in this section, we discuss some works that have been published regarding wireless sensor networks to greenhouse environments.

In [43, 44] authors use wireless sensor networks to deal with micro-climate in greenhouses. Authors in [45, 46] examine greenhouse environments, control greenhouse equipment, and have come up with various suitable services to clients including handheld devices such as a PDA living in rural areas.

The author [47] talks about a design for mobile agents based on the combination of data, whose routing plan is integrated by using an improved flooding algorithm.

In [48, 49], authors suggest a Web-based management system with an embedded control platform where the system provides a p.c. and control-platform for the wireless sensor network of a greenhouse.

The work in [50] presents the design, development and deployment of an Internet-accessible wireless sensor network for managing and analysing temperature, humidity, and illumination of a controlled environment. The authors state that the ultimate goal of their system is to extend the network lifetime, offer ease of deployment and reliability, and provide remote querying and configuration.

The work in [51, 52] implements a wireless sensor network system based on ZigBee technology.

The work in [53] considers a wireless sensor node for greenhouse monitoring that implements a sensor platform provided by Sensinode Ltd. with three commercial sensors able to measure four climate variations.

The work in [54] state a way to cut down energy usage of sensor nodes within glass greenhouses and ensure stable network operation through effective energy routing between sensor nodes by using the Direct Diffusion and Gossiping algorithm.

In [55] authors execute a wireless sensor network prototype with a two-part framework for greenhouses. The beginning consists of a certain amount of sensor nodes to measure temperature, light and soil moisture. A sink node with an embedded terminal based on the ARM processor was built inside to collect and transmit data wirelessly to a remote PC using Short Message Service (SMS). In the second part, a GSM module and the management software based on database running on a remote PC is observed.

Greenhouse Control and Management

Greenhouse monitoring and control is separated into three tasks which are measurement, calculation and adjusting [56]. The measured values of the climate variables of the greenhouse are changed from analog to digital and then sent to a computer which is located outside due to the high levels of moisture in the greenhouse. The sensors give signals which are weak because without signal amplifier, cabled sensor units are not able to transmit data properly. Needless to say, WSN's do not have this problem. Measured data can be sent to the gateway node which is plugged into the computer. It might also be sent out in a multi-hop manner via router nodes if the distance between the measuring nodes and the computer go beyond the length of a single radio link. The computer also provides users with climate variable values and statistics on top of data collecting and control calculation. It also manages the greenhouse climate control algorithm.

The computer shows control output signals with low voltage. The electronic relay is connected to each output which switches the equipment under its control on or off through the second relay, which in turn gives the input voltage to the device. Computer decides how long each relay is turned on after calculating the intermediate time from the output signal [56].

A modern greenhouse has their own local climate variable settings consisting of several parts which are why several measurement points may be needed.

A greenhouse might have numerous distributed local stations and one central station where each local station is in charge of collecting the greenhouse climate parameters by the sensors for temperature, humidity and light. The sensors are connected to a microcontroller which has embedded ADCs. A ZigBee transceiver is connected to the microcontroller to provide a wireless connection with a central station. Implementation of the central station was done by a PC at which the set value for each parameter is confirmed and compared with others from each local station. The central station gives the control requirements at each location based on the measure and set assessments of the parameters. These control actions are sent back to the local stations via ZigBee module. Lastly, the microcontroller will establish the necessary control signals for the actuators and arrange their operation accordingly after receiving the control actions by the local station.

Actuation System

An actuator is a device producing movement if a signal is given. Basically, actuators are the mechanisms behind output in control applications. In a computer controlled greenhouse, the actuators obtain control signal from the microcontroller to control the inside climate variables of the greenhouse. A system may include the following actuators:

- A ventilation fan whose speed establishes the exchange between inside and outside air causing natural ventilation.
- Heating system consisting of heaters allocated along the greenhouse.
-Thermal/shade screen extended along the roof of the greenhouse preventing the loss of heat obtained during the day (for cold months). It also ensures that the crop is not damaged from excess solar radiation and reduces the temperature (for hot months).
- Evaporative cooling system consisting of an exhaust fan and a pump circulating water through and over a cellulose pad.
- Irrigation system where water is pumped through polyethylene tubes for drip irrigation.
- Artificial lighting lamps to apply light radiation over plants to elongate the photoperiod.

Application of Zigbee Wireless Sensor Networks in Greenhouse Climate

There are three types of topologies in ZigBee based wireless networks: star topology, mesh topology and cluster tree topology [57]. The role of the network coordinator is played by the central station and sets up the communication between it and the local units. A PAN identifier is chosen by each local unit, not used by any other station within the radio sphere of influence. This helps each star network to work separately. As Figure 11 suggests, the central station creates its own network and becomes the network coordinator as soon as it is activated for the first time. Then it introduces its hardware, stack and application variables, broadcasts beacon frames to the local stations and elects a new PAN identifier of zero. The local stations will ask to be a part of the network as soon as they receive the beacon frame. As the central station receives the request, it will return a response and add them as a child device in its neighbor list. Upon adding the central station as its parent in their neighbor list, the local stations will return an acknowledgement. The central station starts monitoring all network nodes in real-time by maintaining the network information database.

A device sends data to the PC via a wireless communication link. The PC works as a base station controlling and managing the whole network. If a remote device is out of range in the radio-effective area of the PC, its data signal is still picked up by other devices and reaches the PC. A remote device can communicate with the PC with the help of other devices.

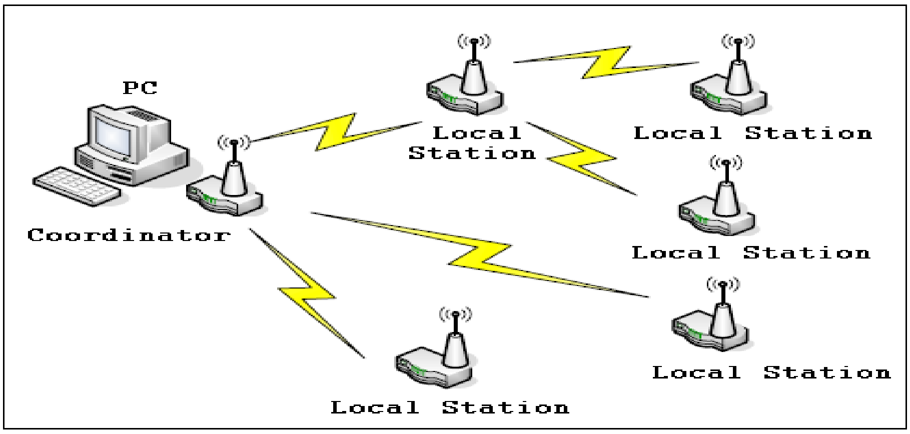


Figure 8: A typical network topology architecture

Security

128-bit keys are used by Zigbee to execute security mechanisms. A key can be related either to a network, where it can be used by both ZigBee layers and the MAC sublayer, or to a link, obtained by pre-installation, agreement or transport. Link keys are recognized based on a master key controlling link key correspondence. Finally, a secure medium (transport or pre-installation) is necessary to get the initial master key as the entire network security is reliant upon it. Link and master keys are noticeable to the application layer. In order to prevent leaks and security risks, various services use different one-way variations of the link key.

Key distribution is one of the most significant security functions of the network. One special device is assigned by a secure network while other devices trust for the allocation of security keys which is the trust center. Devices will have the trust center address and central master key pre-installed; if a temporary susceptibility is seen, it will be sent as outlined above. Applications without the need for specific security may use a network key given by the trust center (through the initially insecure channel). Therefore the trust center is responsible for the network key and point-to-point security. Devices will only accept communications from a key by the trust center, except for the initial master key.

3.3 Global Connectivity to Internet and Web Services

In modern day world internet connectivity is treated as a complete necessity [58]. Nowadays no one takes a business seriously unless it has a valid website. This immense popularity has sparked several greenhouse researchers to design their system with internet capability. But internet has faced issues about privacy since users do not wish to disclose information constantly being transmitted and received from devices. When it comes to greenhouse, privacy becomes important since the user will not want any outsider gaining access of the system. A slight mishandling of the system can cause damage to the plants inside the greenhouse.

A set of application programming interfaces (APIs) placed at an isolated location and any application with proper access can handle the data is the main concept of web services. Its architecture helps to integrate with systems through internet in a very simple manner that provides smart publication and discovery options. Consequently web service based frameworks are commonly employed to conveniently access different devices such as sensors through the internet [59].

Web services help to integrate application by using open standards, protocols and languages that are generally accepted on the internet. The core of its architecture is handled by HTTP, and XML message are exchanged through it using the SOAP (Simple Object Access Protocol). SOAP, being strictly defined XML based rules, provides the luxury of using various programming languages such as PHP, Java, C++ and .NET to develop various components in the system [59].

Several suggestions have been made to integrate WSN to the internet for a strong flexible system [15] [60] [61]. WSNs are usually connected to the internet using a central gateway that extends control over the internet [15]. Gateways are meant for managing and stabilizing the entire network, collecting and transmitting the sensed data to the backend server through communication network. Researchers use the sensed data through the backend server and users can monitor and browse the data from anywhere if they have access to the internet. Therefore, developing a gateway with good capability in computing and data storage is important to achieve the optimum utilization of resources.

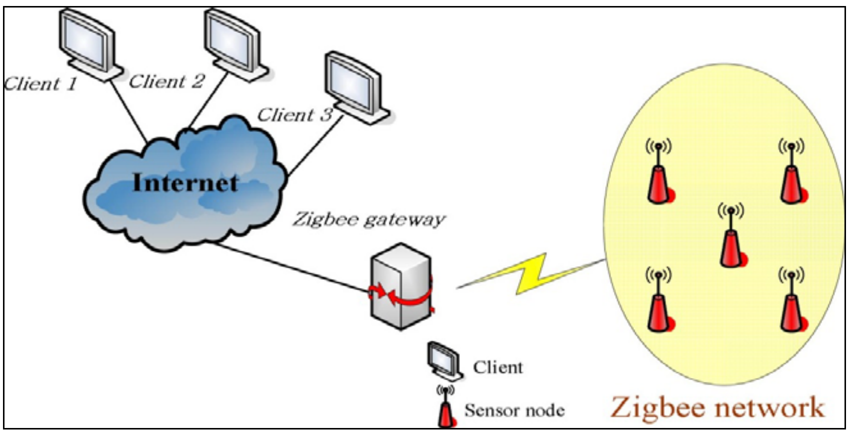


Figure 9: Zigbee networks and Internet Communication System.

3.4 Internet Integration

The gateway provides a simple easy setup through which different protocols can be translated to IP packets [15] [62]. Zigbee based gateways can be either implemented using a regular computer as gateway or used much more in a streamline manner by using microcontrollers.

The gateway approach for integrating WSN to the internet is preferred as sensing applications will result in small amount of data per packet, but IPv6 has large amount of header information per packet [63]. Low-powered sensing devices will cause smaller header information to result in little data to be transmitted, thus consuming less power.

6lowpan [64] is a protocol based on IEEE 802.15.4 preferred for greenhouse automatic monitoring and control systems. It is known as an acronym of IPv6 over Low power Wireless Personal Area Networks [64]. The 6lowpan concept came from the notion that "the Internet Protocol could and should be applied even to the smallest devices," [65] and devices that use less power and also have limited processing abilities should take part in the Internet of Things [66]. Encapsulation and header compression mechanisms have been classified by the 6lowpan group allowing IPv6 packets to be sent to and received from IEEE 802.15.4 based networks. IPv4 and IPv6 are the main workforces behind data delivery for local-area networks, metropolitan area networks, and wide-area networks such as the Internet. Similarly, sensing communication-ability in the wireless domain is accessible by IEEE 802.15.4 devices.

