

**IMPLEMENTATION OF SELECTED KEY PERFORMANCE  
INDICATORS FOR ENHANCED RICE PRODUCTION IN A REMOTE  
GEO-LOCATION USING WIRELESS SENSOR NETWORK**

**BY**

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**A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL  
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COMMUNICATION ENGINEERING**


**FEBRUARY, 2023**

## CERTIFICATION

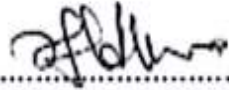
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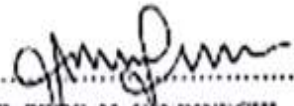
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## **DEDICATION**

This research work is dedicated to the loving memory of my dear mother, late Mrs. Roslyn Oyigbo, who inspired my quest for knowledge, particularly this programme but unfortunately could not live to see the end of it.

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## LIST OF ABBREVIATIONS

WSN – Wireless Sensor Network  
ZC – Zigbee Coordinator  
KPI – Key Performance Indicator  
OPNET - Optimized Network Engineering Tool  
6LoWPAN - IPv6 over Low-Power Wireless Personal Area Networks  
IEEE - Institute of Electrical and Electronics Engineers  
HART - Highway Addressable Remote Transducer  
LAN – Local Area Network  
WLAN – Wireless Area Network  
OS – Operating System  
PAN – Personal Area Network  
MAC – Medium Access Control  
WPAN – Wireless Personal Area Network  
PHY – Physical Layer  
NWK – Network Layer  
TDMA – Time Division Multiple Access  
WFDs – Wireless Field Devices  
TDMA – Time Division Multiple Access  
TCP – Transfer Control Protocol  
TCP/IP – Transfer Control Protocol/Internet Protocol  
IETF – Internet Engineering Task Force  
IPv6 – Internet Protocol version 6  
 $\mu$ IP – Micro-Internet Protocol  
CSMA – Carrier Sense Multiple Access  
USB – Universal Serial Bus  
Tcl -Tool Command Language  
GUI – Graphical User Interface  
HFGCS – High Frequency Global Communication Systems  
GPRS – General Packet Radio Service  
PV – Photovoltaic  
CSMA/CA – Carrier Sense Multiple Access with Collision Avoidance  
ZED – Zigbee End Device  
ZR – Zigbee Router  
SPDT -Single Pole Double Throw  
SMPS – Switching Mode Power Supply

## ABSTRACT

This study was conducted to implement selected key performance indicators (KPIs) for enhanced rice production by addressing five major challenges that face rice farmers especially in Nigeria which include non-availability of water/rain for year-round cultivation, disproportionate application of fertilizer, weed control/prevention, pest/disease control, and rodents and birds invasion. In order to achieve this, a Zigbee-based Enhanced Wireless Sensor Network (eWSN) was used to model various network scenarios to demonstrate data sensing of different environmental variables in a given farm land. This was achieved by varying network devices at different scenarios using OPNET simulator and understudying the network performances. Each new set of network devices are integrated to a Zigbee Coordinator (ZC) which assigns an address to its members and forms a personal area network (PAN), thus representing data sensing of a particular environmental variable. In all, three different scenarios were designed and simulated. Each of the temperature and humidity, motion and soil nutrient sensors generated about 29bps of traffic. At the Coordinators, steady stream of traffic was received. The temperature and humidity Coordinators, received a traffic of 64bps each, while the soil nutrient Coordinator received data traffic of 96bps. The result of the design showed effective communication between different network components and further gave insight into how WSN could be used to monitor a number of different environmental variables on a farm field simultaneously, yet co-operatively. By implementing the KPIs, the result equally showed an estimated yield increase from 2.2 to 8.7 metric ton per hectare of a rice farm.

*Key words: Wireless Sensor Network, Zigbee, Coordinator, Router, End Device, Sensor Node, OPNET Simulator, Multi-input Power*

# CHAPTER ONE

## INTRODUCTION

### 1.1 Background of the Study

Food is one of the basic necessities of life, thus, the need for improved production strategy. Nigeria has been a mono-economic country, with revenue from oil accounting for over 90% of her foreign exchange earnings (Agbaeze et al., 2015). Due to the failure of her successive governments to properly explore and develop other sectors of the economy especially agriculture, the need for improved system of agricultural sector development cannot be over emphasized considering the exploding population in the face of dwindling oil revenue.

Rice is unarguably considered a universal food crop, being a staple food for well over half the world population, particularly of India, China and a number of other countries in Africa and Asia (FAO, 2006). It has become a highly strategic and priority commodity for food security in Africa (Macauley, 2015). Consumption is growing faster than that of any other major staple food on the continent because of high population growth, rapid urbanization and changes in eating habits (Seck et al., 2013). It is proven to be the single most important source of dietary energy in West Africa and the third most important for Africa as a whole (Macauley, 2015).

The importance of rice in Nigeria is no longer the question but rather how the growing demand can be met to reduce its importation and be self-sufficient. Many theories and hypotheses were tried for our rice production systems yet the self-sufficiency level has not been achieved (Fashola et al., 2007). Rice is the fourth largest crop produced in Nigeria after sorghum, millet and maize (Fashola et al., 2007). Over the years, production has increased 6 folds with Nigeria producing 3.3 and 3.6 million tons of paddy rice in 2000 and 2005 respectively (FAOSTAT, 2007).

This production growth has continued up to the anticipated 4.8 million tonnes (2.9 million tonnes, milled basis) for 2015, though, down by 3 percent from the 2014 all-time high (FAO, 2015). Despite the increase in rice production in the country, it is still clear that the production has consistently fallen below the national demand (Abba and Mohammed, 2000). The consumption of rice has increased drastically. This was confirmed by Hirose and Wakatsuki, (2002) that in Nigeria consumption per capita had jumped from 2.9kg in the period of 1970 – 1974 to 24.1 kg between 1995 and 1999. Recently, rice consumption in Nigeria stands at an all-time high of 7 million Metric Tonnes (MT) with only 2.7 million MT produced by the farmers in Nigeria (ThisDay Newspaper, November 5, 2016). This means that there is a gap of 4.3 million MT to be cushioned by importing it into the country. What this figure represents is that only about 39 per cent self-sufficiency ratio is available.

Nigeria has a potential land area for rice production of about 4.6 billion hectares. Of this abundance, only about 1.7 million hectares representing 35% of the Nigerian total land mass is grown with rice (Imolehin and Wada, 2000). The limited capacity of the Nigerian rice sector to meet the domestic demand has been attributed to several factors; notable among them is the declining productivity due to low adoption of improved production practices and non-availability of indigenous technologies. This has caused a wide gap to exist between potential and actual yield per hectare. According to Oyekanni, Okeleye and Okomji (2008); Nwite, Igwe and Wakatsuki (2008) from their research analysis based on their on-station and on-farm trials, showed that adoption of technologies and improved management practices could lead to substantial yield increase in rice production and help to attain the much needed growth in the Nigerian rice sub-sector. There is no gainsaying that availability of indigenous and sustainable agricultural technology for Nigerian resource-poor rice farmers is important especially now

that government yearns for economic diversification due to the continued fall in oil revenue and her effort to achieving food security.

In-lieu of the rice supply shortage in Nigeria occasioned by poor production output by Nigerian farmers, the researcher looks at developing an environmental monitoring system of a selected key performance indicators (KPIs) that utilizes wireless sensor network technology for improved rice production, capable of alleviating the production deficit of the country and engendering for export. The proposed solution is a multi-functional and integrated system. It is an enhanced Wireless Sensor Network (eWSN) technology solution that can do more than just irrigation work as has been widely reported by other researchers on the subject matter. Consequently, the researcher designed an eWSN system that is capable of:

- Ensuring automated irrigation of a rice field for year-round production.
- Adaptable for disease control/prevention via automated application of pesticides.
- Adaptable for weed control/prevention via automated application of herbicides.
- Adaptable for rodents and birds control/prevention via automated buzzer activation mechanism for scaring animals.
- Adaptable for even and right proportion of fertilizer application.

The solution when adopted would greatly improve rice production in Nigeria and help to revive her ailing economy.

## **1.2 Problem Statement**

Rice farmers especially in Nigeria are faced with five major challenges that cause loss in man-hour and other scarce resources, which hitherto limit production. They include non-availability of water/rain for year-round cultivation,

disproportionate application of fertilizer/manure, weed control/prevention, pest/disease control, and

rodents/birds invasion. These challenges have been identified as key performance indicators that would engender increased yield if addressed using technology.

### **1.3 Objectives of the Study**

The aim of this thesis is to Implement Selected Key Performance Indicators (KPIs) for Enhanced Rice Production in a Remote Geo-location using Wireless Sensor Network.

The specific objectives include:

- I. To model the Selected Key Performance Indicators using Stochastic Model to determine the effect of additional technology input to the overall yield of a rice farm.
- II. To model the Wireless Sensor Network using WSN modelling software such as OPNET for the purposes of data collection and transmission between the various component units of the network.
- III. To design a multi-input power system for the Coordinator (Sink node), and evaluate the required amount of power for the wireless sensor devices and for the actuator system using circuit wizard.
- IV. To simulate the WSN design, analyze data transmitted by the WSN nodes and generate the graphical representations of the characteristic system performance.

## **1.4 Justification of the Study**

The primary aim of every innovation is usually to improve upon an existing practice by simplifying a process (es) and ultimately making life more comfortable than it were in terms of labour and increased revenue.

Thus, the implementation of the selected key performance indicators for enhanced rice production using Wireless Sensor Network (WSN) technology was expected to be of benefit in the following ways:

1. The multi-functionality of the system will no doubt increase rice yield per hectare of farm land because of its versatility, and that in turn would guarantee national rice self-sufficiency and ultimately rice export.
2. It will create new job opportunities and encourage the youths to become rice farmers.
3. In terms of revenue generation, there shall be more income to the farmers due to bumper harvests and a source of foreign exchange earning to the government from exports.
4. The system would eliminate losses in man-hour and wastages in farm inputs.
5. The system would generally ensure availability of farmland for year-round production since farming has become mechanized.

## **1.5 Scope of the Study**

Available literature revealed that most of the literally works done in the area of WSN application to agricultural product development at farm level were based on irrigation system. The literature described WSN framework showcasing how temperature and humidity sensors can be used to monitor farm environment and activate an irrigation system automatically. Leveraging on this ideology, some

authors have developed and built a working and functional WSN based irrigation system.

This thesis expanded on the existing knowledge of WSN design by incorporating into its model, intrusion detection system for rodents and bird control, adaptable

feature for pesticide and herbicide application and an automated system for soluble fertilizer

application as key performance indicators for enhanced rice production. The researcher used software system (OPNET) to model the enhanced WSN technology. The system was further integrated on software level and simulations using OPNET 14.5A demonstrated to study some performance metrics of the network such as traffic sent (bits/sec), traffic received (bits/sec), End-to-End (ETE) delay, throughput (bits/sec) and Media Access Control (MAC) load (bits/sec).

The work did not cover those areas in WSN technology such as Routing Algorithm designs and battery life optimization techniques.

## CHAPTER TWO

### LITERATURE REVIEW

#### **2.1 Wireless Sensor Network Overview and Historical Development**

A Wireless Sensor Network (WSN) consists of spatially distributed autonomous sensors to monitor physical or environmental conditions (i.e., temperature, sound, vibration, pressure, humidity etc.) and to cooperatively pass their data through the network to a main location (Manoj Ahlawat, 2013). WSN is built of few to several hundreds or even thousands of sensors or nodes, where each node is connected to one (or sometimes several) sensors. Each sensor network node has typically several parts: a radio transceiver with an internal antenna or connection to an external antenna, a microcontroller, an electronic circuit for interfacing with the sensors and an energy source (i.e., battery or an embedded form of energy harvesting). The topology of the WSNs, from a simple star network to an advanced multi-hop wireless mesh network can vary. The propagation technique between the hops of the network can be routing or flooding. A wireless sensor network is made up of three components: Sensor Nodes, Task Manager Node (User) and Interconnect Backbone as shown in figure 2.1. Each Sensor Node can contain various sensors and actuators that are used to collect the data and control physical processes. The collected data is transferred to the user through the network that can include Internet segments. Besides collecting the data and controlling actuators, a node may need to perform some computation on the measured data. Direct communication between individual nodes can also be required. The Task Manager Node (User) performs tasks in data storage, analysis and display.

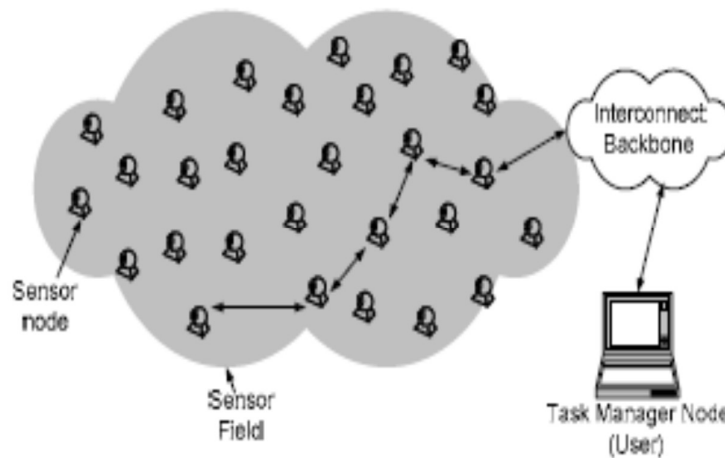


Figure 2.1: Wireless Sensor Network (WSN) (Manoj Ahlawat, 2013)

The origin of the research on WSNs can be traced back to the Distributed Sensor Networks (DSN) program at the Defense Advanced Research Projects Agency (DARPA) at around 1980 (Qinghua and Ilangko, 2010). By this time, the Advanced Research Projects Agency Network (ARPANET) had been operational for a number of years, with about 200 hosts at universities and research institutes (Chong & Kumar, 2003). DSNs were assumed to have many spatially distributed low-cost sensing nodes that collaborated with each other but operated autonomously, with information being routed to whichever node was best able to use the information. At that time, this was actually an ambitious program. There were no personal computers and workstations; processing was mainly performed on minicomputers and the Ethernet was just becoming popular (Chong and Kumar, 2003). Technology components for a DSN were identified in a Distributed Sensor Nets workshop in 1978 (Yechian Yemini, 1978). These included sensors (acoustic), communication and processing modules, and distributed software. Researchers at Carnegie Mellon University (CMU) even developed a Communication-oriented operating system called Accent (Rashid and Robertson, 1981), which allowed flexible, transparent access to distributed resources required for a fault-tolerant DSN.

A demonstrative application of DSN was a helicopter tracking system (Myers et al., 1984), using a distributed array of acoustic microphones by means of signal abstractions and matching techniques, developed at the Massachusetts Institute of Technology (MIT). Even though early researchers on sensor networks had in mind the vision of a DSN, the technology was not quite ready. More specifically, the sensors were rather large which limited the number of potential applications. Further, the earliest DSNs were not tightly associated with wireless connectivity. Recent advances in computing, communication and microelectromechanical technology have caused a significant shift in WSN research and brought it closer to achieving the original vision. The new wave of research in WSNs started in around 1998 and has been attracting more and more attention and international involvement. In the new wave of sensor network research, networking techniques and networked information processing suitable for highly dynamic ad hoc environments and resource constrained sensor nodes have been the focus. Further, the sensor nodes have been much smaller in size and much cheaper in price, and thus many new civilian applications of sensor networks such as environment monitoring, vehicular sensor network and body sensor network have emerged. Again, DARPA acted as a pioneer in the new wave of sensor network research by launching an initiative research program called SensIT (Kumar and Shepherd, 2001) which provided the present sensor networks with new capabilities such as ad hoc networking, dynamic querying and tasking, reprogramming and multitasking.

## **2.2 Hardware Platform for WSN**

The basic hardware components of a sensor node include a radio transceiver, an embedded processor, internal and external memories, a power source and one or more sensors (Qinghua and Ilangko, 2010). One widely used sensor node platform is the Mica2 Mote developed by Crossbow Technology.

### **2.2.1 Transceiver**

A transceiver is responsible for the wireless communication of a sensor node. The various choices of wireless transmission media include Radio Frequency (RF), Laser and Infrared. RF based communication fits to most of WSN applications. The operational states of a transceiver are Transmit, Receive, Idle and Sleep. Mica2 Mote uses two kinds of RF radios: RFM TR1000 and Chipcon CC1000. The outdoor transmission range of Mica2 Mote is about 150 meters.

### **2.2.2 Embedded Processor**

In a sensor node, the functionality of an embedded processor is to schedule tasks, process data and control the functionality of other hardware components. The types of embedded processors that can be used in a sensor node include Microcontroller, Digital Signal Processor (DSP), Field Programmable Gate Array (FPGA) and Application Specific Integrated Circuit (ASIC). Among all these alternatives, the Microcontroller has been the most used embedded processor for sensor nodes because of its flexibility to connect to other devices and its cheap price. For example, the newest CC2531 development board provided by Chipcon (acquired by Texas Instruments) uses 8051 microcontroller, and the Mica2 Mote platform provided by Crossbow uses ATMega128L microcontroller.

### **2.2.3 Memory**

Memories in a sensor node include in-chip flash memory and RAM of a microcontroller and external flash memory. For example, the ATMega128L microcontroller running on Mica2 Mote has 128-Kbyte flash program memory and 4-Kbyte static RAM. Further, a 4-Megabit Atmel AT45DB041B serial flash chip can provide external memories for Mica and Mica2Motes (Hill, 2003).

#### **2.2.4 Power Source**

In a sensor node, power is consumed by sensing, communication and data processing. More energy is required for data communication than for sensing and data processing. Power can be stored in batteries or capacitors. Batteries are the main source of power supply for sensor nodes. For example, Mica2 Mote runs on 2 AA (1.5v battery size) batteries. Due to the limited capacity of batteries, minimizing the energy consumption is always a key concern during WSN operations.

To remove the energy constraint, some preliminary research working on energy-harvesting techniques for WSNs has also been conducted. Energy-harvesting techniques convert ambient energy (e.g., solar, wind) to electrical energy and the aim is to revolutionize the power supply on sensor nodes. (Sudevalayam & Kulkarni, 2008) have provided a survey about the energy-harvesting in sensor nodes.

#### **2.2.5 Sensors**

A sensor is a hardware device that produces a measurable response signal to a change in a physical condition such as temperature, pressure and humidity. The continual analog signal sensed by the sensors is digitized by an analog to-digital converter and sent to the embedded processor for further processing. Because a sensor node is a micro-electronic device powered by a limited power source, the attached sensors should also be small in size and consume extremely low energy. A sensor node can have one or several types of sensors integrated in or connected to the node.

### **2.3 WSN Architecture and Protocol Stack**

Nodes of a sensor network are usually scattered in a field as shown in Figure 2.2. Each of these scattered sensor nodes has the capability to collect data and route data back to the sink/gateway and the end-users (Akyildiz and Vuran, 2010). Data are routed back to the end-user by a multi-hop infrastructureless architecture through

the sink as shown in Figure 2.2. The sink may communicate with the task manager/end-user via the Internet or satellite or any type of wireless network (such as WiFi, mesh networks, cellular systems, WiMAX, etc.), or without any of these networks where the sink can be directly connected to the end-users.

In WSNs, the sensor nodes have the dual functionality of being both data originators and data routers.

Hence, communication is performed for two reasons:

- i. **Source function:** Source nodes with event information perform communication functionalities in order to transmit their packets to the sink.
- ii. **Router function:** Sensor nodes also participate in forwarding the packets received from other nodes to the next destination in the multi-hop path to the sink.

