Quality-of-service based framework for wireless sensor networks in precision agriculture applications

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DEDICATION

I dedicate this achievement to the following people:

Firstly, my father, General I.M. Akakandelwa; who has been my role model all my life. Thank you for the moral support, financial support and continuous encouragement. I will forever be thankful for you, I pray the Lord blesses you abundantly.

To my siblings; Boyd, Lubasi, Waluka, and Maggie, thank you guys so much for always showing me your love and support.

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DECLARATION

I, WARREN AKAKANDELWA, hereby declare that this research project titled *"Quality-of-service-Based Framework for Wireless Sensor Networks in Precision Agriculture Applications"* is my own work conducted at the North-West University, Mafikeng Campus and has not been submitted in any form for the award of any degree at any university or institution of tertiary education or published earlier. All data and information used as source has been duly acknowledged both in the text and reference.

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ABSTRACT

Wireless Sensor networks (WSNs) are a growing technology in the world today, with the advancements in micro-electro mechanical technologies. With this surge in popularity of sensor networks technology comes the need to find areas for its application. Precision Agriculture (PA) is just one of many areas in which sensor networks are applied. The aim of precision agriculture is to improve productivity in agriculture practices by employing technology that maximizes resources and provides high quality of service (QoS). However, providing QoS in wireless sensor networks is not an easy task and researchers continue to seek better methods of achieving this endeavor. This work proposed a WSN focused on providing QoS in precision agriculture applications in maize farming by exploring conditions needed for improved maize production to selecting appropriate network parameters for WSN. The framework merges a web-based agriculture management application for maize production (AgriSensApp), with a physical wireless sensor network to assure QoS for precision agriculture. A comparative QoS evaluation was carried out on two sensor network topologies designed to provide a high QoS network backbone for the framework, a grid topology and a nonagonal geometric structured topology. The results of the evaluation showed the nonagon topology perform better than the grid topology when parameters such as throughput and packets dropped were considered. On the other hand, the grid topology performed better when the parameters considered were MAC delay and end-to-end delay. The overall contribution to research from this study was that providing QoS in sensor networks calls for trade-offs to be made on certain quality measures, and the choice of QoS measure must be made on the basis of which measures best suit the particular precision agriculture activity being conducted.

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LIST OF ACRONYMS AND ABREVIATIONS

ACK : Acknowledgment
AgriSensApp : Agriculture Sensing Application
AMS : Agriculture management System
AODV : Ad hoc On Demand Distance Vector
APL : Application layer
APO : Application Objects
APS : Application Sub Layer
APTEEN : Adaptive Periodic Threshold-sensitive Energy Efficient Sensor Network
BPSK : Binary Phase Shift Keying
BS : Base Station
CSMA-CA : Carrier-Sense media Access -with Collision Avoidance
DiffServ : Differentiated Services
DSSS : Direct Sequence Spread Spectrum
FFD : Full-Function Device
FTP : File Transfer Protocol
GIS : Geographic Information System
GPS : Global Positioning System
GUI : Graphical User Interface
HTTP : Hypertext Transport protocol
IEEE : Institute of Electrical and Electronic Engineers
IMS : Irrigation Management System
IoT : Internet of Things
LR-WPAN : Low-Rate Wireless Personal Area Network
LW-WPAN : Low rate Wireless Personal Area Network
MAC : Medium Access Control
NWK : Network layer
OPNET : Optimized Network Engineering Tools
O-QPSK : Offset Quadrature Phase Shift Keying

OS	: Operating System
PA	: Precision agriculture
PAN	: Personal Area Network
PHY	: Physical layer
PREQ	: Packet Request
QoS	: Quality of Service
RFD	: Reduced Function Device
RREQ	: Route Request
RS	: Remote Sensing
RSSI	: Received Signal Strength Indicator
TCP	: Transport Control protocol
UDP	: User Datagram Protocol
WSN	: Wireless Sensor networks
WUSN	: Wireless Underground Sensor Network
XBee	: ZigBee
ZDO	: ZigBee Device Object

CHAPTER 1

INTRODUCTION

1.1 Introduction

Recent advances in telecommunication technologies such as wireless communications and electronics have facilitated the rapid growth of the Internet of Things (IoT) paradigm. The wide acceptance of the IoT paradigm coupled with advances in engineering has given rise to concepts like Wireless Sensor Networks (WSNs), which stem from generic sensor networking technologies and concepts. In the simplest terms, WSNs can be defined as dense and spatially distributed networks made up of several nodes or "tiny devices" which work cooperatively to gather and communicate data untethered [1]. Furthermore, as is often the case with such great advances in technology; there are a myriad of possible applications for WSNs, Precision Agriculture (PA) being one of them [1-3].

Precision Agriculture applications with WSNs have garnered massive attention in recent years from networking and communications researchers as well as agronomists, who desire efficient and effective methods of mitigating and managing risks associated with various agricultural practices. Though much has been achieved in this field, great challenging issues still demand continued research. By their very nature, wireless networks make use of radio waves to facilitate communication. This entails that great consideration must be taken whenever a WSN is to be deployed, because the environment in which the network is deployed will influence the overall performance of the network; and these effects vary with each environment- or, the degree of the environments' adversity will vary. Vougioukas et al in [4] found that in an agricultural environment of any specific, the signal propagation between nodes can be affected by foliage in the observed field. Furthermore, WSN have limitations on power supply and given that the very communication between nodes that is required to serve the purpose of the network, depletes more power than the processing. Thus, deployment in remote locations with no readily available power sources may incur great risks for a project. It is for these and many other limitations and vulnerabilities in

WSN, that finding a balance between trade-offs in sensor operations (or Quality of Service) and generic sensor design limitations is imperative.

This work therefore seeks to determine a balance between sensor design limitations and QoS provisioning in a WSN designed for deployment in agricultural environments, mitigating and navigating around potential risks on the WSN.

WSNs are private networks made up of many nodes with sensing and computing capabilities, which communicate untethered. Typically within a single WSN, a number of nodes would have specific functions to perform; a single WSN could have sensors monitoring conditions such as temperature, humidity and other environmental parameters [5] . The more recent sensor node technologies have been designed to possess a limited amount of data processing capacity, in an effort to reduce data redundancy and minimize processing duties on the coordinator node. A typical sensor node has four major components; a power supply subsystem, a communication subsystem, a sensing subsystem, and a processing subsystem [1] as shown in figure 1.1. The power supply subsystem could be supported by standard battery cells or solar cells. The communication subsystem is responsible for connecting the node to the network. The sensing subsystem comprises of sensors and analog to digital converters (ADCs). Sensors produce signals in analog format, the ADC then converts the signals to digital format. The processing subsystem usually contains a storage component. The storage capability also helps the processing subsystem with managing processes and tasks between sensor nodes.

WSNs have several advantages which have allowed the expansion of their use in several applications, from Military surveillance and monitoring, Precision Agriculture, structural and building monitoring, to smart cities and healthcare monitoring. They are cost-effective, small in size and thus easy to deploy; they have much lower power consumption than Ad hoc networks and most importantly they are self-organizing once deployed; which means that even when deployed in hazardous environment to monitor dangerous phenomena, there is no risk to humans because there is no need to physically organize their communication links. Figure 1.2 illustrates the basic design structure of a typical WSN and the components that form the network. A collection of sensor nodes forms an untethered sensing network which communicates with an external network through a sink node with the capability to connect to the global internet. The efficiency and effectiveness with which a WSN performs the sensing and communication tasks is determined by the QoS measures or metrics adhered to in the design of the sensor network. However, determining which QoS metrics to implement, while also maintaining overall costs to an acceptable threshold will depend on several factors such as the network size and deployment strategy.

This research is meant to use PA as a vehicle for the design and simulation of the network. It will use maize production as an example of PA to implement conditions that are conducive for increased maize production as a parameter for setting the sensor nodes.

1.2 Precision Agriculture

Precision agriculture can be defined as the practice of using advanced technologies in farming activities to enhance crop production. The application of PA allows farmers to maximize financial returns, cut costs, and minimize adverse impacts on the environment. The primary driving factor for the growth of PA is the advancements made in wireless communications and electronics. WSNs make it possible to deploy PA technology across large spaces. However, the use of WSNs in PA presents challenges of how to configure sensor technologies and deploy sensor networks in agriculture fields in a way that will ensure optimum network performance. Deployment planning requires consideration of several objectives such as energy consumptions, sensing coverage, network lifetime, and network connectivity. These objectives often conflict with one another, therefore operational trade-offs must be considered with each network design [6-8]. The deployment strategy adopted must guarantee performance at the highest level or at the very least, function efficiently enough to prevent adverse results in the PA application concerned. Factors such as network robustness and fault tolerance are key aspects of aa good deployment strategy. It is therefore imperative that research continues to be conducted on methods of improving WSN performance and to tackle some of these challenges encountered in the application of PA.

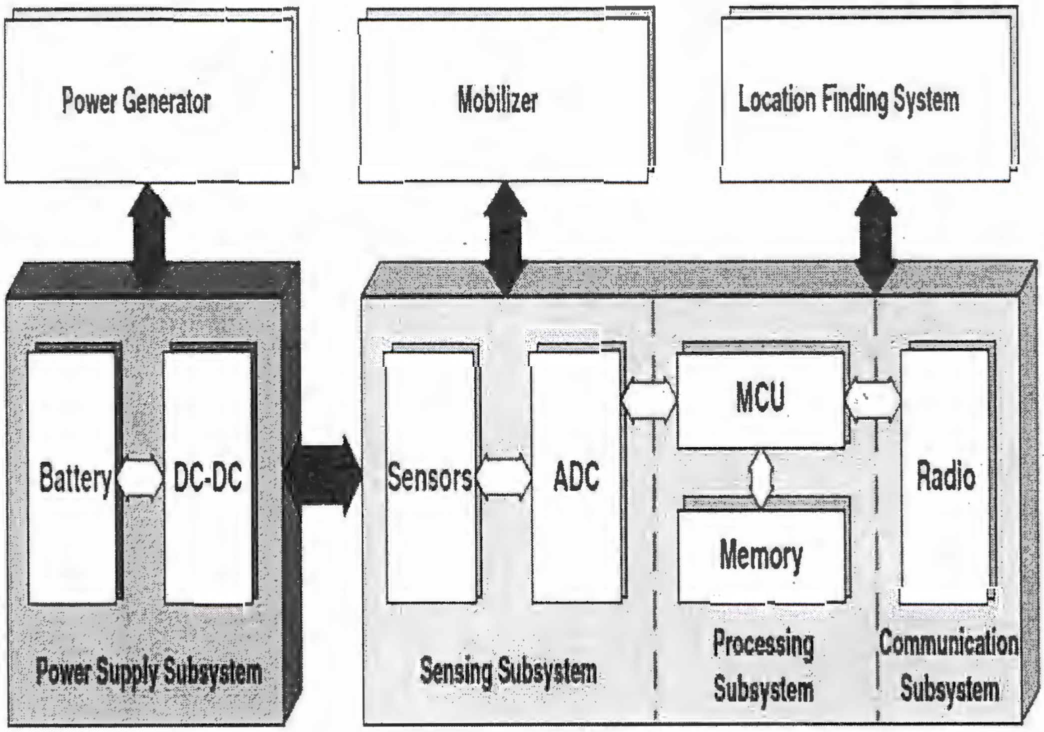

Figure 1.1 Components of a Sensor node [9].

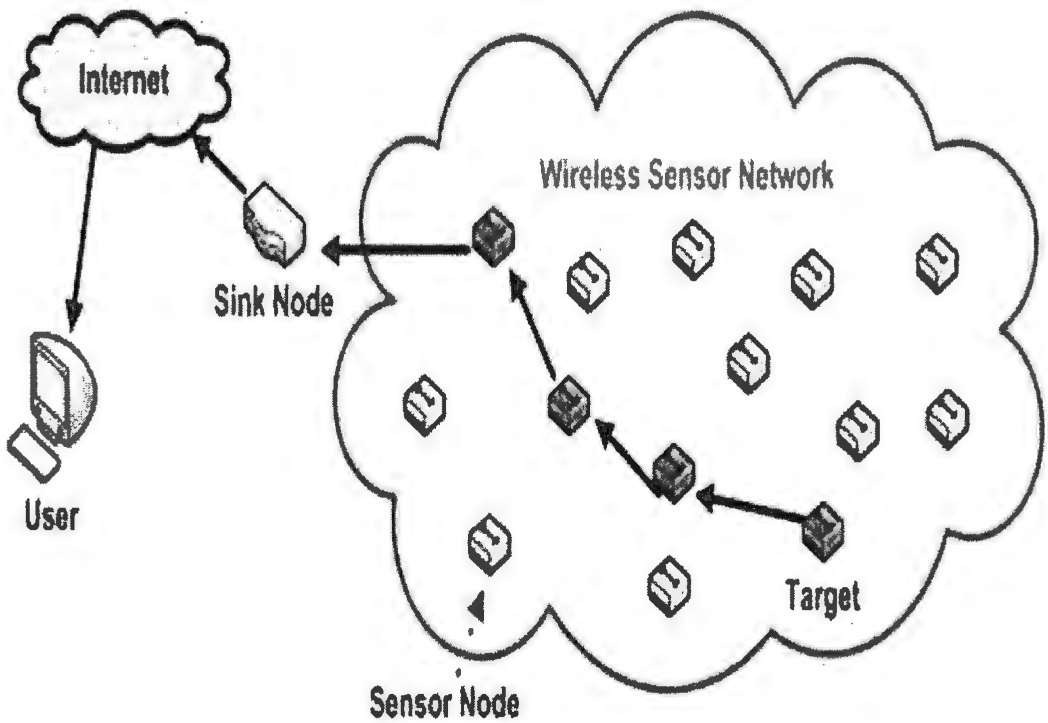

Figure 1.2 Wireless Sensor Network model [10].

1.3 Quality of Service

Evaluating Quality of Service (QoS) in WSNs is a much greater challenge than it is when dealing with traditional end-to-end multimedia networks, since WSNs do not function on an end-to-end single hoop communication principle. So, there is no need to establish communication links from source to destination. Nodes in a WSN communicate to nodes that are direct neighbors to them, continuing in that manner until the last node in the network whose neighbor is the sink node connecting the entire network to the global internet. Owing to the unique characteristics of WSN, analyzing the QoS requirements varies vastly from methods used to analyze traditional networks [11]. Much of the research that has gone into QoS evaluation for WSN has produced few generally accepted performance metrics for QoS provisioning in WSN, network parameters such as exposure, energy cost, coverage, and network life time are the most common.

QoS in WSNs can be evaluated from two general perspectives that can serve as a general umbrella for any WSN's QoS provisioning requirements. The two approaches are: Application based assessment and Network based assessment. With an application-based assessment, QoS parameters such as coverage, exposure, measurement errors, and optimum number of active sensors are taken into consideration. In other words, the specific applications the WSN is being applied to will impose specific requirements on the deployment of sensors, the number of active sensors, and the measurement precision of sensors, all of which are directly related to the quality of applications [12].

In the network based assessment, the focus is on how the underlying communication network can deliver the QoS-constrained sensor data while efficiently utilizing network resources [12].

1.4 Problem Statement

As a promising and growing application area for WSNs, PA is a practice that has global scale significance and implications. Vast research contributions are continuously being carried out in the field, to develop efficient methods of conducting PA practices and ultimately help realize its wide spread deployment; a goal that would have a positive and significant impact on global food security.

The biggest challenge of using WSNs in PA is deploying networks that are both robust and provide the necessary quality-of-service (QoS) requirements for the agriculture application, and thus guarantee efficient performance in the specific environments they are deployed in this case, maize production. This QoS shortfall in wireless sensor network PA applications calls for continued scrutinizing, optimization of design techniques and deployment strategies.

The agriculture environments usually have a degrading effect on the network quality due to its many interfering elements such as plant leaves and varying plant heights. The authors in [4] concluded in their work that plant leaves, if in or close enough to the path of the radio signal path; can have a negative effect on the transmission signal.

Other than the observed environment, the energy consumption of each node and ultimately that of the whole network is a key area of focus, if an acceptable level of QoS provisioning is to be attained. Network lifetime is one of the greatest challenges in sensor networks and it plays a key role towards QoS provisioning, the lifetime of a sensor battery can be improved by carefully selecting energy efficient data transfer algorithms, communication protocols, and the appropriate topology for the sensor network [13, 14]. Designing frameworks for effective wireless sensor networks that boast a longer lifetime and fault tolerance remains an important area of research.

To ensure QoS provisioning, specific optimum WSN parameters must be employed in the proposed framework. The proposed framework is focused on the PA cultivation of maize, for which the goal is to increase yields and reduce cost of production. Therefore, the network parameters that are most integral to the success of the proposed framework are; the network topology, the distance between nodes and the in-field node density, the routing algorithm, and the transmitter power [13]. These parameters are sufficient for the WSN framework to ensure optimum maize yields.

Therefore, our work will seek to improve and add to the design and enhancement techniques for wireless senor networks to optimize them for quality of service provisioning with reference to their use in precision agriculture applications and specifically application in maize cultivation; with focus on deployment topology strategies and management techniques.

1.5 Research Questions

This work seeks to answer the following research questions:

RQ1: To what extent have researchers, device manufacturers, and network developers addressed the challenges associated with the deployment of wireless sensor networks (WSNs) in agricultural environments?

RQ2: How can we utilize existing WSN architectures with ZigBee protocol to improve the performance of WSNs in PA environments?

RQ3: How can we develop efficient WSN frameworks that are optimized to fully utilize existing architectures and ZigBee protocol to address the performance challenges in PA applications?

RQ4: How can we implement a QoS framework for WSNs in the cultivation of the Maize crop?

1.6 Research Goal

The main goal of this research is to design a framework for a Wireless Sensor Networks that is robust, fault tolerant, and optimized for efficient deployment in maize cultivation practices.

1.7 Research Objectives

In order to achieve the research goal presented in section 1.5, the following objectives will be fulfilled:

RO1: Conduct a comprehensive review of relevant literature in the field of Wireless Sensor Networks and Precision Agriculture.

RO2: Investigate precision agriculture implementations based on ZigBee protocol

RO3: Design a WSN framework aimed at providing QoS for PA applications.

RO4: Implement, through Simulation and evaluate WSN framework using OPNET simulation tool.

1.8 Research Methodology

In order to achieve the main goal of this research through the objectives specified, the following research methodologies were quantitatively adhered to:

1.8.1 Literature Survey

An in-depth survey on the current literature was carried out in order to obtain answers to RQ1, RQ2, RQ3, RQ4, and RO1.

1.8.2 QoS framework Design

Based on the surveyed literature, a Wireless Sensor Network Framework for Precision Agriculture application was designed and formulated in order to achieve RO3 stated in section 1.7.

1.8.3 Framework Simulation, Analysis and Evaluation

The framework in section 1.8.2 was implemented/simulated and fully analyzed in OPNET modeler to RO4.

1.8.4 Proof of Concept

As proof of concept, the results from the implemented framework were analyzed and comparisons were made with related works and similar network deployment experiments. And in so doing, achieve RO2 and RO4.

1.8.5 Research Limitations

The scope of this study is limited and focuses mainly on QoS in wireless sensor networks using ZigBee protocol, with respect to precision agriculture applications. The study is also strictly limited to a simulated evaluation of the proposed framework. The simulation of the framework in this study was performed using Optimized Network Engineering Tools (OPNET) modeler, which was chosen for its superior provision of integral components necessary to evaluate ZigBee protocol.

1.9 Dissertation Contributions

This work seeks to aide researchers in precision agriculture and network developers, particularly in the African region, in their efforts to educate and promote research in the field of precision agriculture for large-scale implementation. The work particularly highlights the effect of using multiple routers to reduce connectivity failures in large-scale

WSNs and also introduces a deployment topology that uses a nonagonal geometric structure.

1.10 Chapter Summary and Thesis Outline

This chapter presented the introduction and general overview of this research work. The chapter presented a general understanding of the work in brief, the main goal, objectives, vital research questions, and research methodology were also presented.

The remainder of this research work is organized as follows:

Chapter 2 presents the literature review, in which a brief understanding of wireless sensor networks, precision agriculture, and QoS routing in wireless networks is given. The chapter concludes by presenting the main routing protocol adopted for the research work, the ZigBee protocol and IEEE 802.15.4 standard.

Chapter 3 presents a detailed documentation of the simulation tool OPNET, it also presents the research methodology and experimental setup used to achieve our research goal.

Chapter 4 presents our proposed QoS WSN framework, detailing all the steps involved from the design to implementation in. The chapter presents solutions to RQ4 and RO3, and RO4.

Chapter 5 presents the results obtained from the simulation and their respective analysis. It presents a comparative evaluation of the two deployment structures employed in the framework simulation.

Chapter 6 concludes the whole thesis and briefly presents suggestions for future work. Bibliography and references follows this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Introduction

This chapter reviews literature surrounding wireless sensor networks (WSNs), their application in Precision Agriculture (PA), and the technologies developed for use in WSNs. The chapter also presents concepts on QoS in WSNs and PA. The chapter also presents literature on the ZigBee communication protocol and its use in WSNs.

2.2 Overview

The development of advanced micro technologies in communications and digital electronics has enabled the growth of low-powered, low-cost wireless sensor communications. Sensor networks allow for random deployment in certain areas, this is because the protocols and algorithms used in WSNs are designed to be self-organizing [1] .

The unique nature of sensor networks communications has given rise to a myriad of applications for which WSNs are best suited. WSNs are now prominently used in military applications, medical, agriculture, and smart-home applications. Research continues to be carried out in WSNs to develop new methods of getting the best performance out of this ever-growing communication technology. One of the most challenging areas of WSNs is QoS provision and evaluation. Network researchers have stated that there is no one standard method of evaluating QoS in WSNs, but the same methods used to evaluate traditional networks can be used in WSNs, with a few modifications tailored to handle the multi-hop communication of WSNs.

Providing QoS in WSNs also comes down to the communication protocols and algorithms employed in the network. The IEEE 802.15.4 protocol which is also known as ZigBee, is one of the most popular WSN communication protocols. IEEE 802.15.4 supports basic topologies like star, cluster tree and mesh networks [15]. Topology management techniques can also be used to improve the network QoS by properly managing pre-deployment and post-deployment phases.

2.3 Related Work

The advent of advanced micro-engineering technology has allowed networking researchers and developers to design and develop more advanced and smart Wireless sensor networks, which in the last few years have attracted a lot of interest for application in Farming activities. As stated above in 2.1, WSN have advantages of being self-organizing networks, that's makes them ideal for use in open agriculture practices as they greatly reduce the impact that human intervention would have on the environment. WSNs in PA is still a relevant research issue within the networking and agriculture communities. WSN models have been deployed in practical large-scale experiments to research areas of improvement. Networks have been deployed in different climates ranging from European environments such as Italy, to hash condition areas like India, Egypt, and Malawi [3, 5, 16, 17]. Mafuta et al [3] implemented an irrigation management system (IMS) using WSNs in a maize field in Malawi. The deployment investigated ZigBee radio link performance through measurement of received signal strength indicator (RSSI), which is a measure of the quality of the link between coordinator and a particular in-field sensor node. Their system employed solar photovoltaic and rechargeable batteries to power electrical devices in-field due to a lack of electrical power grid access in the area. The experiment highlighted the negative effect that leaf movements in the field have on RSSI. The authors concluded that the height of the crops had no major degradative impact on the quality of the communication link. This observation however, is most likely as a result of the distance between the nodes being so small that no significant effect could arise from the crop canopy covering the sensor nodes. The study also concluded that there was a correlation between battery level and RSSI and highlighted the serious repercussions that battery performance has on overall WSN robustness in field deployment due to its effect on RSSI.

Keshtgary and Deljoo [5] simulated a wireless sensor network for precision agriculture applications that focused on testing the efficiency of grid and random topologies in direct relation to how they affect power consumption of a WSN and overall QoS guarantee. The simulation employed metrics of throughput by aggregation and delay by averaging number of destinations. The study showed the significant effect that topologies have on the QoS of a WSN.

Sherine et al [9] conducted a study on the use of wireless sensor networks to improve agricultural productions in Egypt. The study was conducted with an economical view of precision farming and how the automation of agricultural production would help manage the agriculture problems faced in Egypt. A WSN was proposed to test the cultivation of potato crop by automating elements such as irrigation and fertilization scheduling. The authors proposed the use of the APTEEN protocol, based on its long network lifetime of approximately 6.5 months, which is long enough to support the growth period or lifetime of the of potato crop in Egypt.

The development of WSNs applications in PA and the systems specifically designed for data acquisition, validation, processing and visualization makes it possible to increase the efficiency, productivity and profitability of agriculture practice, while minimizing the impact of such practices on the environment. Various technologies are used in PA that have the capacity to take measurements or readings of some sort; such as Remote Sensing (RS), Global Positioning System (GPS), and Geographic Information System (GIS) [16].

The use of WSN in PA applications will greatly change and improve methods of data collection in agricultural fields and facilitate the realization of the highly sought after, automated agriculture systems which require an extremely very high level of sensing environmental parameters at the point of interest and then communicating the partially processed data to a local or remote server where the final processing and computation can be done. Ultimately the goal of PA is to provide users with agricultural information such as the identification of pests in crops, drought or increased moisture in the soil or on plant leaves. All of this information helps in ensuring that the decision-making process and control of farm equipment are carried out in real time, thus improving productivity and minimizing risks.