An integral part is software architecture when designing a system with a web front end. Protocol translating methods has an important part in integrating a system to the internet. A personal computer can be used as a hardware server to host the software and also to connect it to the internet. Zigbee protocol is used in [67] to provide the researchers a secure and self-configuring network.

3.5 Conclusion

The literature reviewed in this section outlines the possible methods, techniques and technologies which were used in Zigbee protocol in greenhouse monitoring and control network. Use of Zigbee protocols is very popular among WSN and that's why researchers have taken a special liking to it. Attempt to integrate a greenhouse automatic monitoring and control system with Zigbee wireless sensor network and internet have already been tried several times with gateway based centralised architecture being the most common and favourable approach.

CHAPTER 4

MODELLING AND SIMULATION OF ZIGBEE BASED GREEN HOUSE MONITORING AND CONTROL NETWORK USING OPNET

4.1 Introduction

A number of simulators are available in the market today to simulate different kinds of wireless and wired networks. Among other network simulators such as NS-2/NS-3, OMNET++, NetSim, TOSSIM, WSNsim we have chosen OPNET for our project. Parameters can be changed and new attributes can be added; and the range of parameters is suitable making simulation easy in OPNET.

The OPNET simulation environment help to simulate ZigBee based networks by providing different components of a ZigBee network (ZigBee coordinator, ZigBee router, ZigBee end device which can be fixed or mobile). The objects are explained according to the standard. The OPNET potentials for modeling ZigBee wireless networks were studied from different angles [68-70]. A user can build a network using such components to develop a similar model of a real network to analyze it and configure component attributes [71].

OPNET Modeler Wireless Suite [72-74] is a commercial modeling and simulation tool for different types of wireless networks. Constructed by OPNET Technologies, Inc. (recently acquired by Riverbed: www.riverbed.com) and based on the well-known product OPNET Modeler, a rapid, distinct event simulation engine operating with a 32-bit/ 64-bit fully parallel simulation kernel available for Windows and Linux is used by the simulation environment. The OPNET Modeler focuses on an object-oriented modeling approach and a hierarchical modeling environment. With no special routing protocols available for wireless sensor networks, various propagation and modulation techniques including a ZigBee (802.15.4) MAC layer are provided and additional modules have to be personalized from the beginning. Simulations of wireless networks can be run as discrete event, hybrid or analytical, encompassing terrain, mobility and path-loss models.

Libraries along with other simulators can be incorporated to the OPNET Modeler due to the open interface external object files. In addition, the OPNET Modeler Wireless Suite provides grid computing support to execute simulations in a distributed manner [75].

4.2 The OPNET Simulation Model of IEEE 802.15.4

Open-ZB [76] is an open source implementation of IEEE 802.15.4 /ZigBee [77]. OPNET and TinyOS have the simulation models available. The OPNET simulator has version 1.0 of the exact simulation model of the slotted IEEE 802.15.4 programmed for itself. PHY has a transmitter and a receiver working at 2.4 GHz frequency, 2 MHz bandwidth and QPSK modulation. The MAC layer has slotted CSMA/CA, generates beacon frames and synchronizes nodes with a PAN Coordinator. The battery module determines used and surplus energy levels. The APP 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, BER, propagation delay etc. Figure 18 depicts a structure of the IEEE 802.15.4 Simulation Model [73].

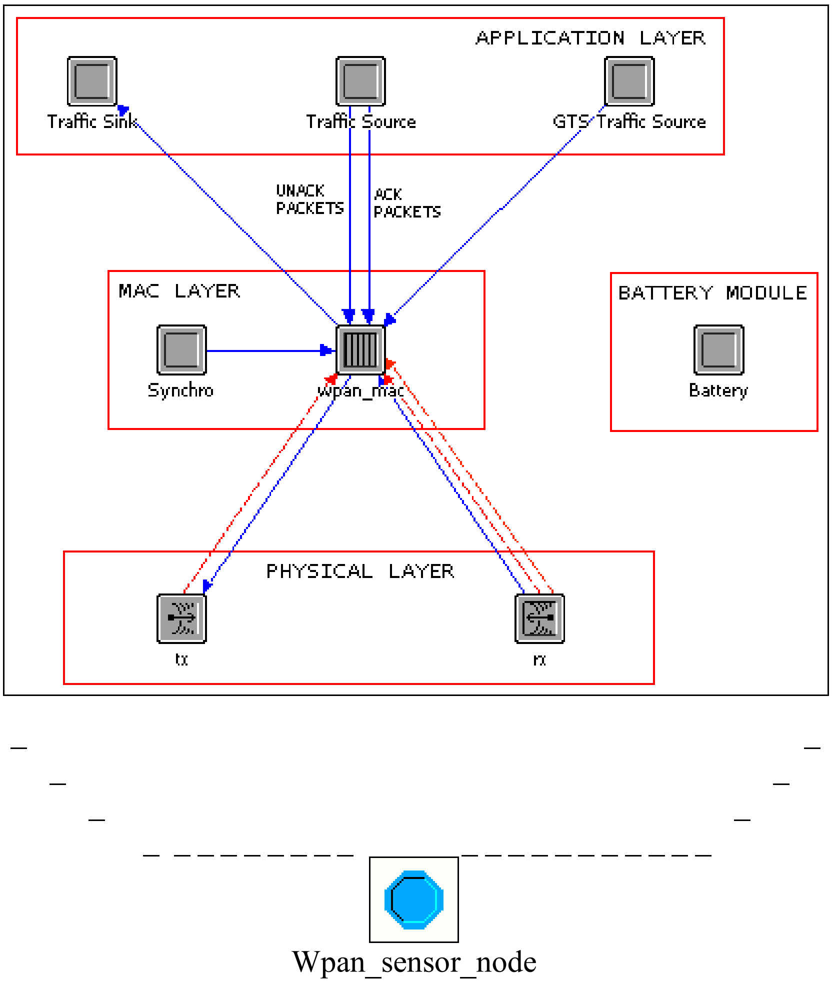


Figure 10: The structure of the IEEE 802.15.4 Simulation Model [73]

4.3 Advantages of OPNET Modeler for Zigbee WSNs

There are certainly a lot of advantages of OPNET Modeler for Zigbee WSNs. OPNET has great potential in simulating Zigbee WSNs since it can provide a wide range of reports and statistics at varying network layers (especially at the MAC layer) for an individual node or for the entire WSN. It is also well-known that Zigbee WSNs are easier to use when compared to other WSN simulators. IEEE 802.15.4/Zigbee networks themselves are battery powered applications which is renowned for characteristics such as low power, low cost, low data rate and long battery life. The

Zigbee protocol is an advanced solution to low power wireless networks since it is reliable, secure and generally easy to implement in hardware.

4.4 Simulation Scenarios

There are seven scenarios studied in this project. The first six scenarios are compared with each other. There is just one ZigBee coordinator in each topology, therefore it just forms a single personal area network (PAN). The comparison monitors these global statistics: end-to-end delay, throughput, loss of packets, number of nodes, power, load, data arrival rate, traffic sent and traffic received. We will compare end-to-end delay, throughput, loss of packets against number of nodes, power, load and data arrival rate of all these six scenarios. Traffic sent and received of all the six scenarios will also be compared.

Scenario 1

Scenario 1 consists of a single greenhouse with a single Zigbee coordinator, 9 routers and 10 end devices resulting in a total of 20 nodes. The nodes are placed at a distance of 20 meters from each other with default transmission power level. The design logic is very simple. 9 routers and 10 end devices are used to cover the whole field at a distance of 20 m from each other which is why so many nodes are used in the first place.

Scenario 2

Scenario 2 consists of a single greenhouse with a single Zigbee coordinator, 9 routers and 10 end devices resulting in a total of 20 nodes. The nodes are placed at a distance of 10 meters from each other with default transmission power level.

Scenario 3

Scenario 3 consists of a single greenhouse with a single Zigbee coordinator, 9 routers, 10 end devices resulting in a total of 20 nodes but with increased transmission power level. In this case, power is increased 2 times than the power in other scenarios. This is done to compare it with scenario 1 and 2.

Scenario 4

Scenario 4 consists of 20 greenhouses separated in an area of 1000m x 800m with each GH measuring 200m x 200m. It consists of a single coordinator, 150 routers and 227 end devices resulting in a total of 378 nodes.

Scenario 5

Scenario 5 consists of 20 greenhouses with a single coordinator, 150 routers and 227 end devices resulting in a total of 378 nodes. But the difference with all other scenarios is that the end devices and routers are set to send the destination traffic to random node.

Scenario 6

Scenario 6 is replication of 50 greenhouses with default settings stretched in an area 2000m x 1000m. It consists of a single coordinator, 500 routers and 445 end devices resulting in a total of 946 nodes.

Scenario 7

The last scenario is based on a real life approach of a very large farming land area for e.g. in this case we have taken District A, where there might be a number of greenhouses in five respective sub-areas. Now we will take all these greenhouses of those five areas under consideration and simulate a whole scenario of greenhouses under District A. Therefore the user or the owner having access to internet from anywhere in the world can browse and monitor this information of all the greenhouses of District A for e.g. humidity, soil temperature, carbon dioxide level etc.

We are using single co-ordinator only in any number of greenhouses. This is because if we use two co-ordinators, we will have problems knowing which co-ordinator is the central one and which one is secondary. They all will have the same priority. There are no specs like this in Zigbee standards to have master / slave redundancy. Routers extend the range of the Zigbee circle or we can say that the radius of the Zigbee greenhouse can be extended in the desired direction with the help of routers since nodes cannot support other nodes.

We have replicated only the number of nodes and routers in a greenhouse in all scenarios except scenario 5. Each router has the capability of supporting up to 2 nodes and another router. Co-ordinator will only connect to nearby routers or nodes, and then the range can be only extended by adding routers or another co-ordinator there. Here routers are the connecting elements. The drop in joined packets considerably falls down as the numbers of router nodes are increased. The idea is to have central node from where the internet connection can be used to monitor the greenhouses so we have used central node (coordinator) to collect all the statistics.

There is of course degradation in efficiency of transmission as the number of greenhouses is increased. We will see later from the results section that the effective number of connections / throughput was falling down.

Global statistics present information relating to the entire system. During a simulation many different objects may contribute to one global statistic. For example, every node in a network model may use the same global statistic for the end-to-end delay experienced by the received packets. The outcome is one statistic for the network's end-to-end delay performance. Global statistics are approved by process models and supported by the global statistic probe object. Only the name of the statistic is used as no objects are referenced in a global statistic probe.

The sole objective is to simulate the scenarios in OPNET properly with given system variables. In most cases, a vast amount of system variables and metrics are available for collection in OPNET, which offer two types of user-defined statistics: local and global, in general. Local statistics are ideal for reporting activity that is private to a particular node in the system model. However, in the case of network performance evaluation, we are more interested in obtaining quantitative information about the system as a whole. Therefore, the present study works on the data collected from global statistics.

The values of end device parameters are listed in Figure 11 and the values of router parameters are shown in Figure 12.