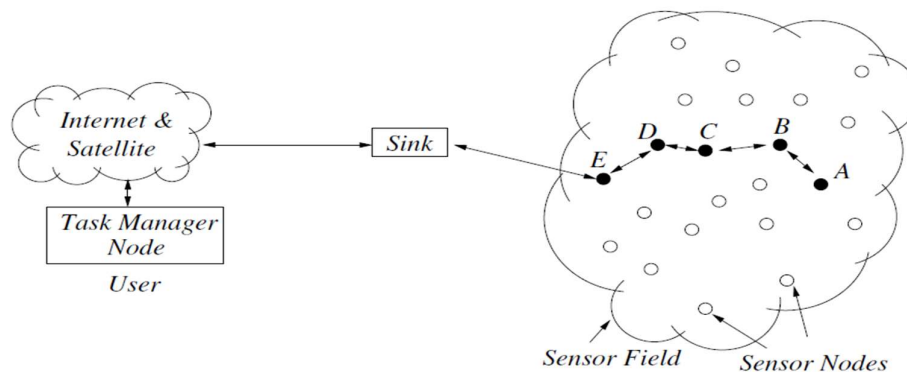


Figure 2.2: Sensor nodes scattered in a sensor field (Akyildiz and Vuran, 2010)

The protocol stack used by the sink and all sensor nodes is as shown in figure 2.3. This protocol stack combines power and routing awareness, integrates data with networking protocols, communicates power efficiently through the wireless medium, and promotes cooperative efforts of sensor nodes. The protocol stack consists of the physical layer, data link layer, network layer, transport layer, application layer, as well as synchronization plane, localization plane, topology management plane, power management plane, mobility management plane, and task management plane.

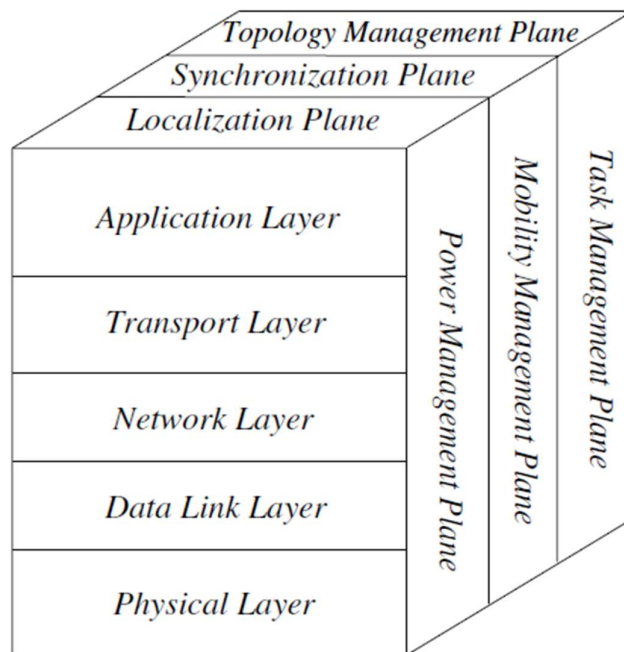


Figure 2.3: The sensor network protocol stack (Akyildiz and Vuran, 2010)

The physical layer addresses the needs of simple but robust modulation, transmission, and receiving techniques. Since the environment is noisy and sensor nodes can be mobile, the link layer is responsible for ensuring reliable communication through error control techniques and manages channel access through the Medium Access Control (MAC) to minimize collision with

neighbors' broadcasts. Depending on the sensing tasks, different types of application software can be built and used on the application layer. The network layer takes care of routing the data supplied by the transport layer. The transport layer helps to maintain the flow of data if the sensor network application requires it. In addition, the power,

mobility, and task management planes monitor the power, movement, and task distribution among the sensor nodes. These planes help the sensor nodes coordinate the sensing task and lower the overall power consumption.

The power management plane manages how a sensor node uses its power. For example, the sensor node may turn off its receiver after receiving a message from one of its neighbors. This is to avoid getting duplicated messages. Also, when the power level of the sensor node is low, the sensor node broadcasts to its neighbors that it is low in power and cannot participate in routing messages. The remaining power is reserved for sensing. The mobility management plane detects and registers the movement of sensor nodes, so a route back to the user is always maintained, and the sensor nodes can keep track of their neighbors. By knowing these neighbour sensor nodes, the sensor nodes can balance their power and task usage. The task management plane balances and schedules the sensing tasks given to a specific region. Not all sensor nodes in that region are required to perform the sensing task at the same time. As a result, some sensor nodes perform the task more than others, depending on their power level. These management planes are needed so that sensor nodes can work together in a power-efficient way, route data in a mobile sensor network, and share resources between sensor nodes. Without them, each sensor node will just work individually. From the standpoint of the whole sensor network, it is more efficient if sensor nodes can collaborate with each other, so the lifetime of the sensor networks can be prolonged.

### **2.3.1 The Physical Layer**

The physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation, and data encryption.

### **2.3.2 The Data Link Layer**

The data link layer is responsible for the multiplexing of data streams, data frame detection, and medium access and error control. It ensures reliable point-to-point and point-to-multipoint connections in a communication network. A further discussion on medium access and error control gives a better understanding of their strategies for sensor networks.

#### **i. Medium Access Control (MAC)**

The MAC protocol in a wireless multi-hop self-organizing sensor network must achieve two goals. The first goal is creation of the network infrastructure. Since thousands of sensor nodes can be densely scattered in a sensor field, the MAC scheme must establish communication links for data transfer. This forms the basic infrastructure needed for hop-by-hop wireless communication and provides the self-organizing capability. The second objective is to fairly and efficiently share communication resources between sensor nodes. These resources include time, energy, and frequency. Several MAC protocols have been developed for WSNs to address these requirements. Regardless of the medium access scheme, energy efficiency is of utmost importance. A MAC protocol must certainly support the operation of power saving modes for the sensor node. The most obvious means of power conservation is to turn the transceiver off when it is not required. Though this power saving method seemingly provides significant energy gains, it may hamper the connectivity of the network. Once a transceiver is turned off,

the sensor node cannot receive any packets from its neighbors, essentially becoming disconnected from the network. Moreover, turning a radio on and off has an overhead in terms of energy consumption due to the startup and shutdown procedures required for both hardware and software. In fact, if the radio is blindly turned off during each idling slot, over a period of time the sensor may end up expending more energy than if the radio had been left on. As a result, operation in a power saving mode is energy

efficient only if the time spent in that mode is greater than a certain threshold. There can be a number of such useful modes of operation for the wireless sensor node, depending on the number of states of the microprocessor, memory, A/D converter, and the transceiver (Akyildiz and Vuran, 2010). Each of these modes can be characterized by its power consumption and the latency overhead, which is the transition power to and from that mode.

## ii. **Error Control**

Another important function of the data link layer is the error control of transmission data. Two important modes of error control in communication networks are forward error correction (FEC) and automatic repeat request (ARQ), and hybrid ARQ. The usefulness of ARQ in sensor network applications is limited by the additional retransmission cost and overhead. On the other hand, decoding complexity is greater in FEC, as error correction capabilities need to be built in. Consequently, simple error control codes with low-complexity encoding and decoding might present the best solutions for sensor networks. In the design of such a scheme, it is important to have a good knowledge of the channel characteristics and implementation techniques.

### 2.3.3 The Network Layer

Since sensor nodes are scattered densely in a field either close to or inside the phenomenon as shown in figure 2.2, the information collected relating to the phenomenon should be transmitted to the sink, which may be located far from the sensor field. However, the limited communication range of the sensor nodes prevents direct communication between each sensor node and the sink node. This requires efficient multi-hop wireless routing protocols between the sensor nodes and the sink node using intermediate sensor nodes as relays.

The existing routing techniques, which have been developed for wireless ad hoc networks, do not usually fit the requirements of the sensor networks. The networking layer of sensor networks is usually designed according to the following principles:

- i. Power efficiency is always an important consideration.
- ii. Sensor networks are mostly data-centric.
- iii. In addition to routing, relay nodes can aggregate the data from multiple neighbors through local processing.
- iv. Due to the large number of nodes in a WSN, unique identifiers (IDs) for each node may not be provided and the nodes may need to be addressed based on their data or location.

An important issue for routing in WSNs is that routing may be based on data-centric queries. Based on the information requested by the user, the routing protocol should address different nodes that would provide the requested information. More specifically, the users are more interested in querying an attribute of the phenomenon rather than querying an individual node.

One other important function of the network layer is to provide internetworking with external networks such as other sensor networks, command and control

systems, and the Internet. In one scenario, the sink nodes can be used as a gateway to other networks, while another scenario is to create a backbone by connecting sink nodes together and making this backbone access other networks via a gateway.

#### **2.3.4 The Transport Layer**

The transport layer is especially needed when the network is planned to be accessed through the Internet or other external networks. TCP, with its current transmission window mechanisms, does not address the unique challenges posed by the WSN environment. Unlike protocols such as TCP, the end-to-end communication schemes in sensor networks are not based on global addressing.

These schemes must consider that addressing based on data or location is used to indicate the destinations of the data packets. Factors such as power consumption and scalability, and characteristics like data-centric routing, mean sensor networks need different handling in the transport layer. Thus, these requirements stress the need for new types of transport layer protocols. The development of transport layer protocols is a challenging task because the sensor nodes are influenced by hardware constraints such as limited power and memory. As a result, each sensor node cannot store large amounts of data like a server in the Internet, and acknowledgments are too costly for sensor networks. Therefore, new schemes that split the end-to-end communication probably at the sinks may be needed where user datagram protocol (UDP) type protocols are used in the sensor network.

For communication inside a WSN, transport layer protocols are required for two main functionalities: reliability and congestion control. Limited resources and high energy costs prevent end-to-end reliability mechanisms from being employed in WSNs. Instead, localized reliability mechanisms are necessary. Moreover, congestion that may occur because of the high traffic during events

should be mitigated by the transport layer protocols. Since sensor nodes are limited in terms of processing, storage, and energy consumption, transport layer protocols aim to exploit the collaborative capabilities of these sensor nodes and shift the intelligence to the sink rather than the sensor nodes.

### **2.3.5 The Application Layer**

The application layer includes the main application as well as several management functionalities. In addition to the application code that is specific for each application, query processing and network management functionalities also reside at this layer.

## **2.4 WSN Standards and Specifications**

The heterogeneity in the available sensor platforms results in compatibility issues for the realization of envisioned applications (Akyildiz and Vuran, 2010). Hence, standardization of certain aspects of communication is necessary. To this end, the

IEEE 802.15.4 standards body was formed for the specification of low-data-rate wireless transceiver technology with long battery life and very low complexity. Three different bands were chosen for communication, i.e., 2.4GHz (global), 915MHz (the Americas), and 868MHz (Europe).

Besides the IEEE 802.15.4 standard, several standard bodies have been formed for the development of low-power networks in various areas. It is widely recognized that standards such as Bluetooth and WLAN are not well suited for low-power sensor applications. On the other hand, standardization attempts such as ZigBee, Wireless HART, WINA, and SP100.11a, which specifically address the typical needs of wireless control and monitoring applications, are expected to enable rapid improvement of WSNs in the industry. In addition, standardization

efforts such as 6LoWPAN are focused on providing compatibility between WSNs and existing networks such as the Internet.

Three major standardization efforts namely, ZigBee, Wireless HART, and 6LoWPAN will be briefly discussed.

#### **2.4.1. ZigBee**

The ZigBee standard is developed by the ZigBee Alliance, an international, nonprofit industrial consortium of leading semiconductor manufacturers and technology providers. The ZigBee standard was created to address the market need for cost-effective, standard-based wireless networking solutions that support low data rates, low power consumption, security, and reliability through wireless

personal area networks (WPANs). Five main application areas are targeted: home automation, smart energy, building automation, telecommunication services, and personal health care.

The ZigBee standard is defined specifically in conjunction with the IEEE 802.15.4 standard. Therefore, both are usually confused. However, as shown in Figure 2.3, each standard defines specific layers of the protocol stack. The PHY and MAC layers

are defined by the IEEE 802.15.4 standard while the ZigBee standard defines the network layer (NWK) and the application framework. Application objects are defined by the user. To accommodate a large variety of applications, three types of traffic are defined; Firstly, periodic data traffic is required for monitoring applications, where sensors provide continuous information regarding a physical phenomenon. The data exchange is controlled through the network controller or a router. Secondly, intermittent data traffic applies to most event-based applications and is triggered through either the application or an external factor. This type of traffic is handled through each router node. To save energy, the

devices may operate in disconnected mode, whereas they operate in sleep mode most of the time. Whenever information needs to be transmitted, the transceiver is turned on and the device associates itself with the network. Finally, repetitive low-latency data traffic is defined for certain communications such as a mouse click that needs to be completed within a certain time. This type of traffic is accommodated through the polling-based frame structure defined by the IEEE 802.15.4 standard.

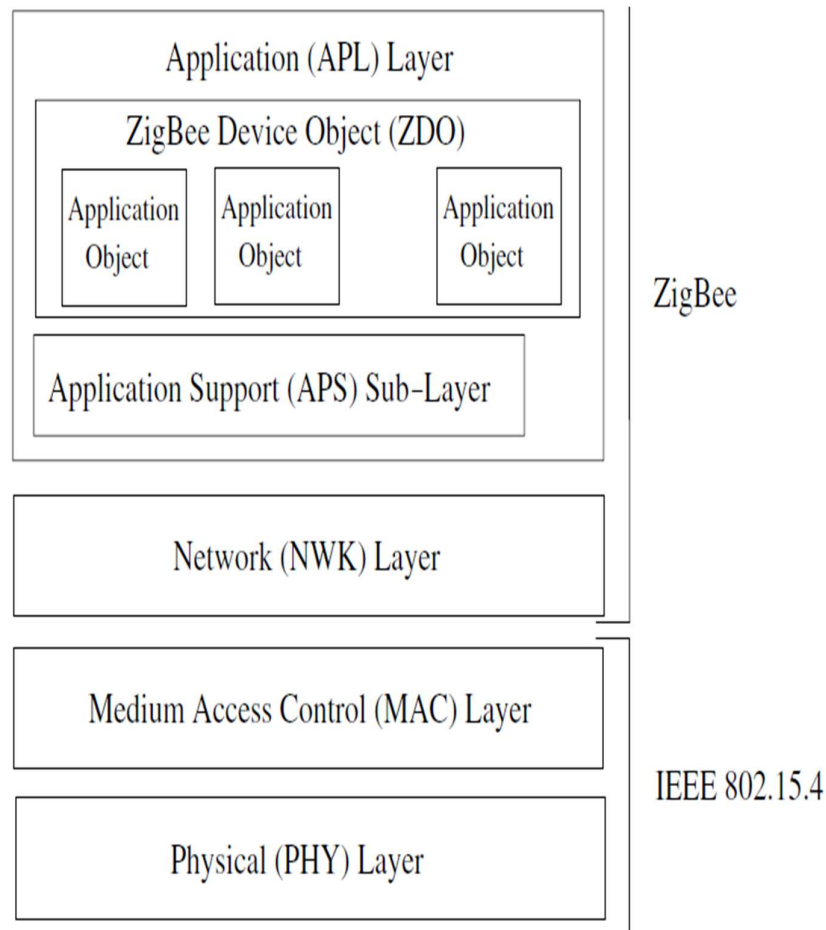


Figure 2.4: IEEE 802.15.4 and the ZigBee protocol stack (Akyildiz and Vuran, 2010)

The ZigBee network (NWK) layer provides management functionalities for the network operation. The procedures for establishing a new network and the devices to gain or relinquish membership of the network are defined. Furthermore, depending on the network operation, the communication stack of each device can be configured. Since ZigBee devices can be a part of different networks during their lifetime, the standard also defines a flexible addressing mechanism. Accordingly, the network coordinator assigns an address to the devices as they join the network. As a result, the unique ID of each device is not used for communication but a shorter address is assigned to improve the efficiency during communication. In a tree architecture, the address of a device also identifies its parent, which is used for

routing purposes. The NWK layer also provides synchronization between devices and network controllers. Finally, multi-hop routes are generated by the NWK layer according to defined protocols.

#### 2.4.1.1 Types of ZigBee Devices

There are three different types of ZigBee devices as shown in figure 2.5.



Figure 2.5: Types of Zigbee devices in OPNET (Shah Nawaz, 2015)

##### i. ZigBee Coordinator (ZC)

The Coordinator in every network is responsible for the creation of a network, selection of a channel, and permission to other nodes to connect to the network.

All the data that is transferred from the connected node will be stored in a coordinator. It works like a router or a bridge between different networks (Petr Jurčík and Anis Koubâa, 2007).

**ii. ZigBee Router (ZR)**

A router may act as an intermediate device between the end device and Coordinator or between routers for passing data from other End Devices to the Coordinator. In some networks, End Devices may transfer data directly to the Coordinator or from End Devices to other routers. A router can act as an end device and during time, its

routing functionality will be inactive. Routers use less memory than ZigBee Coordinators, and cost less, and have the ability to work with all types of topologies. The network with tree and mesh topology will need at least one router (Mohammad Reza Sahraei, 2009).

**iii. ZigBee End Devices (ZED)**

The end devices are the end point of any network connected to routers and a Coordinator. It does not have the routing functionality. End devices may have contact with only parent node (either Coordinator or Router). End devices go to sleep mode to save battery power and do not have many duties compared to the Coordinator and Routers, which makes them less costly (Mohammad Reza Sahraei, 2009).

**2.4.1.2 ZigBee Specifications**

Table 2.1 presents the basic specifications of the Zigbee standard (Boris Mihajlov and Mitko Bogdanoski, 2011, modified)

Parameters	Zigbee Value
------------	--------------

Transmission Range (meters)	1-100
Battery life (days)	100 – 1000
Network Size(No. of nodes)	>64000
Throughput(kb/s)	20-250
Transmission Band	868MHz, 915Mhz, 2459MHz
Complexity	Low
Wake up Delay	15mSec
Maximum Power	1mW
Maximum Child	254

#### **2.4.2. Wireless HART**

Wireless HART has been developed as a wireless extension to the industry standard Highway Addressable Remote Transducer (HART) protocol. HART is the most used communication protocol in the automation and industrial applications that require real-time support with a device count around 20 million (Akyildiz et al., 2002). It is based on superimposing a digital FSK modulated signal on top of the 4–20mA analog current loop between different components. HART provides a master/slave communication scheme, where up to two masters are accommodated in the network. Accordingly, devices connected to the system can be controlled through a permanent system and handheld devices for monitoring and control purposes.

The Wireless HART standard has been released as part of the HART 7 specification as the first open wireless communication standard specifically designed for process measurement and control applications (Akyildiz and Vuran, 2010). Wireless HART relies on the IEEE 802.15.4 PHY layer standard for the 2.4GHz band. Moreover, a Time Division Multiple Access (TDMA) based MAC protocol is defined to provide several messaging modes: one-way publishing of process and control values, spontaneous notification by exception, ad hoc request

and response, and auto-segmented block transfers of large data sets. The network architecture of the Wireless HART standard is shown in Figure 2.6. Accordingly, five types of components are defined: *Wireless HART* Field Devices (WFDs) are the sensor and control elements that are connected to process or plant equipment. Gateways provide interfaces with wireless portions of the network and the wired infrastructure. As a result, host application and the controller can interact with the WFDs. The network manager maintains operation of the network by scheduling communication slots for devices, determining routing tables, and monitoring the health of the network. In addition to the three main components, the Wireless HART adapters provide backward compatibility by integrating existing HART field devices with the wireless

network. Finally, handhelds are equipped with on-board transceivers to provide on-site access to the wireless network and interface with the WFDs.