PA is defined by Srbinovska et al [17] as "the art and science of using advanced technology to enhance crop production". In their work, they presented a wireless sensor network application for PA which was deployed in a pepper vegetable greenhouse. The focus of their work was an experimental setup of a WSN centered on data measurement and data collection from the monitored environmental parameters such as temperature, humidity, and illumination. The work showed that depending on the height of crops or rate of growth of the crop, data losses can occur in the WSN which could disrupt the continuous monitoring of environmental parameters and ultimately affect final data results. One solution to this problem is to place the sensor nodes at the same height as that of a fully-grown pepper plant. The experiment also theorized the use of gossip algorithms to get around node failure problems and reduce communication costs between nodes, thereby extending overall network lifetime.

Dong et al [18] conducted an open field experiment with wireless underground sensors to develop an autonomous precision irrigation system by integrating a center-pivot with wireless underground sensor networks (WUSN). Their experiment was deployed in a maize field, with an above ground sensor placed at 2.5M above ground to counter the effect of crop canopy on the network.

Rashid Hussain et al [19] proposed an agriculture water management method for application in Indian rice farming. The method used wireless sensors set up in a mesh topology to perform tasks such as monitoring water levels, keeping track of soil moisture, pests, diseases, and climate change effect on the crops. The authors designed the proposed method to shift the farming environment in India from a predication-based system to one in which farmers know the exact values required for beneficial farming.

2.4 Wireless Sensor Networks

In the simplest terms, WSN could be defined as a collection of specialized self-organizing sensors that communicate wirelessly, intended to observe environmental conditions at any location and to communicate their data to a designated main station for processing [15] . Sensor nodes are primarily small in size and usually communicate at low data rates and at short ranges. This means that due to the small size of sensor nodes, a WSN can be constructed with multiple nodes. A single network can have up to hundreds or thousands of nodes each monitoring a specific condition, for instance; humidity, temperature, and soil composition. Figure 2.1 shows an overview of WSN applications. The range of WSN applications is only limited by the scope of sensors. This research work focuses on WSNs as applied in agriculture.

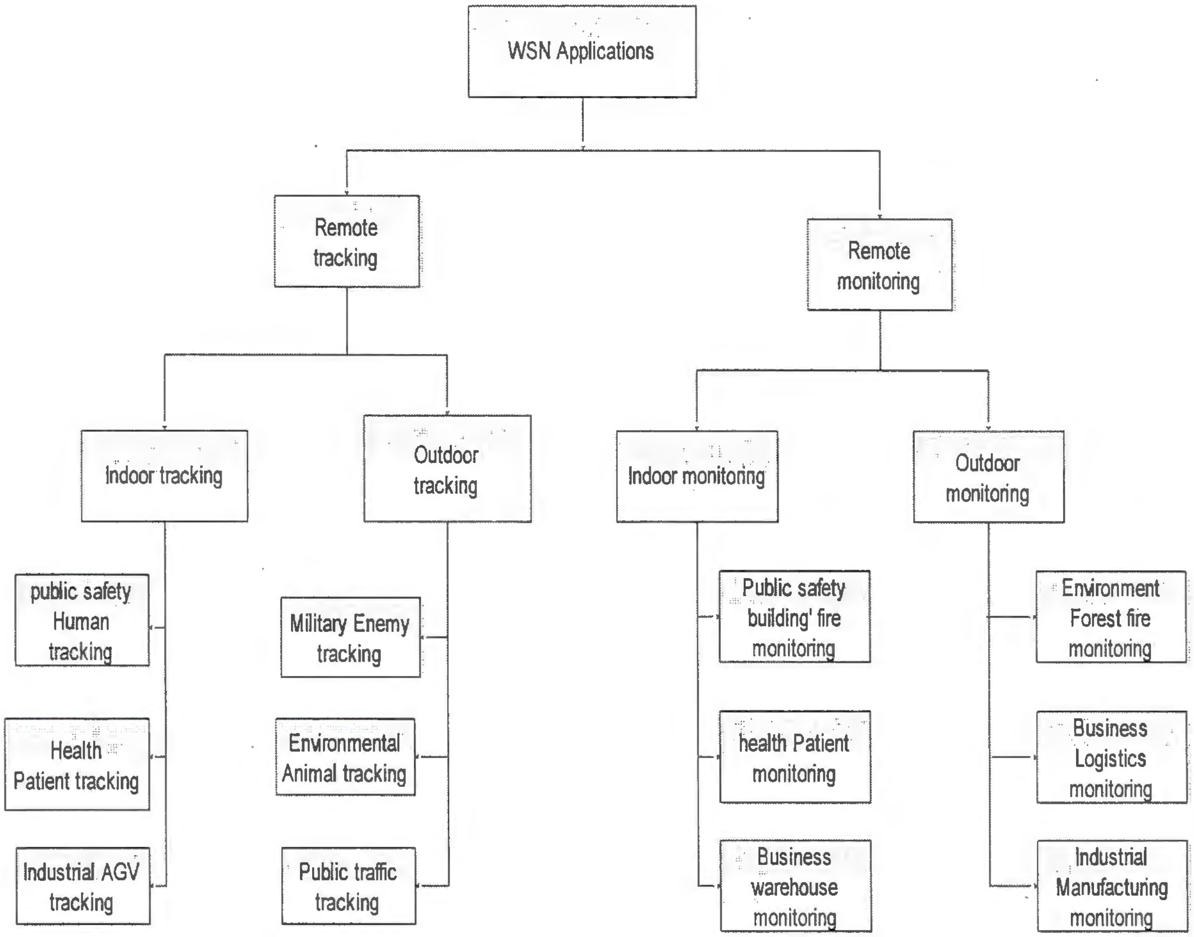

Figure 2.1 WSN Applications [15].

2.4.1 Wireless Sensor Network Components

The components of a wireless sensor network (WSN) allows untethered connectivity within a network, connecting an application platform at one end of the network with sensors or actuators in any area of the network. Wireless networks have very specific components used in establishing connectivity, namely gateways and end nodes. A communication route is created to carry data between the application platform and the physical world.

The range of a sensors communication path in a network can be extended by adding a relay node between the sensor node and its next hop destination. A brief description of the basic components of a Wireless network is given below [20].

a) **Coordinator:** A coordinator acts as an interface between the application platform and the wireless sensors in WSN relaying information back and forth between the WSN and the application. Sensing Information received from the sensor nodes is aggregated and processed by the gateway before being forwarded to the application.

b) **Routers:** Also known as relay nodes, routers are full-function devices (FFD). This simply means that they have the ability to implement a full-function IEEE 802.15.4 stack, which allows them to become coordinators for a PAN and can initiate and manage the entire network. As a result of this capability, routers are normally used to extend coverage area of a network and circumvent obstacles in a network [15].

c) **End Node:** An end node or leaf node, is a reduced-function device (RFD). RFDs are devices that can implement the basic functions of the IEEE 802.15.4 stack. While an RFD cannot be employed to initiate and manage a network, it can be used to execute simple tasks like connecting to sensors or actuators and pass sensor readings to the network. RFDs usually consume less power than FFDs, and can there last longer than FFDs [15].

d) **Sensor/Actuator:** These are the actual devices used to interact with the physical system is targeted for monitoring. For instance, sensors monitoring temperature and humidity in a field, or sensors that activate an irrigation system in a greenhouse.

2.4.2 Hardware Components

Wireless sensors are typically characterized by their miniature size and their ability to monitor phenomena in an environment by way of radio waves communication. This capability is made possible because of the addition of independently powered radio transceivers and transducers on to the sensor's microcontroller board [21].

Sensors, actuators and processing nodes are the essential components of distributed systems with wireless sensor nodes. To successfully implement WSN-based applications, nodes forming the network must be able to perform functions such as:

- Sufficient processing capabilities and data storage capacity
- Analyze processed data to generate the necessary next instruction prompt
- Device or machine Activation
- Scheduling and execution of the measurement tasks
- Node management tasks like reprograming and reconfiguring processing algorithms
- Scheduling and execution of communication and networking tasks
- Forwarding or transmitting data packets received by the node

Full-function devices (FFDs) like coordinator nodes can either be simple low-power embedded devices or very powerful workstations or servers and they need to be able to perform all the functions described above. On the other hand, reduced-function devices (RFDs) are characteristically limited to embedded devices and can only perform a few of the described functions [20].

Research and development efforts in the field of wireless sensor networks, have produced a number of quality wireless devices that are used to construct WSNs. The most popular devices include the Waspmote, MICAz motes, and the TelosB motes. And as research continues, more advanced devices are being produced frequently. Having a wide range of wireless sensor technologies gives the advantage of having more choices of platforms that are best suited for the application of interest. Wireless sensors owe much of their inexpensive nature to their limited capabilities in transmission range, memory and processing. Application developers usually code sensor components like the microcontroller in C- language as it allows for a finer code development that suits the constrained memory size of the wireless sensor [1, 9, 20, 21]. Basic sensor node components are shown in figure 2.2, which are similar components shown in figure 1.1 but with reference to internal functions.

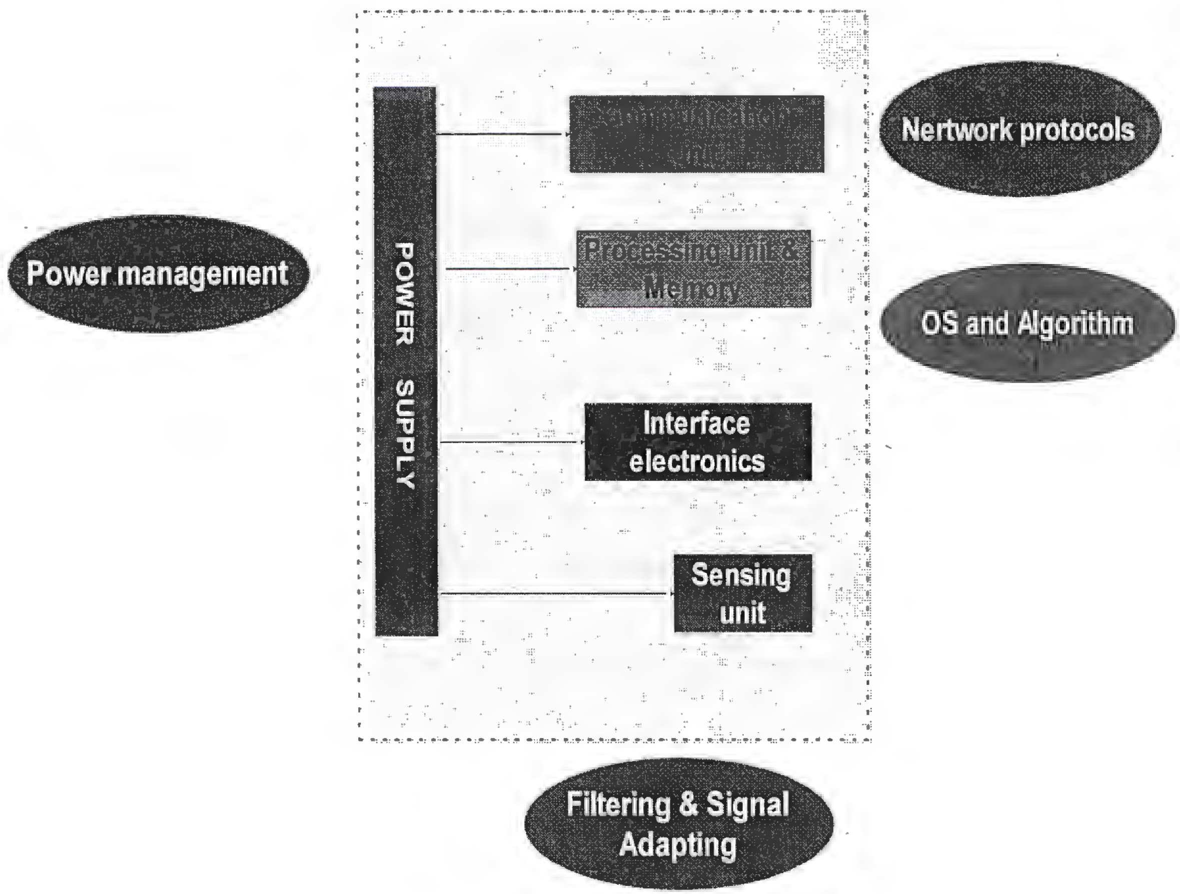

Figure 2.2 Sensor node functional components [22].

2.4.3 Software and Operating Systems

Software considerations for this research are focused on the operating systems developed for WSNs and in particular, the most prominent communication standard used in wireless sensor network design, which is the IEEE 802.15.4 standard. We also focus on the single IEEE 802.15.4 communication protocol chosen to be the evaluation protocol for our work, the ZigBee protocol. IEEE 802.15.4 and ZigBee are presented in detail at the end of this chapter.

Operating systems for WSNs are very different from standard operating systems running on platforms like Windows or Linux. Designing operating systems for WSNs must take into consideration, the limited hardware capabilities of the sensors. Factors like limited memory management and insufficient file system support must be considered with each OS development. Some of the most common operating systems for WSNs are; Contiki, TinyOS, SensorOS, and SOS. A brief description of these operating systems is given below.

2.4.3.1 TinyOS

TinyOS [23] is coded in nesC, which is an extension to C language. It's an OS that supports event-driven component-based programming. This means that TinyOS basically breaks down a program into fully functional independent components. The independent components communicate by exchanging messages through interfaces. The main advantage of this component-based approach is the reusability of components. NesC and TinyOS are both open-source tools maintained by the networking research community. TinyOS is the original operating system of the Tmote, but it has now also been integrated into to other WSN hardware platforms. The one disadvantage of TinyOS is that it cannot dynamically load a new executable before replacing the image completely and rebooting. However, despite this short-coming, TinyOS is still the go-to tool for WSN programming.

2.4.3.2 Contiki OS

Contiki [24] is an open-source operating system with high memory efficiency designed for embedded network devices. Contiki offers typical OS qualities like proto-threads, timers, random number generator, clock and a file system support. It includes an IPv6 stack with support for TCP and UDP connections, as well as the Rime radio communication stack. Contiki is supported by an event-driven core with small footprint. The Contiki core comprises of a lightweight event scheduler that forwards events to running processes and periodically requests processes polling handlers. All program executions are initiated by events transmitted by the core or through the polling process. Contiki supports two types of events, namely synchronous and asynchronous. The Contiki core does not pre-empt an event handler once it has been scheduled [20].

2.4.3.3 SensorOS

SensorOS [25] is a multi-threading OS that adopts a pre-emptive priority- based scheduling mechanism, and a finely divided timing and message passing inter-process communication. "It has been implemented for resource-constrained Tampere University of Technology WSN (TUTWSN) nodes. In TUTWSN node platform with 2 MIPS PIC microcontroller unit, SensorOS kernel uses 6,964-byte code and 115 bytes of data memory" [20]. Unlike other event-handler cores like TinyOS or ContikiOS, SensorOS supports coexistence of several time sensitive application duties.

2.4.3.4 SOS

SOS [26] expands on TinyOS by offering dynamic memory allocation, loadable components and a kernel. Application coding is done in C language. The kernel manages network messaging, dynamic memory allocation and module loading and unloading. For over-the-network reprogramming, while TinyOS requires that the whole sensor image be replaced and the sensor reboot, SOS permits the use of smaller components that can be loaded dynamically.

2.5 Precision Agriculture

Precision agriculture (PA) can be defined in the simplest terms as the integration of technology into agricultural practices to facilitate optimum management of variations in crop productivity with a goal to maximize yields, profits, minimize waste and cost; with consideration of spatial and temporal variabilities. The implementation of PA heavily depends on the collection of large quantities of data from the target field, documentation and analysis of such data for decision making and farm management [17, 27, 28].

The advancements made in PA research in recent years have largely been due to sensor networking technology becoming inexpensive and ubiquitous. Sensors are the backbone of PA, they are the technology that facilitate the implementation of several PA systems. There are numerous types of sensors, each designed to sense specific conditions. Some of the most common sensor types are soil sensors, yield sensors, field sensors, and crop sensors. Some sensors are used as controller sensors integrated with farming machinery to initiate tasks like automated irrigation, harvesting, or application of herbicides [6].

2.5.1 Spatial and Temporal Variabilities

Spatial variability occurs when a reading of a quantity taken at different spatial locations exhibits readings that vary across the locations. Temporal variability by definition is a variation with respect to time. Space and time variations have a crucial impact on agriculture production and production variability, and PA seeks to decrease such variability on a much greater scale. We define a few categories of variabilities below.

a) **Field variability:** concerns the landscape or topography of the field. Field variability involves factors such as slopes and elevation of the field.

b) **Soil variability:** involves issues concerning soil elements like fertility, chemical composition, soil texture, moisture, and water density.

c) **Yield variability:** This variability concerns records of yield distribution, both current and past.

d) **Crop variability:** Refers to crop properties in a field such as the height of crops, crop water and nutrient stains, grain quality of grain, and physical and biological properties of plan leaves.

There are two approaches used for handling of these variabilities: the sensor-based approach and the map-based approach. The map-based approach is generally regarded as being the easier method to implement. It is an approach that involves generation of site-specific maps and then using these maps to implement a variable-rate applicator. It generally requires grid sampling of a field, carrying out laboratory analysis of soil samples. The sensor-based approach focuses on reading desired properties elements such as plant and soil properties, and then using these readings to implement variable-rate applicator controls using real-time sensors.

2.6 Quality of Service (QoS)

Quality of Service has varying definitions in networks, usually, depending on the particular field of interest. In some literature, QoS is defined in computer networks as: "*The capability to control traffic-handling mechanisms in the network such that the network meets the service needs of certain applications and users*". A network that supports QoS must have some form of mechanisms to control the allocation of resources among applications and users [29]. In order to facilitate QoS, a network must have guarantees on the limits of concerned parameters as these limitations form the basis upon which the QoS of the network is evaluated.

2.6.1 QoS parameters

Any network that supports QoS will depend on certain performance measures that ensure QoS. Specific factors or measures have been defined that enable proper quantification of QoS performance and guarantees for a network.

The most common QoS parameters are the throughput, latency (packet delay), jitter, packet loss. These parameters are standard for generic Ad hoc networks, extending QoS to WSNs warrants the consideration of other integral measures like network coverage, network life time, and energy consumption. A brief description of generic Ad hoc network QoS parameters is given below.

a) **Throughput:** throughput is the bit rate that can be provided to a certain data stream. It is the average rate of successful message delivery over a communication path or channel. The throughput can be greatly affected by network congestions in a situation where scheduling priorities are handled poorly.

b) **Latency:** also known as packet delay, describes the time delay each packet takes to reach its destination. The delay could be caused by packets being held up in long congested queues, or in some cases; a packet may take an alternative or less direct route in an effort to avoid congestion. Latency has three components to it, namely, transmission delay, propagation delay, and switching delay [29].

c) **Transmission delay:** is the time it takes a device to synchronize a packet on a specified output rate. The transmission delay is a function of the bandwidth and the packet size.

d) **Propagation delay:** is the time it takes a bit to travel from source to destination (transmitter to receiver), it's a function of the distance travelled and the link medium [29].

e) **Switching delay:** is the time lag between receiving a packet and starting to retransmit it. It is a function of the device speed [29].

f) **Jitter:** one characteristic of packet delay is that different packets can have varying delay times i.e. each packet arrives at the destination with different delays. Jitter is the direct consequence of packets arriving with different delay times.

g) **Packet loss:** packet loss is an integral parameter of QoS; it can be caused by packet drops at congestion points in the path and/or corrupt packets on the transmission path.

2.6.2 Levels of QoS

Not all applications require the same level of QoS, so providing QoS also has to consider the specific requirements of an application. In other words, QoS operates on two extremes; on one end we have applications do not require any guarantees and on the other extreme we have applications that require absolute guarantees to function. Three main types are defined to accommodate these varying levels of QoS:

Best effort service, Soft QoS, and Hard QoS.

a) **Best effort service:** the best effort service provides zero guarantees, in fact, it is rarely considered a QoS. Nonetheless it is widely used by many network applications such as the File Transfer Protocol (FTP), whose only criterion is whether the transfer was completed successfully or not [29, 30].

b) **Soft QoS:** also called differentiated service (DiffServ), implements a form prioritized service. Tasks are given different priorities and packets are marked according to the service they require, no absolute guarantees are given, instead; a queuing strategy is employed to perform the expected function in response to the markings and set priorities [29, 30].

c) **Hard QoS:** this level of QoS is what most multimedia applications require, it's a level that caters to applications that require absolute guarantees in order to function properly. Usually, some form of resource reservation request on the network is performed beforehand so the network can provide or deny the requested resource in time.

2.6.3 QoS Routing

The demand for QoS networking and the challenges this carries with it have given rise to ever growing ambitions to develop faster networks designed and targeted at meeting these demands and tackle the challenges present. New technologies are being developed that allow for an increased capacity in transmission rates. However, as is common with technological advancements, with improved capabilities of networks; there comes an even higher demand for applications to take full advantage of these improved capabilities. Different applications require various levels of QoS, and so designing QoS networks must take into consideration all the factors that may or may not be required by each application the network is going to serve. It is important to remember that not all applications demand absolute guarantees, some applications have no constraints altogether. Therefore, the most feasible routing mechanisms will need to be capable of handling all levels of QoS.

One of the crucial factors in WSN routing is that of nodes maintaining some level of state information. Usually each node in the network maintains its local state and then all the local states are aggregated to form the global state information of the network stored at an elected node by means of an algorithm, which could either be a: Distance-vector algorithm or a Link-state algorithm. Now, the state information of each node needs to be updated periodically and herein lays the other challenge to the development of QoS networks. There are many factors that cause the state update process to have some inconsistencies and as a direct result, the global state information will more than likely be inaccurate, and this will in turn lead to other routing complications.

There are mainly two categories into which QoS routing algorithms are classified, namely; Unicast routing and Multicast routing. The classification is primarily based on the nature or criterion by which a path to destination is acquired.

a) **Unicast Routing:** In a unicast routing algorithm, the challenge is to search for a path from source node to the destination based on a set of pre-defined parameters/constraints.
b) **Multicast Routing:** In a multicast routing algorithm, the path search is performed from source node to a set of destination nodes that fall in the most desirable network

tree based on whatever pre-designated parameters there are. Figure 2.3 shows the basic structure of a multicast routing network.

In other cases, QoS routing algorithms could simply be classified by the strategies employed in the path search mechanisms. There are mainly three routing strategies, namely: source routing, distributed routing, and hierarchical routing, these strategies mostly involve methods by which feasible paths are computed from source to destination. We elaborate a little on each of these below.

a) **Source Routing:** source routing has the main advantage of a localized storage of the network state information and also having a centralized computation of the path. The best path is calculated locally at the source node, which has its own maintenance mechanism of the network global state information [29]. The fact that the path computation can be done locally by the source node means less computational complexity which in turn makes source routing algorithms easier to design and implement. The problem with source routing is in the inaccuracy of state information as was touched on above and this may ultimately result in a desirable path not being found.

b) **Distributed Routing:** Distributed routing basically distributes the computation of paths i.e. the computation of a path is done by involving more than just one node like say, the source node in source routing, instead; nodes exchange control messages and the global state information stored locally at each node. Of course, in this strategy, not all algorithms require the maintenance of the global state. The distributed routing has a significantly shorter response time and better scalability owing to its distributed computation of the feasible path, however, there is a trade-off in that the reduced response time and higher scalability come at the cost of higher network traffic due to increased number of message exchanging and because there are a lot of nodes to which the computation of path is distributed, it means that distributed routing cannot be loop-free like source routing is [29-32].

c) **Hierarchical Routing:** In the hierarchical strategy, clusters of nodes are formed by grouping nodes and recursively grouping these clusters into more levels ultimately forming a multi-level hierarchy. The aggregated global state information is maintained at an elected node in each cluster instead of having each node store its own state. The hierarchical strategy has a higher scalability than other strategies and the traffic in the network is not as extreme as it is in distributed routing. It has been noted however, that the aggregation of the network states introduces its own imprecision [29, 30, 32].