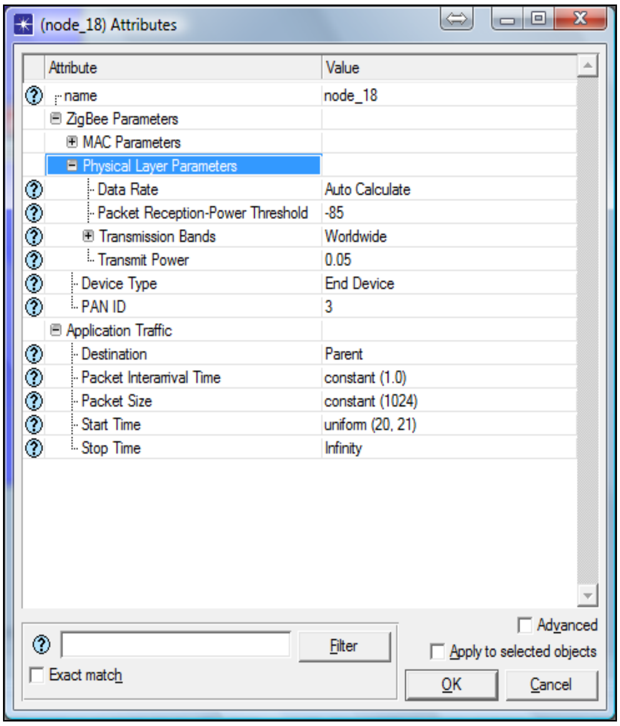


Figure 11: End Device Parameters

The packet arrived rate might be a bit too high for a sensor network but given the circumstances and nature of the simulation, it works perfectly for the given scenarios. The CSMA/CA parameters are set to default because this satisfies the conditions of our scenarios perfectly.

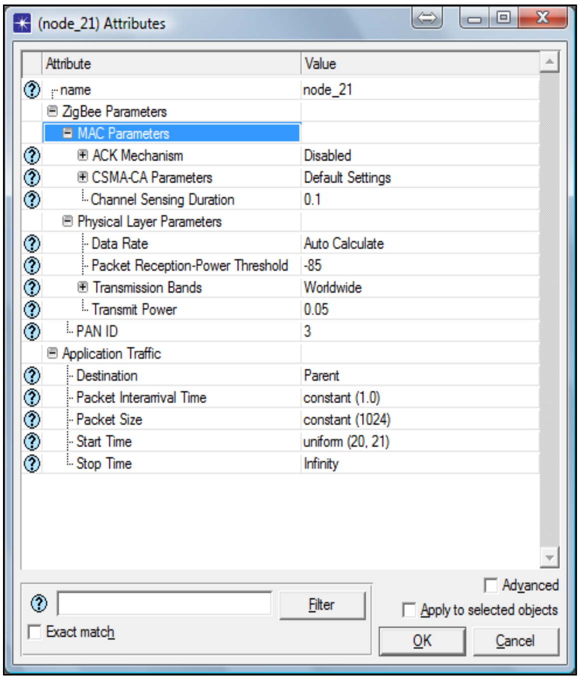


Figure 12: Router Parameters

Scenario 3 with increased transmission power level is shown in Figure 13. The transmit power is set to 0.1 W as shown below which is double to all the other scenarios.

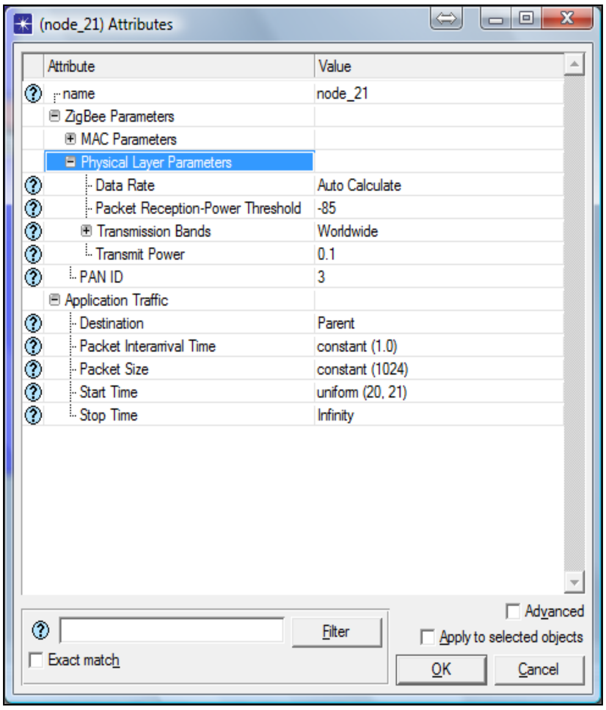


Figure 13: Router Parameters for Scenario 3.

The Zigbee Coordinator parameter is shown below in Figure 14.

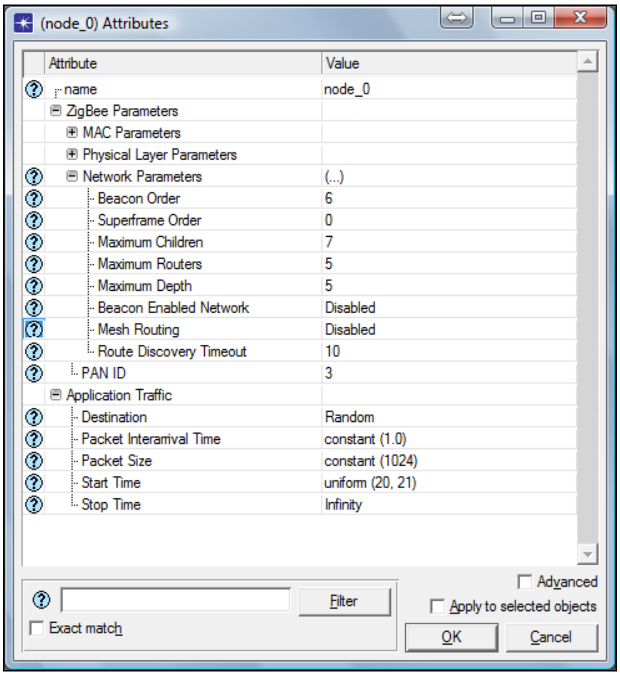


Figure 14: Zigbee Coordinator Parameter.

The simulation times for the scenarios are shown in Figure 15.

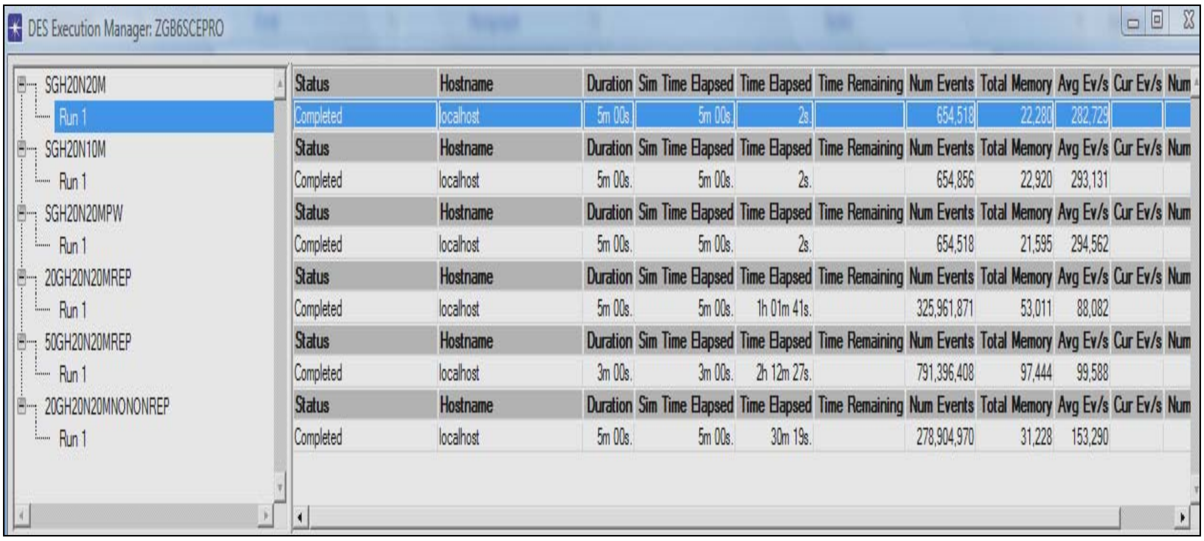


Figure 15: Simulation Time for the scenarios.

4.5 Zigbee Simulation Using OPNET

The ZigBee library for OPNET used is OPNET v17.0. Unfortunately, the ZigBee model is still incomplete and lacks some functions of ZigBee (will be discussed later in the Discussions and Conclusion section).

ZigBee performs route discovery to determine the optimal path for messages to take them to its destination. This section will show the layout of various scenarios simulated on OPNET; Steady case with single coordinator, stability in the presence of moving end devices, case of variable bit rate transmitted, and some limitations observed possibly due to an incomplete ZigBee library model.

4.6 Layout of the Scenarios

Overall there are seven scenarios. The first scenario we simulated is a single greenhouse where we examined a network consisting of one coordinator with 20 nodes placed at a distance of 20m from each other. The second scenario consists of a single greenhouse with 20 nodes placed at a distance of 10m from each other. The third scenario consists of a single greenhouse with a total of 20 nodes but with increased transmission power level. The power used for this scenario is twice compared to other scenarios. The fourth scenario consists of 20 greenhouses with a single coordinator, 150 routers and 227 end devices resulting in a total of 378 nodes. The fifth scenario also consists of 20 greenhouses but here compared to other scenarios, the end devices and routers are set to send the destination traffic to random node. The sixth scenario consists of 50 greenhouses with a single coordinator, 500 routers and 445 end devices. The seventh scenario is completely different from the rest and is based on a real life approach of a city for e.g. in this case we have taken Auckland, where there might be a number of greenhouses in five respective areas. We will simulate a whole scenario of all these greenhouses of those five areas under one district (District A). Each area might have different number of greenhouses.

4.6.1 Scenario 1

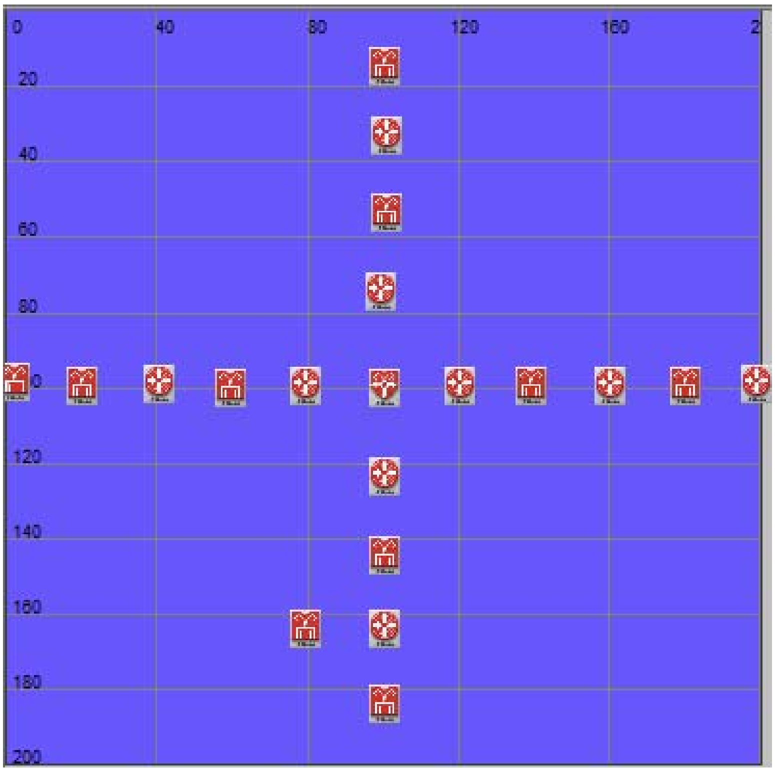


Figure 16: Scenario 1 of Single greenhouse (20m)

Scenario 1 with a single greenhouse consists of a single Zigbee coordinator, 9 routers and 10 end devices (total 20 nodes) with the sensors placed 20m from each other. The maximum area covered by one ZigBee station in specific OPNET conditions should be determined. As long as the devices are within range of one another, they will be able to communicate.