Based on these components, a full protocol stack has been defined by the Wireless HART standard. As explained above, at the PHY layer, the IEEE 802.15.4 standard is employed and a TDMA-based MAC protocol is used at the data link layer. In addition, the network topology is designed as a mesh network and each device can act as a source or a router in the network. This network topology is very similar to what is generally accepted for WSNs. At the network layer, table-based routing is used so that multiple redundant paths are established during network formation and these paths are continuously verified. Accordingly, even if a communication path between a WFD and a gateway is corrupted, alternate paths are used to provide network reliability greater than  $3\sigma$  (99.7300204%). In addition to established paths, source routing techniques are used to establish ad hoc communication paths. Moreover, the network layer supports dynamic bandwidth management by assigning allocated bandwidth to certain devices. This is also supported by the underlying TDMA structure by assigning appropriate

numbers of slots to these devices. The bandwidth is allocated on a demand basis and can be configured when a device joins the network.

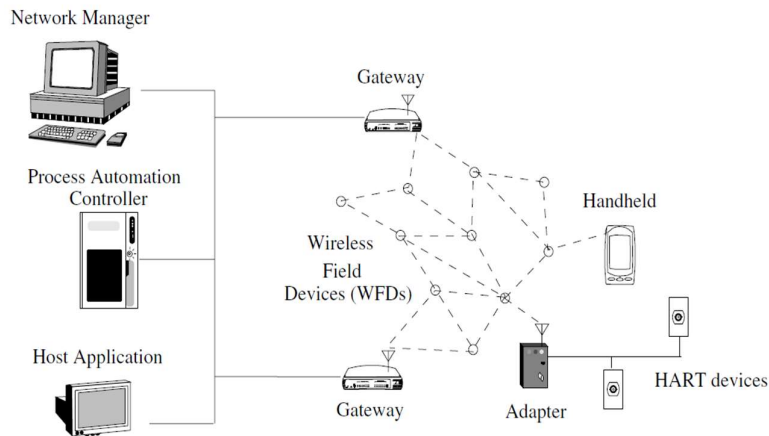


Figure 2.6: Wireless HART architecture and components (Akyildiz and Vuran, 2010)

The transport layer of the Wireless HART standard provides reliability on the end-to-end path and supports TCP-like reliable block transfers of large data sets. End-to-end monitoring and control of the network are also provided. Accordingly, WFDs continuously broadcast statistics related to their communication success and neighbours, which is monitored by the network manager to establish redundant routes and improve energy efficiency. Finally, the application layer supports the standard HART application layer, where existing solutions can be implemented seamlessly.

### 2.4.3. 6LoWPAN

The existing standards enable application-specific solutions to be developed for WSNs. Accordingly, stand-alone networks of sensors can be implemented for specific applications. However, these networks cannot be easily integrated with the Internet since the protocols based on IEEE 802.15.4 are not compliant with the IP. Therefore, sensors cannot easily communicate with web-based devices, servers, or browsers. Instead, gateways are required to collect the information

from the WSN and communicate with the Internet. This creates single-point-of-failure problems at the gateways and stresses the neighbours of the gateway.

To integrate WSNs with the Internet, the Internet Engineering Task Force (IETF) is developing the IPv6 over Low-power Wireless Personal Area Network (6LoWPAN) standard. This standard defines the implementation of the IPv6 stack on top of IEEE 802.15.4 to let any device be accessible from and with the Internet. The basic challenge in integrating IPv6 and WSNs is the addressing structure of IPv6, which defines a header and address information field of 40 bytes. However, IEEE 802.15.4 allows up to 127 bytes for the whole packet including header and payload information. Accordingly, straight forward integration of both standards is not efficient. Instead, 6LoWPAN adds an adaptation layer that lets the radio stack and IPv6 communications operate together. A stacked header structure has been

proposed for the 6LoWPAN standard (Mulligan G. et al, 2007) where, instead of a single monolithic header, four types of headers are utilized according to the type of packet being sent. In addition, stateless compression techniques are used to decrease the size of the header from 40 bytes to around 4 bytes, which is suitable for WSNs.

The four header types are as follows:

- i. **Dispatch header (1 byte):** This header type defines the type of header following it. The first 2 bits are set to 01 for the dispatch header and the remaining 6 bits define the type of header following it (uncompressed IPv6 header or a header compression header).
- ii. **Mesh header (4 bytes):** This header is identified by 10 in the first 2 bits and is used in mesh topologies for routing purposes.
- iii. **Fragmentation header (4–5 bytes):** IPv6 can support payloads up to 1280 bytes whereas this is 102 bytes for IEEE 802.15.4. This is solved

by fragmenting larger payloads into several packets and the fragmentation header is used to fragment and reassemble these packets.

- iv. **Header compression header (1 byte):** Finally, the 40-byte IPv6 header is compressed into 2 bytes including the header compression header. This compression exploits the fact that IEEE 802.15.4 packet headers already include the MAC addresses of the source and destination pairs. These MAC addresses can be mapped to the lowest 64 bits of an IPv6 address. As a result, the source and destination addresses are completely eliminated from the IPv6 header. Similar techniques are used to eliminate the unnecessary fields for each communication and allow these fields to be inserted when the packet reaches a gateway to the Internet.

Header compression is not the only challenge for WSN–Internet integration. The ongoing efforts in the development of the 6LoWPAN standard aim to address some of these challenges including routing and transport control to provide seamless interoperation of WSNs and the Internet.

## **2.5 Operating Systems (OS)**

The traditional OS is system software that operates between application software and hardware and is often designed for workstations and PCs with plenty of resources (Sohraby et al., 2007). This is usually not the case with sensor nodes in WSNs. There are also embedded operating systems such as Vx Works and WinCE, none of which is specially designed for data-centric WSNs with constrained resources. Sensors usually have a slow processor and small memory, different from most current systems.

For these reasons, several software/operating system platforms such as TinyOs, LiteOS, Contik, etc., have been developed specifically for WSNs. Among these, the most accepted platform is the TinyOS because of its versatility and flexibility in the design of WSNs.

### **2.5.1 TinyOs**

TinyOs is an open-source operating system designed for wireless embedded sensor networks. TinyOS incorporates a component-based architecture, which minimizes the code size and provides a flexible platform for implementing new communication protocols. Its component library includes network protocols, distributed services, sensor drivers, and data acquisition tools, which can be further modified or improved based on the specific application requirements. TinyOS is based on an event-driven execution model that enables fine-grained power management strategies.

Most of the existing software code for communication protocols today is written for the TinyOS platform. Coupled with TinyOS, a TinyOS mote simulator, TOSSIM, has been introduced to simplify the development of sensor network protocols and applications (Levis et al., 2003). TOSSIM provides a scalable simulation environment and compiles directly from the TinyOS code. It simulates the TinyOS network stack at the bit level, allowing experimentation with low-level protocols in

addition to top-level application systems. It also provides a graphical user interface tool, TinyViz, in order to visualize and interact with running simulations.

### **2.5.2 LiteOS**

LiteOS is a multi-threading operating system that provides Unix-like abstractions. Compared to TinyOS, LiteOS provides multi-threaded operation, dynamic memory management, and command-line shell support. The shell support, LiteShell, provides a command-line interface at the user side, i.e., the PC, to provide interaction with the sensor node to be programmed.

### **2.5.3 Contik**

Contiki is an open-source, multitasking operating system developed for use on a variety of platforms including microcontrollers such as the TI MSP430 and the Atmel AVR, which are used in the Telos, Tmote, and Mica families. Contiki has been built around an event-driven kernel but it is possible to employ preemptive multithreading for certain programs as well as dynamic loading and replacement of individual programs and services. As a result, compared to TinyOS, which is statically linked at compile-time, Contiki allows programs and drivers to be replaced during run-time and without relinking. Moreover, TCP/IP support is also provided through the micro-internet protocol ( $\mu$ IP) stack.

While several operating systems with additional capabilities have become available, TinyOS is still being widely used in WSN research. One of the main reasons for this popularity is the vast code space built throughout the development of WSN solutions.

## **2.6 Wireless Sensor Network Testbeds**

WSN testbeds are deployed in a controlled environment, generally with public access and ongoing maintenance (Sarammal and Roseline, 2013). It is an intermediate tool between a real deployment and a simulator or emulator. It provides researchers a way to test their protocols, algorithms, network issues and applications. Here, a discussion on some testbeds such as MotLab, SenseLab, and Sensei are presented to aid an understanding of their working operations and relevance to WSNs.

### **2.6.1 MoteLab**

MoteLab consists of a set of permanently deployed sensor network nodes connected to a central server which handles reprogramming and data logging while providing a web interface for creating and scheduling jobs on the testbed (Werner-Alle G. et al, 2005). In its original design, the testbed was comprised from Mica2 nodes, each connected to Ethernet backbone via dedicated Crossbow interface boards, providing TCP forwarding for the serial ports. MoteLab consists of several different software components: MySQL Database Backend, Web Interface, DBLogger and Job Daemon. MoteLab uses a MySQL database to store all information needed for testbed operation. MoteLab uses PHP to generate dynamic web content, and JavaScript to provide an interactive user experience. This allows users to access the lab in a platform-independent way. DBLogger is a Java program started at the beginning of every job. It connects to each node and uses class introspection to parse messages sent over its serial port and insert them into the appropriate MySQL database. The job daemon is responsible for reprogramming each node and starting and stopping system components. MoteLab is also a valuable tool for teaching sensor network concepts, allowing students to experiment with a real testbed. MoteLab is unique in its ability to manage a network of real, network-attached wireless sensor network nodes.

### **2.6.2 SensLAB**

SensLAB is a very large-scale WSN testbed with a total of 1000 nodes deployed at four sites in France (Muhammad & Thomas, 2014). The main goal of SensLAB is to offer an accurate and efficient scientific tool to help in the design and development of large scale WSN. The hardware used in the SensLAB testbed includes different versions of WSN430 nodes. It includes WSN430 heart rate daughter board, WSN430 GPS-Accelerometer daughter board, WSN430 daughter board, WSN430 strain daughter board, WSN430 Bluetooth daughter board, and WSN430 motion capture daughter board. From the software

perspective SensLAB provides support for three operating systems: Contiki, FreeRTOS, and TinyOS. SensLAB provides a software programming library that includes implementation of various OS free Medium Access Control (MAC) protocols i.e., Carrier Sense Multiple Access (CSMA), Time Division Multiple Access (TDMA), and XMAC. Furthermore, it provides an implementation of a localization protocol and a gradient-based routing algorithm. SensLAB provides support for WSN and embedded system simulations in the form of WSNNet, and Wsim. SensLAB is open to researchers of the host institutes and outside users need to request permission in order to use the testbed. SensLAB provides a web-based system to access the testbed.

### **2.6.3 Sensei**

Sensei (Rensfelt et al., 2010) is a nomadic WSN testbed developed at Uppsala University. The distinguishing feature of Sensei is that it provides support for mobile nodes and its nomadic nature makes it possible to evaluate WSN application performance in a range of environments. Wireless sensor nodes, sensor hosts, site manager, and monitors constitute the design of the Sensei testbed. A group of sensor nodes is connected to a sensor host and there are a number of sensor hosts present in the testbed. Wireless sensor nodes connect to the sensor host through the USB

interface. Since the testbed supports mobile nodes, sensor hosts keep track of mobile nodes and inform the site manager about the location of these nodes periodically.

Communication among sensor hosts takes place using the IEEE802.11 standard. For communication between sensor hosts and the site manager, a control channel is setup using the IEEE802.11 standard. The site manager controls the WSN testbed. The site manager has a wire-line connection with the monitor. The site

manager acts as the gateway to the testbed and logs events. The monitor presents the output of the sensor nodes along with other control information to the users. A Java-based desktop client is used to enable users to interact with the testbed. The testbed uses a Linux based Asus WL-500G wireless access point as sensor hosts and TelosB sensor nodes with CC2420 radio transceiver. The testbed provides support for both TinyOS and Contiki operating systems acts as the gateway to the testbed and logs events. The monitor presents the output of the sensor nodes along with other control information to the users. A Java-based desktop client is used to enable users to interact with the testbed.

## **2.7 Simulators for WSN**

Simulation is one of the important technologies in modern time. In this section the most relevant simulation environments such as Network Simulator-2, QualNet, NetSim, Matlab/Simulink and Optimized Network Engineering Tool (OPNET) used to study WSN are introduced, and their main features and implementation issues described.

### **2.7.1 Network Simulator-2(NS-2)**

Network Simulator (NS-2) is a discrete-event, object-oriented, and general-purpose network simulator based on C++ language that can be used to simulate local and wide-area networks (Madani et al., 2010). It was developed to operate primarily in

Linux-based operating systems (OSs), such as Ubuntu. However, it can also be installed in Windows OS with Cygwin support.

To design a model, a program can be written in the Tool Command Language (Tcl) and visualized through the NAM editor. The performance is reliable for node sizes up to 100 nodes and degrades with increased node size.

The disadvantages of NS-2 are the interdependency between the modules and that co-simulation with MATLAB requires special framework definitions (Heimlich et al., 2010). Also, to implement the ZigBee communication protocol, separate patch files must be installed. Even though this network simulation can be used for verifying different algorithms, NS-2 cannot be used easily for hardware–software co-simulation in MATLAB, as it requires separate framework definitions.

### **2.7.2 QualNet**

QualNet is a comprehensive suite of tools for modeling large wired and wireless networks (Yaqoob et al., 2011). It uses simulation and emulation to predict the behavior and performance of networks to improve their design, operation and management. QualNet enables users to:

- i. Design new protocol models.
- ii. Optimize new and existing models.
- iii. Design large wired and wireless networks using preconfigured or user-designed models.
- iv. Analyze the performance of networks and perform what-if analysis to optimize them.

QualNet GUI consists of Architect, Analyzer, Packet Tracer, and File Editor. Architect is a network design and visualization tool. It has two modes: Design mode and Visualize mode. In Design mode, you can set up terrain, network connections, subnets, mobility patterns of wireless users, and other functional parameters of network nodes. You can create network models by using intuitive, click and drag

operations. You can also customize the protocol stack of any of the nodes. You can also specify the application layer traffic and services that run on the network.

In Visualize mode, you can perform in-depth visualization and analysis of a network scenario designed in Design mode. As simulations are running, users can watch packets at various layers flow through the network and view dynamic graphs of critical performance metrics. Real-time statistics are also an option, where you can view dynamic graphs while a network scenario simulation is running. Analyzer is a statistical graphing tool that displays the metrics collected during the simulation of a network scenario in a graphical format. You can customize the graph display. All statistics are exportable to spreadsheets in CSV format. Packet Tracer provides a visual representation of packet trace files generated during the simulation of a network scenario. Trace files are text files in XML format that contain information about packets as they move up and down the protocol stack. File Editor is a text editing tool that displays the contents of the selected file in text format and allows the user to edit files.

### **2.7.3. NetSim**

NetSim is a discrete event simulator developed by Tetcos in 1997, in association with Indian Institute of Science. It has an object-oriented system modeling and simulation (M&S) environment to support simulation and analysis of voice and data communication scenarios for High Frequency Global Communication Systems (HFGCS). NetSim is available in both commercial and academic versions, and can be used for modeling and simulation of various network protocols, including WLANs, Ethernet, TCP/IP, and asynchronous transfer mode (ATM) switches (Kamal et al., 2010). NetSim allows a detailed performance study of Ethernet networks, including wireless Ethernet. The effect of relative positioning of stations on network performance, a realistic signal propagation modeling, the transmission

of deferral mechanisms, and the collision handling and detection processes can also be investigated.

The main strength of NetSim is that the package can be run on a variety of operating systems. However, the use of NetSim is limited to academic environments only.

#### **2.7.4 OPNET (Optimized Network Engineering Tool)**

OPNET is a tool providing a development environment for specification, simulation and performance analysis of communication networks (Shah Nawaz, 2015). The OPNET simulator supports a great range of communication systems, from single LAN to a global satellite networks. The power and versatility is the main difference between OPNET and other simulators. With OPNET, it is possible to work with an OSI reference model on layer 7 and it can work with physical parameters. This tool set is powerful and can create and test large network environments. It is a fast discrete event simulation, which means that the simulator can simulate by modeling the events on the scenarios which the user has set up. OPNET provides powerful graphical support that is used to build network topology and entities from the application layer to physical layer. Object-oriented programming is used to create the mapping from graphical design to the implementation of a real system.

From the foregoing therefore, it is found that OPNET met the most important design specifications, such as customized node design and ZigBee, hence its adoption in this research.

## **2.8 Review of Related Works**

Mafut et al., (2013) demonstrated how an Irrigation Management System (IMS) can practically be implemented by successfully deploying a Wireless Sensor Network (WSN). Specifically, the paper describes an IMS which was setup in Manja Township, City of Blantyre, Malawi, based on advanced irrigation scheduling technique. Since the system had to be self-sustained in terms of power, which is a challenge for deployment in rural areas of developing countries like Malawi where grid power supply is scarce, the researchers used solar Photovoltaic (PV) and rechargeable batteries to power all electrical devices in this system. The system incorporated a remote monitoring mechanism via a General Packet Radio Service (GPRS) modem to report soil temperature, soil moisture, WSN link performance and PV power levels. Irrigation valves were activated to water the field based on the result of the soil temperature and moisture. Preliminary results of the work revealed engineering weakness of deploying such a system. Nevertheless, the work showed that it was possible to develop a robust, fully-automated, solar powered, and low cost IMS to suit the socio-economic conditions of small-scale farmers in the developing world.

Haule and Michael (2014) designed and simulated an Automated Irrigation Management System deployed by using Wireless Sensor Networks (WSN) for Tanzanian semi-arid areas. The designed system consisted of three units; slave unit, master unit and the valve control unit. The slave unit consists of soil moisture sensors, microcontroller and the Xbee module. Soil moisture sensors reads the real time value of the moisture content available in the soil, this value is temporarily stored in the microcontroller. The Xbee module was used to transfer value of soil moisture content to the master unit. The master unit consists of microcontroller, GSM modem, LCD display and Xbee module. The amount of soil moisture content which was sent by the slave unit was then manipulated and compared with the

defined threshold value depending on the type of soil and the nature of the crop planted and the decision to whether or not to irrigate considered. The valve control unit consists of microcontroller, Xbee and valves. The Xbee module was implemented as a receiver, it receives the signal from the master unit, and the microcontroller reads the value and commands the valve to close or open depending on the signal received.

The work of Kuchekar and Pagare (2015) demonstrated the implementation of embedded system for automatic irrigation which has a wireless sensor network placed in the root zone of the plant for real time in-field sensing and control of an irrigation system. Real time data was collected by wireless sensor nodes and transmitted to base station using zigbee. Data was received, identified, saved and displayed at the base station and if it exceeds the desired limit then it will be controlled by android smart phone through GSM network.

Sivasankari A. and Gandhimathi S. (2014), conducted research on Wireless Sensor Based Crop Monitoring System for Agriculture Using Wi-Fi Network. The authors proposed the development and implementation of a wireless sensor network connected to a central node using Wi-Fi, which in turn was connected to a Central Monitoring Station (CMS) through General Packet Radio Service (GPRS) or Global System for Mobile (GSM) technologies. The system also gathers Global Positioning System (GPS) parameters related to the field and sends them to a central monitoring station. The sensor nodes have several external sensors namely leaf wetness, soil moisture, soil pH, atmospheric pressure sensors attached to it. Based on the value of soil moisture sensor, the mote triggers the water sprinkler during the period of water scarcity. Once the field is sprinkled with adequate water, the water sprinkler is switched off, hence water can be conserved. Also, the value of soil pH sensor was sent to the base station and in turn base station intimates the farmer about the soil pH via SMS using GSM modem for appropriate decision to be taken.