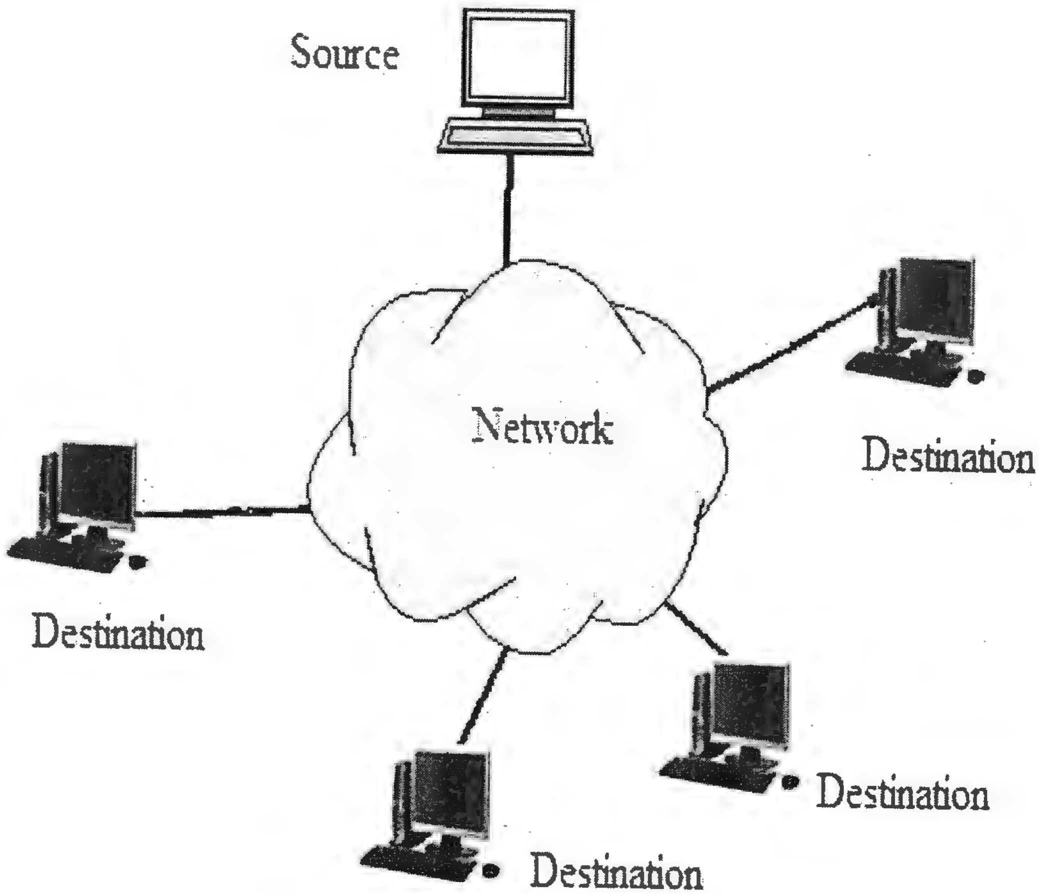

Figure 2.3 multicast routing network [29].

2.7 Overview of IEEE 802.15.4 and ZigBee

ZigBee is maintained by the ZigBee Alliance, an association of companies that researches and develops standards for wireless communications that cost-effective, reliable, and operate at low-powers.

Over the past years, ZigBee technology has gained popularity as a quality wireless networking standard and has been embedded in a wide variety of products and applications across commercial, industrial markets around the world. IEEE 802.15.4 is a communication standard that was designed to support devices operating in low cost, Low rate Wireless Personal Area Networks (LW-WPANs). It specifies the physical (PHY) and medium access control (MAC) layers of the protocol stack. IEEE 802.15.4 supports wireless sensor applications that operate with low power, and short-range communication. ZigBee supports three basic topologies, star, tree, and mesh topology. It also specifies the network layer for these topologies and gives an outline for application programming in the application layer. Further elaboration is made on these two standards in the following subsections [21, 33-35].

2.8 The IEEE 802.15.4 Standard

As mentioned earlier, The IEEE 802.15.4 standard specifies the features of the physical and MAC layers based on the OSI model, for Low-Rate Wireless Personal Area Networks (LR-WPAN). LR-WPANs have the benefit of being inexpensive, they are able to reliably transfer data over short-ranges, and the also have long battery life; all the while keeping an and flexible protocol stack as shown in figure 2.6 [21].

2.8.1 The Physical layer

The physical layer provides three frequency bands for wireless communication; a 2450 MHz band with 16 channels, a 915 MHz band with 10 channels, and an 868 MHz band which only has 1 channel. It is worth noting that all three frequencies use the Direct Sequence Spread Spectrum (DSSS) access mode. The difference is with the modulation techniques employed, the 2450 MHz band uses Offset Quadrature Phase Shift Keying (O-QPSK) while the 868MHz and 915 MHz bands use Binary Phase Shift Keying (BPSK) for modulation. The physical layer also performs channel selection tasks such as energy detection measurement and link quality estimation [21]. Figure 2.4 shows wireless communications standards and their characteristics.

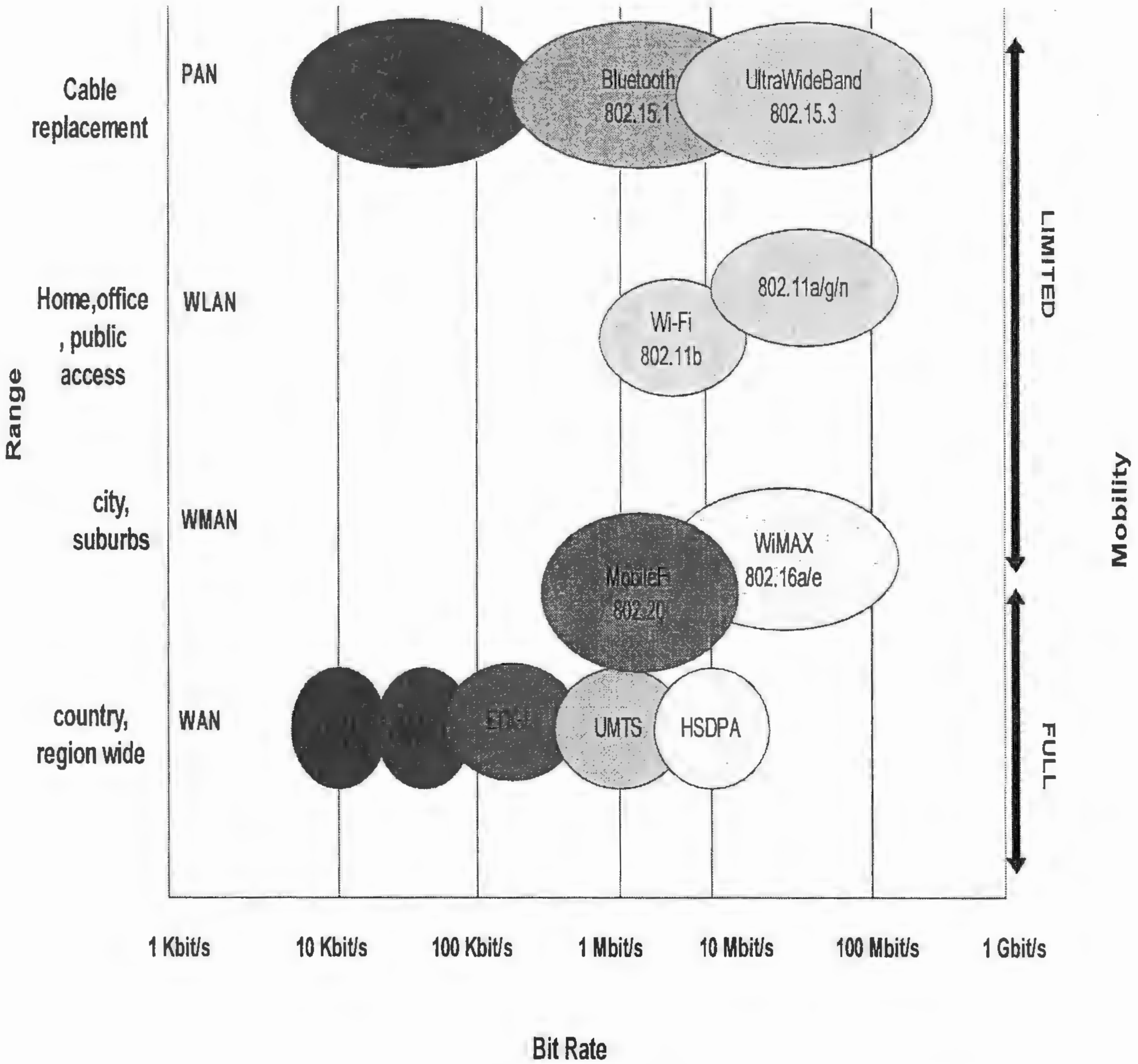

Figure 2.4. wireless communications standards and their characteristics [22].

2.8.2 The MAC layer

The MAC layer specifies the two types of nodes that were described earlier in section 2.4.2: Reduced Function Devices (RFDs) and Full Function Devices (FFDs). FFDs are fully stocked with a complete set of MAC layer functions, which allows them to operate as a network coordinator or a network end-device. When FFDs are operating as a network coordinator, they transmit beacons that facilitate synchronization, communication and network join services. On the other hand, RFDs can only operate as end-devices and usually come fitted with sensors like transducers. IEEE 802.15.4 standard has two main types of network topologies; the star and peer-to-peer topologies [21, 35].

2.9 The ZigBee Standard

ZigBee standard regulates the upper layers of the protocol stack. The network layer (NWK) is responsible for establishing and arranging routing over a multi-hop network (constructed over the IEEE 802.15.4 functionalities). The Application Layer (APL) aims to facilitate a framework for distributed application development and communication. The APL is made up of the Application Framework, the ZigBee Device Object (ZDO), and the Application Sub Layer (APS). The Application Framework can hold up to a maximum of 240 Application Objects (APOs), these are user defined application components which are part of a ZigBee application. The ZDO offers services that enable the APOs to detect each other and form a distributed application. The APS provides an interface to data and security facilities to the APOs and ZDO [21]. The architecture of the ZigBee protocol stack is shown in figure 2.6.

2.9.1 Network layer

ZigBee recognizes three types of devices. A ZigBee end-device, which relates to an IEEE 802.15.4 FFD or RFD operating as a simple device. A ZigBee router qualifies as an FFD with routing abilities. The ZigBee coordinator, of which only one is allowed in the network, is an FFD controlling the entire network. The ZigBee network layer also supports topologies such as star, mesh, and the cluster-tree as shown in figure 2.5 (a,), (b), and (c) respectively. The network layer also performs tasks such as multi- hop routing, route discovery and route maintenance. As can be seen from figure 2.5 (a), a star topology only requires a coordinator and end nodes to complete the network. The mesh topology in 2.5 (b) is a derivative of the star topology, therefore it shares the same characteristics. The tree topology in 2.5 (c) requires additional intermediary nodes (Routers) to link the coordinator to the end nodes, this is most likely in a situation where the network requires expansion. Figure 2.6 details the components and inter-relations of the ZigBee functional layers architecture and stack protocol.

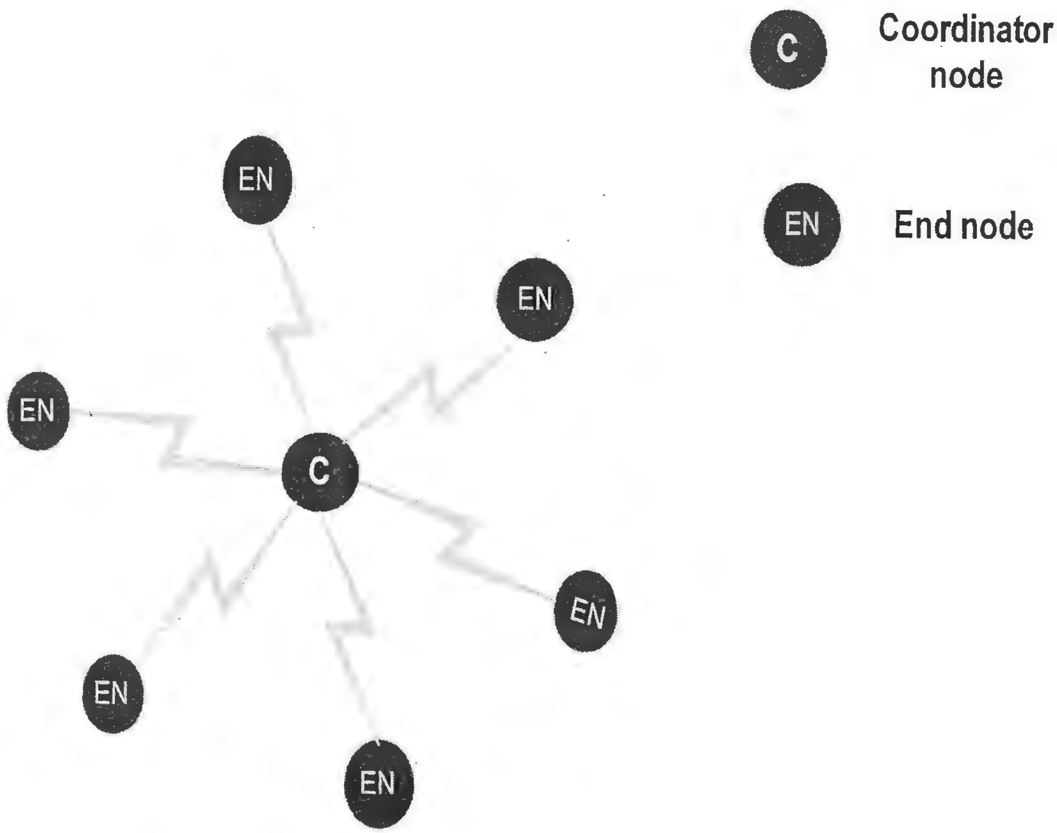

Figure 2.5 (a). ZigBee star topology [15].

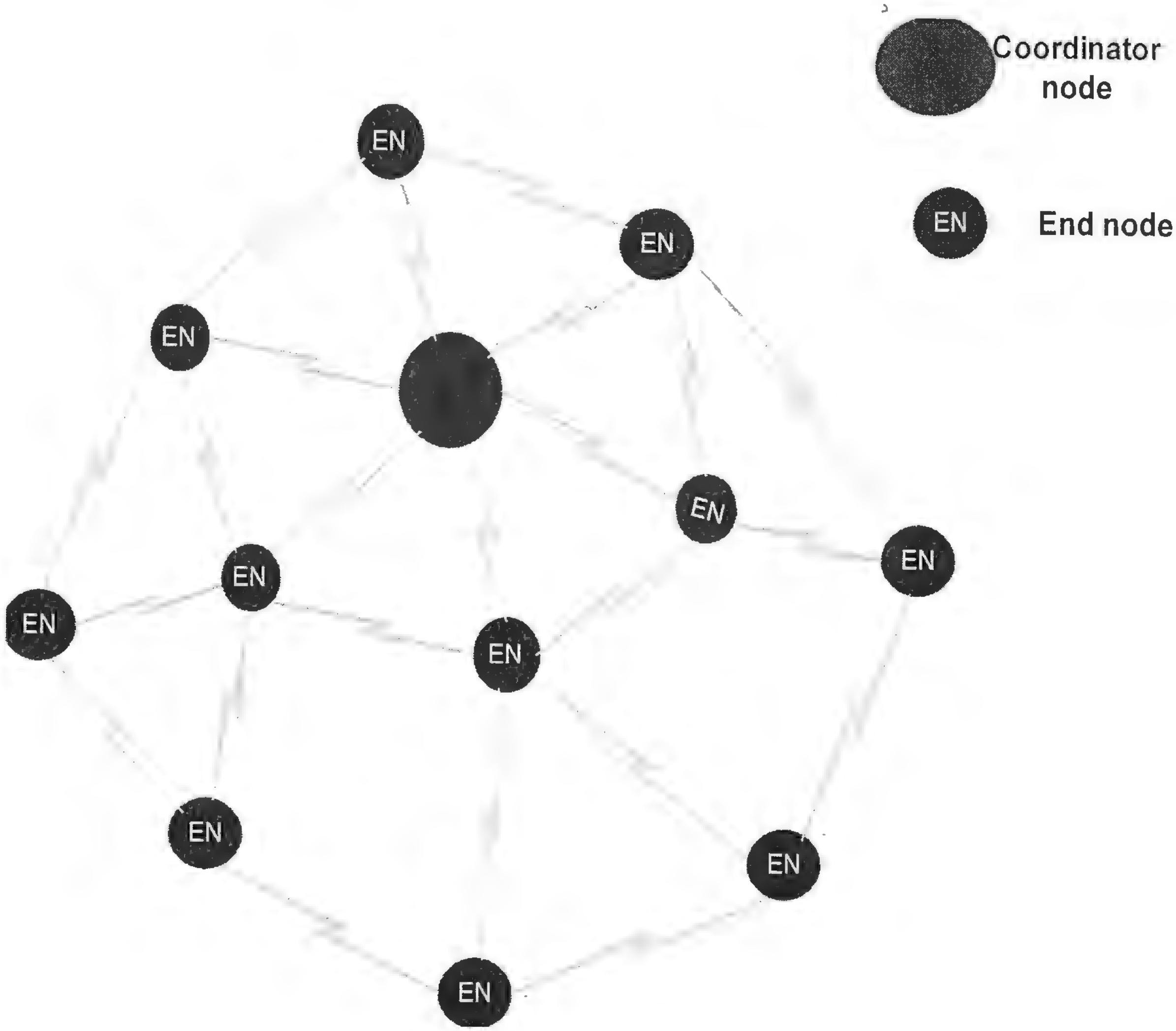

Figure 2.5 (b). ZigBee mesh topology [15].

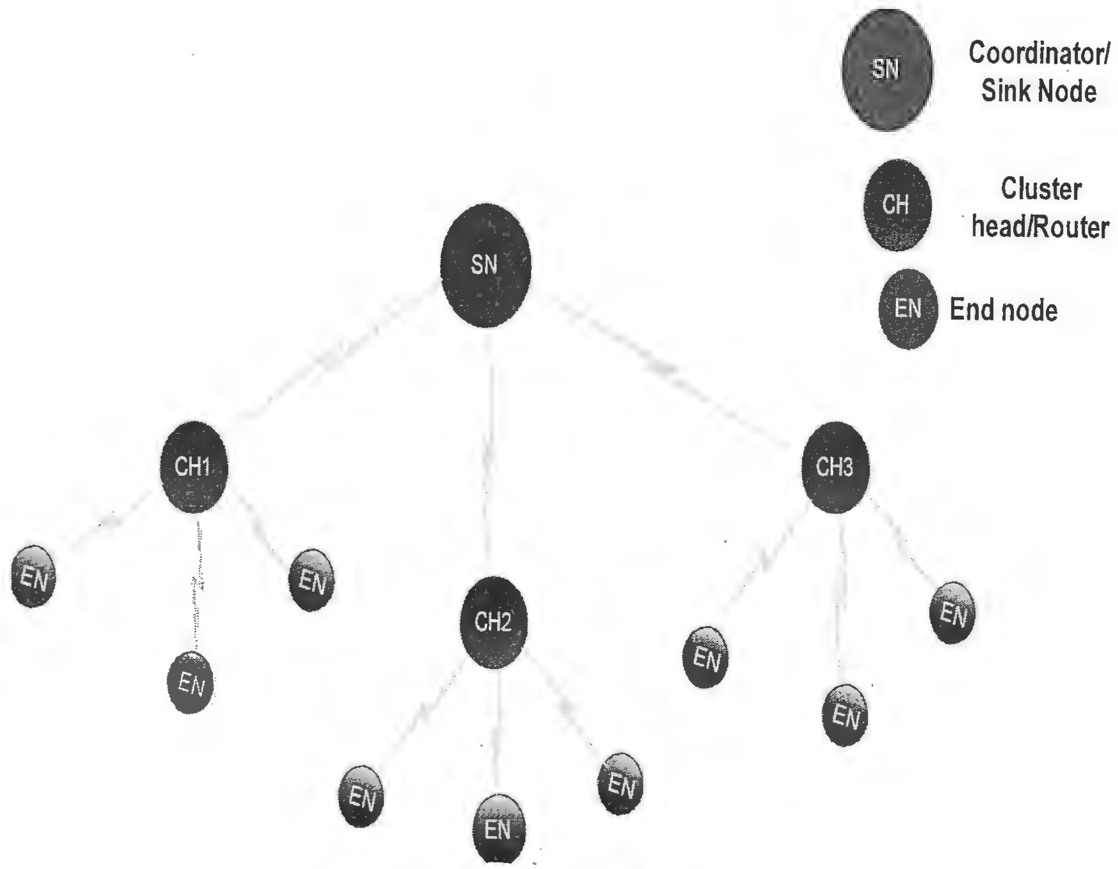

Figure 2.5 (c). ZigBee Cluster-tree topology [15].

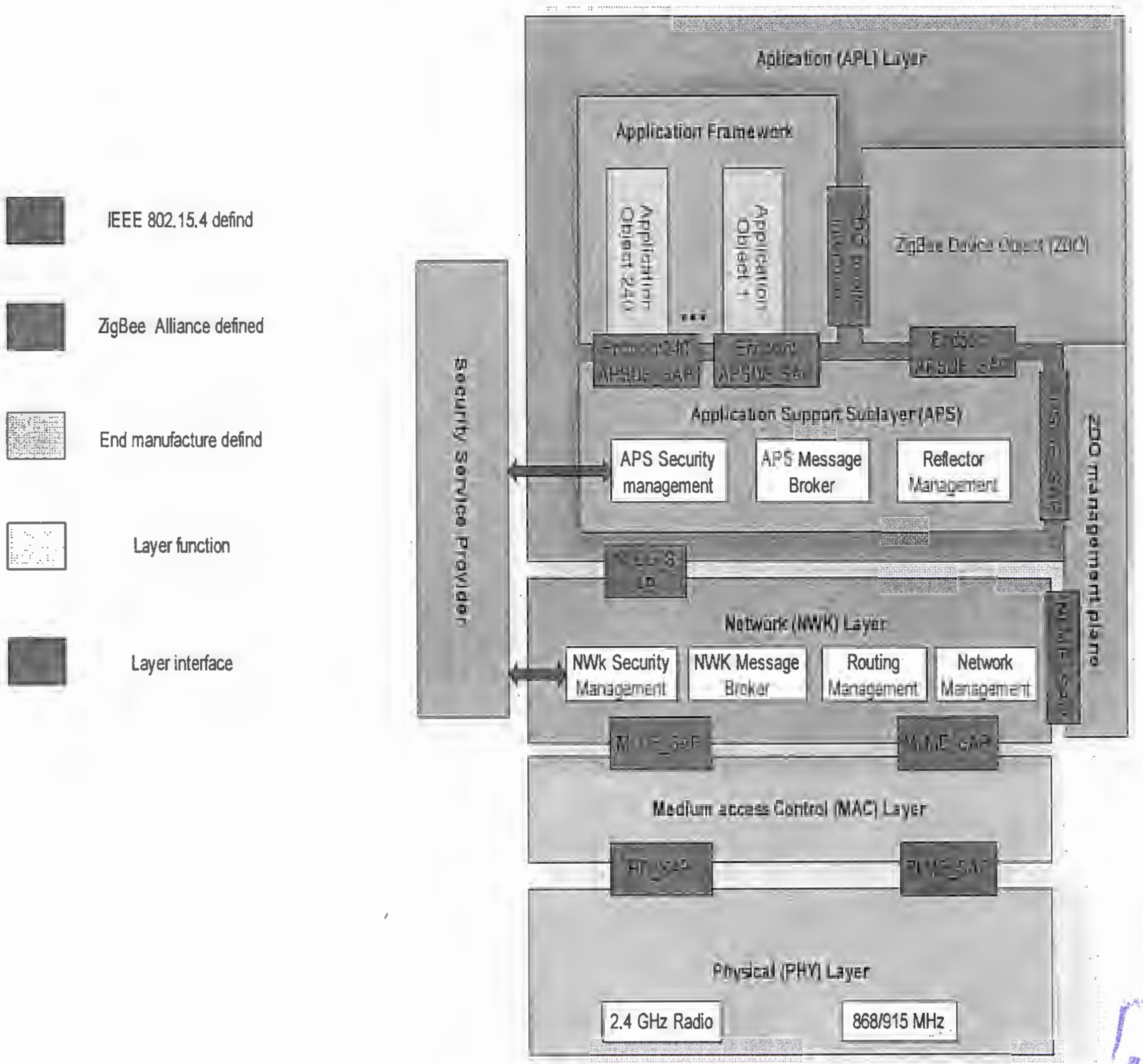

Figure 2.6. ZigBee functional layer architecture and stack protocol [15].

2.9.2 ZigBee Routing

The routing algorithm is usually determined by the topology employed in the sensor network. In a tree topology for instance, routing only takes place along the parent-child paths created as a result of join operations. Routers only keep their own address and the address information related to their children and parent. A router that wants to forward a message can simply verify whether the destination belongs to a tree rooted at one of its router children or is one of its end-device children. If so, it routes the packet to the proper child; otherwise it routes the packet to its parent. While this is not essentially a very energy-efficient routing algorithm, it is a very easy algorithm to execute and it also enables routers to function in a beacon-enabled network. All ZigBee routers and ZigBee coordinator broadcast beacons, communicating over a slotted CSMA-CA protocol and then sleep in the idle part of their super frame [21]. A routing protocol flow chart is shown in figure 2.7.