4.6.2 Scenario 2

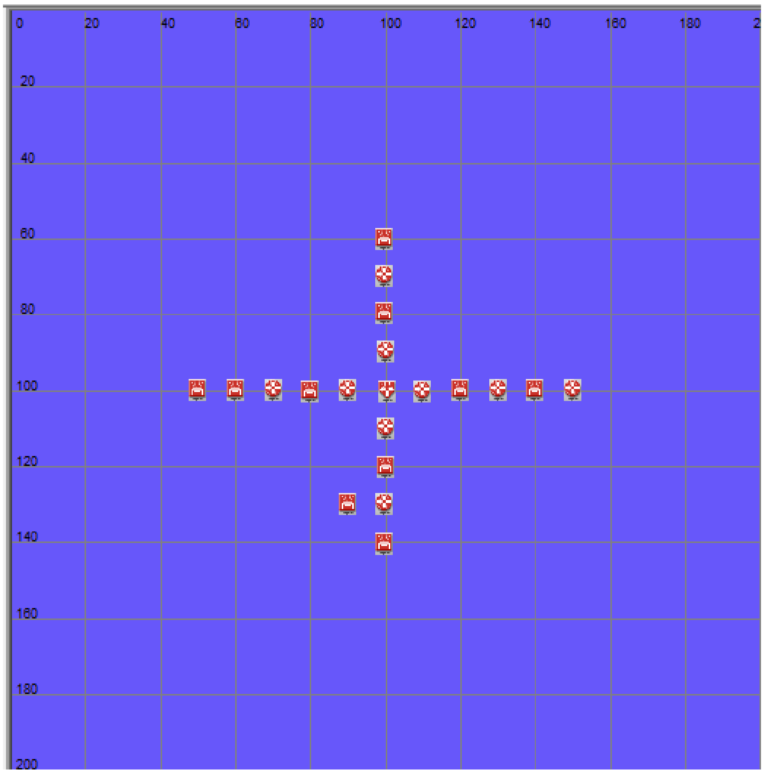


Figure 17: Scenario 2 of Single greenhouse (10m)

Scenario 2 with a single greenhouse consists of a single Zigbee coordinator, 9 routers and 10 end devices (total 20 nodes) with the sensors placed 10m from each other.

4.6.3 Scenario 3

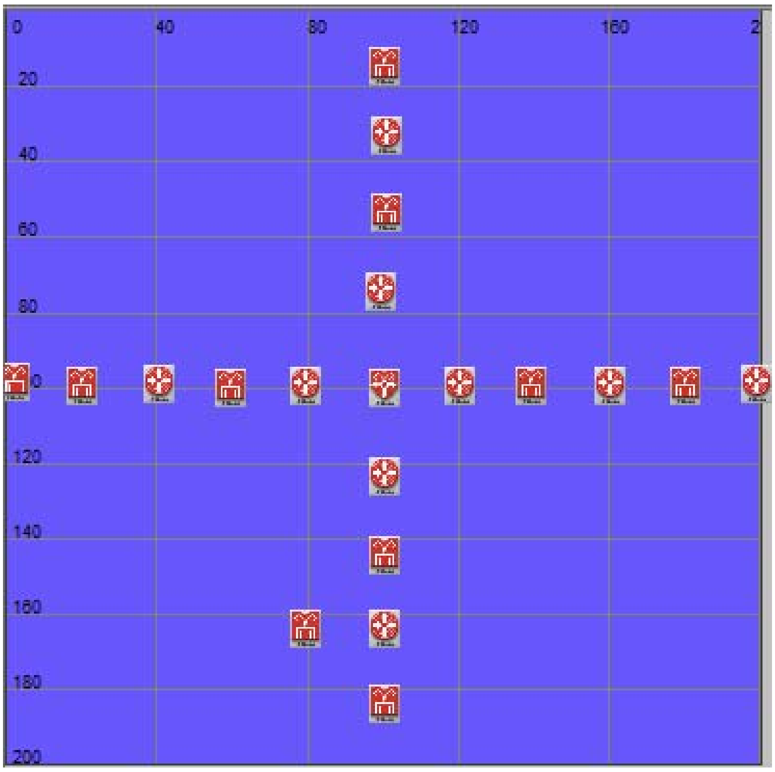


Figure 18: Scenario 3 of Single greenhouse with increased transmission power level

Scenario 3 is same as scenario 1 in design; only difference is that power level is increased by 2 in scenario 3.

We have used colored squares to show the separate greenhouses in scenarios 4,5 and 6 due to the sheer number of devices.

Small black dots are showing the devices with red one as coordinator.

Each greenhouse is of dimension 200 m x 200 m.

Scenario 4 and 5 are 1000m x 800m in dimensions.

Scenario 6 is 2000m x 1000m in dimension.

4.6.4 Scenario 4

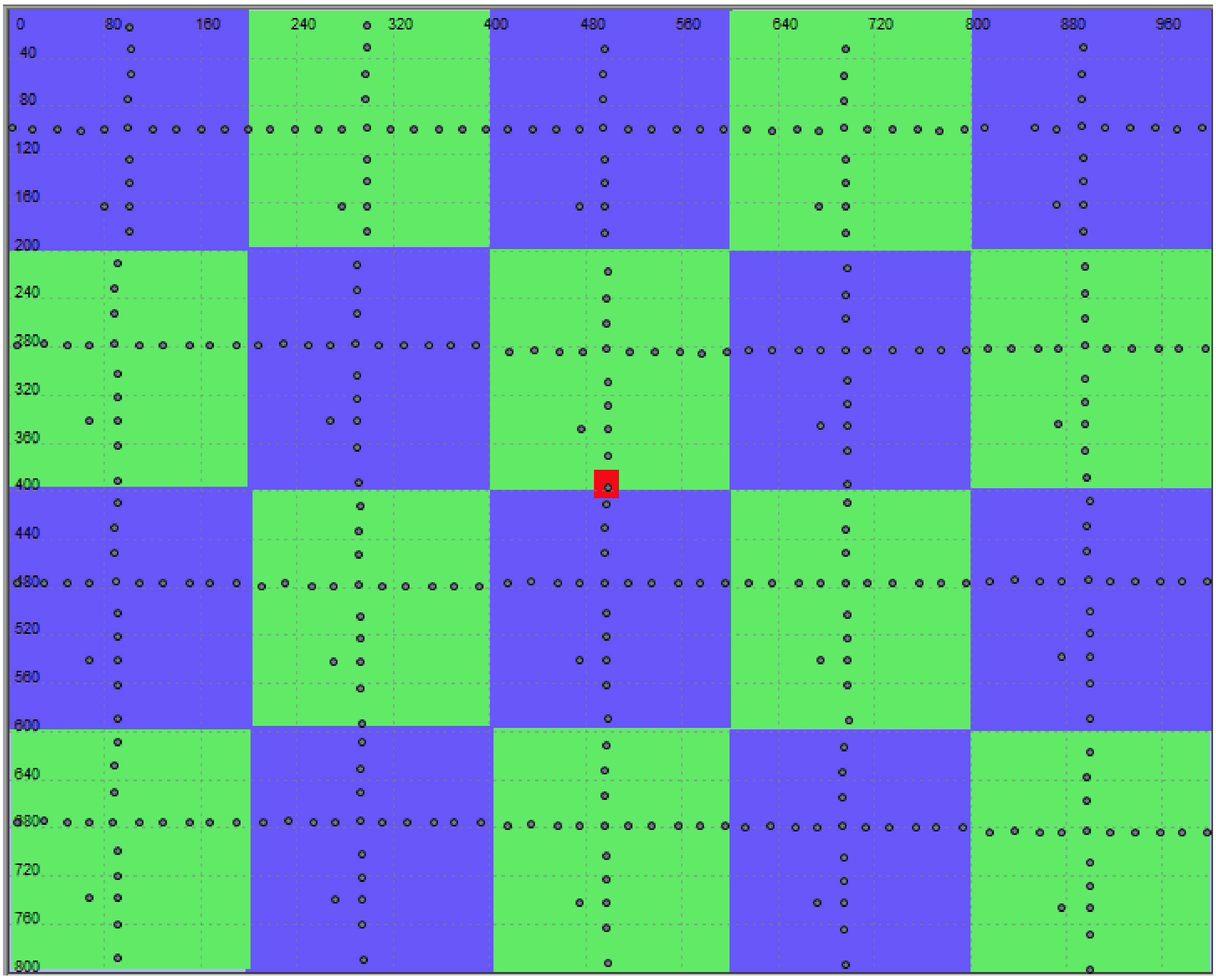


Figure 19: Scenario 4 of 20 greenhouses

Scenario 4 with 20 greenhouses consists of a single Zigbee coordinator, 150 routers and 227 end devices (total of 378 nodes). We have used partial-mesh topology in our project as all the nodes are not connected to each other; in full mesh, all nodes are connected to each other while in partial-mesh, nodes are connected partially. As we used the coordinator in the middle of the topology, we can also say that it is centric topology which is characteristic of star topology.

4.6.5 Scenario 5

Scenario 5 with 20 greenhouses consists of a single Zigbee coordinator, 150 routers and 227 end devices (total of 378 nodes). Scenario 5 is same as scenario 4 in topology and design looks, only difference is that the nodes are set to send traffic to random destinations unlike those of other scenarios in which traffic destination is set as parent node only.

4.6.6 Scenario 6

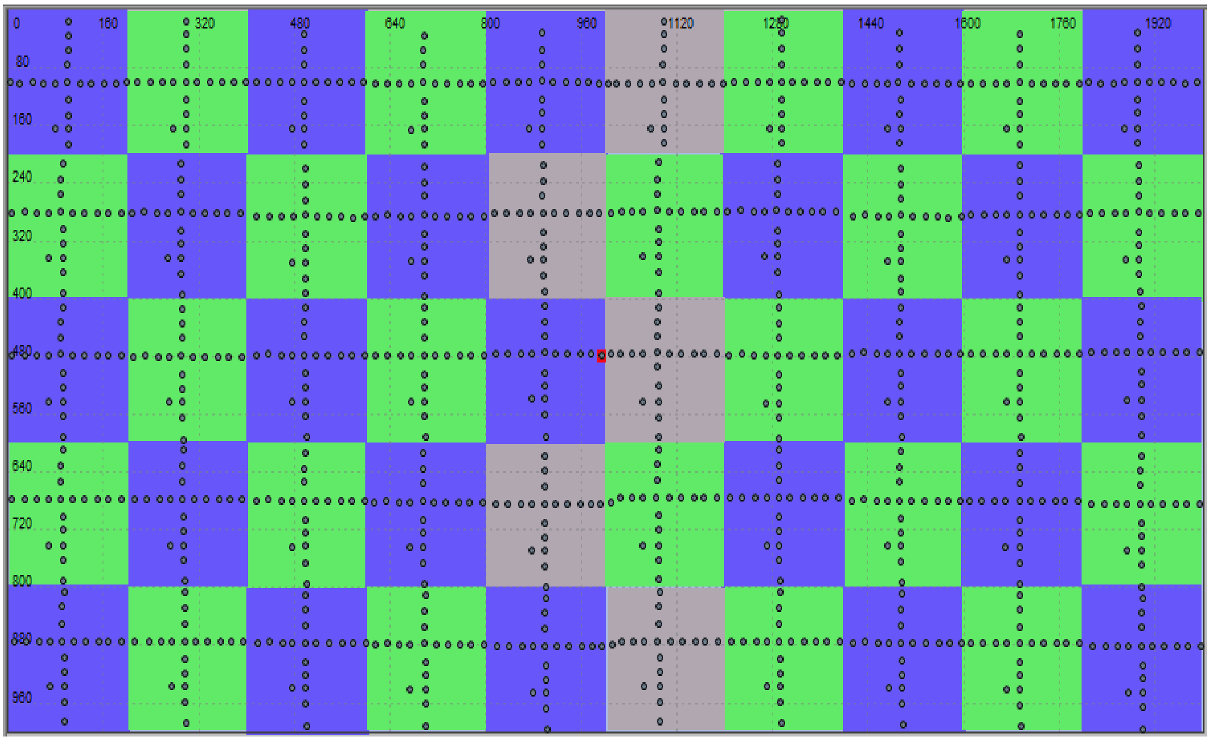


Figure 20: Scenario 6 of 50 greenhouses.