Abdurrahman and Hussain Md. (2015), analyzed the simulation on wireless sensor network for low-cost wireless controlled and monitored irrigation solution using Zigbee/IEEE802.15.4. The research model used was a simulation model. The results, performance measures of delivery ratio, energy consumption and lifetime analysis of the work paved way for an efficient dimensioning of an Zigbee/IEEE 802.15.4 cluster-based mesh topology for monitoring and controlling of water and irrigation systems. The focus of the work was the construction of a Beacon Cluster-based mesh topology, i.e., constructing a Cluster-based mesh topology using the beacon mode as against the three topologies available in the Zigbee standard, i.e., mesh topology, star topology and Cluster-Tree topology. In their technique, they considered the device type factor and the energy factor to choose Cluster Heads (CH) and relay nodes. The static sink node was located in the edge of the rectangle sensor network, and sensor nodes were deterministically deployed in the rectangle area. Each sensor node was located at equal distance to CH sensor nodes forming a circular cluster base and having different distance to the static sink node. Each sensor node sets up a table to store the residual energy, CH set up a table to store distance and the relative node ID and the information of the distance will be kept in the sink node. The CH nodes were able to determine the maximum and the minimum distance to the sink node. The work clearly showed that in single sink IEEE 802.15.4/Zigbee wireless networks applied to monitoring and control of water and irrigation systems, beacon mode gave the longest battery life (lowest power consumption) and the best delivery ratio at all tested data rates in computer simulations. From the results presented in the paper, IEEE 802.15.4 in beacon mode results in significantly lower power consumption (higher battery life) and a good delivery ratio.

Agbetuyi et al., (2016) designed and implemented an Automatic Irrigation System Based on Monitoring Soil Moisture. The method employed was to

continuously monitor the soil moisture level to decide whether irrigation was needed, and how

much water was needed in the soil. A pumping mechanism was used to deliver the needed amount of water to the soil. The work was grouped into four subsystems namely; power supply, sensing unit, control unit and pumping subsystems which made up the automatic irrigation control system. A moisture sensor was constructed using probes made from corrosion-resistant conductor which were stuck into soil sample to measure the electrical resistance of the soil. Voltage levels corresponding to the wet and dry states of the soil sample were computed by measuring the resistance between the moisture detector probes and matching them to output voltages of a comparator circuit. A regulated 12 volts power supply unit was constructed to power the system; the control circuit was implemented using operational amplifier and timer; and the pumping subsystem consisting of a submersible low-noise micro water pump was constructed using a small dc-operated motor. System response tests were carried out to determine the time taken for the system to irrigate potted samples of different soil types having different levels of dryness. The system was tested on three types of soil and from the result analysis, sandy soils required less water than loamy soils and clay soils required the most water for irrigation.

## **2.9 Research Gap**

Various related works were reviewed to determine the extent of research on the subject matter. It was quite revealing that scholars have done a great deal of extensive work including implementation of automatic irrigation system based on WSN. However, lack of water resource is not the only problem that limit crop production especially rice. Such other challenges like pest and disease invasion, problem with method of fertilizer application, birds/rodents invasion, and weed control are major factors (KPIs) to contend with. None of the reviewed work

suggested the use of WSN in agriculture in such an integrated manner for the purposes of solving these problems.

Therefore, this work takes a step further to suggest the design of a single multi-functional and integrated WSN application in agriculture adaptable to irrigate, control pests and weeds, apply fertilizer and deter birds and rodents in a rice farm at the same time, as key performance indicators for enhanced production, using OPNET Modeler 14.5A to design and simulate a model of the farm on Zigbee based Wireless Sensor Network.

## CHAPTER THREE

### MATERIALS AND METHODS

#### 3.1 Materials

The following materials were used for the realization of the work:

- i. Optimized Network Engineering Tools (OPNET): This was used to model the network. The choice of OPNET is made because of its rich graphical editor which can be used to build network topology and entities from the application layer to the physical layer. Fig 3.1 shows the project editor window of OPNET 14.5A.

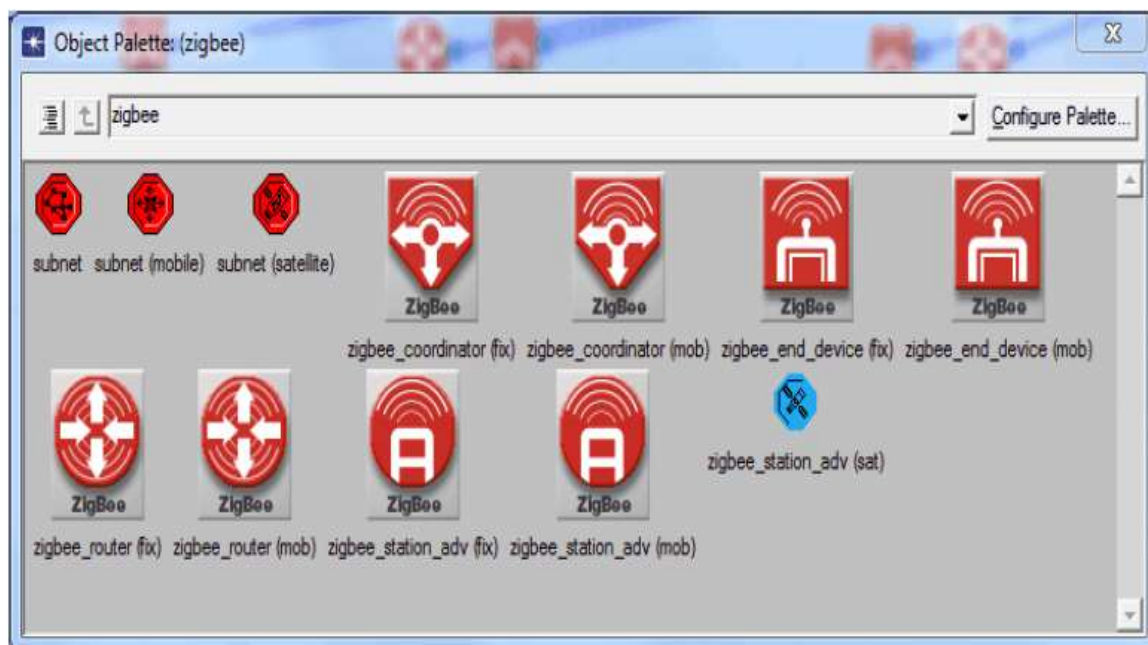


Figure 3.1: OPNET Project Editor Window.

The project editor (network domain) was used to specify the physical topology, node and links of a communication network and may be used for all simulation tasks which define the position and interconnection of a communication network. Simulation projects and scenarios can be managed by the Project Editor (Lu and Yang, 2012).

- ii. **Circuit Wizard:** An electronic simulation software used for designing electronic circuits. The choice of Circuit Wizard was made because it provides all the tools necessary to produce an electronics project from start to finish – even including on-screen testing of the Printed Circuit Board (PCB) prior to construction; and with friendly graphical user interface (GUI). It was used to design the 5v circuit of the power system.

Fig. 3.2 shows the interface of circuit wizard.

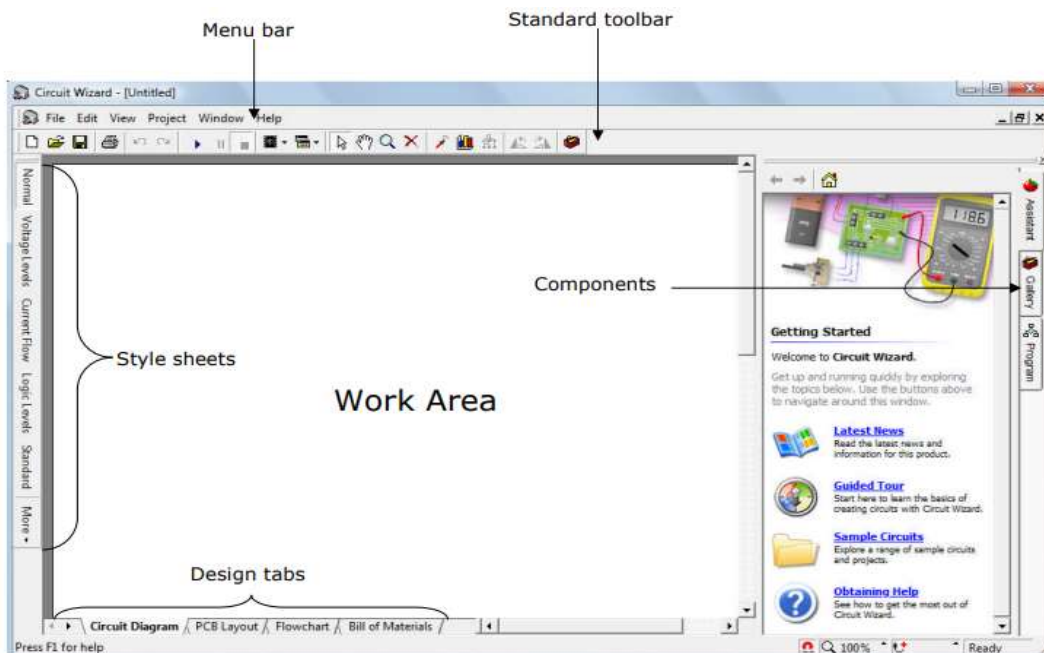


Figure 3.2: Circuit Wizard interface.

- iii. The various sensor types were represented as Zigbee End Devices (ZED) and the following were proposed based on their comparative advantages:
- a. Motion sensors for sensing the presence of birds and rodents. Passive InfraRed (PIR) sensor has been adjudged to be best suitable for motion sensing. Panasonic's AMN41121 PIR sensor was proposed because of its comparative advantages of extremely compact with built-in amplifier, adjustable sensitivity, and noise withstanding capability.
  - b. Temperature and Humidity sensors to detect change in temperature and to measure the amount of water vapour within the farmstead. Sensirion Inc. SHT75 was proposed because of its ability to measure temperature and humidity to the highest precision; and it is relatively inexpensive with impeccable continuity and minimal size.
  - c. Biological sensors: Biological sensor has the ability to sense the presence of weed, pests, insects, eg. WeedSeeker.
  - d. Soil moisture sensor to measure the amount of moisture on the farmstead. VG400 (a frequency domain reflectometry sensor) from Vegetronix Inc. was proposed because it is less expensive and uses less power.
  - e. Soil nutrient sensor to measure soil micronutrients such as nitrogen (N), phosphorus (P) and potassium (K). Teralytic<sup>(R)</sup> sensors were proposed. They can measure Soil electrical conductivity, moisture, pH, Nitrates, Phosphates, Potassium, and temperature at 3 different depths and sample every 15 minutes.

## 3.2 Method

The method employed in this thesis involves computer-based simulation design approach because it provides for varied conditions and the investigation of the resulting outcomes.

### 3.2.1 Conceptual Model for Selected Key performance Indicators (KPIs)

Stochastic model was adopted to determine the effect of the additional technology input to the overall yield of a rice farm. The Stochastic frontier for crop yield response is viewed as a good approximation and is widely used in crop yield response analysis (Sheahan et al., 2013).

Let a farmer's amount of produce (yield) per a hectare of rice farm be a function of his adoption of best technology practice.

This can be represented as:

$$Y_{eft} = f(X_{eft}) + \alpha \quad (3.1)$$

Where  $Y_{eft}$  = yield per hectare (ton) on farm  $e$  for farmer  $f$  in season (time)  $t$ ,

$X_{eft}$  = technology input variables,

And  $\alpha$  = unforeseen natural/environmental factors (other agronomic conditions).

For a multi-technology input farm, yield for a given farming season can be given as:

$$Y_{eft} = X_{0eft} + X_{1eft} (\text{Irr.}) + X_{2eft} (\text{Irr.} + \text{Fer}) + X_{3eft} (\text{Irr.} + \text{Fer.} + \text{Pst.}) + X_{4eft} (\text{Irr.} + \text{Fer.} + \text{Pst.} + \text{Herb}) + X_{5eft} (\text{Irr.} + \text{Fer.} + \text{Pst.} + \text{Herb.} + \text{Bird \& Rdnt Ctrl}) + \alpha \quad (3.2)$$

Where:

$Y_{eft}$  and  $\alpha$  are as defined above;

$X_{0eft}$  = Rainfed variable;

$X_{1eft} (\text{Irr.})$  = Irrigation variable;

$X_{2eft} (\text{Irr.} + \text{Fer})$  = Irrigation and Fertilizer application variable;

$X_{3eft} (\text{Irr.} + \text{Fer.} + \text{Pst.})$  = Irrigation, Fertilizer and Pesticide application variable;

$X_{4eft} (\text{Irr.} + \text{Fer.} + \text{Pst.} + \text{Herb})$  = Irrigation, Fertilizer, Pesticide and Herbicide application variable;

$X_{5eft} (\text{Irr.} + \text{Fer.} + \text{Pst.} + \text{Herb.} + \text{Bird \& Rdnt Ctrl})$  = Irrigation, Fertilizer, Pesticide, Herbicide application and Birds/Rodents Control variable.

The general form of equation 3.2 can be written as:

$$Y_{eft} = \sum_i^n (X_{eft}) + \alpha \quad (3.3)$$

### 3.2.2 Data Evaluation from Technological Input Variable

Data from comparative study of yield for rainfed (Lowland) and irrigated rice farm by Ezedinma (2005) and Potential Yield from Grant et al. (2009) for some selected Nigerian states was used. The average yield (ton/ha) for rainfed rice farm stood at 2.2, while average yield (ton/ha) for irrigated rice farm was 3.5. This shows a percentage difference of 37.14%.

Drawing from the model equation and using the data above as basis, the computation of the effect of additional technology-input variable results in the figures of Table 3.1 with the following working:

$$\text{Change in Average Yield (metric ton/ha)} = \Delta y$$

$$\text{Yield Percentage Change} = \frac{\Delta y_{iel}}{y_{ield}} * \frac{100}{1}$$

Yield increase and additional technology input are considered linear. Therefore, any additional technology input results in proportionate percentage yield change.

$$\text{Hence, } Y_{3eft} = Y_{2eft} + \Delta y; \dots Y_{neft}$$

$$(3.4)$$

Table 3.1: Estimated Average Rice yield(ton/ha) by additional technology-input variable

<b>Production System</b>	<b>Major Nig. State Covered</b>	<b>Average Yield (metric ton/hectare)</b>	<b>Yield % Change</b>
Rainfed (Lowland)	Benue, Ebonyi, Cross River, Niger	2.2	0
Irrigated	Benue, Ebonyi, Cross River, Niger	3.5	37.14
Irrigated + Fertilized	Benue, Ebonyi, Cross River, Niger	4.8	64.22
Irrigated +Fert. +Pest. Appl.	Benue, Ebonyi, Cross River, Niger	6.1	85.53
Irrigated +Fert. +Pest. + Herb.	Benue, Ebonyi, Cross River, Niger	7.4	103.09
Irrigated +Fert. +Pest. + Herb. + Birds/Rodent Control	Benue, Ebonyi, Cross River, Niger	8.7	118.03

### 3.2.3 Wireless Sensor Network Modelling

This study was realized through modelling various network scenarios to demonstrate data sensing of different environmental variables in a given farm land. This was achieved by varying network devices at different scenarios using OPNET simulator and understudying the network performances such as traffic sent (bits/sec), traffic received (bits/sec), end-to-end delay(second), throughput (bits/sec) and media access control (MAC) load (bits/sec). The idea of varying network devices is a

design approach adopted in this study to demonstrate integration of different sensor types monitoring different environmental variables simultaneously, yet constituting a single unit of WSN working cooperatively. Each new set of network devices are integrated to a Zigbee Coordinator (ZC) which assigns an address to its members and forms a personal area network (PAN), thus representing data sensing of a particular environmental variable.

Mesh topology was adopted for the design because of its ability to cover limitless area with the power to route data across different paths.

The modelling of the eWSN is based on Zigbee standard (IEEE 802.5.4) using OPNET Modeler 14.5A. The Zigbee wireless sensor network consists of three types of nodes. They are the end device nodes, the router nodes, and the gateway node (coordinator). The end device and router nodes are used to manage the data collection of various environmental variables (temperature & humidity, soil nutrients level, soil moisture level, presence of pests and rodents) and then the collected data are sent to the coordinator for processing, and control.

For implementation, the various sensor types can be integrated on Imote2 mainboard (by Crossbow) which allows a user/network designer to add new sensors to the mainboard.

### **3.2.2.1 System Block Diagram**

Figure 3.3 shows the block diagram of the WSN model. Sensed data from individual sensor types are routed through the Router to the Coordinator (Sink node) for further processing and control. The monitoring sub-network is equally connected to the Coordinator for both on-the-premise and remote monitoring as maybe deemed

necessary. Irrigation, pesticide application, herbicide application, and soluble fertilizer application can be done from any of the 4 compartments (Liquid A - D) connected to a water source through the irrigation pipe by the activation of the solenoid depending on the type of instruction received from the controller (Coordinator). The other actuator systems can be for the alarming system to deter birds and rodents from the farm.

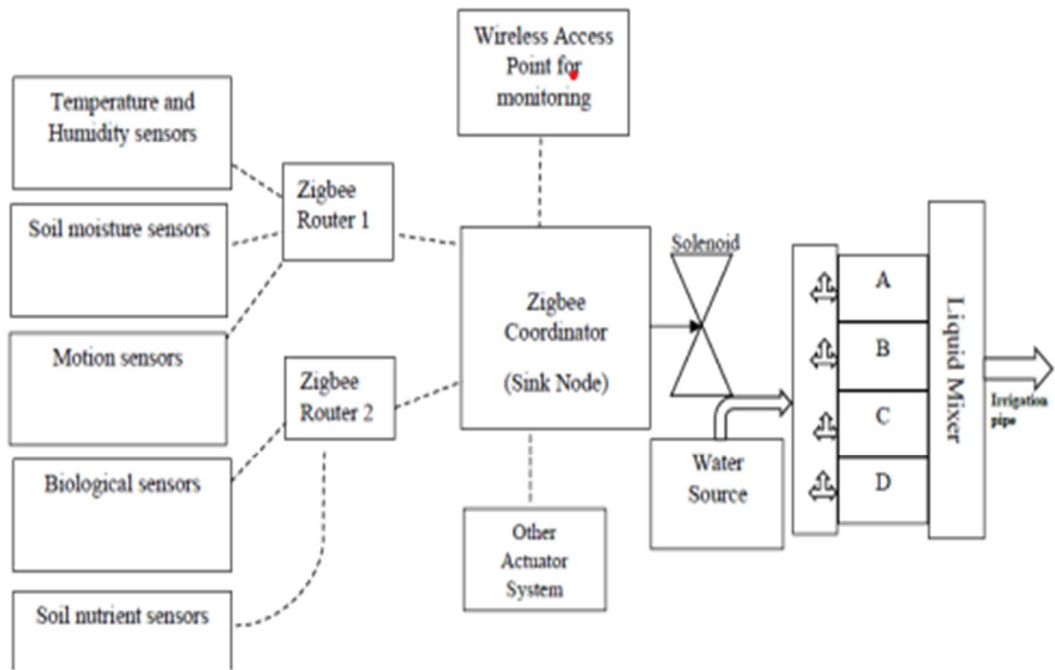


Figure 3.3: The System Block Diagram

### 3.2.2.2 Design flow chart

Figure 3.2 is the sensor designed flow chart showing sequence of events to realizing the system.