ZigBee route discovery is based Ad hoc On Demand Distance Vector routing algorithm (AODV). Whenever a node requires a route to a particular destination, it sends out a route request (RREQ) message that navigate through the network until it arrives at the destination. As the PREQ message moves through the network, accrues a forwarding cost value, which is an aggregate of the costs of all the paths it navigated. The cost of a path can be a preset constant value, or it could be dynamically computed based on a path quality approximation provided by the IEEE 802.15.4 interface. Each RREQ message carries a RREQ ID which the instigator increases each time it broadcasts a new RREQ message. This enables the RREQ ID and source address be used as unique references for a route discovery process. Once a RREQ is received, it initiates a search within the RDT for a record corresponding to the route discovery. If the search yields no matches, a new RDT entry is initiated for the discovery process and a route request timer is launched (once the timer expires, the RDT entry will be deleted). If on the other hand a record is found in the RDT, the node relates the path cost for the RREQ message to the matching value in the RDT entry. If the path cost is higher it drops the RREQ message, else it updates the RDT record. Finally, if the node traversed is not the route discovery destination, it assigns an RT entry for the destination, with a status discovery, and retransmits the RREQ after updating its path cost field. If the node turns out to be the intended final destination, is replies to the instigator with a route reply (RREP) message that traverse back along the path [21, 36]. Figures 2.8 and 2.9 show the RREQ and RREP block diagrams respectively.

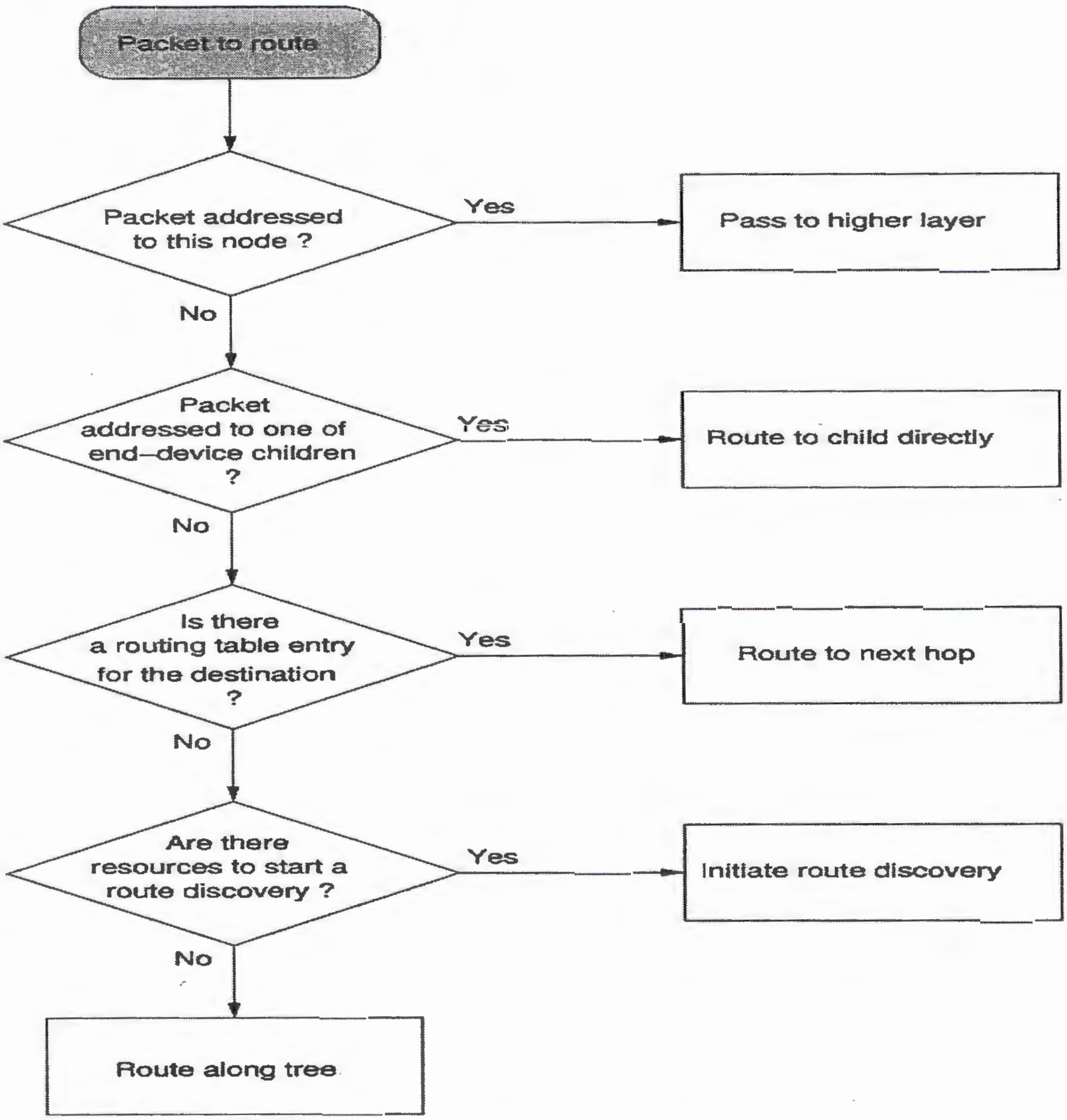

Figure 2.7. Routing protocol flow [21].

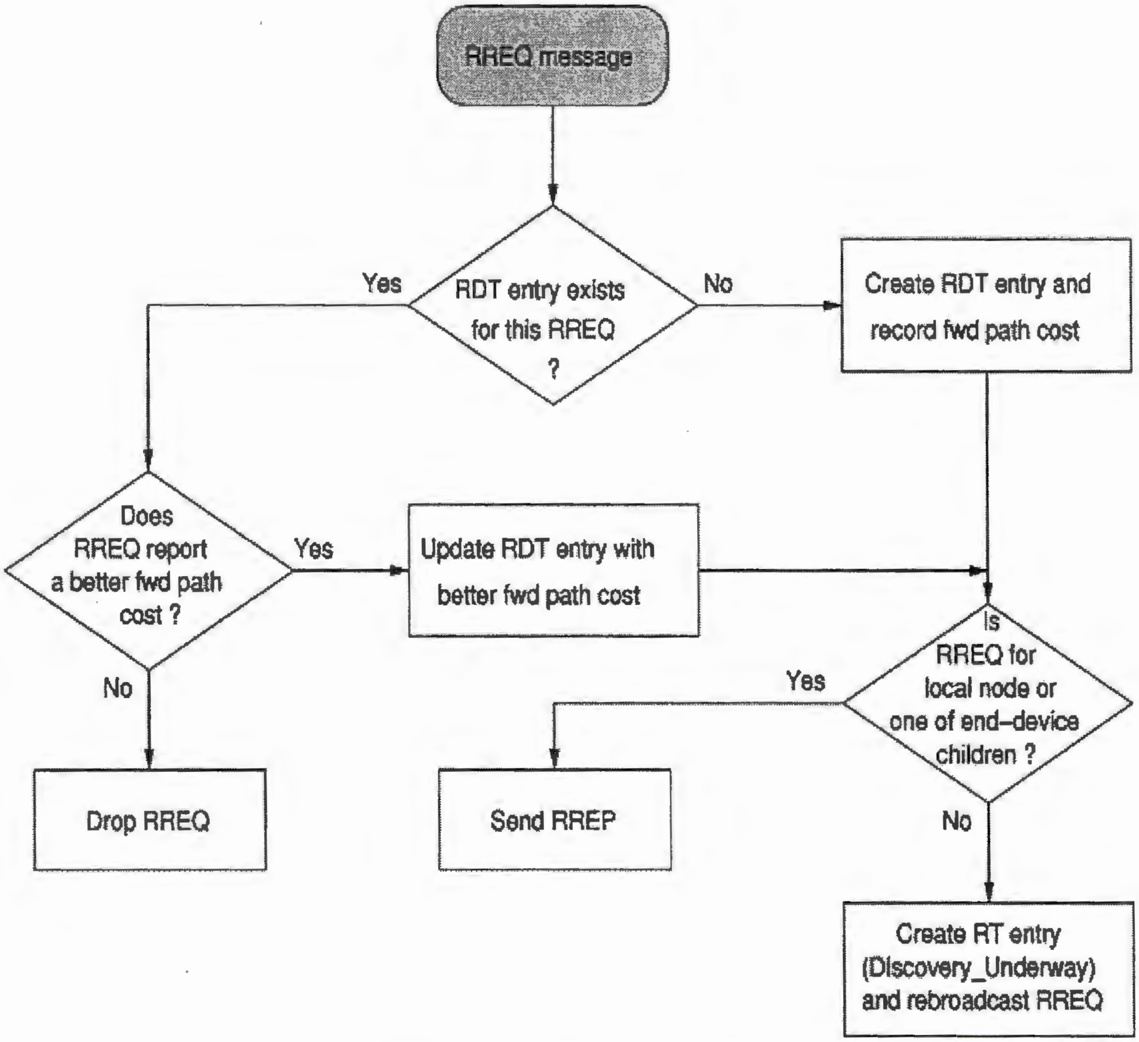

Figure 2.8. RREQ processing [21].

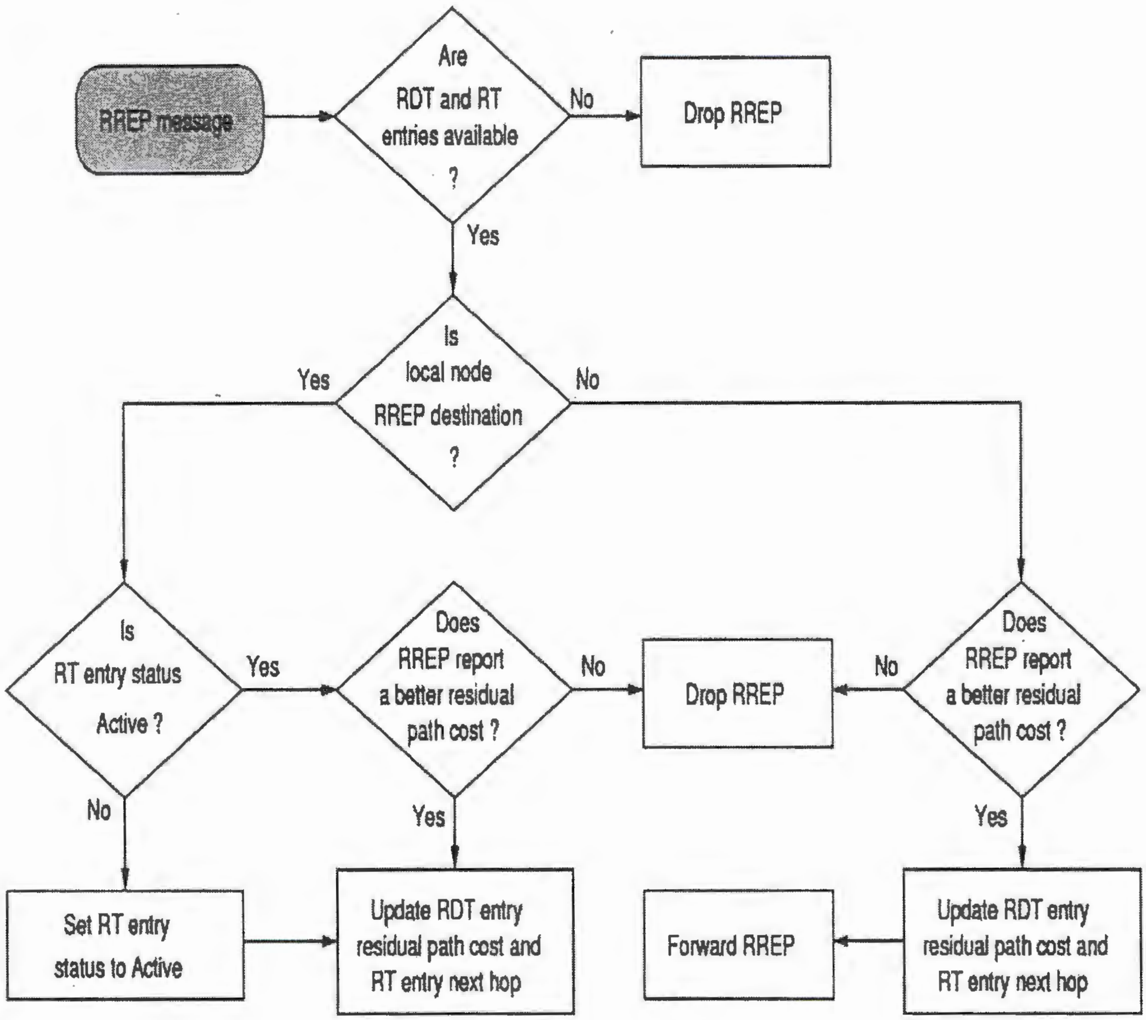

Figure 2.9. RREP processing [21].

2.10 Chapter Summary

The chapter started with an introduction of some of the literature surrounding wireless sensor networks and how they are applied in agriculture activities to improve productivity. The chapter also presented concepts of QoS measures and QoS routing. The chapter concluded by presenting ZigBee protocol and discussing the main features concerned with ZigBee and ZigBee routing, linking it to chapter three in which the simulation setup is carried with ZigBee as the main protocol.

CHAPTER 3

RESEARCH METHODOLOGY AND EXPERIMENTAL SETUP

3.1 Chapter Overview

The quality of service of a wireless sensor network relies on its robustness and tolerance to faults. Achieving these properties requires a strict adherence to designing strong network topologies and using the best suited network devices. Our framework QoS is evaluated on a network topology basis, where we design two topologies and then set them with the same network parameters to see which topology best fits into the implementation of our framework and provides the best QoS for a WSN in the cultivation of maize.

This chapter presents the setup of our simulation and discussions in more detail, about the OPNET simulation software used to carry out this research, as was stated in the previous chapter. We also present a detailed design of the network topology adopted for our framework. The QoS analysis of the ZigBee protocol is evaluated on the basis of three performance metrics, the throughput, end-to-end delay, and data dropped. A brief description of these metrics is given, as well as an outline of the performance parameters that will guide the simulation.

3.2 Methodology

We employ a quantitative research approach in this research work. Network simulation at any level requires a quantitative analysis of performance as this is the method best suited to irrevocably quantify the technical behaviour of sensor networks.

3.2.1 The Structure of OPNET

OPNET is developed with a user interface to assist a developer to build network applications. The interface is built on C and C++ source code with a vast library of OPNET functions to handle the numerous requirements of the developer. OPNET is broken down into three main domains which are designed to simplify the entire experience of network simulation. These domains basically allow a developer or researcher to simulate elements of a computer network with the flexibility of implementing different logical network scenarios.

The three domains of OPNET form the hierarchical structure of the OPNET model. The domains names are; the Network domain, the Node domain, and the Process domain.

3.2.2 The Network Domain

The network top-most domain of the model and is mainly concerned with networks and subnets, network topologies, geographical coordinates, how the objects connect, mobility of the objects and the statistics selected for the particular network. The network domain represents the overall network that is being modeled, as shown in figure 3.1.

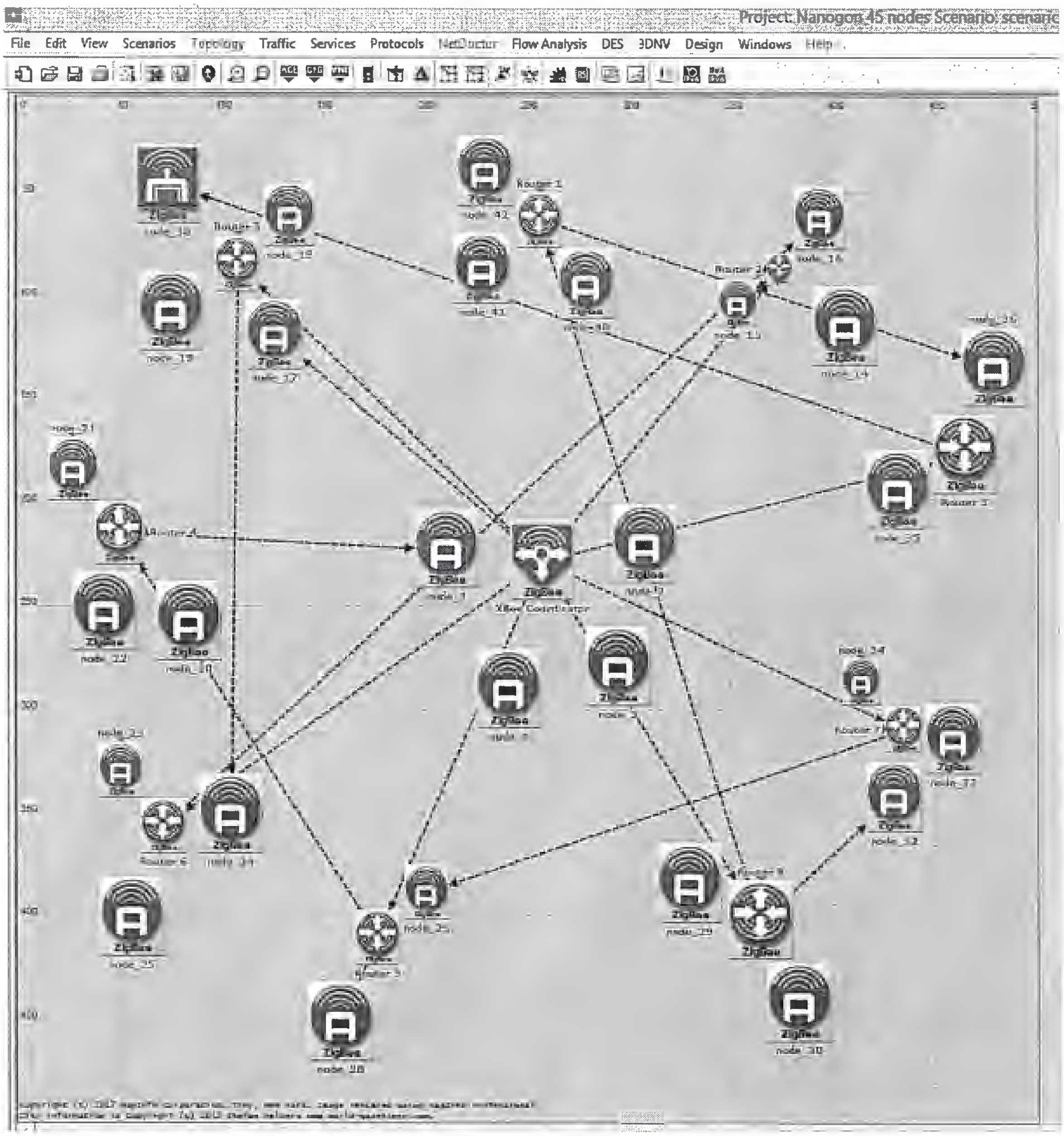

Figure 3.1. ZigBee Network Domain

3.2.3 The Node Domain

The node domain in OPNET specifies the internal structure of the nodes in the network. These nodes include workstations, remote sensors, routers, packet switches, servers, satellite terminals. The nodes can be of type fixed, mobile, or satellite. Figure 3.2 illustrates node domain architecture.

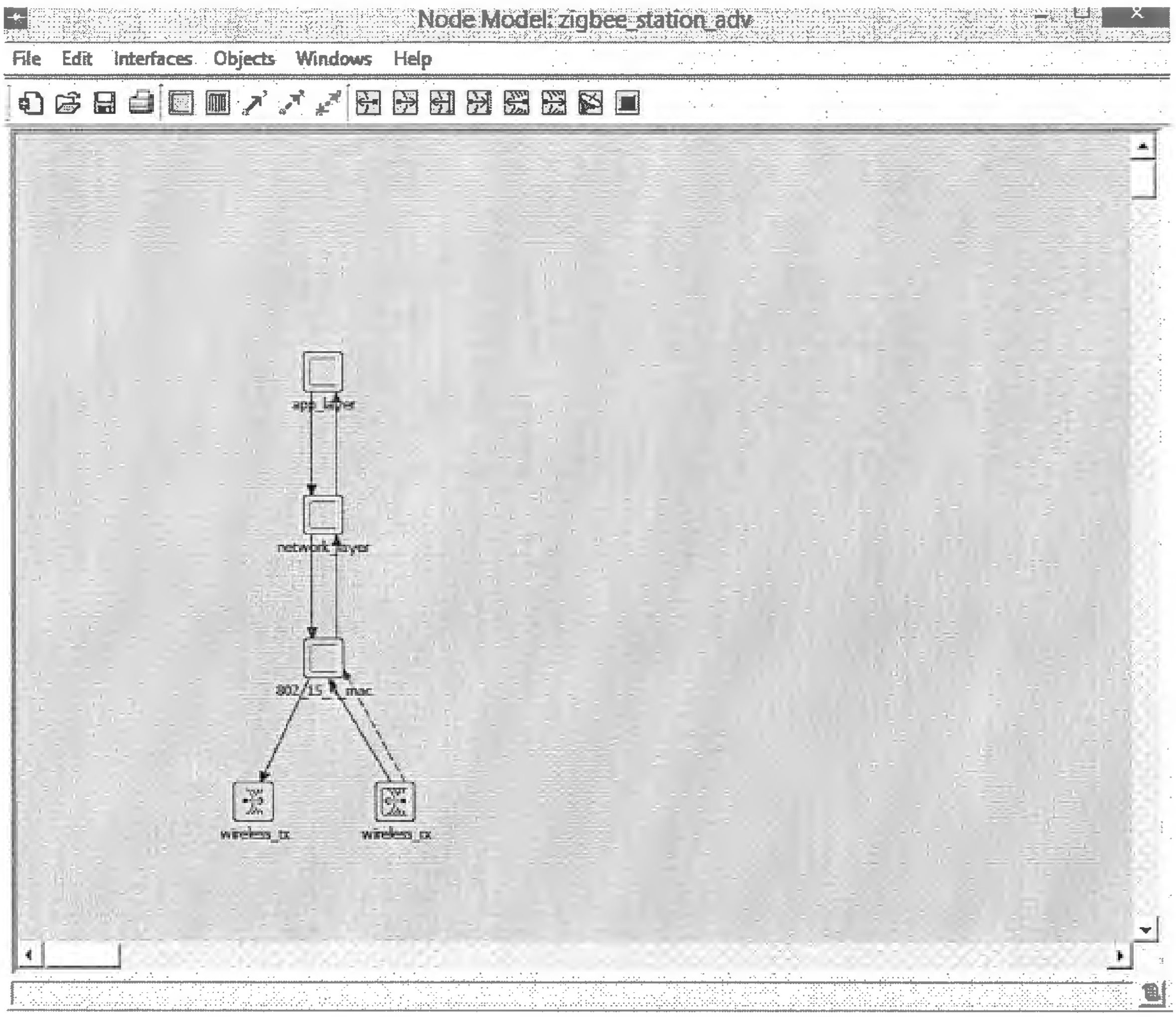

Figure 3.2. ZigBee Node Model

3.2.4 Process Domain

The process domain is used to specify the behavior of processor and queue modules which exist in the node domain. The process model is essentially the code level domain of the OPNET model, where the C and C++ code block is found. The process domain is shown in figure 3.3 with source code. ZigBee is not an open source tool, it is therefore not possible to acquire the full proprietary source code. The source code presented is specifically for the ZigBee process domain as designed by the manufacturer.

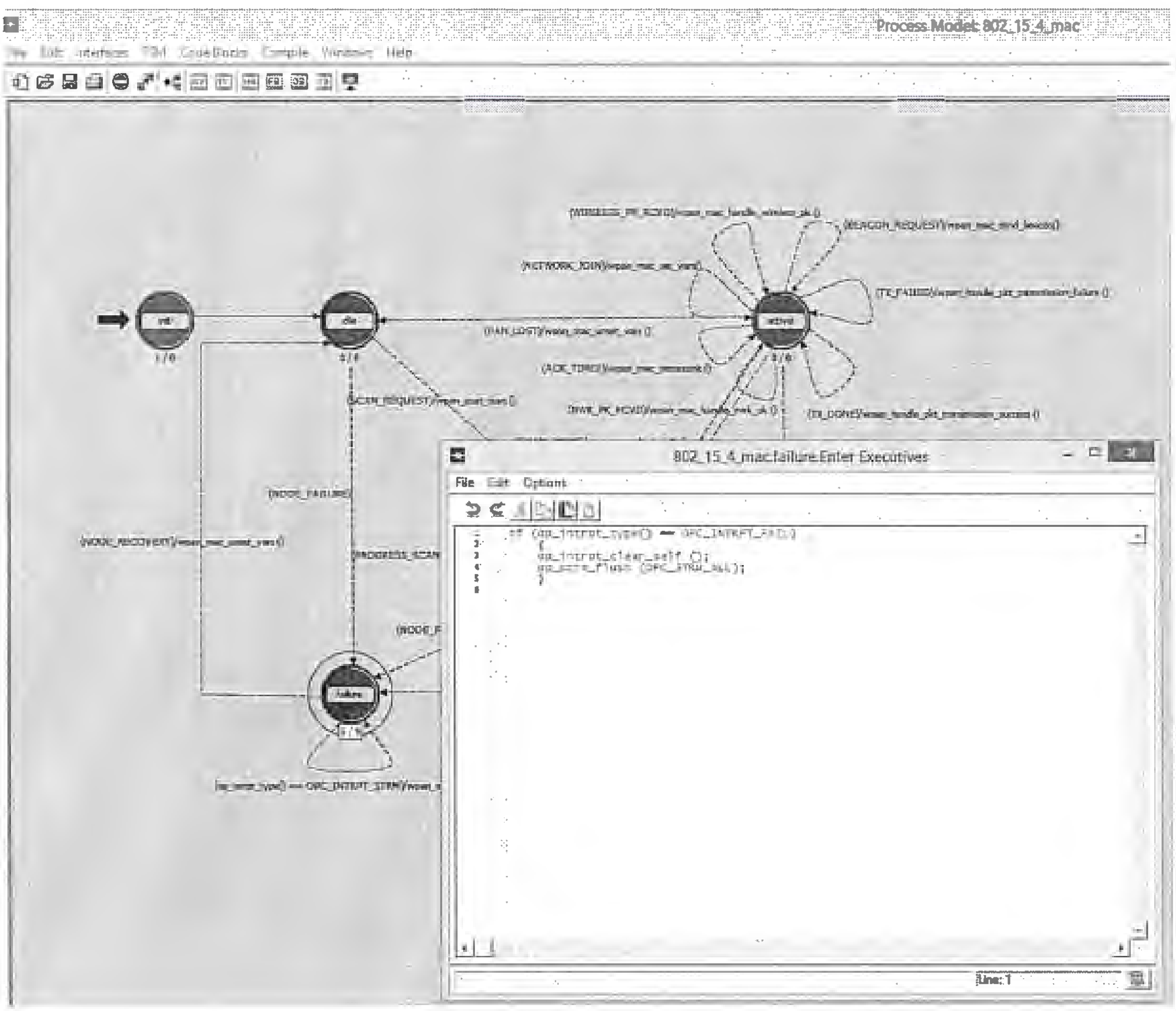

Figure 3.3. ZigBee Process Domain with source code

3.2.5 Modelling and Simulation Cycle

Modeling is a scientific activity the aim of which is to make a particular or feature of the world easier to understand, define, quantify, visualize, or simulate by referencing it to existing and commonly accepted knowledge. Modelling requires selecting and identifying relevant aspects of a situation in the real world. A scientific model seeks to represent empirical objects, phenomena, and physical processes in a logical and objective way. OPNET provides specific tools to help researchers and developers to go through three of five step by step phases of the design cycle, i.e. the design and creation of a network model/framework, the execution of a model, and the analysis of results. Figure 3.6 shows the workflow cycle of our framework.