Scenario 6 consists of 50 greenhouses with a single coordinator, 500 routers and 445 end devices (total of 946 nodes).

In Figure 22, the particular PAN (id.3) has fixed default parameters which were not changed before simulation run. Thus maximum number of children, maximum depth and maximum number of routers were restrained to 7,5,5 respectively. With these constraints in place the topologies with extended tree arms in both X & Y axis would not be able to work well. Thus it is required to set those parameters before the simulation runs to see if there are any differences.

The three important system parameters are the maximum number of children of a router (Cm), the maximum number of child routers of a router (Rm), and the depth of the network (Lm). The point to note is that, a child of a router can be a router or an end device, so Cm ≥ Rm. Zigbee has recommended a distributed address assignment scheme regarding Cm, Rm and Lm. Though it is simple, the scheme might forbid a node from accepting a child router/device set by these parameters. When a node cannot associate with any parent router, it becomes an orphan node with unused address spaces still remaining. This is called the orphan problem [78].

Thus we may try one more round of simulation with following parameter values:
Cm =7
Rm = 5
Lm = 30 (this is maximum in our scenarios, default depth is 5)

Maximum number of children of a router is set to 7 and maximum number of child routers of a router is set to 5 since we know that Cm ≥ Rm.

4.6.7 Scenario 7

The last scenario is based on all of the greenhouses of District A where there might be a number of greenhouses in five respective areas. Now we will take all these greenhouses of those five areas under consideration and simulate a whole scenario of greenhouses. Therefore the user, on availability of internet, can have access to data from anywhere in the world.

But the last scenario could not be carried out due to incomplete Zigbee model library in OPNET. To carry out this particular scenario we needed Zigbee gateway to have 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. Without the Zigbee gateway, the five areas all containing greenhouses could not be connected with each other and could not be brought under one single roof meaning a user could not have access to all the greenhouses under District A.

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 and therefore the five respective areas around city A each containing innumerable greenhouses was just another extended scenario of the five previous ones.

So we have greenhouses centrally controlled by single co-ordinator which can be then connected to internet / http / https server for sending reports and controlling the greenhouse parameters remotely. Only reason why we were not able to connect http server is that OPNET does not support connection between any Zigbee elements to devices running tcp services.

Recently some work has been done to solve this problem. The paper [79] proposes an architecture to connect Internet with Zigbee sensor networks based on IEEE802.15.4 standard. It is basically a web-sensor gateway to send data between Internet protocol and Zigbee/IEEE802.15.4 protocol. The common gateway interface (CGI) technology is used to help users on the web browser to monitor the Zigbee sensor network universally and a simulation prototype is proposed. It uses a small μIP TCP/IP stack on the small sensor node to help users gain access of the sensor node while the sensor nodes communicate each other over their own protocol [80]. An IP host is thought of as a virtual sensor node to route packets like a physical sensor node. The drawback is to make sure of incidental stack in an IP host which needs to be deployed [81]. Generally the significant applications of WSNs call for collaboration with the Internet. The web-sensor gateway in this paper acts as a media to access the essential sensor data from Internet to sensor networks with a simple use of a web browser. It is basically an architecture of an embedded web server, its gateway translation layer, and the OPNET modeling of the web-sensor gateway and its components [76].

The followings are some of the facts and findings on which this simulation is based and results which are derived after simulation :

- Power used is 0.05 W for these 5 scenarios (1,2,4,5 and 6) and 0.1 W for scenario 3 only (2x more power). The standard supports 100 mW.
- In flat terrain nodes can communicate longer distances upto 500 m [82].
- It is found that increasing the number of routers results in the decrease of packets dropped (unjoined requests).

Table 4 summarizes the parameters used in the seven scenarios.

Scenario	Number of greenhouses	Coordinator	Routers	End Devices	Total number of nodes
1	1	1	9	10	20
2	1	1	9	10	20
3	1	1	9	10	20
4	20	1	150	227	378
5	20	1	150	227	378
6	50	1	500	445	946
7	–	–	–	–	–

Table 4: Parameters used in the six scenarios.

CHAPTER 5

SIMULATIONS AND RESULTS ANALYSIS

5.1 Introduction

The results collected from simulations with OPNET modeler are presented and analyzed in this chapter. The performance of the first 6 scenarios are compared with each other and analyzed in terms of end-to-end delay, throughput, loss of packets, load, power, number of nodes, data arrival rate, traffic sent and traffic received to measure the QoS of these Zigbee based greenhouse wireless control and monitoring networks. The last scenario could not be carried out due to the non-availability of a proper Zigbee-Internet Gateway in the modeling software package. A possible diagram of a Zigbee-Internet Gateway is presented at the end of this chapter.

5.2 End-to-End Delay against Number of Nodes

The first two parameters that we should consider are number of nodes and end-to-end delay. Figure 7.1 shows number of nodes against end-to-end delay for five scenarios. Scenario 5 performed so badly that it did not generate any spikes in the graph or if it did, then it is so negligible that it cannot be seen in any of the graphs. End-to-end delay is an OPNET global statistics. It is the entire delay between the invention and reception of application packets. Global statistics give us relevant information concerning the overall system and measures the effect on real-time monitoring. It also controls a large number of nodes in the network.

The light blue fluorescent represents single greenhouse with 20m distance, the light green represents single greenhouse with 10m distance, the yellow represents single greenhouse with increased power, the dark blue represents 20 greenhouses and the red line represents 50 greenhouses.

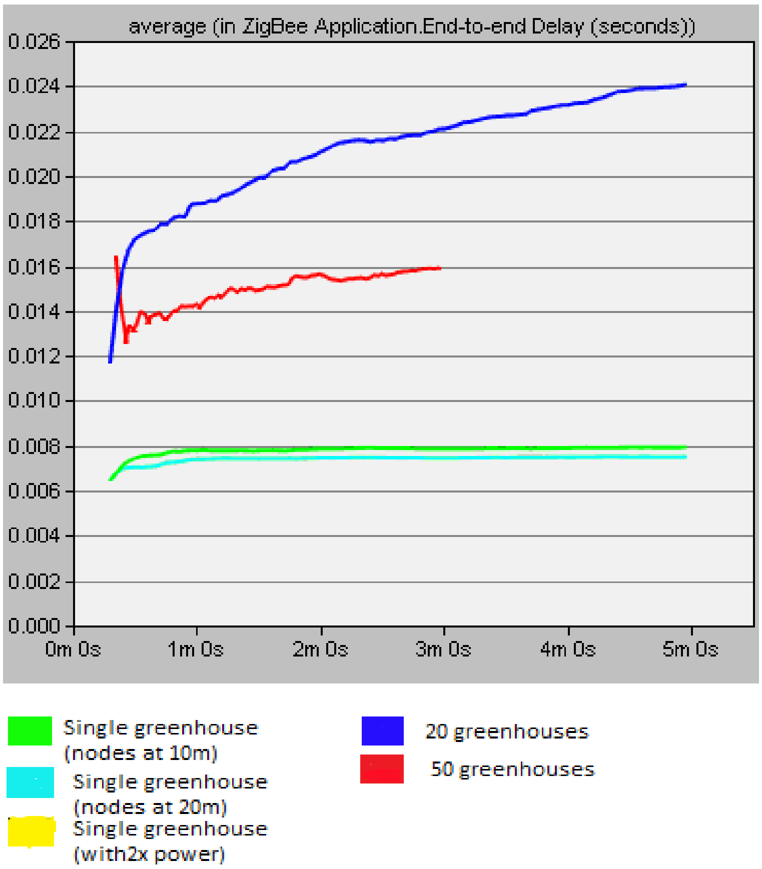


Figure 5.1: End-to-End Delay against Number of nodes

As can be seen from the graph the delay increases as the number of greenhouses increase. However initial delay for 50 GH scenario (0.0165s) was higher compared to 20 GH scenario (0.012s) but later due to many unjoined nodes, there was sudden fall in the delay for 50 GH scenario as the far end devices were not communicating at all with the coordinator. The yellow line (Scenario 3) could not be seen because it is negligible or close to zero. This is a multihop scenario.

5.3 Number of nodes against Loss of Packets

Packet loss is a key metric for evaluating the reception of data packets from source to destination. There are several reasons why a packet may become "lost" on its way to its destination. These factors include: signal degradation over the network medium, network links that become oversaturated and faulty packets, hardware and drivers, etc [6].

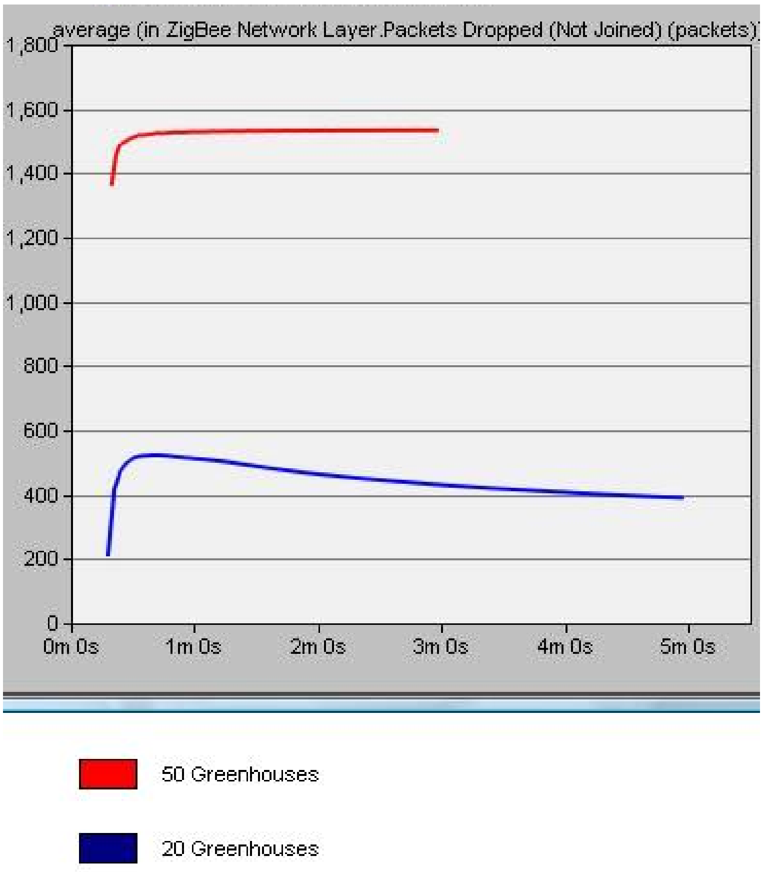


Figure 5.2: Number of nodes against Loss of Packets

As can be seen the packet drops are only observed in 2 scenarios, scenario number 4 and 6. Scenario 4 with 20 GHs has packet drops between 400–500 approximately, while the packet drops in scenario 6 are way beyond 1500. Therefore we can conclude that as the number of greenhouses increase, the packet loss also increases.