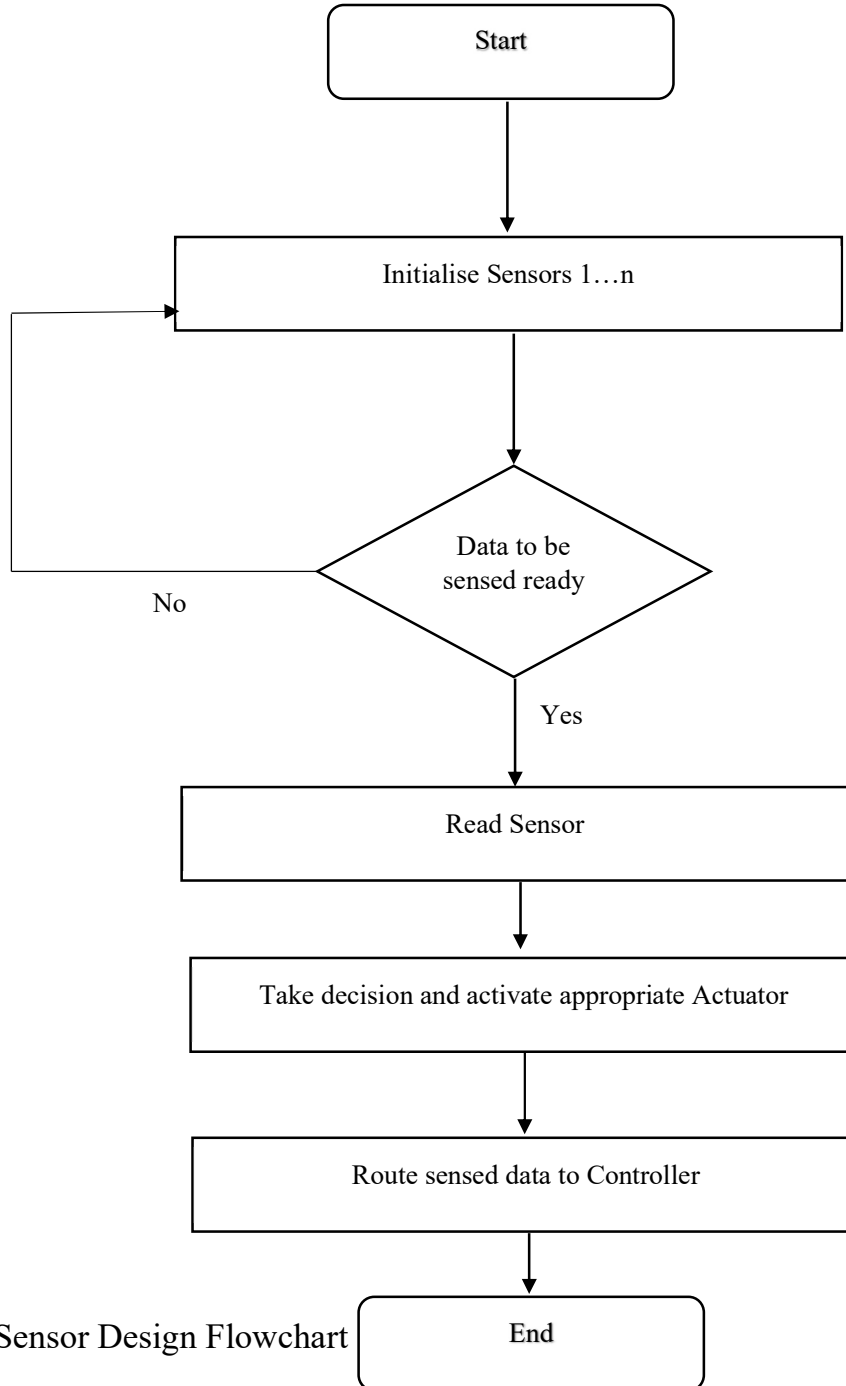


Figure 3.4: Sensor Design Flowchart

### 3.2.2.3 Model Farm Network Design

A farmland of 100m x 100m was used as a baseline for the study. Sensors were sparsely distributed across the farmland consisting of zigbee end devices (ZED), zigbee routers (ZR), zigbee coordinator (ZC) and actuators. The WSN is connected to a monitoring point via an access point gateway, with a wireless database server and a PC for on-the-premise monitoring while a host computer was connected via an internet protocol (IP) cloud for remote monitoring.

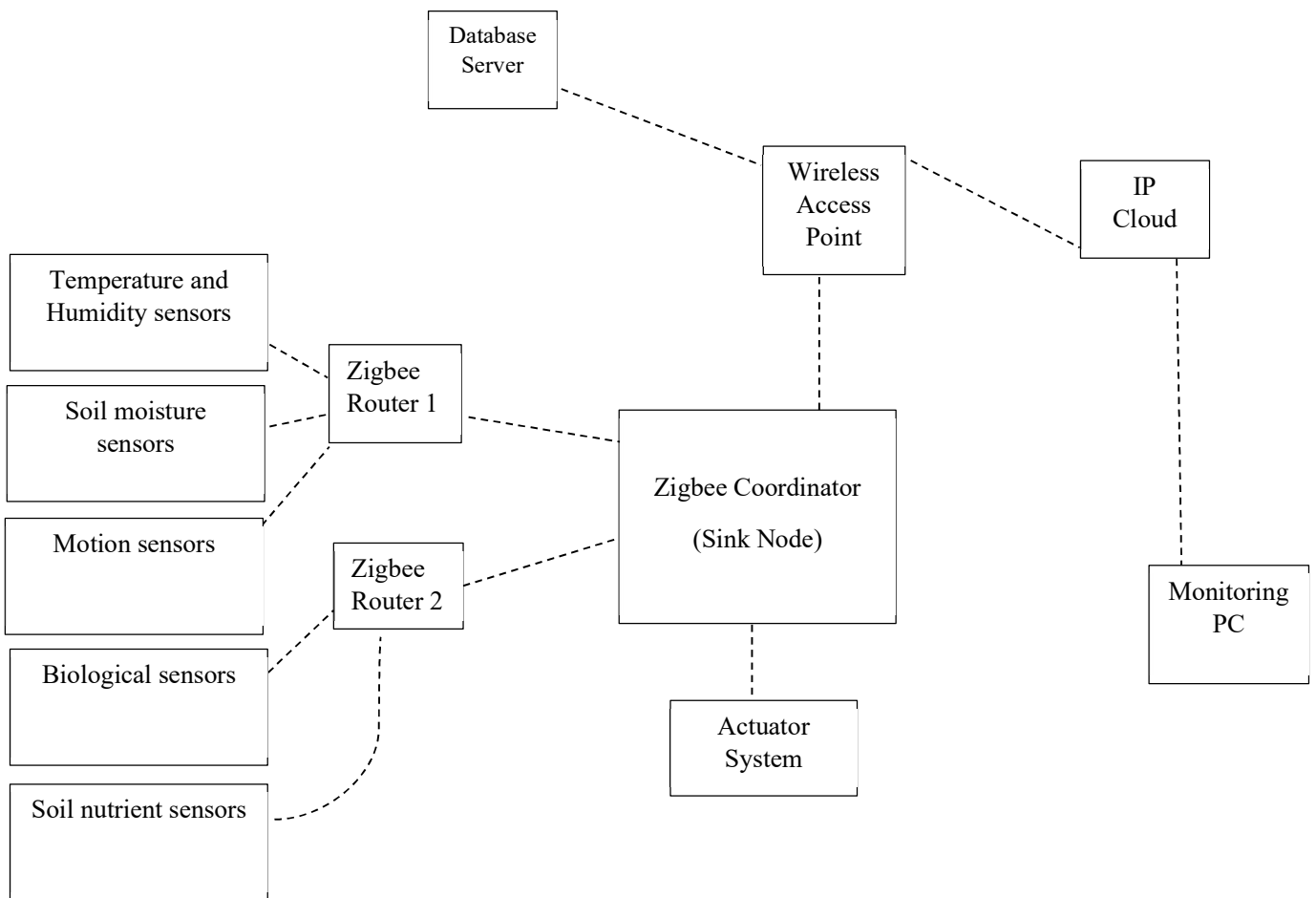


Figure 3.5: Model Farm Network Block Diagram

### **3.2.2.4 Simulation Scenarios Design**

Three network scenarios were created to demonstrate data sensing of different environmental parameters by varying number of network devices while watching out for network performance. New set of Zigbee devices are added to the ideal network (network of one sensor type) and configured to form a personal area network with an identifier for its members.

Scenario 1: consists of 4 Sensor Nodes, 2 Routers, and 1 Coordinator; to represent data sensing of temperature and humidity variables.

1. Scenario 2: consists of 8 Sensor nodes, 4 Routers, and 2 Coordinators. The second Coordinator is for the new set of sensor types; representing data sensing of soil nutrients, it is configured to route its traffic to the central Coordinator.
2. Scenario 3: consists of 12 Sensor nodes, 6 Routers, and 3 Coordinators. Again, the third Coordinator is for the next new set of sensor types; representing data sensing of motion variable, while the first Coordinator remains the central Coordinator while traffic from Soil Nutrition Coordinator is equally configured to be routed to it.

#### **i. Parameter Description for the Simulation of Scenario 1**

The global frequency and maximum bit rate of the network parameter of the coordinator was set at 2.4GH and 250kbps respectively (zigbee standards).

#### **ii. Media Access Control (MAC) Parameters**

Figure 3.6 shows the MAC configuration of the network. The maximum back-off exponent of the MAC parameter was assigned to 4 and the minimum back-off

exponent was assigned to 3. The value of the maximum back-off exponent executes Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm for 4 times, while the minimum back-off exponent ensures 3 attempts of executing before declaring the channel access failure. Both values were chosen for convenience's sake. Channel sensing duration which was the duration each channel was scanned for beacons after the beacon request has been sent was assigned to 0.1 seconds.

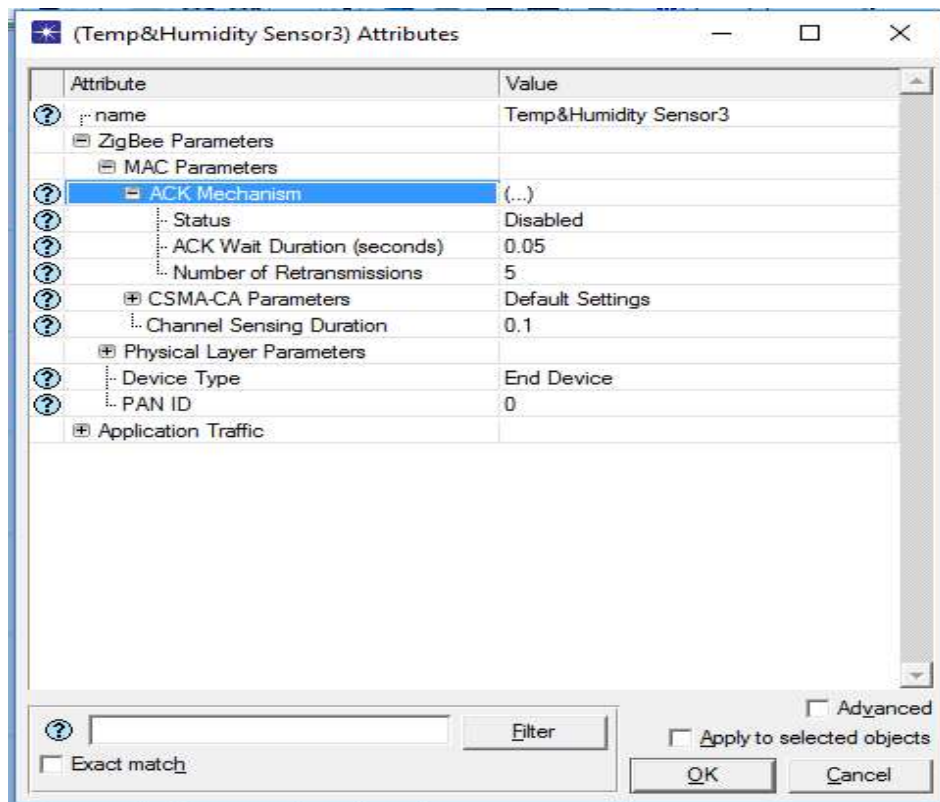


Figure 3.6: MAC parameters configuration

### iii. Network Parameters of the Coordinator

The network configuration parameters for the coordinator are as shown in figure 3.7. The maximum children number specifies the number of sensor nodes, routers and actuators that can be supported by a coordinator or a router. Maximum depth means the number of network trees the coordinator could have while router discovery timeout is the length of time allowable for the network to keep route discovery entries. In scenario 1, the Coordinator established its network with personal area network identifier (PAN ID) of 0; representing data sensing of a single environmental variable (temperature and humidity sensing).

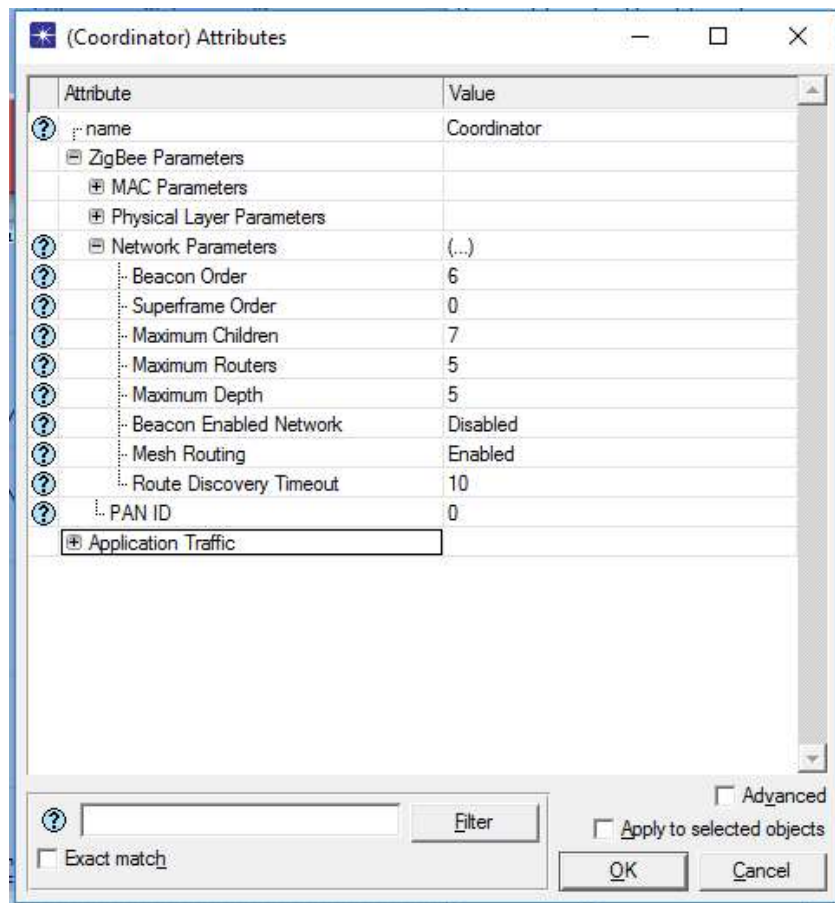


Figure 3.7: Network parameter of the Coordinator

#### iv. Physical Layer Parameters

The physical layer parameters are as shown in figure 3.8. In order to determine whether a node is dead or alive, a packet reception-power threshold was set to -76 dBm (considered optimal).

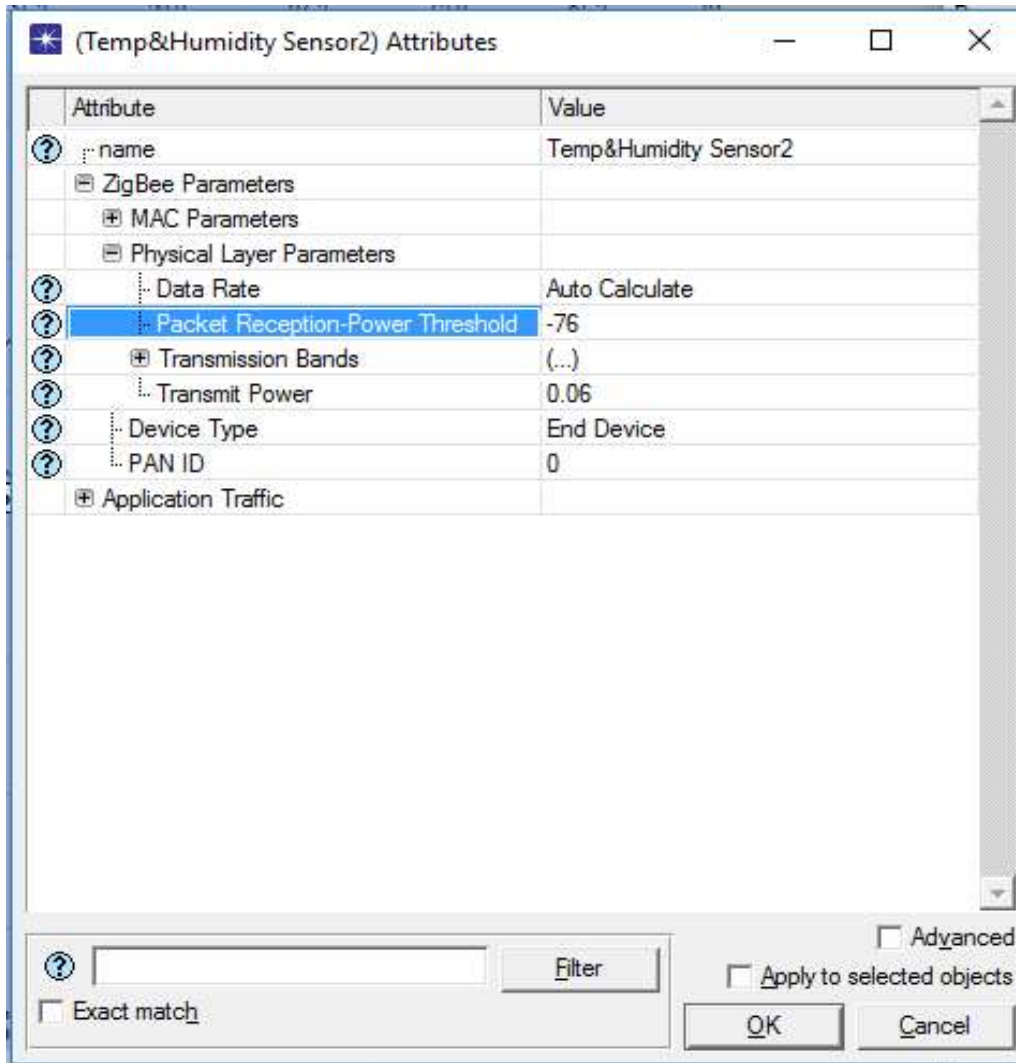


Figure 3.8: Physical Layer Parameters

#### v. Application Traffic Attributes

The application traffic parameters used are as shown in figure 3.9. The packet size of the sensed environmental variables was set to 32 bits; however, they could be an overhead added by each layer of the open system interconnect (OSI) model. The sensed nodes select a random destination within its own PAN. All traffic was started, followed by a distribution of uniform (60, 61) seconds after the simulation starts and traffic generation stopped at the end of the simulation.