3.2.5.1 Design Network Model

A network model is created in the network domain. There is more than one way of creating a network model, the most common methods are listed below.

a. Importing an existing network form from the scenario tab

b. By using the rapid configuration tool

c. By placing nodes taken from the object palette directly into the workspace.

Once the method for creating the network model is selected, the traffic must then be selected. The traffic can be imported or manually specified.

3.2.5.2 Choose Statistics

Statistics are chosen prior to running simulation. Choosing statistics enables the user to fully customize attributes/statistics with respect to the research goal. This stage is important as it ensures that the simulated results exhibit only the specified statistics outcome.

3.2.5.3 Run Simulation

After choosing statistics and making sure that all parameters are properly configured, run the simulation. It is always advisable to run the simulation a number of times before coming up with results. This is done to guarantee the degree of correctness of the created network. The OPNET Modeler has many kinds of analysis that can be implemented:

a. Discreet Event Simulation

b. Flow Analysis

c. Failure Impact Analysis

d. Net Doctor Validation

Discreet Event Simulation is considered to be one of the best analytical approach as compared to the other three methods of analysis. This is because it handles link roads, pair traffic and explicit traffic. One disadvantage it has is that it takes the longest time running, compared to others that generate results faster and answer specific type of questions.

3.2.5.4. Analyze/Evaluate Results

At this stage of the simulation, results are displayed from the Analysis tool. This tool allows the user to extract simulation data as per request. The tool allows the user to choose their customizations in terms of output and displayed results in the various presentation schemes available. Users can select only the required performance metrics. The results browser comes with the capability to link current projects or all the projects performed with the tool. The scenarios or rather project can be selected randomly, and the graphs can be viewed as a collective or as a single project. Figures 3.4 and 3.5 show sample data for number of packets created at the node level and number of packets dropped at the network level respectively, for OPNET outputs as generated by the results analysis tool.

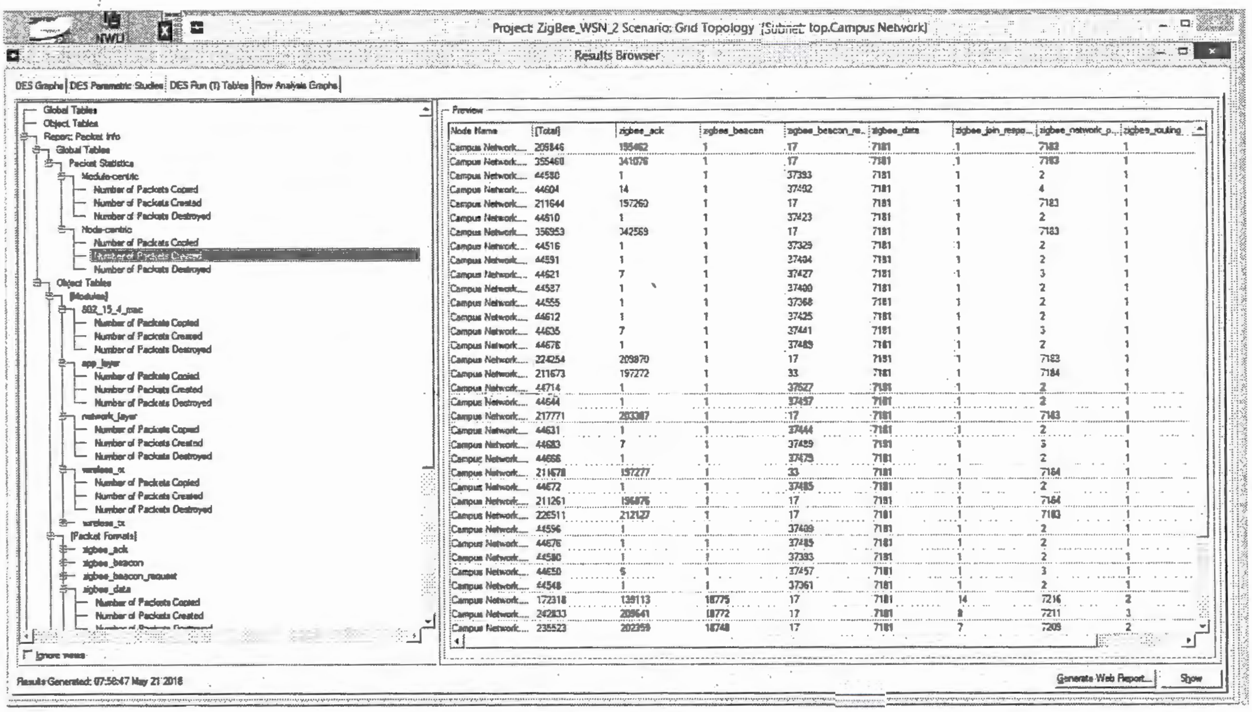

Figure 3.4. Output for number of packets created at the node level.

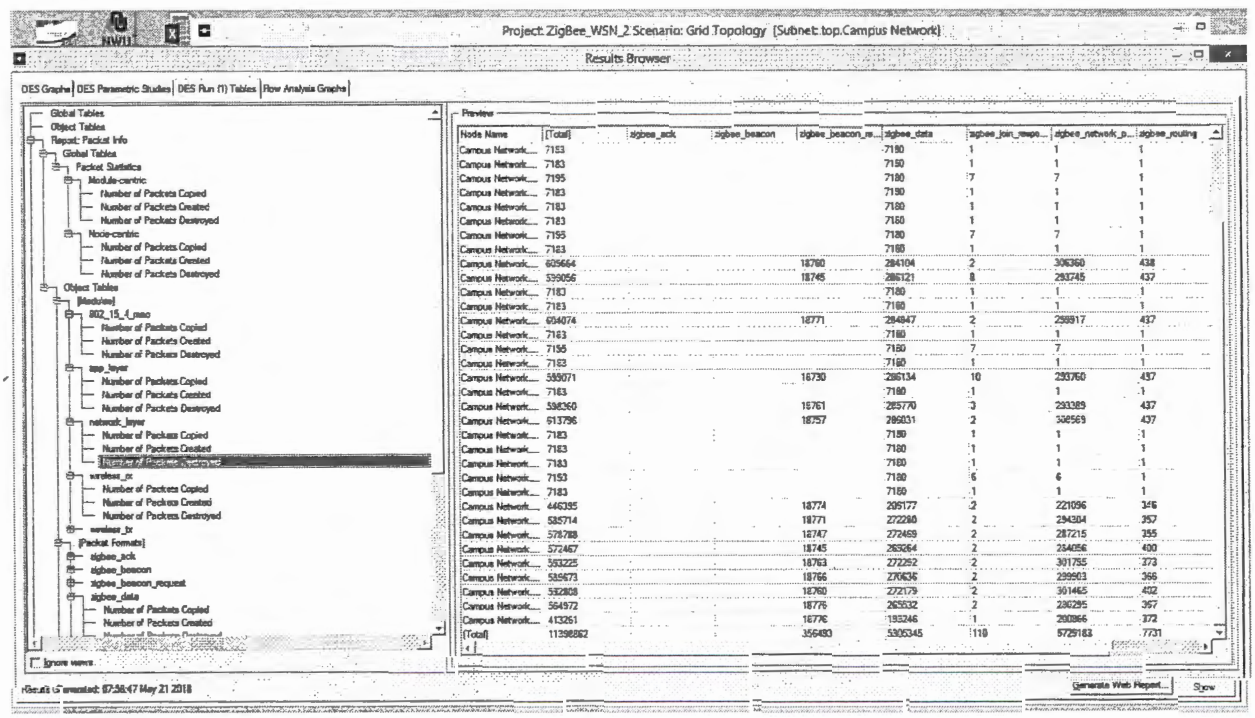

Figure 3.5. Output for number of packets dropped at the network level.

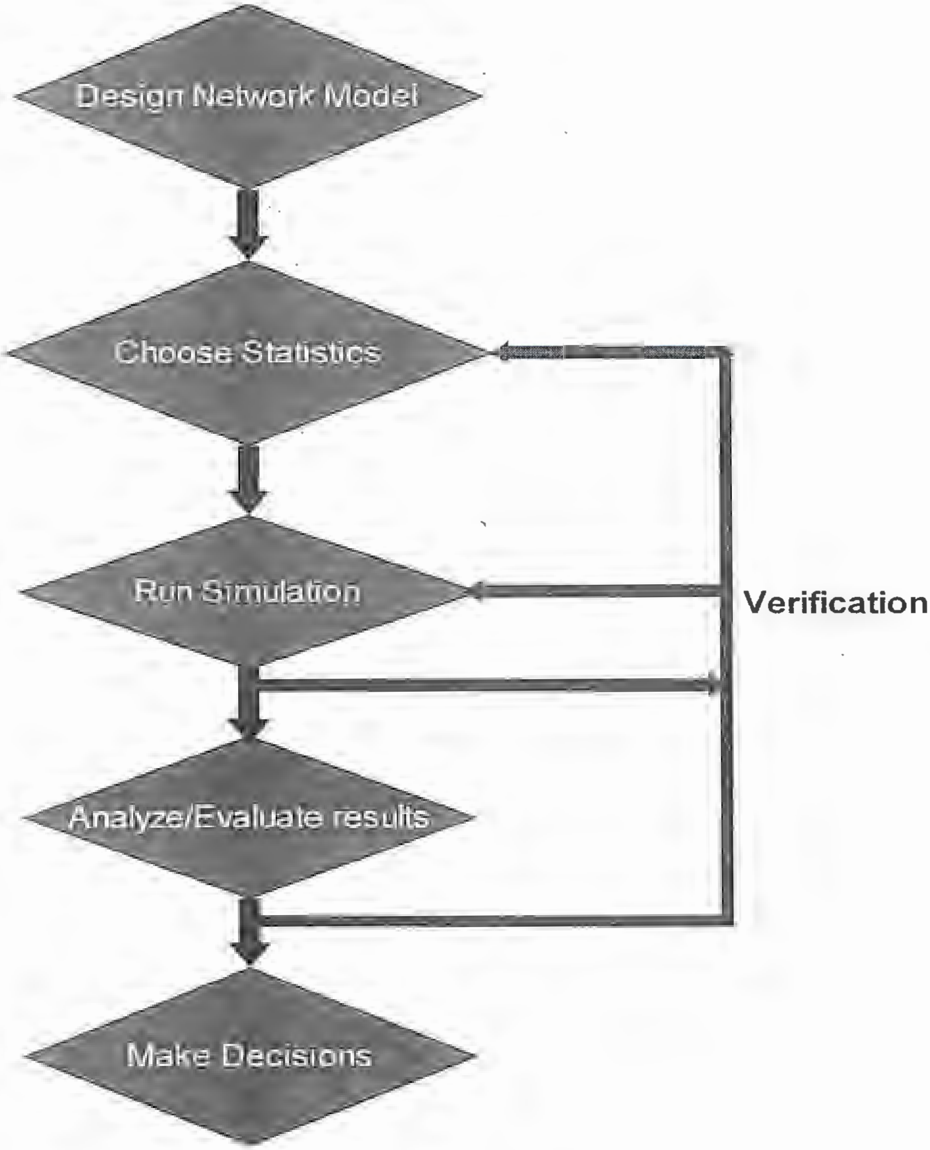

Figure 3.6. OPNET Modeling and Simulation Cycle

3.3 Simulation Study

As stated earlier, this work focuses on the design and evaluation of a wireless sensor network constructed with ZigBee devices and communicating on 802.15.4/ZigBee protocol. The ZigBee protocol and standard has already been discussed in the previous sections. The network and routing protocol QoS are evaluated based on quantitative performance metrics throughput, end-to-end delay (or one-way delay), MAC delay, packets dropped, and data dropped. Two network topologies were designed for performance comparison and derived from concepts introduced in [7, 34, 37, 38]. A grid topology with coordinator in the center, and a nonagonal geometric structure topology, these form our two simulation scenarios. The two topologies are constructed with the same number of nodes, and the same network parameters and statistics. The network topologies; Nonagonal geometric structure and Grid topology are shown in figure 3.7 and 3.8 respectively.

3.3.1 Network Topology

The simulation study was conducted on a campus network setting. Two topology scenarios were implemented and analyzed. Figures 3.7 and 3.8 depict the two network topologies with the traffic routes. The two network models were configured with the same number of end devices over a scale of 1000 by 1000 meters, the geometric topology is however, designed with nine 9 routers. The routers are placed in the vertices around the coordinator node to form the nonagon geometric structure, 32 end nodes are the linked to the routers to form cluster trees. With the grid topology, the number of routers is reduced to 8. The coordinator node is once again placed at the center of the field divided into four quadrants, each quadrant holds 8 end nodes (making a total of 32 end nodes) placed equidistant from the router in their center. The network parameters for the topologies are given in table 3.1.

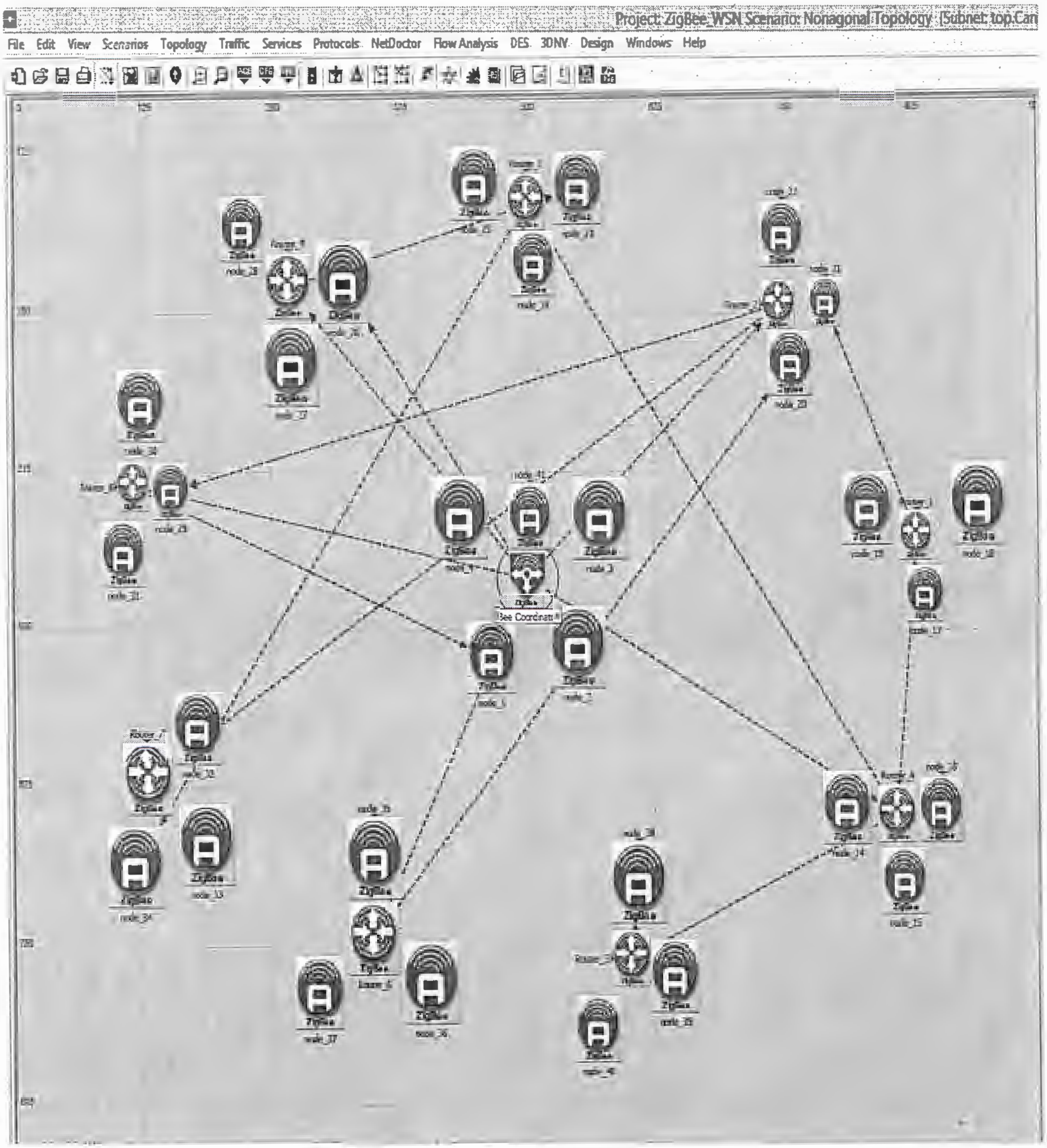

Figure 3.7. Nonagonal Geometric topology structure designed for ZigBee WSN Framework

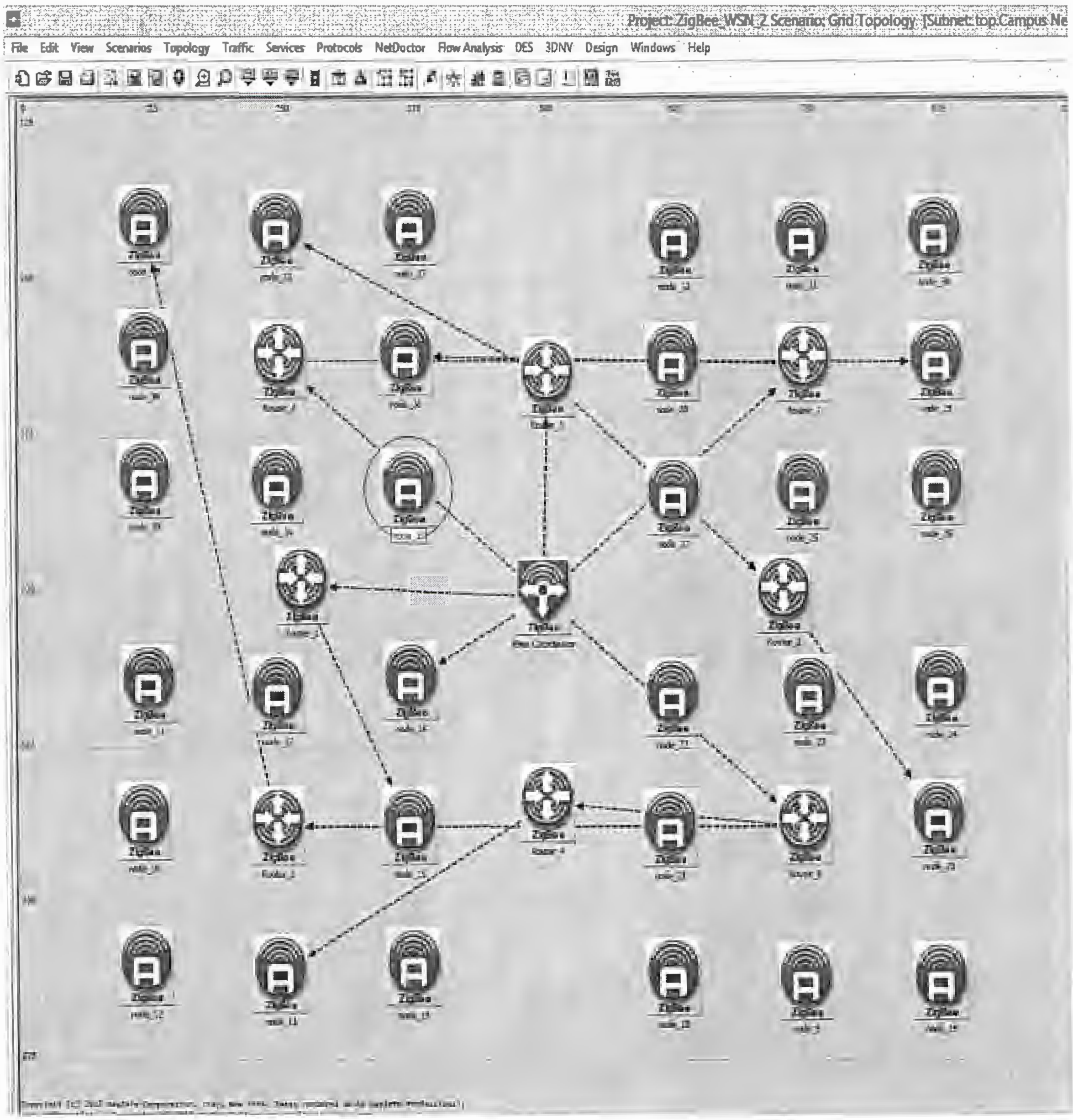

Figure 3.8. Grid Network Topology Designed for ZigBee WSN Framework.

Table 3.1 Simulation Parameter

PARAMETERS	DESCRIPTION
Simulator	OPNET 14.5 Modeler
Communication protocol	ZigBee/802.15.4
Ack Status	Disabled
Number of Retransmissions	5
Frequency Band	2.4 GHz
Data rate	Auto Calculate
Packet Size	Constant (1024)
Packet Interval Time	Constant (1.0)
Packet Reception Power Threshold	-85 dbs.
Transmission Power	0.05 (Coordinator and Router), 0.02 (End nodes)
Traffic Destination (both scenarios)	Routers, End nodes, Coordinator
Channel Sensing Duration	0.1
Number of Coordinators (Both Scenarios)	1
Number of Routers	9 (Nonagonal topology), 8 (Grid topology)
Number of End Devices	32 (Both Scenarios)
Network Dimension	1000m x 1000m
Simulation Time	2 hours

Both network topologies were constructed with specific configuration utilities that enable the efficient use of the simulation tool. The coordinator, router, and end node configurations are defined in figures 3.9, 3.10, and 3.11 respectively.

3.3.2 Coordinator Configuration

The ZigBee coordinator basically manages the entire physical network. We configure our coordinator with traffic destination to all routers, and transmission power of 0.05. We set the PAN ID to 155, arbitrarily. Because the coordinator manages the whole network, the exact number of routers and end devices must be specified within the coordinator, also defined in the coordinator are the maximum and minimum number of children in the cluster-tree, as well as the maximum depth of the tree. Figure 3.9 shows more coordinator configurations.