5.4 Number of nodes against MAC Throughput

Throughput is the amount of bits or packets successfully acquired or transmitted by the receiver or transmitter channel per second.

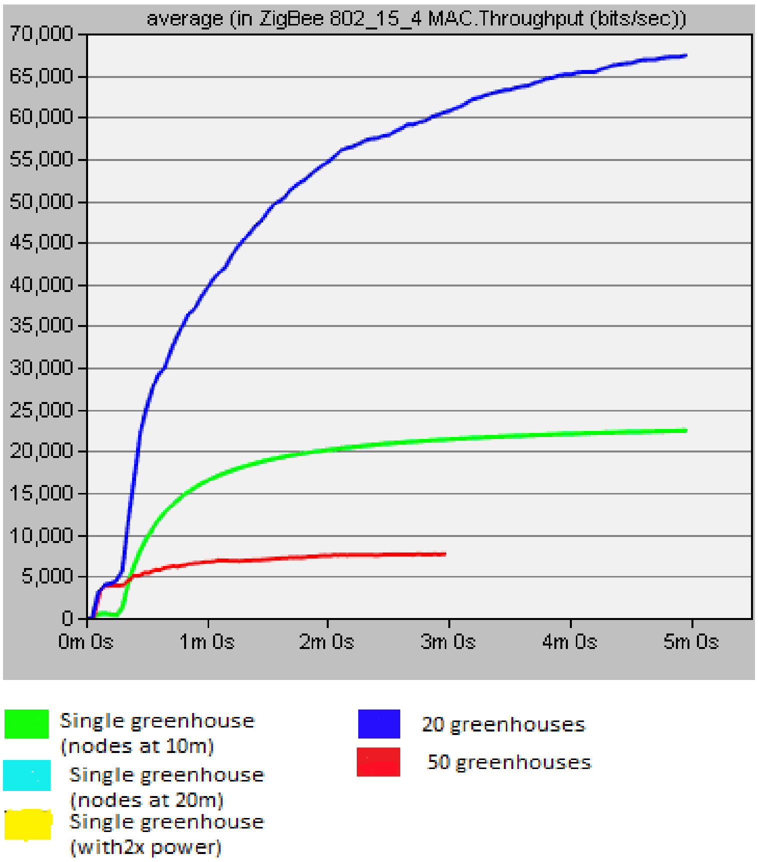


Figure 5.3: Number of nodes against MAC Throughput (bits/sec)

MAC throughput can be seen increasing where the communication between maximum percentage of nodes are working. The scenario with 20 GHs is showing maximum MAC throughput whereas scenario with 50 GHs is showing the least throughput. This shows that the amount of traffic being exchanged in 50 GHs is even less than what is exchanged in scenarios with 20 GHs and single GH at 10m distance from each other. Scenario 1 and 3 GHs (light fluorescent blue and yellow) are negligible here and close to zero because no significant data was generated for them. The expected throughput was 55000 bits/sec for 50 greenhouses.

5.5 Number of Nodes against MAC Load

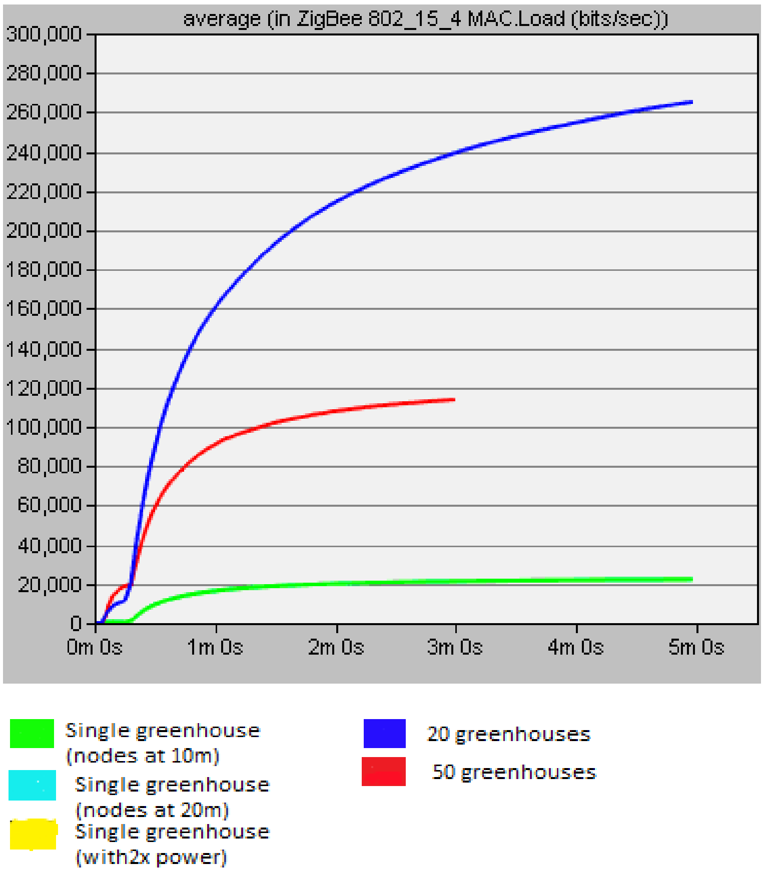


Figure 5.4: Number of Nodes against MAC Load

Again MAC load can be seen increasing in scenario 4 with 20 GHs which indicates that the traffic within this scenario is higher compared to other scenarios. As usual scenario 1 and 3 GH is negligible because no significant data was generated for them. The 20 GH scenario generates more load than the 50 GH scenario because due to many unjoined nodes, the 50 GH could not generate more load and it stopped halfway.

5.6 Load against throughput

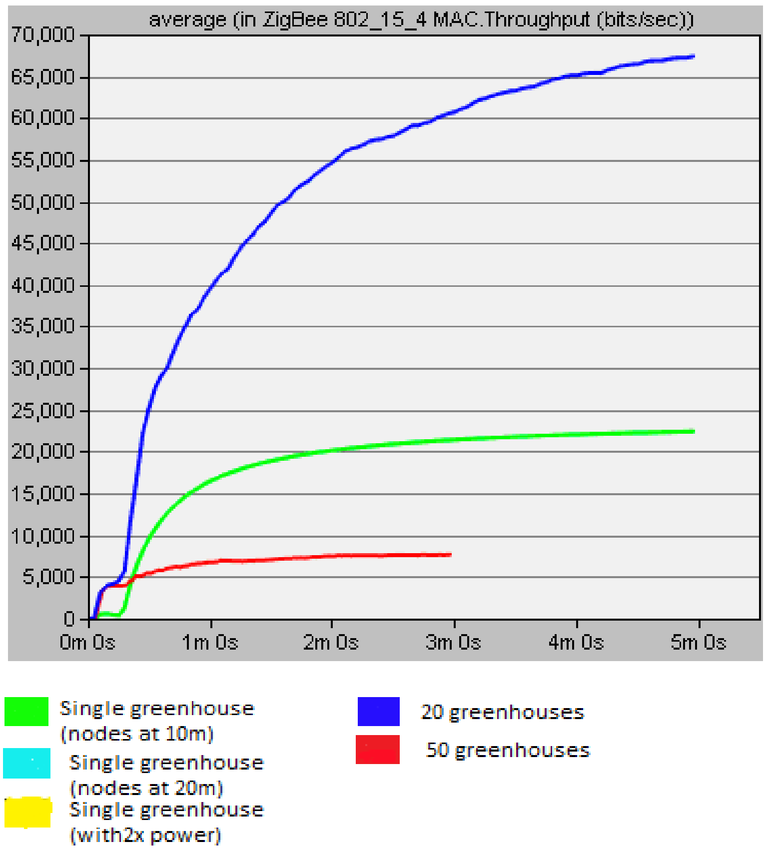


Figure 5.5: Load against Throughput

This is simple comparison of load and throughput in different scenarios, both these parameters are measured at MAC layer. Maximum throughput was obtained for the scenario with 20 GHs while it was the least for 50 GHs and the throughput stayed in between for scenario 2. Scenario 1 and 3 GHs (light fluorescent blue and yellow) are negligible here and close to zero because no significant data was generated for them.

This is different from Fig. 5.3 as Fig.5.3 deals with nodes and throughput whereas this figure deals with load and throughput.

5.7 Load against Loss of Packets

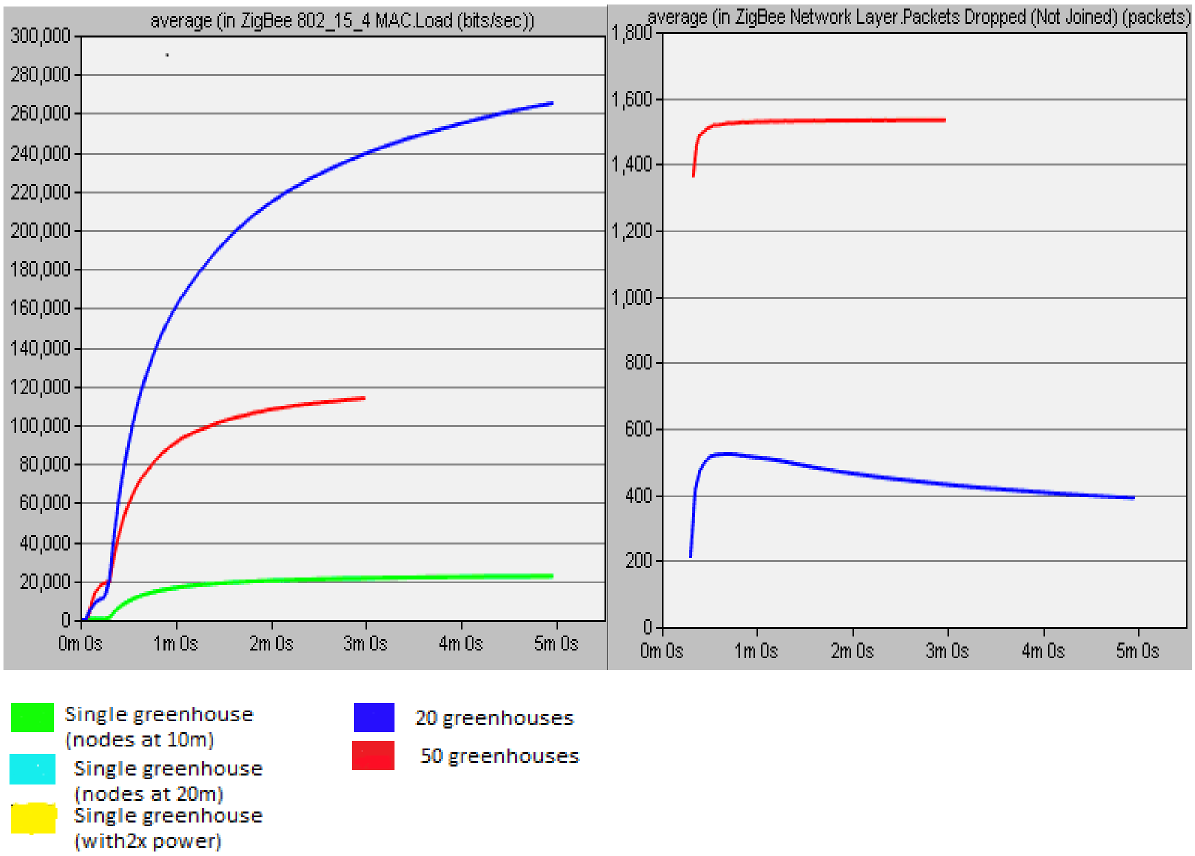


Figure 5.6: Load against Loss of Packets

Loss of packet is way more than the load in this case. Load is showing us how much the wireless paths are loaded and how many packets have been dropped in the scenarios. As can be seen from the graph, packet loss is maximum for the scenario with 50 GHs indicating higher number of traffic. Scenario 1 and 3 GHs (light fluorescent blue and yellow) are negligible here and close to zero because no significant data was generated for them.