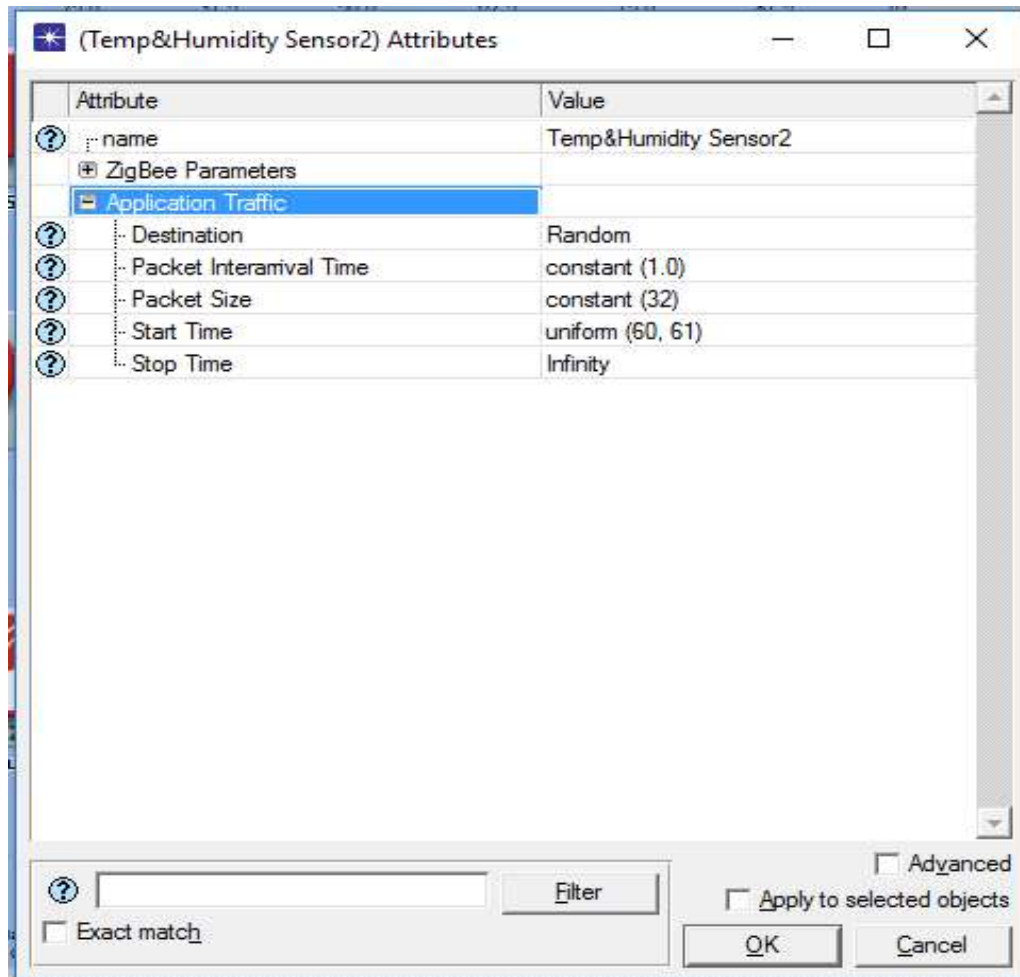


Fig. 3.9: Application Traffic Parameters

**vi. Transmit Power Configuration**

Figure 3.10 shows the transmit power parameter used. A value of 0.06mWatt was chosen because it is considered as optimal transmit power in terms of achieving maximum traffic sent (Shah Nawaz, 2015).

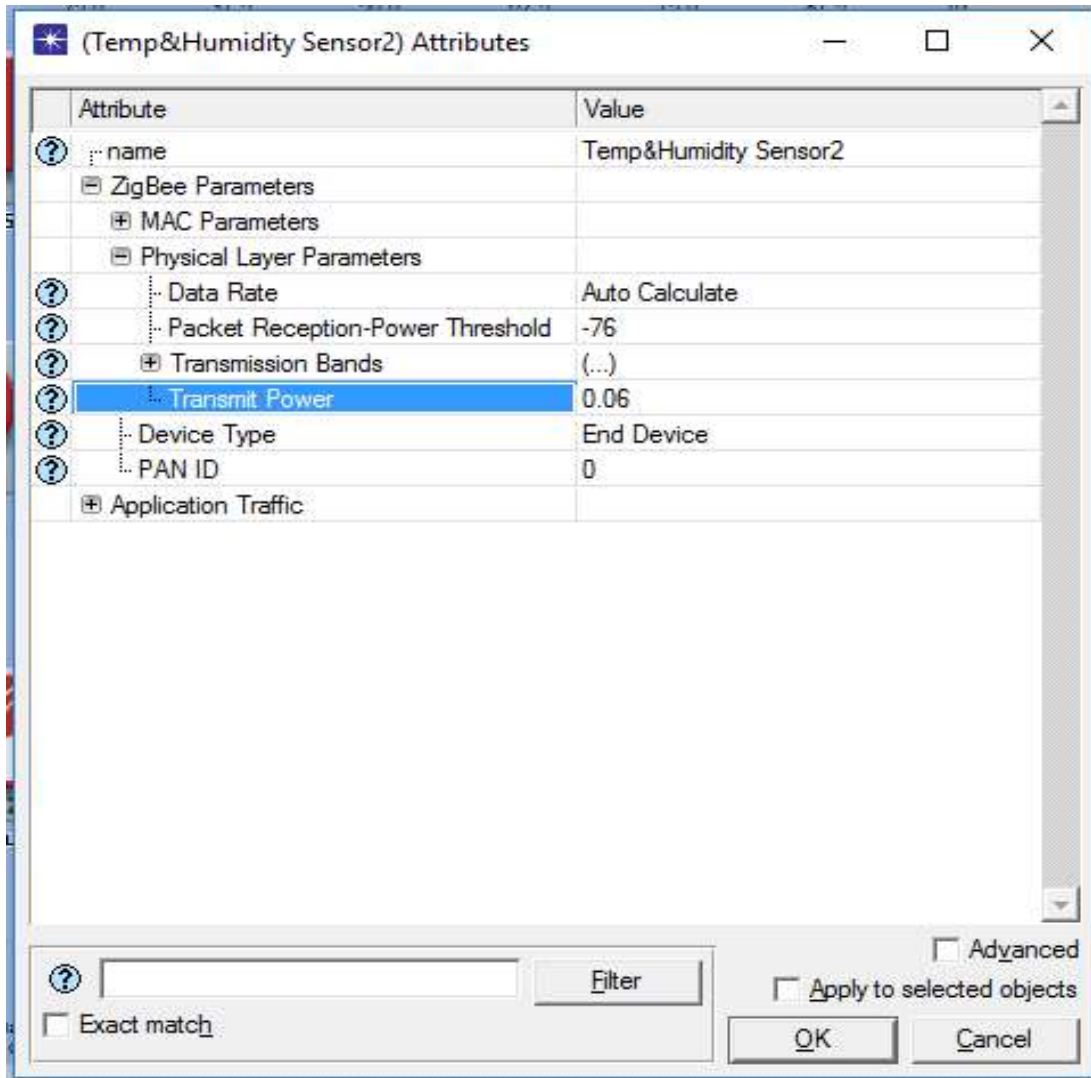


Figure 3.10: Transmit Power Parameter

### 3.2.2.5 Summary of Network Parameter Configurations

Table 3.2 shows the summary of the network parameter configurations of the network scenarios.

Tab. 3.2; Summary of Network Parameter Configuration.

Scenario	No. of ZED	No. of ZR	No. ZC	MAC Layer			PHY Layer	APPL Layer		Transmit Power(mWatt)	ZC PAN ID
				Max. Back-off Expon.	Max. Back-off Expon	Sensing Duration(sec)	Pkt Reception Power(dBM)	Pkt size(bits)	Distri. Time(sec)		
Scenario 1	4	2	1	4	3	0.1	-76	32	60,61	0.06	0
Scenario 2	8	4	2	4	3	0.1	-76	32	60,61	0.06	1
Scenario 3	12	6	3	4	3	0.1	-76	32	60,61	0.06	2

### 3.2.2.6 Device Configuration for the Simulation of Scenario 1

Figure 3.11 shows the device configuration for the simulation of scenario 1. It consists of 4 sensor nodes, 2 routers, and a coordinator. The number of routers is chosen to be 2 to ensure self-healing mechanism of mesh topology should one fail while minimal number of Zigbee End Devices (ZED) were used for visual simplicity. Parameter configurations are as discussed in section 3.2.2.4.

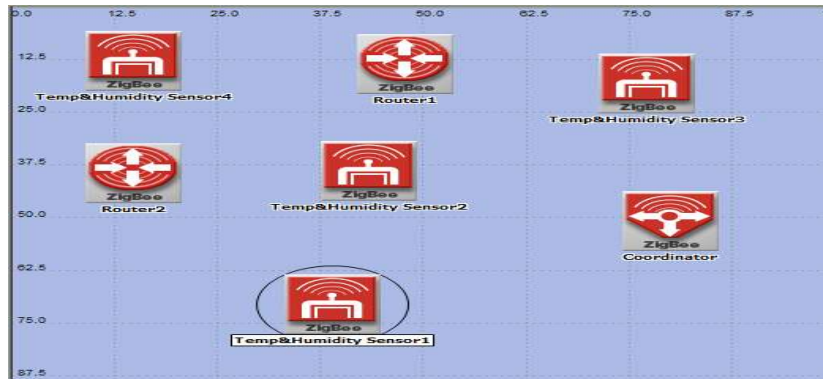


Figure 3.11: Scenario 1 Device Configuration

### 3.2.2.7 Device Configuration for the Simulation of Scenario 2

Figure 3.12 shows the device configuration of Scenario 2. It consists of 8 sensor nodes, 4 routers, and 2 coordinators. The topology of scenario 2 differs from that of scenario 1 in that the number of sensor nodes and routers doubled in size but the second coordinator (Motion\_Coordinator) is set to establish network with its ZED and with the two new routers (Motion\_Router 1 & Motion\_Router 2) with a PAN ID of 1 (PAN ID\_1). These new number of network devices added to the network forms a network sensing different environmental variables (motion detection) from the first set of nodes. Data routed through Motion\_Coordinator from its ZEDs and Zigbee Routers (ZRs) are configured to route to the central Coordinator. Sensor nodes and routers have similar parameter configuration as in scenario 1.

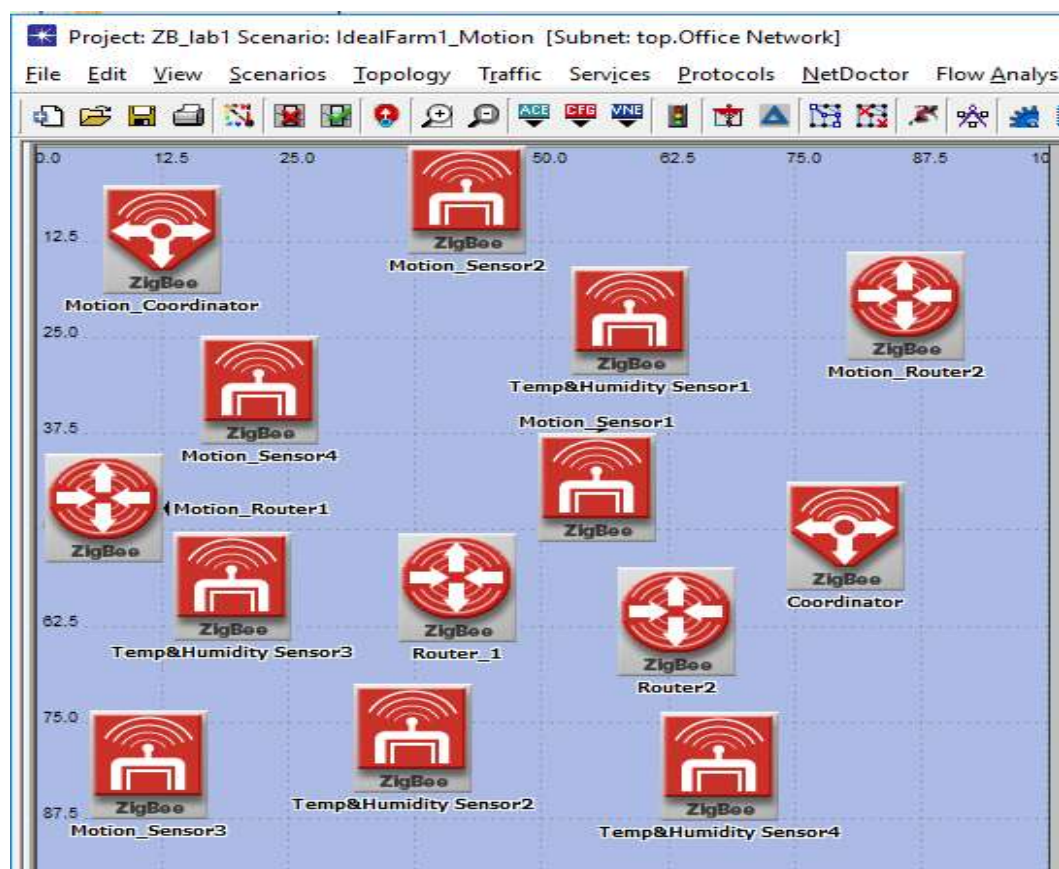


Figure 3.12: Scenario 2 Device Configuration

### 3.2.2.8 Device Configuration for the Simulation of Scenario 3

Figure 3.13 is the device configuration of scenario 3. The network model of scenario 2 was replicated with 12 sensors, 6 routers, and 3 coordinators. The third Coordinator (Soil Nut\_Coordinator) establishes a network with its members (Soil Nut\_Sensor 1 – 4 and Soil Nut\_Routers 1&2) with a PAN ID of 2 (PAN\_2). Sensed data (traffic) from Soil Nut\_sensors are routed through the Soil Nut\_Routers to the Soil Nut\_Coordinator. The Soil Nut\_Coordinator is configured to route its traffic to the central Coordinator. By so doing, another set of environmental variables (soil nutrients: NPK, etc.) different from those of scenarios 1 and 2 are sensed.

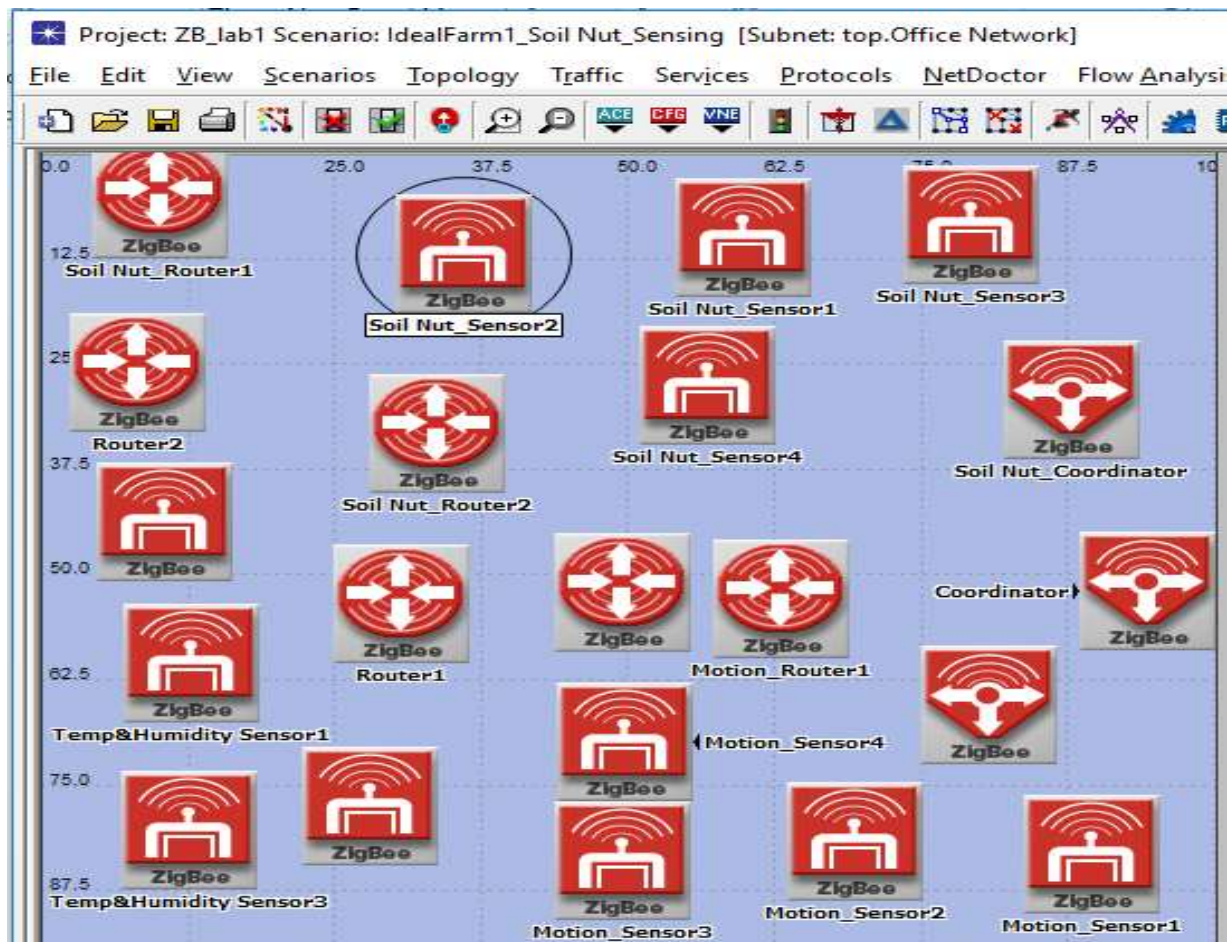
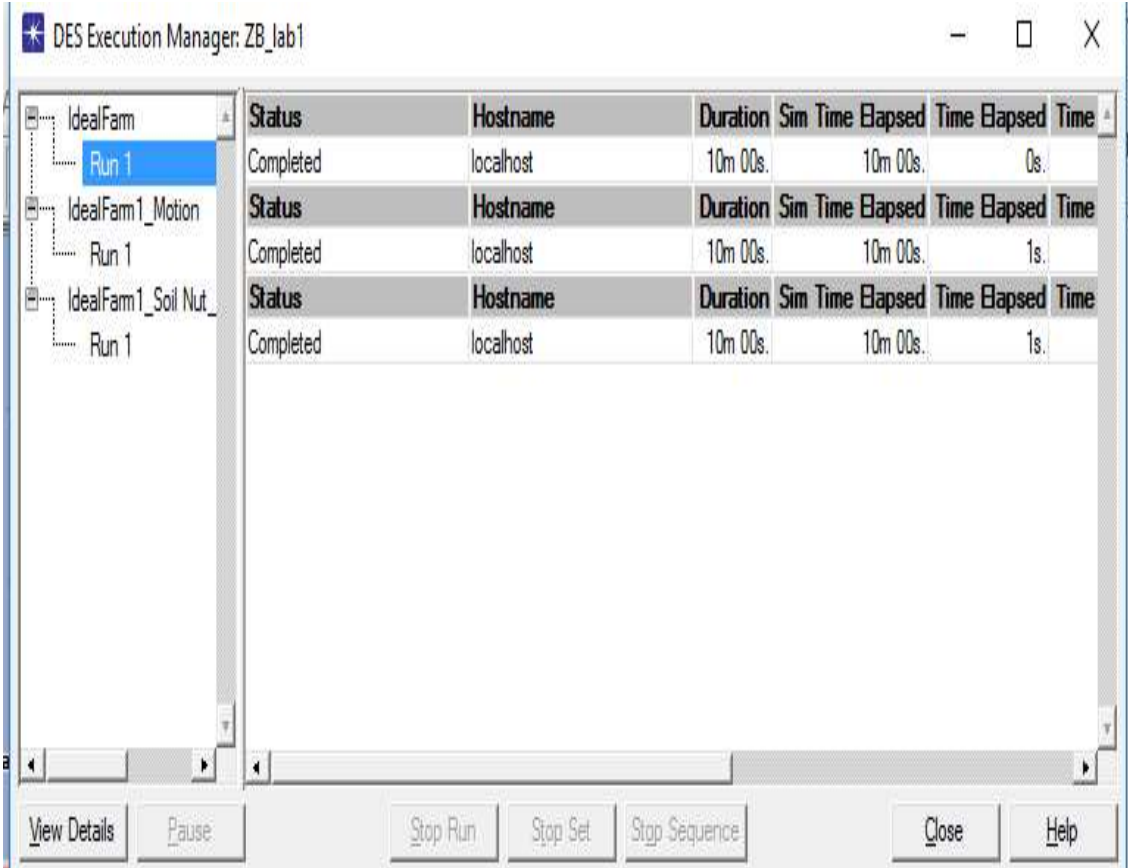


Figure 3.13: Scenario 3 Device Configuration

### 3.2.2.9 Simulation Run-Time

The simulation run-time information for the investigation of the network performance for the three scenarios simulated for 10 minutes is as shown in figure 3.14.



The screenshot shows the DES Execution Manager interface for a job named 'ZB\_Jab1'. On the left, a tree view shows three scenarios: 'IdealFam', 'IdealFam1\_Motion', and 'IdealFam1\_Soil Nut\_'. Each scenario has a 'Run 1' sub-entry. The main area displays a table with the following data:

Status	Hostname	Duration	Sim Time Elapsed	Time Elapsed	Time
Completed	localhost	10m 00s.	10m 00s.	0s.	
Completed	localhost	10m 00s.	10m 00s.	1s.	
Completed	localhost	10m 00s.	10m 00s.	1s.	