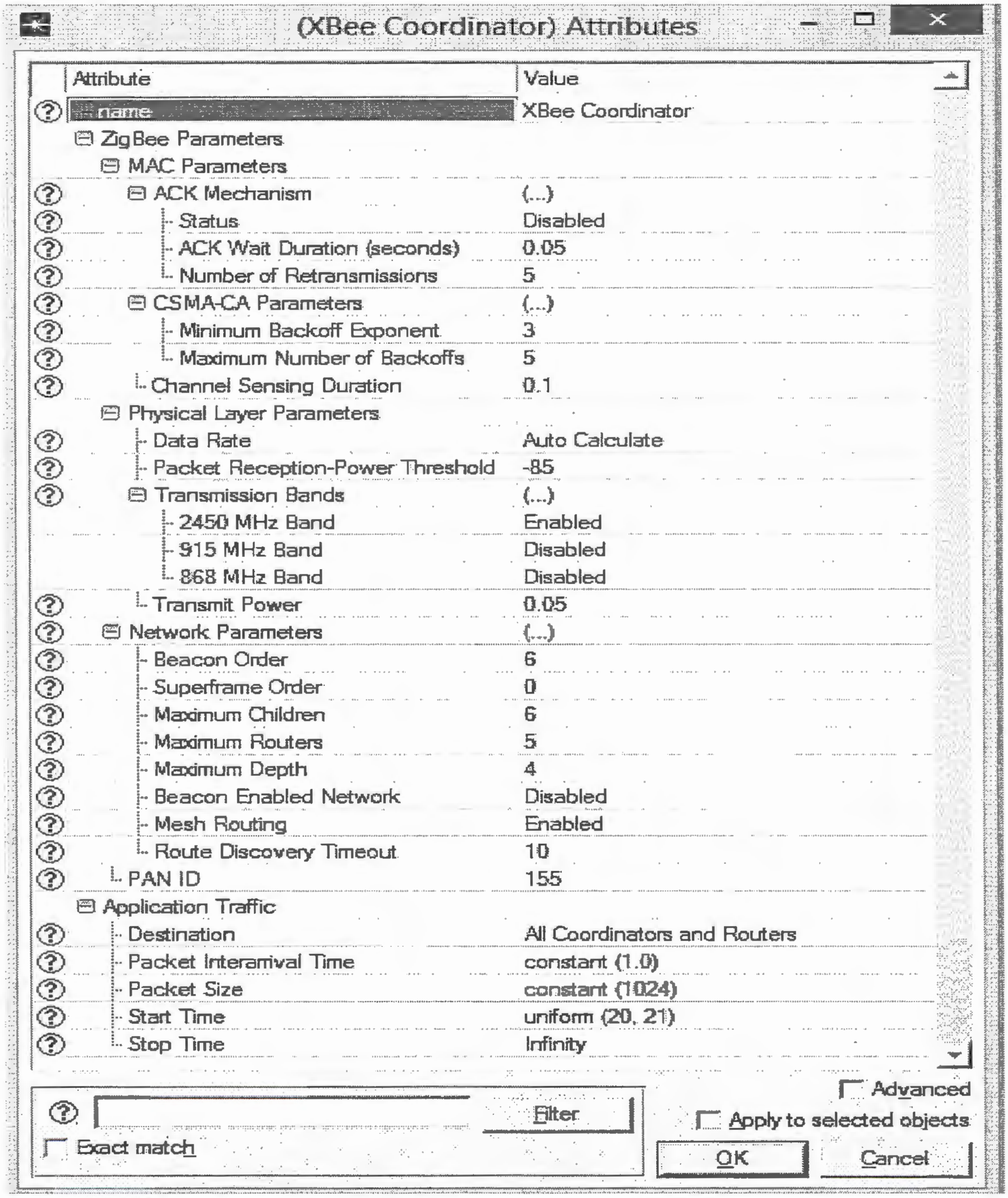

Figure 3.9. Coordinator Configuration

3.3.3 Router Configuration

It is important to note that when configuring multiple routers in a single network, the values and statistics defined must apply to all the routers in the network. We defined the router traffic destination for our network to be the end nodes. The PAN ID defined in the coordinator applies to all devices in the network, since nodes having the same ID will always seek to join a network that also has the same ID as theirs. Figure 3.10 shows the complete router configuration.

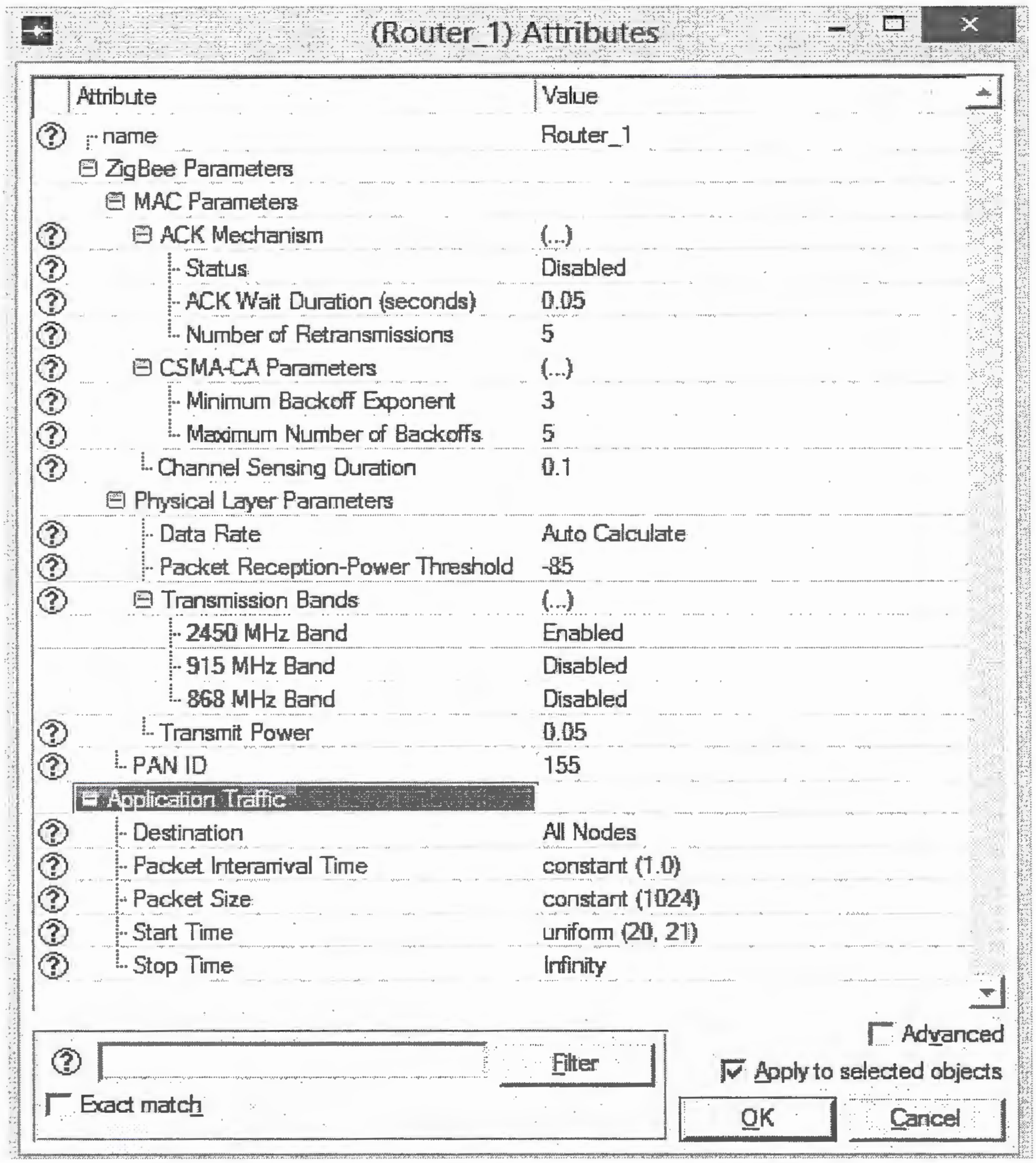

Figure 3.10. Router Configuration

3.3.4 End Node Configuration

Unlike routers, end nodes can be configured with varying statistics if preferred. However, we have elected to employ a uniform configuration for our network. The end node traffic destination is the coordinator, and in an effort to conserve energy, end nodes are configured to transmit at a lower power of 0.02. A complete list of end node definitions is shown in figure 3.11.

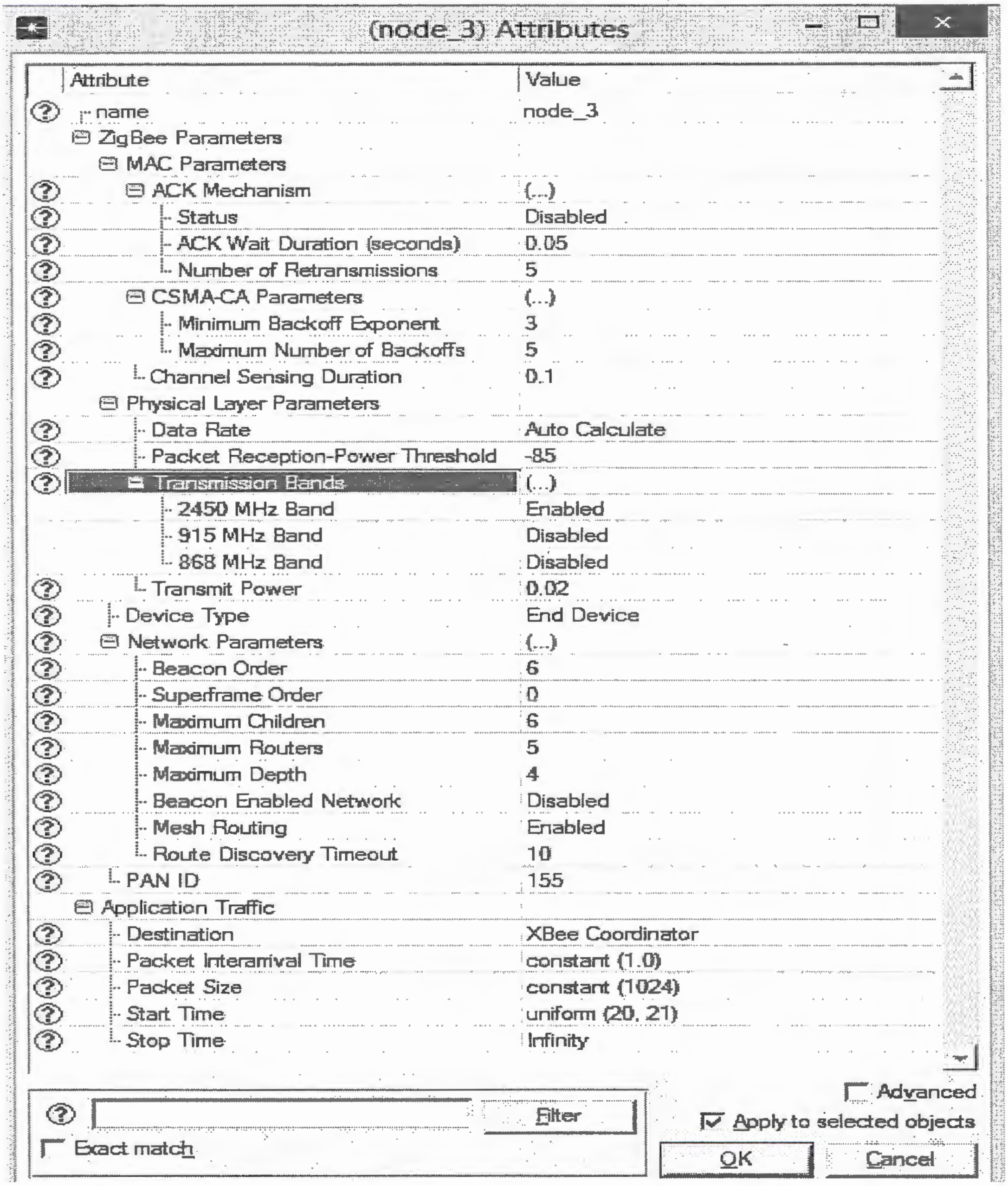

Figure 3.11. End Node Configuration

3.4 Simulation Scenarios

As stated previously, this research work focuses on the simulation of two topology scenarios, a grid topology with total of 41 nodes, and a nonagonal geometric topology with a total of 42 nodes. The design and configuration of network devices described in the sections above are applied to both topologies.

3.5 Quality of Service Metrics for Framework Evaluation

The choice of which parameters to use for our framework was based on the relevance of the parameters to the PA activity our framework is proposed to be applied, which is Maize cultivation. In other words, the parameters were selected based on the environmental properties we assume to be the primary data our WSN will seek to gather. The environmental properties we are most interested in are soil moisture content, soil chemical composition, soil temperature, and humidity, this is excluding the sensors mounted on machinery and irrigation equipped for actuation purposes. This means that there would be at least four distinct types of environmental sensors in the network, all mounted with ZigBee radio communication nodes. The performance metrics employed in this study are: End-to-End (One-way) delay, Throughput, and Data dropped.

3.5.1 End-to-End Delay

It is the total delay between the creation and reception of an application packet (in bits/sec). For ZigBee networks, this metric is dimensioned by the ZigBee Network PAN ID, which has a range from 1 to 255 network IDs.

3.5.2 Throughput

Throughput represents the total number of bit (in bits/sec) forwarded from 802.15.4 MAC to higher layers in all WPAN nodes of the network. At the node level, throughput is the total data traffic in (bits/sec) successfully received and forwarded to the higher layer by the 802.15.4 MAC.

3.5.3 Data Dropped

Represents the total higher layer data traffic (in bits/sec) dropped by all 802.15.4 MACs in the network as a result of consistently failing retransmissions.

3.5.4 MAC Delay

The MAC delay represents the delay of all the packets received by the 802.15.4 MACs of all WPAN nodes in the network and forwarded to the higher layer.

3.5.5 Packets Dropped

Packets dropped refers to the number of total packets dropped by the network layer due to not being joined to a network.

3.6 Chapter Summary

This chapter presented the simulation software (OPNET Modeler) adopted for our research work. The tool was used to simulate two distinct WSN topologies communicating over ZigBee/802.15.4 protocol. The configurations defined for the coordinator, routers, and end nodes were selected as suitable statistic to achieve our goal based on trial simulations run prior to the final experiment. The simulation of the two topologies gave insight into the behavior of WSNs with respect to network topology. We define our framework in the next chapter and detail its operation and how it achieves quality of service for precision agriculture activities.

CHAPTER 4

FRAMEWORK IMPLEMENTATION

4.1 Introduction

This chapter presents a detailed discussion of the proposed QoS wireless sensor network framework and the steps taken in the design of the framework. Also presented is the framework implementation and analysis phase through network simulation. The QoS evaluation of ZigBee protocol is also presented here, along with the QoS parameters selected for this research work. The chapter also presents answers to research questions 2, 3, 4, and research objectives 2, 3, and 4.

4.2 Simulation Environment Used

As indicated before, Optimized Network Engineering tool (OPNET) was chosen to carry out the simulation phase of this research work. OPNET is high level discrete event-based simulation tool developed by OPNET technology, which was recently acquired by RIVERBED technology. OPNET is a powerful network simulation software that allows users to easily design and examine networks that can range from small to large-scale. The specifications of the environment upon which the simulations were carried are as follows;

The simulation tool was run on a Windows 7.0 Professional Operating System (Desktop Computer) running a 3.40 GHz i5 processor, 4.0 GB RAM memory and a 64-bit Operating System. This one advantage is backed by lower costs. OPNET has an extensive range of protocols defined in its library and comes with a collection of ready models available commercially. The software is used for research and development projects both commercially and for academic purposes. It is one the few network simulation software that provides a comprehensive resource package of ZigBee and IEEE 802.15.4 standards, and a Graphical interface that simplifies node configuration and topology design.

4.3 Wireless Sensor Network QoS Framework

Discussion of our proposed framework begins with an overview of the framework and some of the basic concepts that drew us to the design conclusions we arrived at. Following the overview, we delve further into the individual elements that make up the framework.

4.3.1 Framework Overview

We designed a wireless sensor network (WSN) framework based on the need to provide quality of service (QoS) in a precision agriculture application. The provision of QoS encompasses not only the network aspect of the framework, but also the end user's ability to affect changes to the overall network and all peripherals connected with the network in order to fully appreciate the framework's benefits to the PA application its applied in; which is after all the main purpose for which it was designed. Therefore, in an effort to achieve this "global" QoS, our framework includes a web-based agriculture management system called Agriculture Sensor Application (AgriSensApp) shown in figure 4.1. The AgriSensApp is hosted on a remote server and acts as the interface between the end user and the WSN, providing the user with the ability to read, analyze collected data and initiate actuation instructions from any location around the world by accessing the system through the internet.

However, the most important aspect of the framework is the sensor network. In order to realize an acceptable level of QoS provision for the framework, the sensor network must yield reasonable values of QoS performance measures such as throughput, end-to-end delay, and average packet loss. For this reason, ZigBee was chosen as the communication protocol due to its qualities as a protocol having some of the lowest communication rates. This is advantageous because low communication rates translate into low energy consumption, which is another metric for QoS we desire to attain in our WSN. The backbone of the framework is the design and management of a topology that allows for efficient data transfer, high network coverage, connectivity, and low energy consumption. The framework is proposed to operate with environmental sensors equipped with ZigBee motes (ZigBee radio transceivers), for optimum operability and compatibility. We first describe the agriculture management system and its functions, followed by a discussion of the sensor network design. It is imperative we state that the architectural design of our framework was based on concepts proposed in [7], our framework specifies the implementation of a ZigBee WSN and a custom geometric network topology with a high-level data management system. Figure 4.1 shows the framework design with external and internal components; the individual components are discussed in detail in the subsequent subsections.

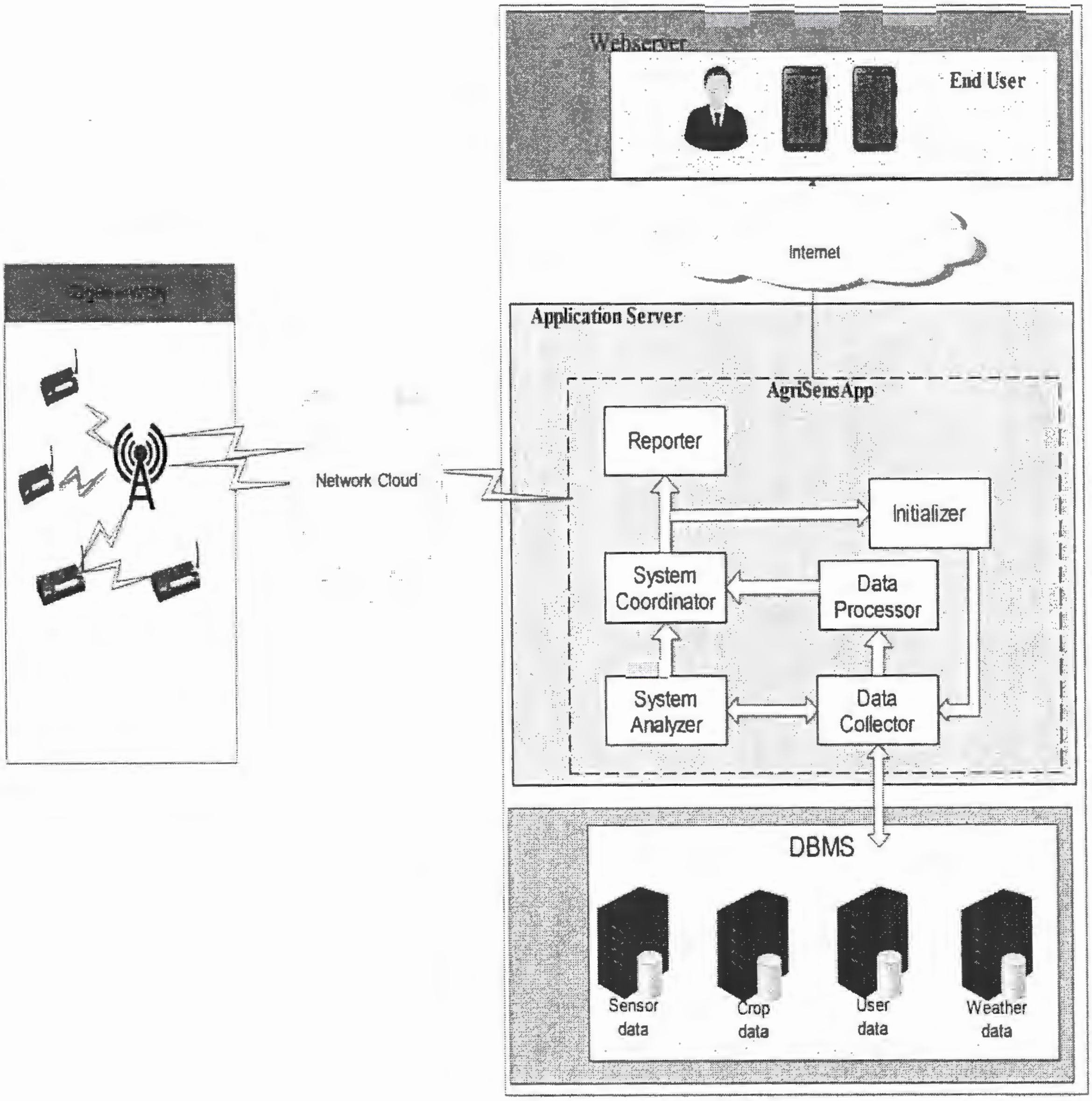

Figure 4.1. Proposed Wireless Sensor Network QoS Framework

4.4.2 Agriculture Sense Application (AgriSensApp)

Quality of service provision in precision agriculture with WSNs goes beyond just developing robust and fault tolerant networks, there is more involved with maximizing agricultural productivity that does not necessarily have to do with the physical network; but is nonetheless a process reliant on the WSN to facilitate a direct relationship. Attaining QoS in PA is predicated on the existence of a good agriculture management system (AMS) to go along with the physical WSN hardware. Agriculture management deals with the organization and control of a farm with the goal of improving productivity whilst dispensing with concerns like consumer requirements, environmental requirements, and agriculture policies.

This wider scope of agriculture activities and challenges therefore validates the design of a PA framework that includes an agriculture management system. Generally, the function of an agriculture data management system is to collect data processed by the sensor network, provide an analysis of the data and provide an interface for the user to access the processed information for decision making and instructions for actuation of farm machinery or reconfiguration of sensor nodes. The user can perform these tasks from any location in the world if the management system is hosted on a global network, as is the case in our framework. Figure 4.2 shows the components of the AgriSensApp, and a description of the components is given.

4.4.3 Data Collector

The data collector serves the function of retrieving sensed data from the database and passing it to the analyzer for processing. The collector's communication with the database is bidirectional since analyzed data also requires storing in specific repository, the data collector also communicates with the system analyzer to provide current network and system data which is subsequently transferred to the reporter for user access.

4.4.4 Data Processor

The data processor, is responsible for processing and analyzing sensed data. The processor is a crucial component of the system, as the data analyzed here is integral to the maintenance of the WSN and management of the overall operations.

4.4.5 System Analyzer

The system analyzer is critical for maintenance of the agriculture management system itself. It is responsible for processing data relating to the system, checking for faults or lacks in operational capacity. It is always in communication with the data collector, data processor and system coordinator.

4.4.6 System Coordinator

The coordinator is responsible for managing the entire systems operations, the coordinator basically enforces instructions given by the user after a report of current status is issued to user and decision is made. This means that when an instruction for actuation is issued, the coordinator is responsible enforcing that instruction to the physical network through the initializer module. Coordinator also regulates resources among the services in the system.

4.4.7 Reporter

The reporter is a module that issues data reports to the user after sensed data has gone through processing. This is the module that the user directly interacts with and it provides information in readable formats like HTML pages.

4.4.8 Initializer

The initializer is essentially the trigger of the system. Any executable instructions given by user are initialized by the initializer. Instructions to activate or deactivate actuators or machinery in the field are all executed here.

4.4.9 Application Server

Our agriculture management system is integrated into the application server on the web. The application server plays a crucial role in the operation of the system as it facilitates reusability of services, which would not be possible with only the web server. The application server serves business logic to application programs through several protocols. It provides services to application programs like graphical user interfaces (GUIs) running on PCs, or even a web server. The application server also manages its own resources and has various functions like transaction processing, resource pooling, messaging, and security.

4.4.10 Web Server

The web server here serves as the user interface, allowing access for users to the system. The web server handles HTTP operations and provides HTML pages for user access to information reported by the system and other functions available.

4.4.11 Database

The database management system serves as a data repository for all data transmitted by the base station from the WSN. Several categories of data are stored in specific locations and they all serve different purposes. Some data is required to provide updates on the state of the system itself, while the majority of stored data concerns the environmental readings obtained by the sensor network.