5.8 Data Arrival Rate against Delay

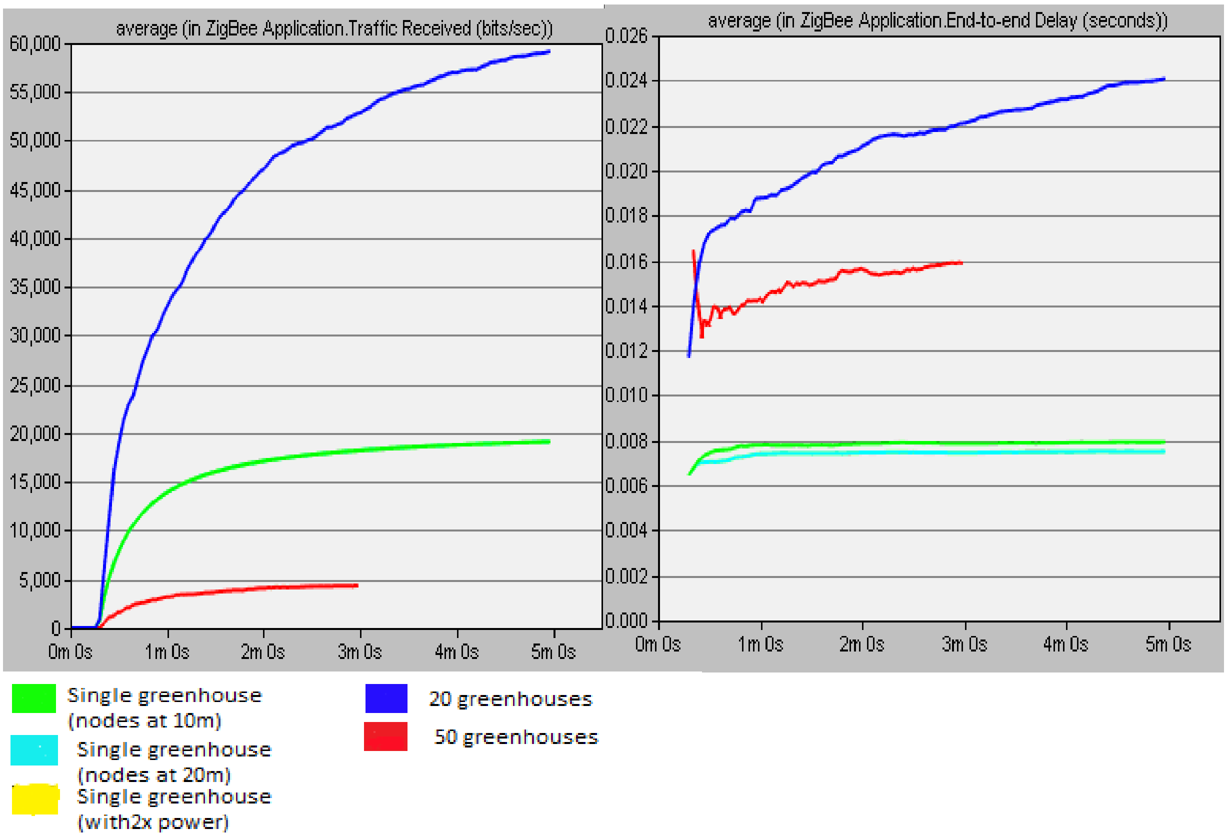


Figure 5.7: Data Arrival Rate against delay

Here the data arrival rate is the highest in scenario with 20 GHs, and the delay as well. The data arrival rate is much low in scenario 6 with 50 GHs showing that there is not much communication going on because of the loss of packets. Scenario 3 GHs (yellow) is negligible here and closes to zero because no significant data was generated for them.

5.9 Data Arrival Rate against Throughput

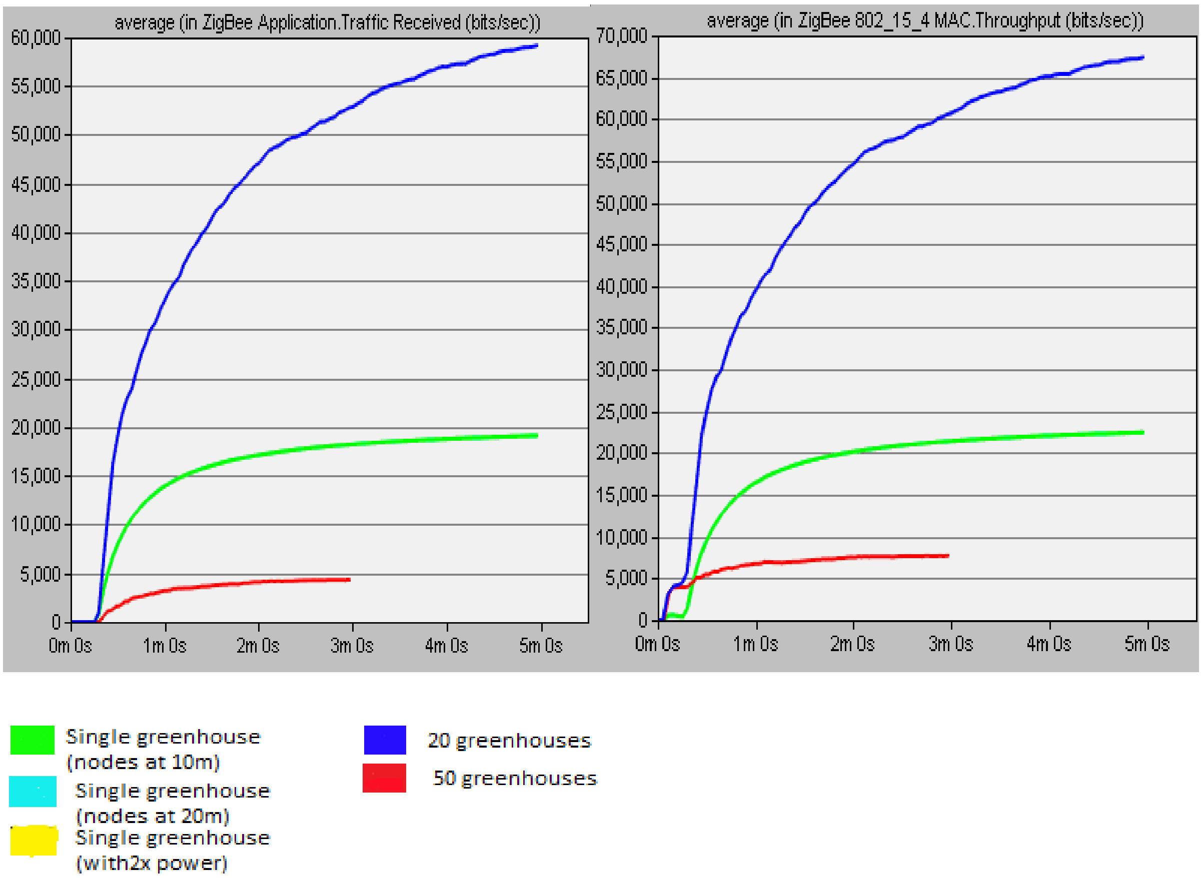


Figure 5.8: Data Arrival Rate against throughput

Throughput and data arrival rates are also higher for scenario with 20 GHs whereas it is the lowest for scenario with 50 GHs. The scenario with single GH woth nodes placed at 10m from each other is between these 2 scenarios. Scenario 1 and 3 GHs (light fluorescent blue and yellow) are negligible here and close to zero because no significant data was generated for them.

5.10 Data Arrival Rate against Loss of packets

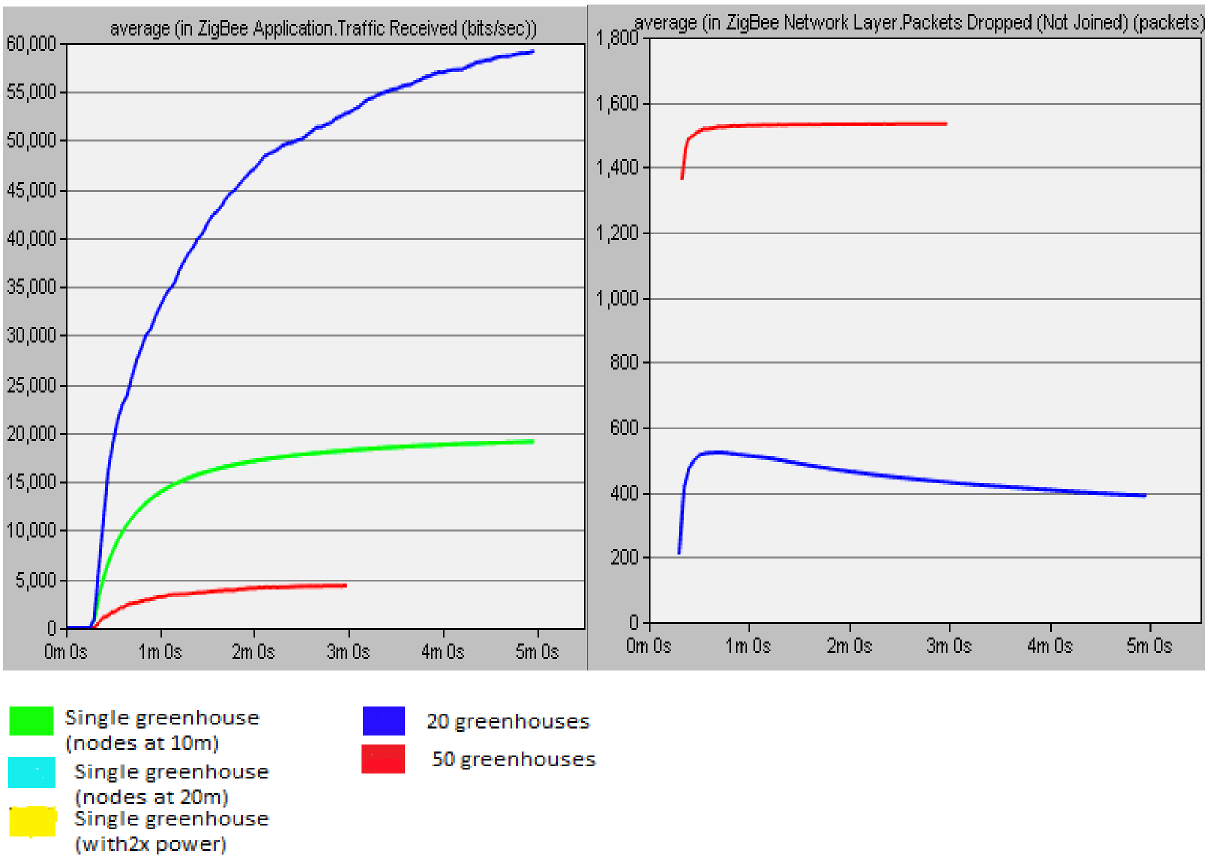


Figure 5.9: Data Arrival Rate against Loss of packets

Data Arrival rate is higher in scenario with 20 GH and packet drops are maximum in scenario with 50 GH. Scenario 1 and 3 GHs (light fluorescent blue and yellow) are negligible here and close to zero because no significant data was generated for them.