At the bottom of the window, there are several control buttons: 'View Details', 'Pause', 'Stop Run', 'Stop Set', 'Stop Sequence', 'Close', and 'Help'.

Figure 3.14: Simulation Run-time for the three scenarios

### 3.2.2.10 Functional Description of Metrics

In order to collect the statistics for the performance metrics, the simulation was run using OPNET Modeler 14.5A. Table 3.3 is a description of the global and object metrics collected, and whose data are presented in appendices A - E.

Table 3.3: Performance Metrics

SN	Name	Description	Group	Capture Mode	Draw Style	Filter
1.	Traffic Sent (bits/sec)	Application traffic sent by the layer in bits/sec.	ZigBee Application	bucket/default total/sum_time	Linear	time_average
2.	Traffic Received (bits/sec)	Application traffic received by the layer in bits/sec.	ZigBee Application	bucket/default total/sum_time	Overlaid	time_average
3.	802.1544_MAC Throughput (bits/sec)	Represents the total number of bits (in bits/sec) forwarded from 802.15.4 MAC to higher layers in all WPAN nodes of the network.	ZigBee 802.15.4 MAC	bucket/default total/sum_time	Linear	As is
4.	802.15.4_MAC Load (bits/sec)	Represents the total load (in bits/sec) submitted to 802.15.4 MAC by all higher layers in all WPAN nodes of the network.	ZigBee 802.15.4 MAC	bucket/default total/sum_time	Linear	As is
5.	End-to-End Delay(bits/sec)	Represents the entire delay between the invention and reception of application packets (bits/sec)	ZigBee 802.15.4 MAC	bucket/default total/sum_time	Linear	As is

### 3.2.3 Design Process for Multi-input Power System

To mitigate the problem of limited power capability associated with WSN, a multi-input power model was designed to supplement the power of the Coordinator (sink node) and the actuator systems while the end devices would utilize battery energy since more processing occur at the Coordinator level.

To achieve this, solar energy was coupled and delivered to the power circuitry of the Coordinator through a charging circuit and was powered by an alternating current (AC) source wirelessly in the event that the solar energy is not available. Figure 3.15 shows the block diagram of the multi-input power model of the network.

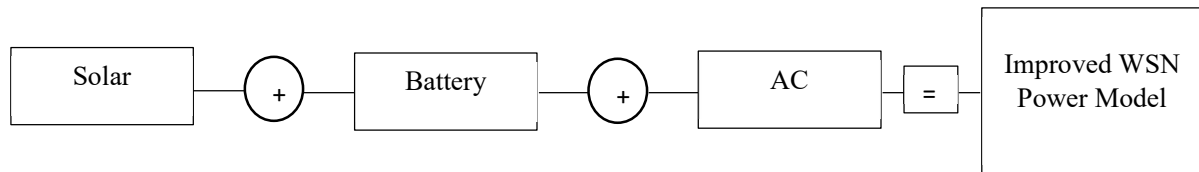


Figure 3.15: Block diagram of the WSN power system.

From figure 3.15;

Let  $S$  = solar energy from the sun.

$B^+$  = Energy stored in the battery backup system.

$W_p$  = Energy obtained from the wireless alternating current (AC) power system.

Mathematically, power supply model can be represented as

$$\sum_n [(S + B^+ + W_p) - \psi] = P_{supply} (j/s) \quad (3.5)$$

Where  $\psi$  is an error factor (0.1 – 0.01, assumed; (Gatheridge, 2014)) of the circuit which represents power loss due to circuit imperfection.

### 3.2.3.1 Power Model Schematic Diagram and Operation

The system was configured such that energy from the solar system was used for charging the battery and/or powering the Coordinator (sink) and the actuator system. The wireless power system was activated by a dark sensor switch when solar energy is unavailable and it transmits energy to the Coordinator if there is a potential/energy difference between the battery terminal and the wireless power sensor terminal coordinated by the relay coil shown in figure 3.17.

It can be seen from figure 3.17 that the solar panel power was fed to a charging circuit, and also to a Single Pole Double Throw (SPDT) relay coil (via a 78L12 voltage regulator). This relay remained activated as long as the solar panel voltage was persistent, and as soon as the voltage fell below threshold, the relay contacts automatically switched the mains Switching Mode Power Supply (SMPS) adapter voltage through the wireless power receiver to the charging circuit which then stores some energy and powers the Coordinator electronics through the regulated adjustable 5-volt circuit model of figure 3.16 designed with electronic circuit wizard. The output voltage was fine-tuned to the desired value (usually 4.5-5.5V) with the help of potentiometer (variable resistor (VR1)) connected just behind the 5-volt regulator. The regulated 5-volt circuit was to be built into the Coordinator power system and the actuator system.

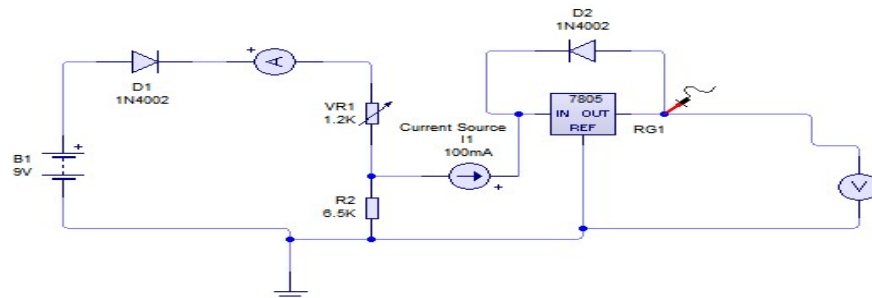


Figure 3.16: Volt regulated power supply model.

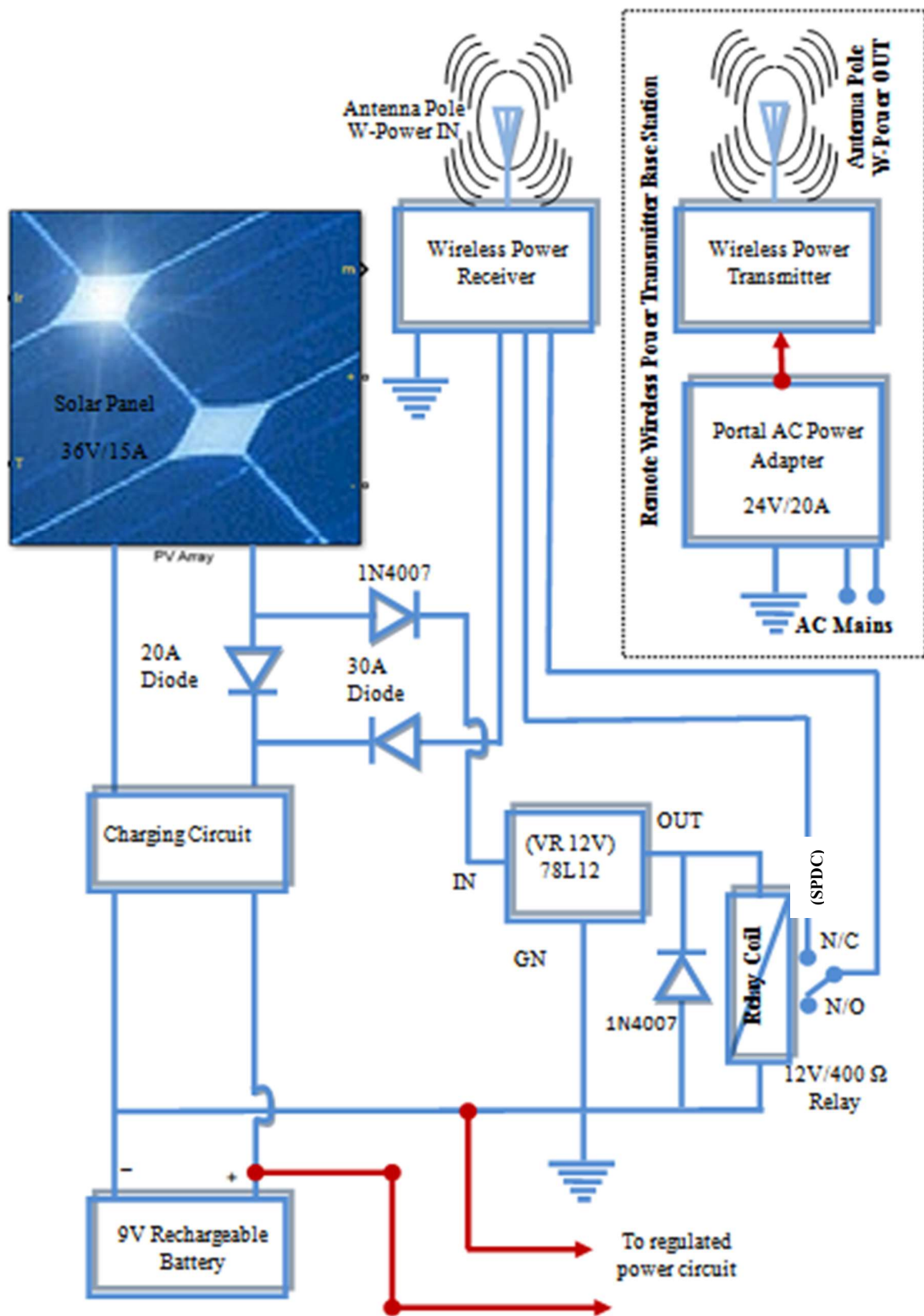


Figure 3.17: Schematic diagram of the WSN power system

### 3.2.3.2 Power System Evaluation for the WSN and the Actuator System

In order to ensure the system performs as expected, it is important to evaluate what the right energy requirement would be.

- **Design Assumptions**

The energy model of the network is developed based on the following design assumptions:

1. Assume that it takes 1 joule/sec (1 watt) of energy to move one unit charge of electric current containing one packet of sensed data from one sensor node to the router node;
2. Same quantity of energy is expended by the router node to move the data to the coordinator;
3. 1 joule/sec (1 watt) of energy is needed to power ON and activate a sensor node. At standby mode, power consumption is equal to zero; for simplicity's sake;
4. It takes 1 joule/sec (1 watt) of energy for a node to sense and gather measurement signals such as temperature, distance etc.;
5. The water pump is fractional horse power (1/3hp, 250Watt) liquid pump, which does not operate all the time except when actuation signal is received.

Also,

Let  $x$  = ON-OFF mode energy in joules (Activation energy);

$y$  = energy required to gather measurement data (temperature, proximity, etc.), that is, Sensing Energy

$t$  = Operation time (1 sec)

$k$  = Gain constant (1-1.5; assumed)

$m$  = pump/actuator energy consumption.

$\lambda$  = Coordinator node energy consumption.

$\beta$  = energy consumption of Router node (Transmit and Reception)

$\alpha$  = energy required to transmit sensed data (propagation energy).

**Energy consumed by a node during active state.**

$$(x + y + \alpha)kt - \psi = P_{tx} = P_{rx} (j / s)$$

(3.6)

**Energy consumed by one node during inactive state.**

$$(x + y + \alpha)kt - \psi = 0 (j / s)$$

(3.7)

**Energy consumed by the router node during active state.**

$$n(\beta + x)kt - \psi (j / s)$$

(3.8)

Where  $n$  is the number of simultaneous operations/quantity of packets arriving at the router at any given time,  $t$ .

**Total Node Energy consumption at any point in time.**

$$\sum_{i,j}^i N(x + y + \alpha)kt - \psi (j / s)$$

(3.9)

**Coordinator Energy Consumption.**

$$n(\lambda)kt - \psi (j / s)$$

(3.10)

### **Gross Farm Field Energy Consumption.**

Sensor node energy + Router node energy + Coordinator energy + Pump/Actuator energy, that is;

$$\sum_{j,j \rightarrow 0}^i ([(x + y + \alpha)kt - \psi] + [n(\beta + x)kt - \psi] + [n(\lambda)kt - \psi] + (m)) = P_{consumed} \text{ (j/s)} \quad (3.11)$$

### **3.2.3.3 Parameter Computation**

From the power consumption model and basic assumptions presented in section 3.2.3, the average energy requirement of each unit and the entire network can be estimated as follows:

#### **Energy Consumption at the Node level.**

From equations 3.6 and 3.7;

At active state:

$$(x + y + \alpha)kt - \psi = P_{TX} = P_{RX} \text{ (j/s)}$$

And at inactive state:

$$(x + y + \alpha)kt - \psi = 0 \text{ (j/s)}$$

From design assumptions;

$$x = y = \alpha = 1 \quad (3.12)$$

With  $k = 1.3$  (mid-range value considered optimal), and  $t(s) = 1$  ;

Eqn. 3.7 now becomes

$$(1 + 1 + 1) 1.3(1) - \psi = P_{TX \text{ (RX)}} \quad (3.13)$$

Applying mid-range value of energy loss,  $\psi$  of 0.055;

$$P_{TX(RX)} = 3.845(j/s)$$

(3.14)

For  $n$  number of nodes, total average energy is

$$n(P_{TX(RX)}) = n(3.845)(j/s)$$

(3.15)

### **Energy Consumption at the Router/Repeater level.**

$$n(\beta + x)kt - \psi (j/s)$$

(3.16)

Where  $n$  is the number of packets from end devices arriving at the router at a given time,  $t$ .

$$n(2)1.3(1) - 0.055 = n(2.545)(j/s)$$

(3.17)

### **Energy Consumption at the Coordinator level.**

$$n(\lambda)kt - \psi (j/s)$$

(3.18)

Where  $n$  is the number of packets arriving at the Coordinator at a given time,  $t$ .

The  $n$  factor at the Coordinator expectedly should be higher than at Router since packets from various routers arrive at the Coordinator for processing.

Following from eqn. 3.18;

$$n(1)1.3(1) - 0.055 (j/s)$$

$$E_{Coordinator} = 0.94n (j/s)$$

(3.19)

### Gross/average power consumption of the farm field.

$$\sum_{j,j \rightarrow 0}^i (P_{node} + P_{router} + P_{Coordinator} + P_{Actuators / pump} + P_{others}) = P_{gross} \text{ (j/s)} \quad (3.20)$$

Where  $P_{others}$  are powers consumed by lighting system, etc.

Assuming  $P_{others} = 10\%$  of Coordinator power =  $0.094n$ , and  $P_{pump/actuator} = 1/3$  of  $1hp = 1/3 * 750 = 250j/s$  then,

$$P_{av} = 3.84 + 2.54n + 0.94n + 0.094n + 250(j/s) \quad (3.21)$$

$$P_{av} = 253.84 + 3.574n(j/s) \quad (3.22)$$

The power model for enhanced WSN is expected to supply  $253.84 + 3.574n(j/s)$  amount of power to the farm, with expansion factor taken into consideration. This means that the computed power can be varied either upward or downward to meet the energy requirement of the proposed farm.

## CHAPTER FOUR

### RESULTS AND DISCUSSIONS

This chapter presents the results obtained from the study and discussions around them.

#### 4.1 Result of the Implementation of Conceptual Model of Selected Key performance Indicators (KPIs)

The intent of this study was to understudy the effect of the introduction of each of the selected KPIs on the overall yield of a rice farm. Rice yield across incremental addition of the KPIs as production inputs followed priori expectation and corroborates the result of previous studies that adoption of improved agricultural production techniques increases yield per hectare of a farmland. For instance, the result showed that with irrigation as an input variable, a yield increase of 1.3 metric ton (MT) per hectare is possible. This representing about 37.14% increase in yield from the rainfed production system. In that order, the combination of the other selected KPIs increased yield per hectare up to 8.7MT as shown in figure 4.1.

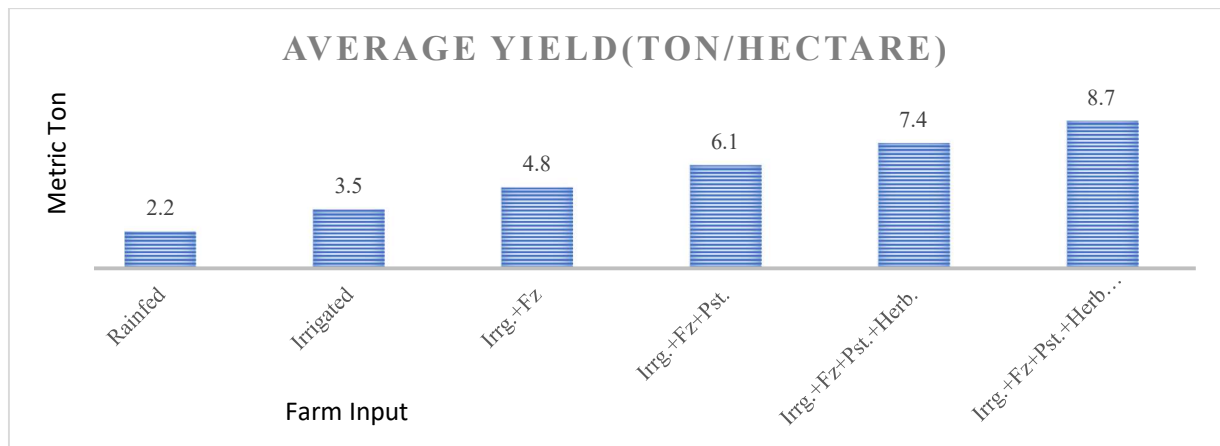


Figure 4.1: Average Yield (ton/ha)

Where: Fz = Fertilizer; Pst = Pesticide; Herb = Herbicide; Bird&Rdnt Ctrl = Birds & Rodent Control.

## **4.2 WSN Modelling and System Simulation Results**

Data sensing and transmission by wireless devices were modelled using OPNET 14.5A. Simulation was run to collect results as follows:

- i. Traffic sent by the 3 sensor types used in the scenarios (bits/sec);
- ii. Traffic received at the individual Coordinators (bits/sec);
- iii. The network End-to-End delay (sec);
- iv. Medium Access Control (MAC) Throughput (bits/sec), and
- v. MAC load per PAN (bits/sec).

### **4.2.1 Traffic Sent by the 3 Sensor Types Used in the Scenarios (bits/sec)**

The focus of this study was to determine if the different sensor types used in the scenarios were able to generate and transmit their traffic (data). Figure 4.2 shows the traffic sent by motion\_sensor1, soil Nut\_sensor1 and Temp and Humidity sensor1 to their respective routers. Data traffic sent is defined as the total number of data bits sent by the source to destination per unit time irrespective of the condition whether all the data bit reach the destination or not.

It can be seen from appendix A that each of the sensor type was able to generate and transmit an average traffic of 29kbps to its router destination. In each instance of the sensors, there was a delay of about 54s from when the simulation starts during which the sensor senses its data and determines the best path to route it.