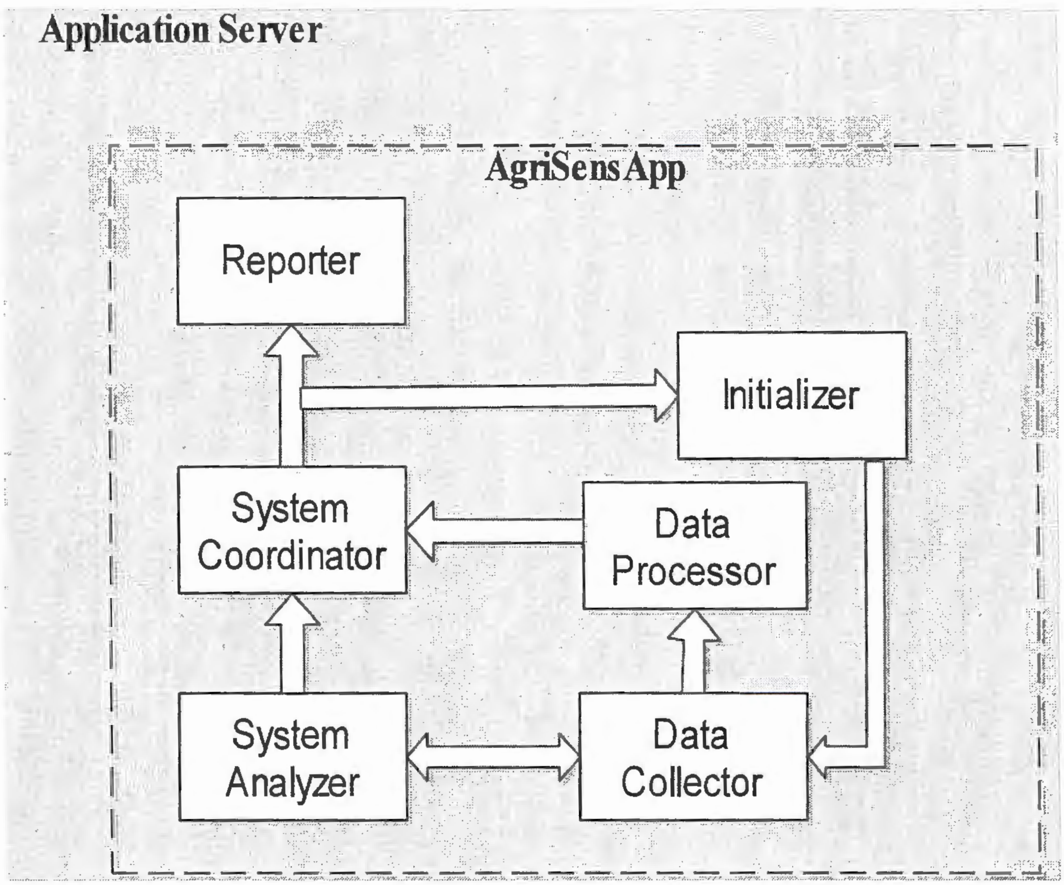

Figure 4.2. AgriSensApp functional architecture [39]

4.5 Physical Wireless Sensor Network

The second part of our framework involves the physical sensor network and specifics of its design that aid the provision of QoS. The network stage is where we evaluate the true QoS of the framework through simulation. The most important aspect of the network is the network topology chosen to implement the framework; the details of the topology design were presented in chapter 3. What we present in this section are the other elements of the network that play a crucial role in developing a robust and fault tolerant WSN, and also how the QoS evaluation in the physical network relates to the software part of the framework; which is the Agriculture management system (AMS).

The integration of the WSN and its QoS evaluation to the AMS is carried out through the base station (BS) and gateway which is the interface between the WSN and the web server hosting the AgriSensApp. The performance of the WSN will therefore directly influence the performance or impact of the AMS on the overall PA activity, the relationship between the physical and software aspects of the framework is shown in figure 4.3.

4.5.1 Base Station Operation and Function

Unlike sensor nodes, a base station has a lot more processing power, larger memory, and is usually connected to a larger power source; mostly power grid. In general, the base station is a door way into the WSN and its primary function is collecting sensed data from sensors in the field. A base station can have many functions depending on desired application, it is capable of functioning as a data analysis and visualization tool. As far as our framework is concerned, the base station for our WSN will also serve the task of forwarding gathered data to the web server application where the AMS will further analyze and process the data and report to users. To enable the base station to communicate with a web server, it must have transceiver that allows connection to internet, this would then make the base station into a gateway to the external network. So, a base station can be an ordinary host computer with base station software and a transceiver. Figure 4.4 shows a schematic view of our physical WSN framework with an illustration of a base station.

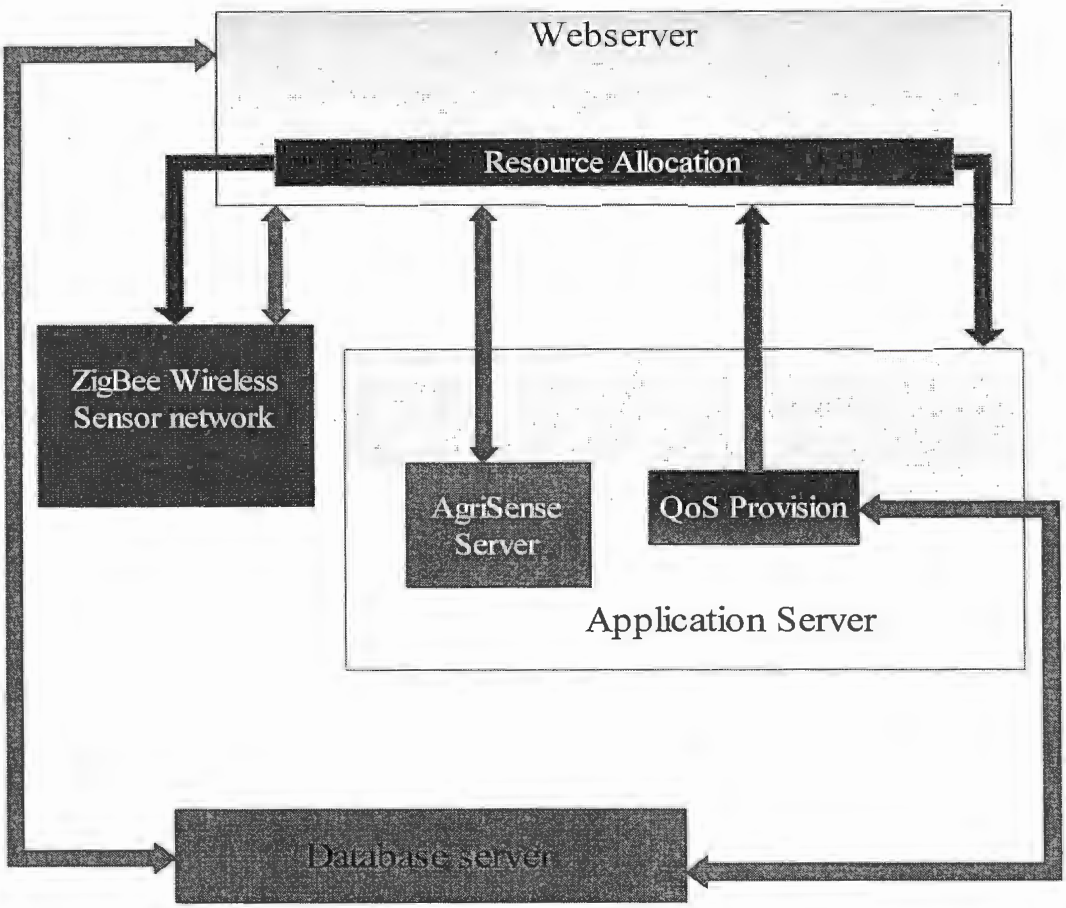

Figure 4.3. Inter-relationship between key components of WSN framework [40].

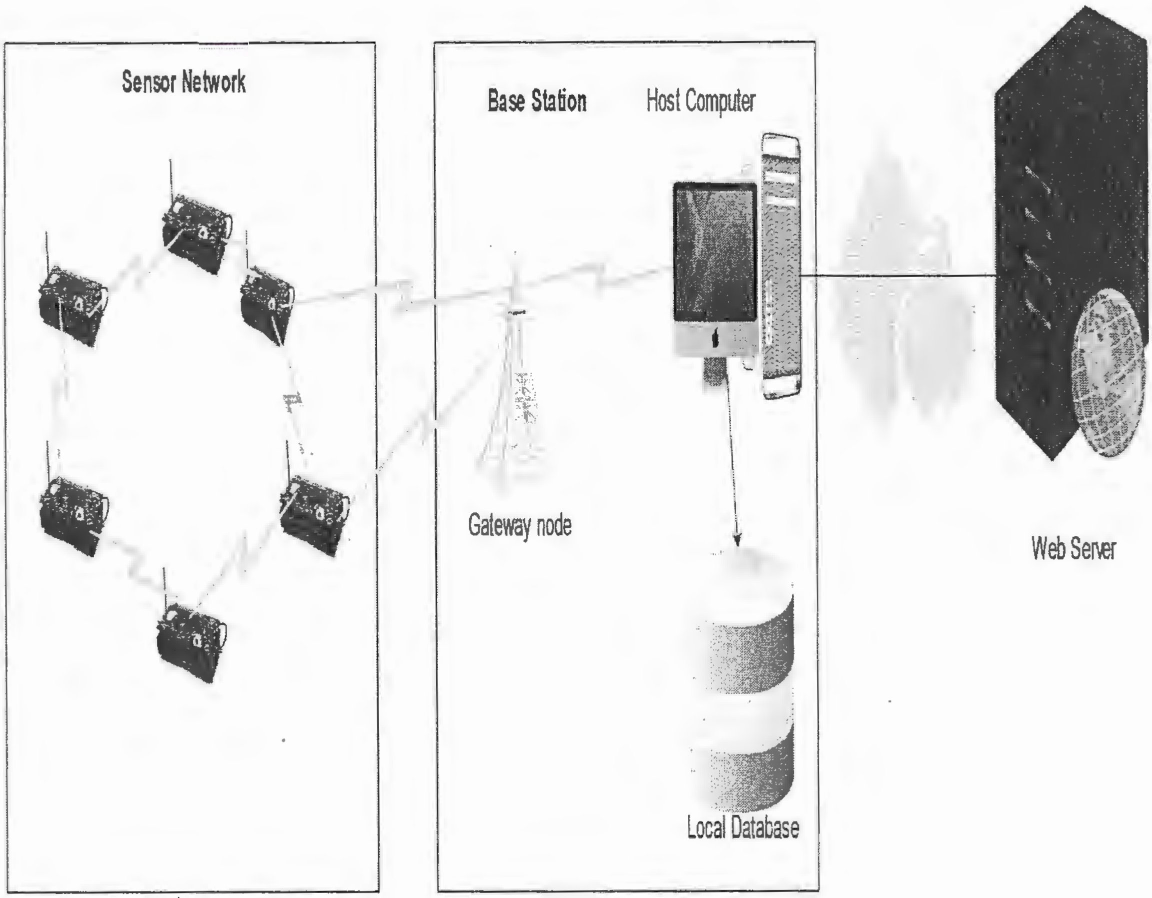

Figure 4.4. Schematic view of WSN framework physical components.

4.6 Framework Operation

It is important to understand first and foremost, that the communication and flow of information in the framework is bidirectional between the local WSN and the agriculture management system (AMS) hosted on the external network, and this is integral to the accomplishment of QoS for the framework. When sensors in the field detect the phenomena as required, their data is converted into bit format and then transferred to the base station where it is partially processed and formatted to a digital format ready to be sent to the web server. So, when a temperature sensor reads the air temperature in the maize field, the ZigBee radio on the sensor finds a communication path to the router in its cluster; the router then finds a path to the coordinator node and then the coordinator sends the data to the base station (or sink node).

At the base station, all the data readings from sensors is converted to a format such as spread sheets and organized into appropriate categories which are readable by the user. The newly compiled data is the promptly sent to the external server through the gateway. Information conveyed from the sensor would be able to inform the user about the condition of crops, the rate of growth, height, soil humidity, water content, fertilizer content and many more details about the state of the field. The translation of the sensed data into such detailed information is precisely what the AMS is designed for. Once the sensed data arrives at the web server, the processing and analysis done by the AgriSensApp system translates the data into commercially reportable information upon which the user can base their informed decision making. Information reports generated by the AMS enable the user to not only make adjustments to the operations of the WSN, but also make economic and corporate decisions. A diagrammatic illustration of the framework operation is shown in figure 4.5. The figure shows the path that sensed data takes from the time it is captured by the sensors in the field, through the intermediary stations, until it gets to the end user and vice-versa. The figure shows the components of the local and external network which combined, form the complete framework.

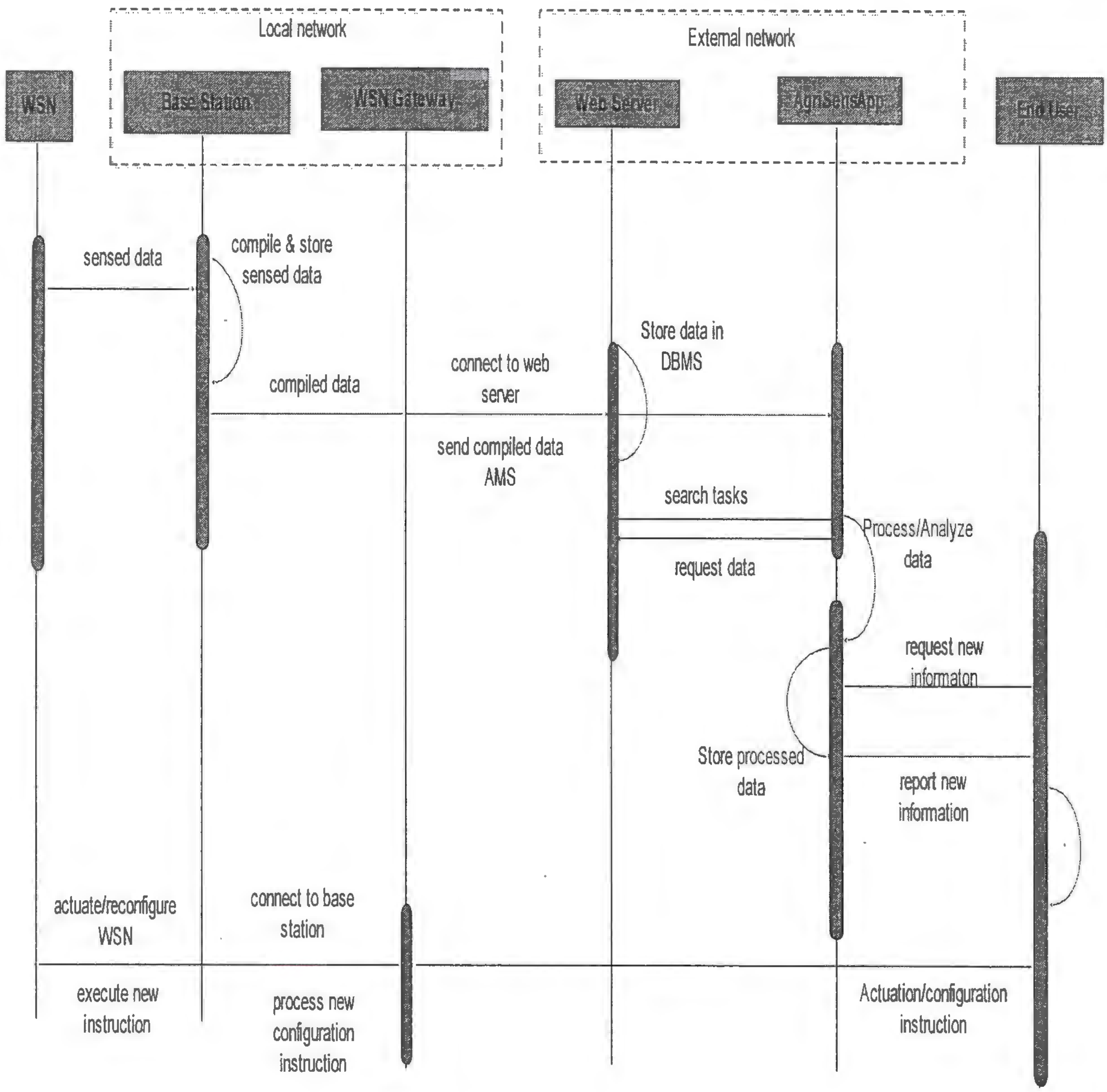

Figure 4.5. Framework operation

4.7 Chapter Summary

The proposed framework emphasizes the need for a broader scope when dealing with QoS in precision agriculture, given that by definition, PA encompasses all aspects of agriculture production, not just the field aspects of it. This is the justification for the inclusion of an agriculture management system into the sensor network. We have demonstrated the relationship between the physical WSN quality of service and the management application (AgriSensApp) designed to translate and interpret sensed data into commercially useable information, or as feedback instructions for the maintenance of the physical network. The inter-operability of the two phases of the framework is what we judge to be the key element towards achieving the desired quality of service and improving yield and productivity of maize cultivation.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Overview

In this chapter, we present a comparative analysis of the two WSN topologies simulated in the previous chapter. A nonagonal geometric structure topology and a grid topology were constructed using ZigBee communication devices and simulated with ZigBee 802.15.4. It is important to state that the results obtained here are based on the analysis of parameters at different layers of ZigBee protocol.

5.2 End-to-End Delay (One-way delay)

End-to-end delay is the amount of time taken for a packet to be transmitted from source to destination through the network. Figure 5.1 shows the compared results of end to end delay for the two topologies. The Y-axis represents end to end delay in seconds and the X-axis is simulation time in hours and minutes.

5.2.1 discussion

The results show end to end delay for the nonagon topology to be higher than that of the grid topology. The results graph indicates that in the first 2 minutes of simulation start, end to end delay for grid topology is at a constant 0.38 seconds, approximately, before spiking to about 0.47 seconds in a space of 2 to 5 minutes of simulation. But, from about 6 minutes into simulation, grid topology maintains a constant fluctuating end to end delay between 0.45 seconds and 0.48 seconds.

The nonagon topology on the other hand, showed a sharp spike in end to end delay right from the start of simulation. End to end delay increased constantly from start of simulation to around 5 minutes into simulation, then gradually decreased from a peak of 1.37 seconds. The decrease was kept to within the range of 1.35 seconds to 1.3 seconds delay until the 45-minute mark of simulation time, when it maintained at 1.3 seconds delay until end of simulation. One possible explanation for difference in end to end delay for the two topologies could be the router positioning in the networks. Grid topology routers are positioned in a way that allows traffic to travel the shortest route to the sink node, and thus take lesser time to reach the destination.

For cultivation of maize, end to end delay is a measure that could be over looked if the values do not exceed extreme levels such that they cripple the network. The reasoning for this decision is the type of data usually sensed in a maize field is not particularly time sensitive. For instance, the effect of delayed temperature or humidity readings would not have extreme consequences on the health of the crop, provided a reasonable amount of data reaches the destination. However, if the preference is a network with low end to end delay, then the grid topology would be the best strategy to implement.

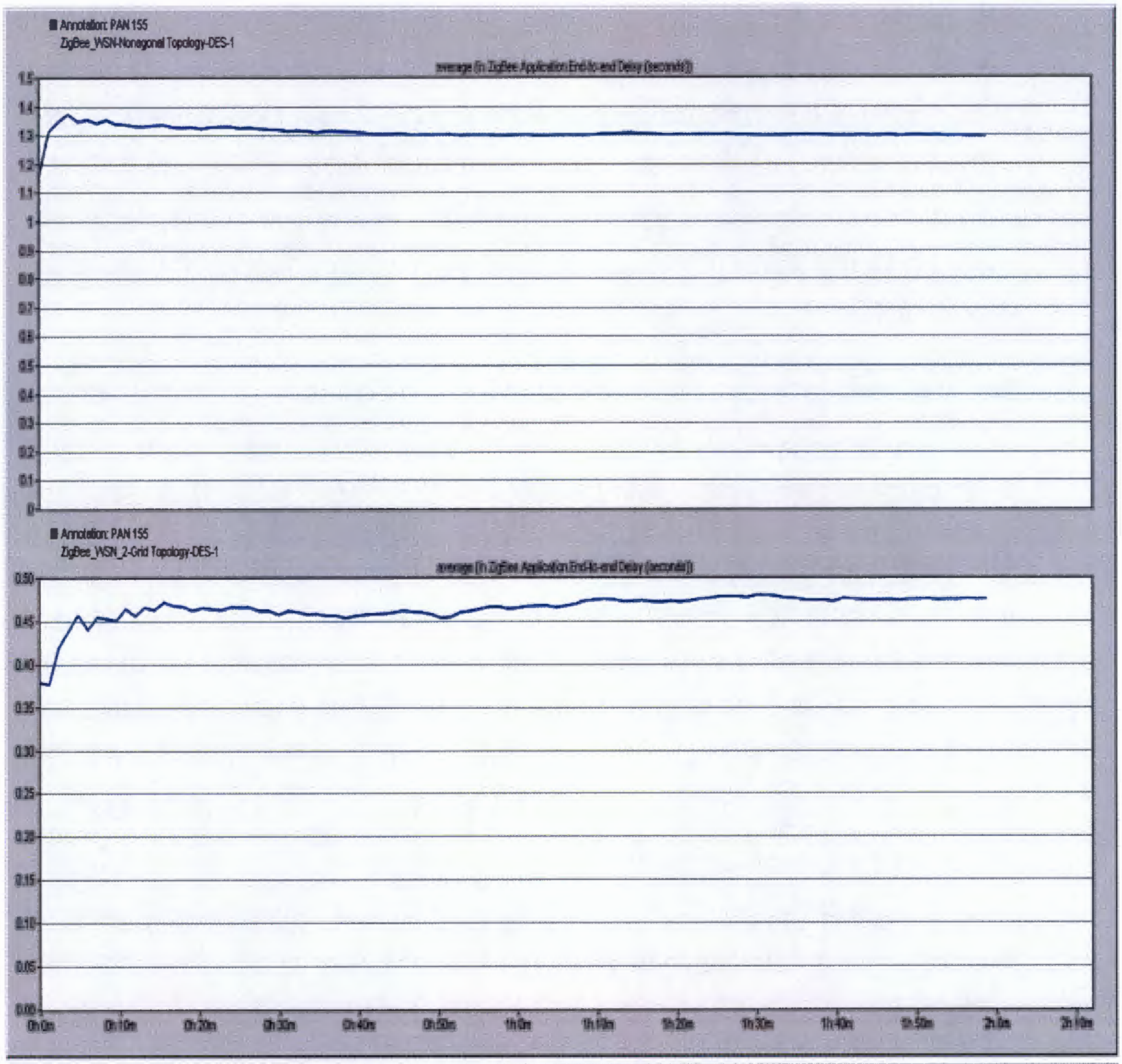

Figure 5.1. End-to-End Delay for Grid and Nonagon Topologies

5.3 MAC Throughput

The MAC throughput is defined as the total number of bits forwarded from the ZigBee MAC layer to the higher layer in all WPAN of the network [34].

5.3.1 Discussion

The results indicate a higher throughput for the Nonagon topology than for the grid topology. As can be seen from the graph, Nonagon throughput increased sharply from about 1,300,000 bits/sec to 1,700,000 bits/sec in the first 8 minutes of simulation. From 8 minutes to 2 hours, which is the end of simulation, Nonagon throughput maintains a gradual increase from 1,700,000 bits/sec to just under 1,800,000 bits/sec. Observing this trajectory, it suggests that this steady increase would continue in the same manner if the simulation time were extended.

The grid topology throughput on the other hand, did not show a similar trajectory. After rising from about 280,000 bits/sec to 320,000 bits/sec in the first 2 minutes of simulation, grid throughput maintains a constant value of 320,000 bits/sec until end of simulation.

The high throughput of the nonagon topology is a desirable PA attribute for maize production, making nonagon topology the preferred topology for throughput implementation. Efficient PA performance requires an abundance of data from which informed decisions could be made, a high throughput network guarantees a high volume of data delivered to the destination. If we consider a field probe for primary maize cultivation nutrients like Nitrogen, Phosphorus, and Potassium; it would only be prudent to conduct such a test if an adequate amount of data is provided by the WSN, otherwise the test would produce inconclusive results. A sensor network with high throughput guarantees adequate data for extensive testing, informed decision making, and ultimately increased crop production.