5.11 Traffic Sent

Data traffic sent is defined as the total number of data bits sent by the source to destination per unit time irrespective of the condition whether all of the data bits reach the destination or not [6].

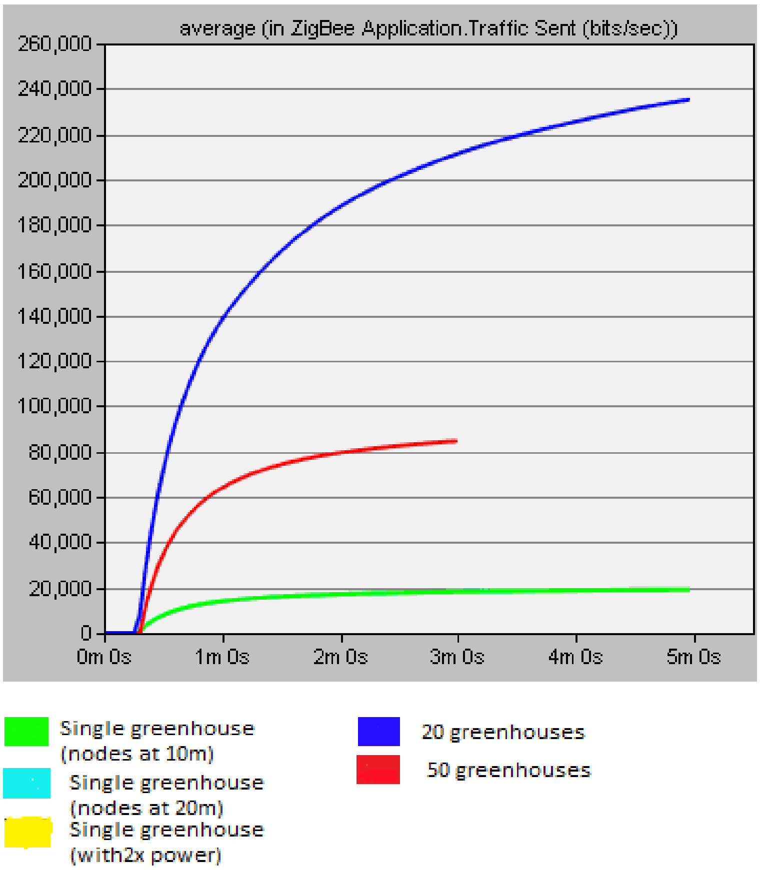


Figure 5.10: Traffic sent (in bytes/sec)

Traffic sent in scenario with 20 GH is reaching the IEEE 802.15.4 industry specification of 250 kbps showing that the data is being sent at maximum possible rates for this scenario. Scenario 1 and 3 GHs (light fluorescent blue and yellow) are negligible here and close to zero because no significant data was generated for them.

5.12 Traffic Received

It is defined as number of bits the data receives per unit time.

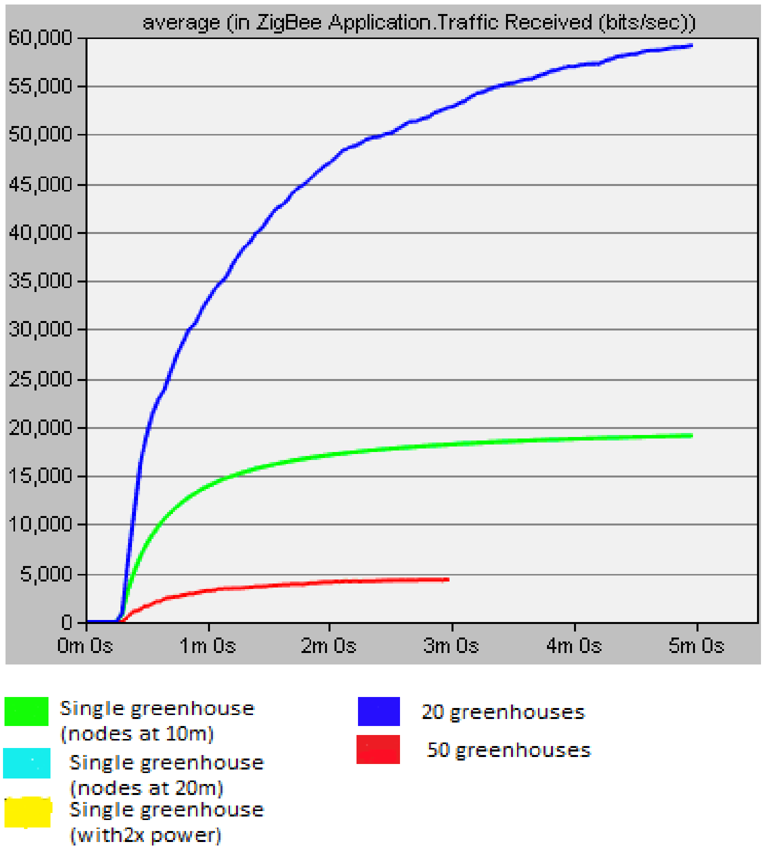


Figure 5.11: Traffic received (in bytes/sec)

Traffic received is maximum in scenario 4 with 20 GHs while it is the lowest in scenario 6 with 50 GHs. The green line denoting a single greenhouse with nodes placed at 10m distance from each other lies in between these 2 scenarios. Scenario 1 and 3 GHs (light fluorescent blue and yellow) are negligible here and close to zero because no significant data was generated for them.

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 Discussions and Conclusion

Some of the important observations of the simulation are discussed below:

Delay

Delay increases as the number of greenhouses increase, however delay for 20 GH scenario is higher than 50 GH scenario. Initial delay was greater for 50 GH scenario but later due to many un-joined nodes, there was sudden fall in the delay as the far end devices did not communicate at all with the coordinator.

With 20 nodes spaced at 10 meters/ 20 meters, the delay was 7-8 micro seconds. But as we increase the number of nodes, delay gradually increased to double reaching 13-16 micro seconds for 50 GHs scenario and 22-24 micro seconds for 20 GHs. The anomaly here is that delay stayed less for 50 GH scenario, while for 20 GH it was 3 times higher than the single GH. This can be explained on the basis of number of nodes which were able to join the PAN 3 coordinator.

Throughput

MAC throughput can be seen as increasing where the communication between maximum percentages of nodes is working. The scenario with 20 GHs is showing maximum MAC throughput whereas the scenario with 50 GHs is way below on the graph showing that the amount of traffic being exchanged is even less than the single GH scenario of 20 nodes.

This supports the anomaly in end-to-end delay as well. Less delay and less throughput in 50 GH scenario signifies that many nodes were not able to participate in the network since Zigbee standard defines the range from anywhere between 25 meters to 100 meters or even 400 meters in a line of sight field.

For the 20 node single GH scenario, the throughput gradually reached 68-70 kbps maximum, for scenario with single GH spaced at 10 meters the throughput stayed between 20-25 kbps, and for the 50 GH scenario it did not reach further than 7-8 kbps. It shows that with 20 meters nodes distance in the single GH, we are getting maximum throughput.

Packet Loss

From the graphs it can be seen that the packet drops are only observed in 2 scenarios, scenario 4 and 6 respectively. Scenario 4 with 20 GHs has packet drops between 400–500 approximately, while the packet drops in scenario 6 are way beyond 1500. The large number of packet drops in 50 GH scenario shows that the routers are dropping the joining or relay requests from end devices as they are too busy in processing requests from other end devices.

If the setup is as big as 50 GHs, we can’t rely on single coordinator setup as it is too far for the nodes to hop all the way; standards show that the routers can handle 14 other nodes including parent devices (coordinators / routers). But from the implementation it seems that each router is not able to handle the children nodes effectively when the numbers increased beyond 20 GH setup.

Traffic

Traffic sent in scenario with 20 GH is reaching the IEEE 802.15.4 industry specification of 250 kbps showing that the data is being sent at maximum possible rates in this scenario. When number of nodes is less as in scenario with 20 nodes, it is sending data at rates much lower, about 20 kbps inside the PAN 3. For 50 GH scenario, the data being sent is 80 kbps approximately. This shows that even with large number of devices, the sending rate is not as higher as scenario with 20 GH.

Practical (Real Life) Implementations

In one of the practical real life scenarios (as in Gothenburg city for about 270,000 houses) [84], 8000 concentrators were used there among the multiple nodes with multiple repeaters to boost the range. In our setup there are no repeaters or multiple coordinators, but real life implementation of this setup is possible with 20 GHs. With only a single coordinator, the scenario with 20 GHs and nodes spaced at 20 meters covering an area of 1000 meters x 800 meters has shown satisfactory results for all the parameters such as throughput, delay and traffic.

Problems Faced

The main problem in this design was that the simulation of 50 GH with nodes more than 1000 took a lot of computer resources and it was really slow. It was impractical to simulate for more than 5 minutes (not simulation but actual minutes). For 5 minutes simulation, it took more than 4 hours on a hardware with 2 GB RAM and dual core processor.

Another issue is that, the router can connect up to 14 other nodes (from a theoretical perspective of the Zigbee standards) but in simulation, it was not possible. Thus the results are not very satisfying for the design, even with 5 possible adjoining nodes. Thus it is also needed to find the optimal ratio of number of routers needed per couple of end devices and parent devices.

Throughout this project, we have learned some of the limitations about the ZigBee model in OPNET. It has been widely popularized that internet connection to a Zigbee network is something which can make monitoring, observation, tracking and managing Zigbee controlled environment smoother & meaningful. Indeed there are applications in agriculture, health industry building facilities automation which can be only possible if there is an interface between Zigbee network & IP-based internet. As per Zigbee alliance “The Gateway specification defines a Remote Procedure Call-based (RPC) API to ZigBee functionality and the management of the IP gateway itself.” [85]
Since Zigbee was designed with expectations of low cost, long battery life, low duty cycles and smaller sizes the protocol stack also was designed so that the processing power required to run the stack fit just inside the hardware specifications, there were no heavy data communication protocols like IP / TCP /UDP included. Absence of such IP interfacing protocols made it really difficult to connect Zigbee environment with the Internet in our simulation model. When we tried to

implement Internet connection, we noticed that OPNET doesn't support ZGD (Zigbee Gateway Device) (OPNET versions 14.5/15.5/16.5/17.2).

6.2 Future Work

Zigbee gateway is unavailable as an object in the OPNET object palette. Another drawback is that OPNET doesn't provide any parameter change for distances. Only way to check if the range is correct is via trial & error method when a check is needed to made between 2 devices. Therefore, developing a model of Zigbee Gateway and implementing with the simulation package will be a useful research in the future.

No element is available for interfacing Zigbee PAN to the internet. Therefore one may also try out the possibility of using coordinator to Ethernet connection to see if it solves the problem. Future work might also include setting up a test-bed to compare the theoretical work done in OPNET with a practical implementation of the whole project. In that way, one might be able to compare the actual results between the two set-ups and further improve the model.

We learned the different functionalities and models of OPNET including some of its limitations despite the ZigBee model being only a small portion of the OPNET. We were a bit disappointed with the incomplete ZigBee model library. Despite the problems mentioned before we believe we made the right choice using the OPNET simulation tool; the results we obtained look promising and realistic to our knowledge and can be compared with others produced by similar models in future studies.

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