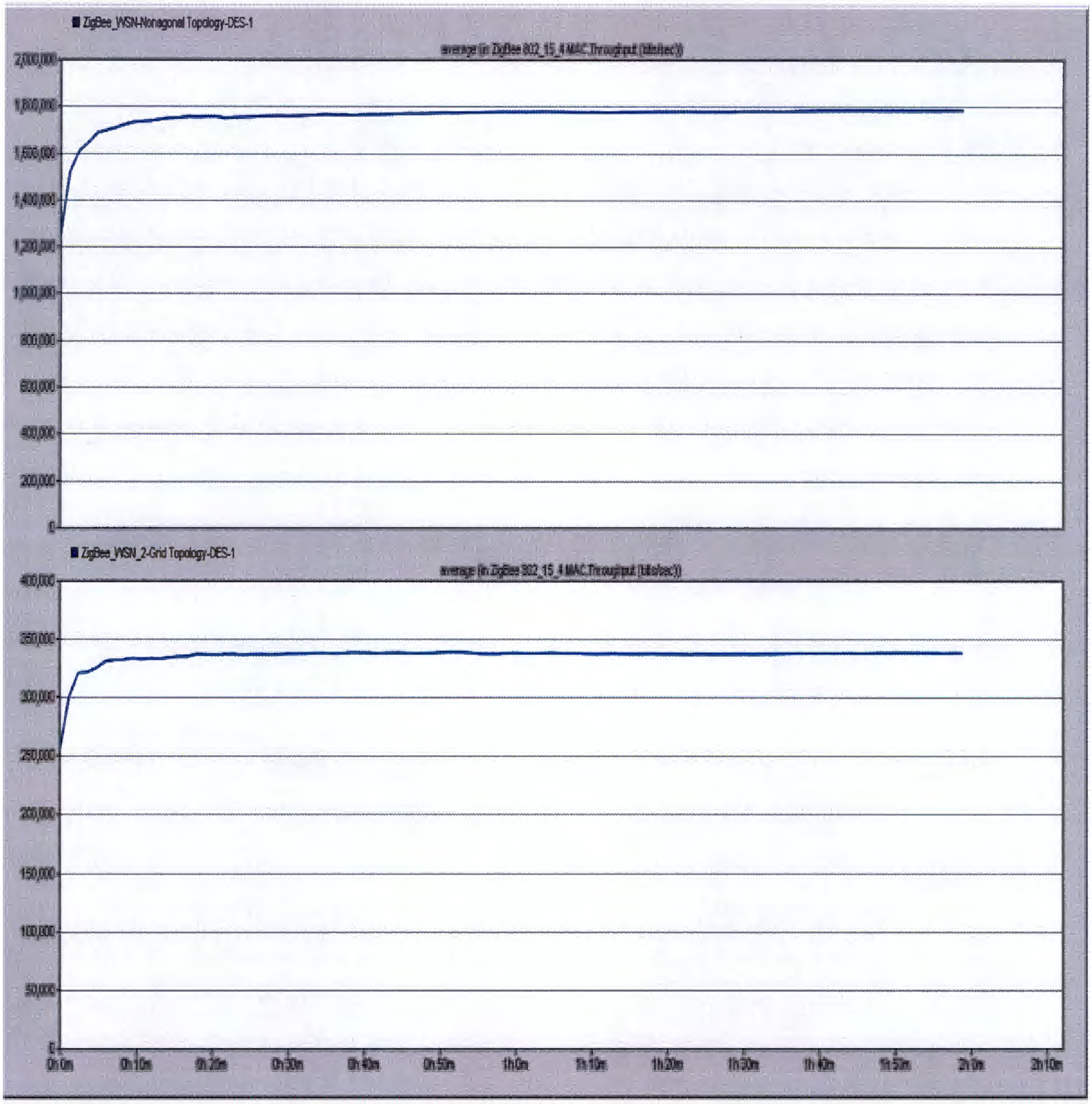

Figure 5.2. MAC Throughput for Grid and Nonagon Topologies

5.4 Packets Dropped

This metric represents the number of data packets dropped by the network layer due to not being able to join a network. Figure 5.3 shows the packets dropped results compared for the two topologies. The Y-axis represents the number of packets dropped while the X-axis is the time in hours and minutes.

5.4.1 Discussion

The results showed grid topology to have a higher number of packets dropped at the network layer than the nonagon topology. Both topologies showed a dramatic increase in packets dropped at the start of the simulation. In the nonagon topology, the number of packets dropped dramatically increased from 1,220 packets to 1,600 packets during the first 10 minutes of simulation then maintained a gradual increase from 1,600 to 1,650 packets at 45 minutes into simulation. From there, it maintained a constant 1,650 packets dropped until end of simulation.

On the other hand, grid topology had a dramatic spike from 1,260 packets dropped to 1,650 packets dropped in the first 8 minutes of simulation. It then maintained a gradual increase until 44 minutes into simulation, rising to a peak of 1,750 packets dropped, this value was maintained until the end of simulation.

Nonagon topology's low packets dropped is a suitable attribute for PA implementation of maize cultivation. A high number of packets dropped means that the sensor network is not delivering complete data to the base station for processing, which translates to unreliable data and inconsistent field readings. This is especially essential when monitoring conditions such as temperature or humidity, which could have multiple variations in a short space of time. It is therefore important in maize cultivation, to have a WSN that guarantees a low and consistent number of packets dropped.

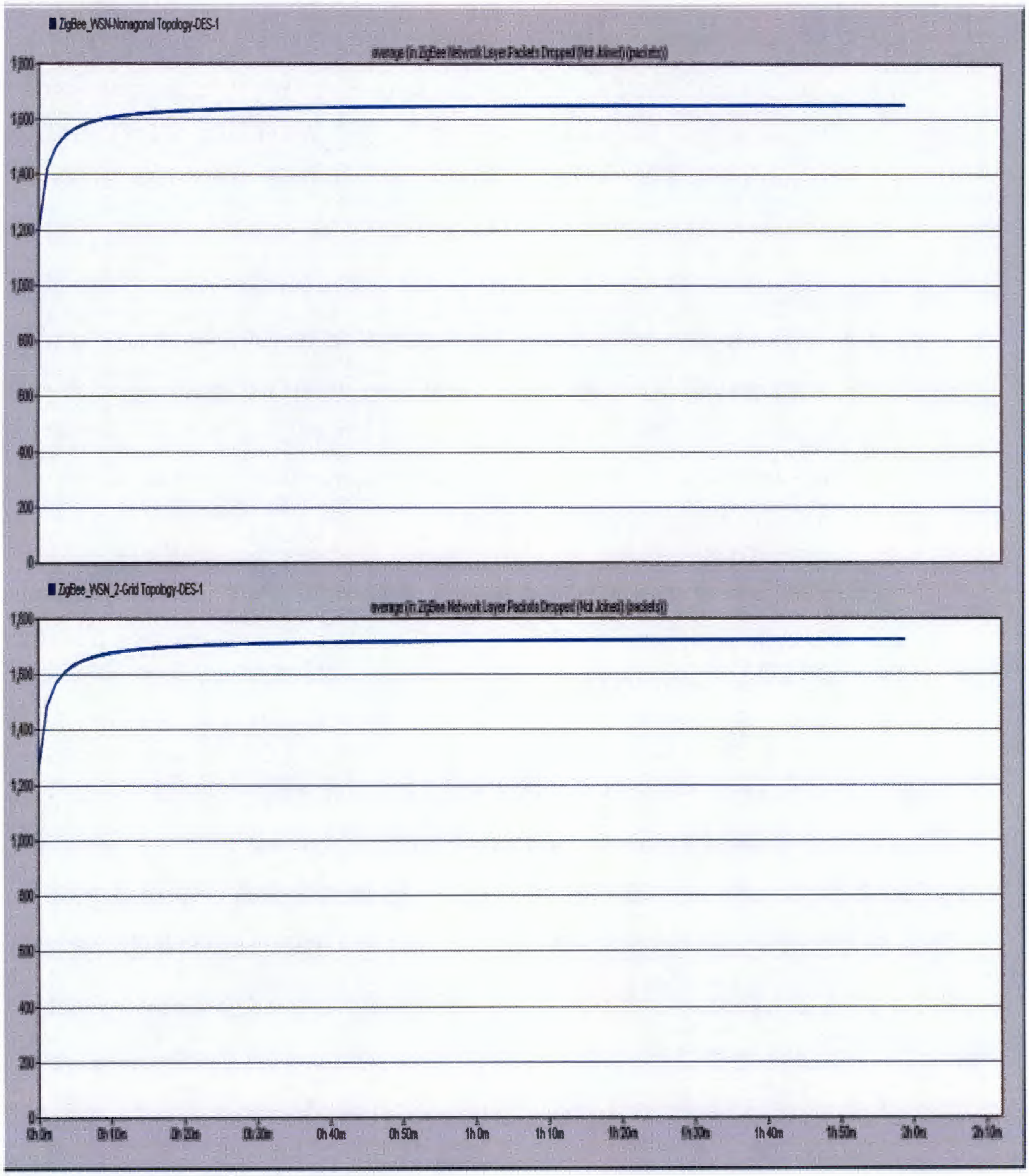

Figure 5.3. Packets Dropped for Grid and Nonagon Topologies

5.5 MAC Delay

MAC layer delay defines the end-to-end delays of all the packets received through the ZigBee MACs of all WPAN nodes in the network and forwarded to the higher layers. This delay has a large impact on the overall performance of the network, since all data packets are sent to the MAC layer for further processing. Figure 5.4 illustrates the delay at the MAC layer for the two topologies. The Y-axis and X-axis represent MAC delay in seconds and simulation time in hours and minutes respectively.

5.5.1 Discussion

The graph indicates that the nonagon topology had a higher Mac delay than the grid topology. At the start of the simulation, nonagon delay increases sharply from 0.077 seconds to 0.080 seconds after 2 minutes into simulation, before peaking at 0.082 seconds after 13 minutes into simulation. From then on, the topology maintains a constant delay of 0.080 seconds at around 47 minutes into simulation.

The grid topology also showed a short spike in delay at the start of simulation, increasing from 0.030 seconds to about 0.033 seconds. But from then on, it maintained a constant delay of 0.033 until the end of simulation.

In a maize field, MAC delay represents the end to end delay of each parameter being monitored by the WSN. So, a high MAC delay means delayed temperature, humidity, soil chemical and biological data readings throughout the network. It is essential to keep the value of this parameter to a minimum, to ensure an uninterrupted cycle of data sensing and data processing. In this case, a grid topology is a better choice for implementation as it ensures a high volume of data packets sent to MAC for processing.

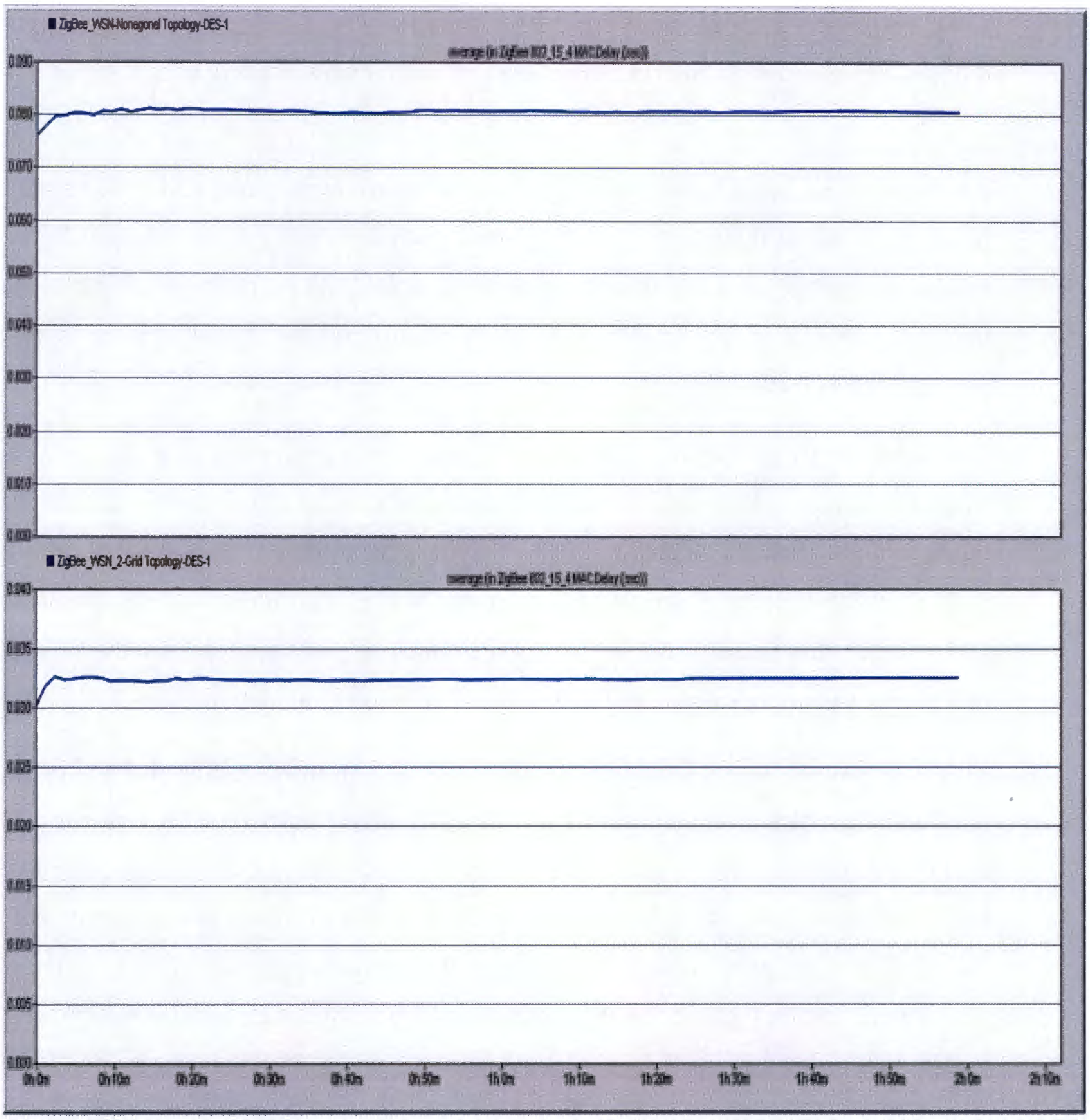

Figure 5.4. MAC Delay for Grid and Nonagon Topologies

5.6 Data Dropped

This metric represents the total higher layer data traffic (in bits/sec) dropped by all the ZigBee MACs in the network as a result of consistently failing retransmissions. Figure 5.5 shows the results of data dropped for both topologies. The Y-axis and X-axis represent data dropped in bits/sec and simulation time in hours and minutes respectively.

5.6.1 Discussion

Disabling the acknowledgement (ACK) status, as shown in the simulation configuration and parameter setup in the chapter 3 above, forced the number of packets dropped to zero (0) packets for both topologies. This outcome was expected, we purposefully elected to disable the ACK status to reduce transmission delays due to queuing. This helps overall network performance as well.

Figure 5.5 illustrates the outcome if ACK status is enabled, note that the framework's parameter setup is designed to have a disabled ACK status. The results indicate that the nonagon topology had a higher data drop than the grid topology. Nonagon data drop spikes from 57, 000 bits/sec to a peak of 61,000 bits/sec in the first 5 minutes of simulation. It then maintains at this value until end of simulation. The grid topology on the other hand, maintained a constant value of 4, 000 bits/sec from start of simulation till end.

This is an integral metric for PA because dropped data means lost information, and all data is essential for high crop productivity and the efficient application of PA processes. A high data dropped value means that the sensor network is not efficient in its management of data traffic, which in turn means that adequate information about the crops is not being collected for analysis. The grid topology's low data drop makes it a more suitable strategy for deployment in this scenario, as it registers more successful data retransmissions and thus greater chances of getting all the necessary data delivered to destination.

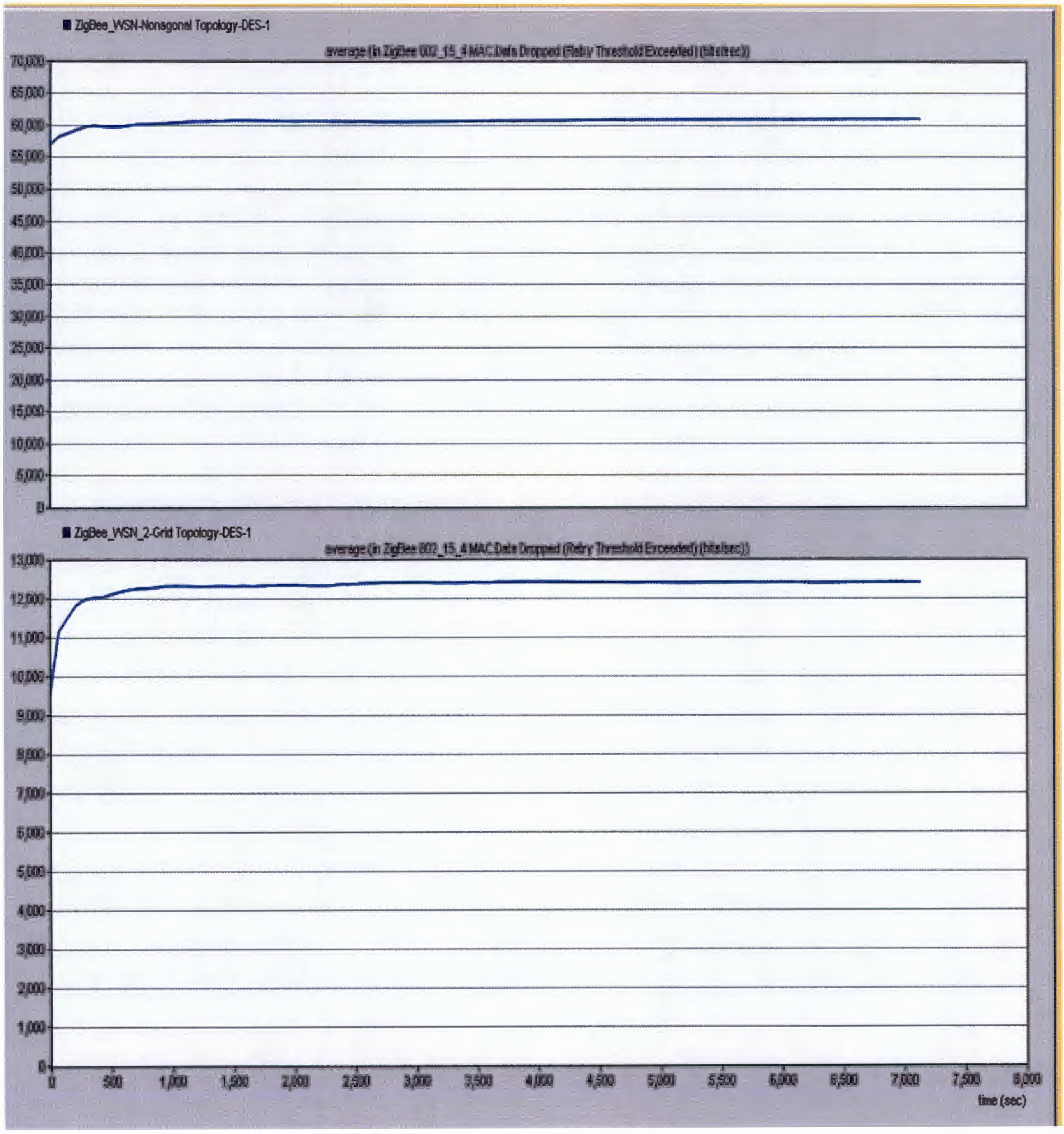

Figure 5.5. Data Dropped for Grid and Nonagon Topologies (ACK Status enabled)

5.7 Chapter Summary

In this chapter, we presented the results obtained from the simulations performed on the two network topologies. A comparative analysis of the two sets of results, and discussions were also presented, giving a better understanding of the performances of the topologies with respect to quality of service. The behavior of ZigBee 802.15.4 protocol was analyzed at different layers of the protocol to examine how data traffic behaves at each layer of a sensor node, understanding this behavior is important because in a WSN deployed in a field; the level of node sensitivity is hampered by many obstacles that limit the efficiency of a sensor to detect high percentages of environmental parameters. the analysis showed the nonagon topology to be better at delivering the highest amount of data to the destination, while the grid topology had lesser delays in its traffic.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Overview

This chapter covers the final observations on the simulation results and analysis presented in the previous chapter. The chapter gives a general overview of the entire research work. Overall conclusions on the results obtained and performance of the proposed framework are presented, in relation to the main aim and objectives of this research work. Suggestions for future areas of research interest and expansion are also presented here.

6.2 Summary

A research study was carried out on Wireless Sensor Networks (WSNs) and their application in Precision Agriculture (PA) activities. The study was focused on the design of a WSN framework that offered quality of service (QoS) in PA application of maize cultivation.

The need to improve crop production and increase profits in the agriculture industry will always exist, however, there are many challenges to this pursuit. The desire for more efficient methods of farming and increasing crop yield led to a need for integrating technology into common agriculture practices, with a goal of increasing crop yields, profits, and reduce waste of resources.

The study highlights the design of a PA framework combining a physical WSN, and a conceptually designed agriculture management system (AMS) called Agriculture Sensing Application (AgriSensApp). The application is a web-based system that serves the function of interfacing the user with the physical network, by allowing users to access the system through a GUI and visualize, manipulated, sensed data in the form of web pages and datasheets within the system. In essence, the AMS is the user's remote access key to the physical network from any location in the world provided they have internet connectivity. The user is able to set new instructions or commands to active actuators remotely, to initiate irrigation process or to re-configure the network.

WSNs have become integral to the expansion of PA on a commercial scale. This is mainly because they are small, inexpensive, and easily deployable technologies that do not require a lot of human interaction or monitoring once the network has been deployed. WSNs have the advantage of being self-organizing and self-configuring networks. Meaning that if one or two sensors in a network failed, the network would simply re-configure its connections with the remaining operational devices. This durability and ability to repair their own communication links is what has made WSNs the best option for guaranteeing QoS in PA.

QoS in PA could be viewed as the capacity or ability to efficiently utilize available resources to maximize production. To this end. Efficient communication protocols such as ZigBee 802.15.4 were developed specifically for low-data, low-power communications like WSNs. Research shows ZigBee protocol to be one of the best performing communication protocols, on account of its low energy consumption and support for large-scale network deployment. It has the capability to sustain networks with up to 64, 000 devices, this makes ZigBee very suitable for use in WSNs for monitoring large-scale farms with high crop densities.

This research study carried out simulations on WSNs operating with ZigBee protocol. Using Optimized Network Engineering tool (OPNET) modeler, two WSN topologies were designed for simulation; a Nonagonal geometric structured topology and a Grid topology. The two topologies were designed to evaluate the performance of ZigBee protocol and the effect of WSN topologies on QoS provision. Another purpose for conducting the simulation was to determine which topology was best suited for implementation in a large-scale sensor network deployment, and for integration into the overall framework designed for PA.

The results of the simulations generally showed the nonagon topology to have a more desirable performance, as it performed better than the grid topology for the parameters that are considered most essential in PA cultivation of maize. The evaluation of QoS was based the metrics; throughput, end-to-end delay, MAC delay, packets dropped, and data dropped. For throughput and packets dropped, the nonagon topology had better performance. However, the grid had the better performance for delays. This split in the average performances of the two scenarios highlighted a crucial problem in the decision-making process for selecting network deployment strategies, the choice of network topology or design strategy will almost always have to consider trading off certain performance metrics and keep those that are judged as most required. In the case of PA for maize cultivation, it is logical to reason that a WSN that guarantees an abundant volume of sensed data is delivered for processing is preferable to a network that delivers incomplete and inadequate data, but at a faster rate.

In general, the research demonstrated the behavior of WSNs with regards to topology manipulation, and the effect of topology changes on QoS performance. Beyond that, the study also sheds light on the practical implications of PA and the potential benefits of an efficient agriculture management system on a large-scale farming process.

6.3 Conclusion

We conducted this research study on the quality of service provided by a wireless sensor network constructed with ZigBee devices and communicating over ZigBee 802.15.4 communication protocol. Two network topologies were constructed on OPNET modeler 14.5. We designed a nonagonal geometric structure topology with 9 routers forming its vertices, and a grid topology with router overload for short-path relay communication. Network parameters used were; throughput, end-to-end delay, MAC delay, packets dropped, and data dropped.

The simulation results showed that the nonagon topology had a better throughput and maintained a lower count of total packets dropped than the grid topology. On the other hand, the grid topology performed better than the nonagon topology for both MAC delay and end-to-end delay. These results are directly related with each other. The nonagon throughput is higher because the number of packets dropped in its traffic is lesser than that of the grid topology. Likewise, the grid end-to-end delay being less is directly the reason for its MAC delay being less as well. The delay is a factor of the packets queuing in the network. Grid topology having a lower delay value could be interpreted has being the result of the topology having shorter queues, compared to the nonagon topology. This is one of the benefits of using routers as relays positioned closer to the sink node.

Ultimately, we can conclude with closer inspection of the results that the two topologies both exhibit desirable and undesirable results with respect to the parameters evaluated. However, it would be prudent to note that these variances in performance with respect to specific metrics are unavoidable in most, if not all sensor network communications. This means that trade-offs must be made in accordance with user preferences.

Finally, we can conclude that the study successfully presented the design and evaluation of a nonagonal geometric structured wireless sensor network topology that exhibited acceptable QoS performance with respect to desired communication performance parameters, and consequently met all the objectives and goals set forth in chapter 1. This conclusion also led us to elect the nonagon topology to be the backbone of our framework based on the following reasoning:

While the nonagon topology exhibited higher levels of delay than the grid topology, the parameters that are essential to our particular precision agriculture activity; in the PA cultivation of maize, the desired network performance is the quantity of sensed data delivered to the destination for processing. Therefore, a network topology that exhibits a high level of throughput is preferred to one that only displays low delays. Moreover, the nonagon topology also has the capacity for expansion by increasing the number of end devices. For the purpose of our framework, network delay is a measure that can be traded-off if the alternative is high data volume delivered. However, to assure continued QoS in the network, any existing delays in the network must be kept at a reasonable level.

The ability to expand a WSN over large land spaces is a massive goal for PA researchers. The introduction of geometric structures into WSN topologies and the positive results that these topologies have shown so far presents a possibility of expansive sensor networks in the future. The results presented by other researchers conducting similar works paint a bright future for the technology, and broader, positive implications for the global food environment. The successful deployment of a WSN in the Malawian farming environment [41] yielded positive implications for that country's food production capabilities, if such research is allowed to continue on. Similar projects were conducted in Egypt which indicated that applying PA technology to the local industry would yield benefits over time [28].

6.4 Future Work

In the future, we intend to expand on our framework by conducting a full-scale field deployment to the specifications proposed in this study, so as to study the real-life implications of the framework. The deployment would also include a full implementation of the web-based agriculture management system we designed to work in conjunction with the physical WSN.

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