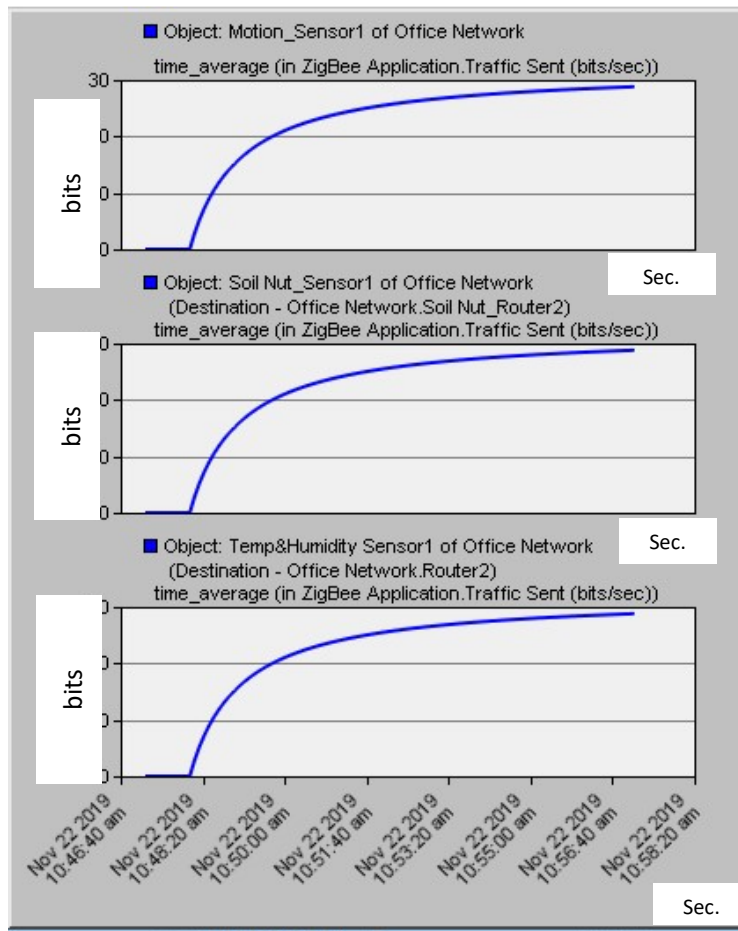


Figure 4.2: Traffic Sent by the 3 Sensor Types (bits/sec)

## 4.2.2 Traffic Received at the Individual Coordinators (bits/sec)

Figure 4.3 shows the traffic received at the individual Coordinators used in the simulation. Traffic received is defined as the total number of data bit received per unit time. The data was collected as object statistics and presented as overlaid. It can be seen from appendix B that each of the coordinators received steady stream of data without disruption. The amount of data received by Temp&Humidity coordinator (blue) and that of the Motion\_Coordinator (red) is 64bps for each, hence the overlap while that of the Soil Nut\_Coordinator (green) is 96bps.

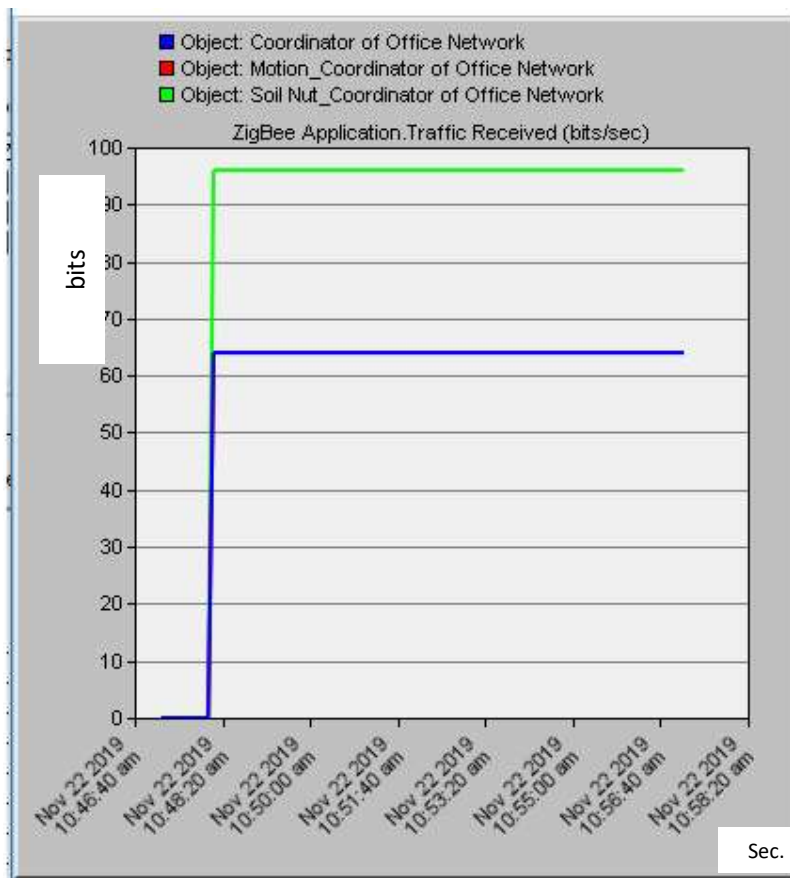


Figure 4.3: Traffic Received at the Individual Coordinators (bits/sec)

### 4.2.3 Network End-to-End (ETE) Delay (seconds)

Figure 4.4 shows the end-to-end (ETE) delay for the three PANs of the network. End-to-end delay is an OPNET global statistics. It is the entire delay between the generation and reception of application packets. Global statistics give relevant information concerning the overall system and measures the effect in real time monitoring. As can be seen from appendix C, the average delay for the 3 PANs showed a consistency in the amount of ETE delay. It showed that the zigbee end devices (blue line) of PAN 0 connect to their routers with a delay of 0.01s, PAN 1 (red line) with a delay of 0.003s and PAN 2 (green line) with a delay of 0.007s. On the average, the ETE of the network stood at about 0.007s. Significantly, the average ETE of the network is low due to ability of mesh routing process to find more efficient route.

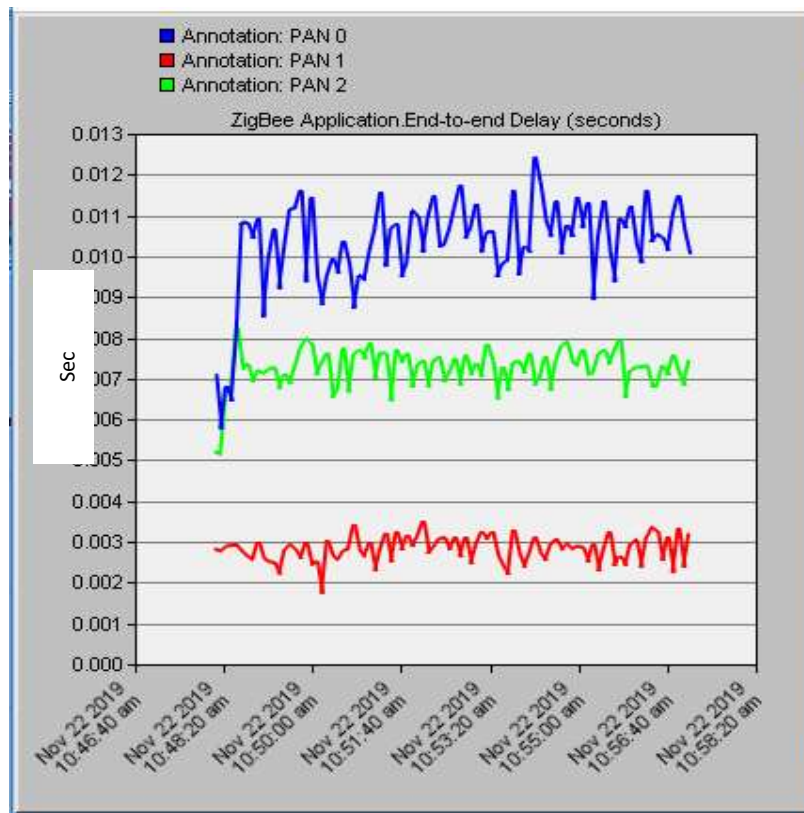


Figure 4.4: Network End-to-end Delay (second)

#### 4.2.4 Medium Access Control (MAC) Throughput (bits/sec)

Figure 4.5 shows the MAC throughput of the 3 scenarios. The MAC throughput was collected as a global statistics. It is the amount of bits or packets successfully acquired or transmitted by the receiver or transmitter channel per second. The spike for each of the scenarios at the beginning and at some point of the simulation are indications of management and control traffic sent and received to determine the presence of devices as well as the optimal route. As can be seen from appendix D, the throughput for the scenarios showed same pattern with the farm of one sensor type (blue line) having a throughput of 1368bps, 3192bps for the farm of two sensor types (red line) and 3977bps for the farm of three sensor types (green line).

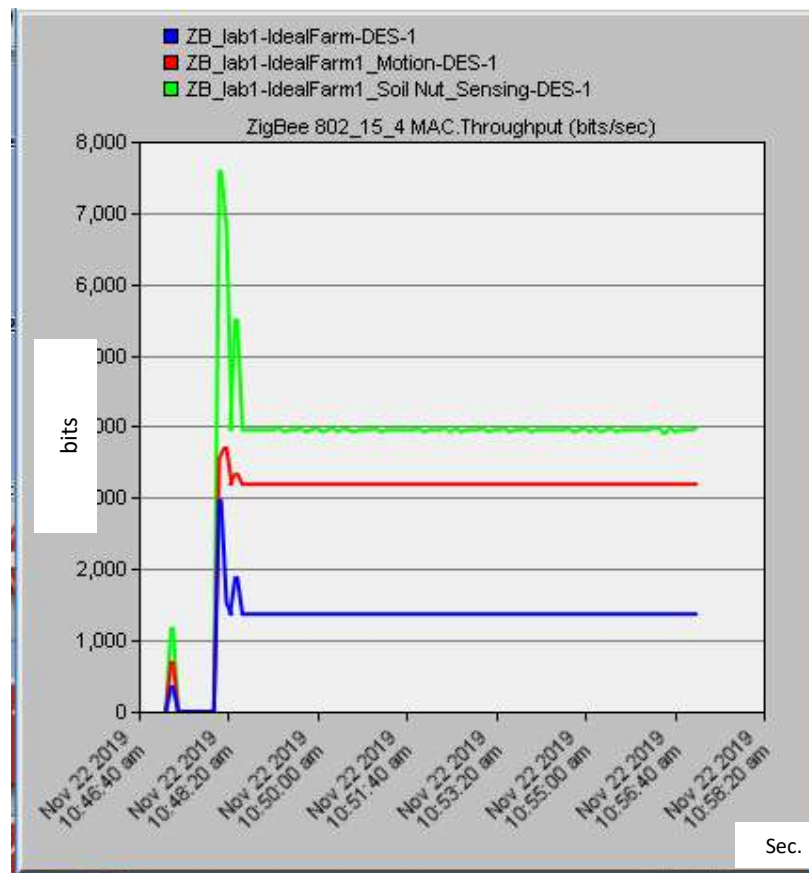


Figure 4.5: Medium Access Control of the 3 scenario (bits/sec)

#### 4.2.5 MAC Load per PAN (bits/sec)

Figure 4.6 is the graph of the global MAC load per PAN of the simulation. MAC load represents the forwarding load for each PAN to transfer the packets to the IEEE 802.15.4 MAC layer, i.e., physical layer, by the upper layers. The MAC load for PAN 0 (blue line) is 1976 bits/sec, while that of PAN 1 (red line) is 304 bits/sec and PAN 2 (green line) is 1849 bits/sec respectively as can be seen from appendix E. There is a spike in each of the PAN at about 6 seconds when the simulation started and later at about 60 seconds. This is due to the routing messages being broadcast at those times.

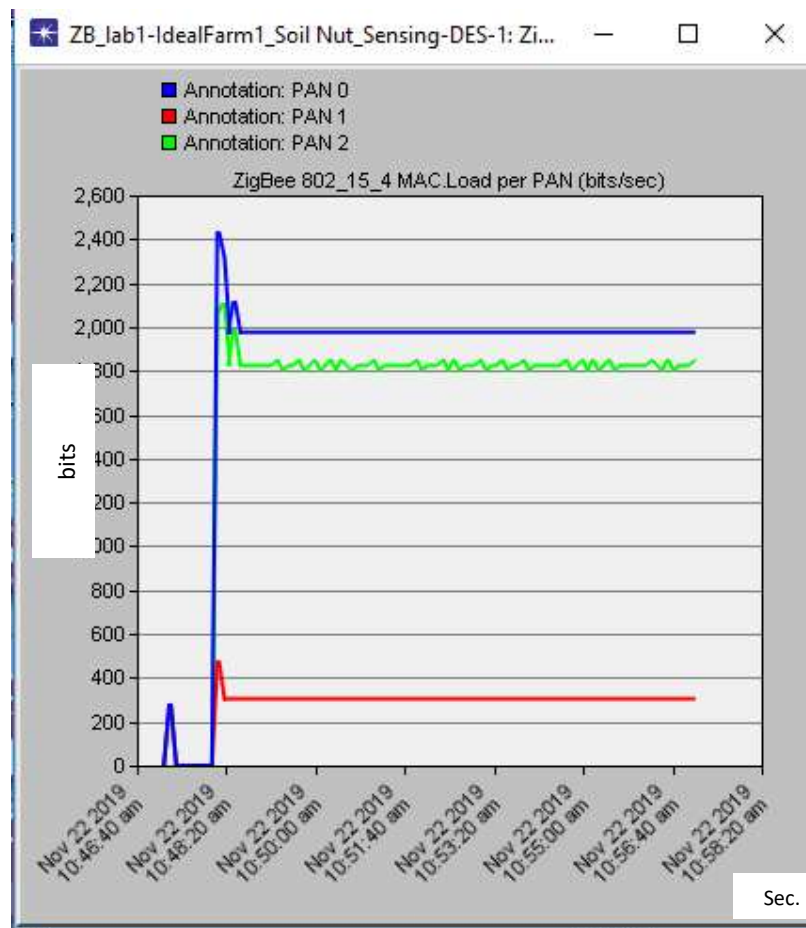


Figure 4.6: MAC Load per PAN (bits/sec)

### 4.3 Result of Multi-input power system Design

The 3-power sources designed for the farm were modelled and represented mathematically as a combination of the various sources shown as equation 3.5 as follows:

$$\sum_n [(S + B^+ + W) - \psi] = P_{supply} (j/s)$$

Expectedly, the equation of the power combination is suggestive of the fact that the system would be sustained for a longer period of time than it would have been for a single source of power. This is true since any of the sources, say, the battery can independently power the system but can get drained up much faster.

#### 4.3.1 Result of Power System Evaluation for the WSN and the Actuator System

The energy requirement for each component unit of the WSN and actuator system was evaluated and presented.

For ZigBee end devices (ZEDs), the amount of energy required to sense its data and transmit same is given by

$$(x + y + \alpha)kt - \psi = P_{tx} = P_{rx} (j/s).$$

While the amount of energy required by Zigbee Router (ZR) during active state is given by

$$n(\beta + x)kt - \psi (j/s).$$

And the amount of energy required by a Zigbee Coordinator (ZC) during active state is given by

$$n(\lambda)kt - \psi (j/s).$$

The result of the computation indicated that about 3.84 (j/s) was required by a Zigbee end device for its operation during active state.

For Zigbee router, the computed energy is  $2.54n$  (j/s) while for ZigBee coordinator, the value is  $0.94n$  (j/s). The  $n$  factor is the amount of data packets arriving from Zigbee end devices for the router, and from ZigBee routers for the coordinator. It is expected that the value of  $n$  is higher at the coordinator than at the router. This is so since all the routers route their data to the coordinator.

Energy requirement of the pump/actuator is a fractional horse power ( $1/3\text{hp}$ ), i.e.,

$$\frac{1}{3} (750) = 250 \text{ (j/s)}$$

Although the computed energy values for Zigbee end device, Zigbee router and the coordinator are low, they can be seen to be high in comparison with standard energy definition for Zigbee devices. This is understandable since parametric values were assumed for simplicity of computation.

## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATION

#### 5.1 Conclusion

The main aim of this research was to implement selected key performance indicators (KPIs) for enhanced rice production by addressing five major challenges that face rice farmers in developing countries especially in Nigeria which include non-availability of water/rain for year-round cultivation, disproportionate application of fertilizer/manure, weed control/prevention, pest/disease control, and rodents and birds invasion.

In order to achieve this, a Zigbee-based Enhanced Wireless Sensor Network (eWSN) was used to develop a simulation-oriented model of the farm where devices such as Zigbee end devices, Zigbee routers, and Zigbee coordinators were used. The design and simulation of the system was done using OPNET modeler 14.5A because OPNET has a module for WSN designs and a friendly graphical user interface. Computer based simulation design approach was used over direct measurement and mathematical analysis because it provides for varied conditions and the investigation of the resulting outcomes.

Since energy is a scarce commodity in most rural areas in Nigeria and to ensure network longevity, an external power source with solar energy integration which has the capability of transmitting power wirelessly to the coordinator was designed. In all, three different scenarios were designed and simulated. The design involved varying the number of network devices (sensor nodes, routers, and coordinators). To demonstrate data sensing of different environmental variables, new set of network devices (ZEDs, ZR, and ZC) were added to the ideal network (network of one sensor type) and configured to form a personal area network with an identifier for its

members to represent sensed data from different sensor types (temperature and humidity sensor, motion sensor, biological sensor and soil nutrient sensor).

The performance of the network was analysed based on some metrics such as packet sent, packet received, end-to-end delay, throughput and load per PAN. Each sensor type used in the simulation was able to generate and transmit its data (traffic). Each of the temperature and humidity, motion and soil nutrient sensors generated about 29bps of data.

At the coordinators, steady stream of traffic were received. The temperature and humidity coordinators received a traffic of 64bps each, while the soil nutrient coordinator received data traffic of 96bps.

The average end-to-end delay of the 3 PANs of the network stood at 0.007s. MAC throughput of 1368bps, 3192bps and 3977bps were obtained for the scenarios with one, two and three sensor types respectively, while the MAC load per PAN of the network were 1976bps, 304bps and 1849bps for each of PAN\_0, PAN\_1, and PAN\_2 respectively.

By implementing the KPIs, the result equally showed an estimated yield increase from 2.2 to 8.7 metric ton per hectare of a rice farm.

From the results of the quality of service (QoS) analysed, the design indicated good network performance suitable for data sensing in a typical rice farm. The design approach has shown it is possible to have a network of different sensor types integrated and working cooperatively to sense different environmental variables.

The learning experience in the course of this study is that an integrated and enhanced wireless sensor network (eWSN) is realizable and suitable for improved rice production especially in Nigeria since it has the capability of managing and maintaining the scarce resources at the farmer's disposal.

For example, based on the reading of the current temperature and humidity, the water pump can automatically be triggered for irrigation purpose and turned off when the set value is attained.

## **5.2 Recommendations**

An enhanced wireless sensor network system for data sensing of different environmental variables adaptable for improved rice production has been designed and simulated at software level using OPNET 14.5A. The result of the simulation of the design and some quality of service (QoS) of the network analysed indicated possibility of integrating different sensor types to work cooperatively to sense different environmental variables simultaneously. It is recommended therefore that Original Equipment Manufacturers (OEMs) in the business of wireless sensor manufacturing should implement and commercialise the designed model bearing in mind cost effectiveness and ease of deployment.

It is equally recommended that agricultural ministries at all levels of government should, as a matter of policy, adopt the technology in order to achieve national rice sufficiency and for foreign exchange earnings accruing from rice export.

Since it is recommended that OEMs produce the model in commercial quantities at effective cost and ease to deploy form, it is also recommended that even peasant farmers and farmers' co-operative societies should adopt the use of the product for increased productivity and income generation.

It is further recommended that educational and research institutions should extend future work on more energy efficient WSN system including energy harvesting design implementation adaptable for use especially in developing countries like Nigeria, interoperability with existing standard protocols and quality of service (QoS) in the experimental monitoring and controlling testbed.

### **5.3 Contribution to Academic Knowledge**

Having established how it is possible to integrate different wireless sensors to work co-operatively yet simultaneously, a rice farmer's major challenges of irrigation, fertilizer application, pest and disease control, and birds/rodents invasion can be addressed by integrating such sensors to monitor environmental variables and activating appropriate actuator system based on the instruction from the controller.

Up till this research, no work has suggested the use of WSN in agriculture in such an integrated manner for the purposes of solving the selected key performance indicators for enhanced rice production especially in developing country such as Nigeria.

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**APPENDIX A: Simulation Data for Traffic Sent (bits/sec)**

<b>Time (sec)</b>	<b>Traffic_Sent_MotionSensor</b>	<b>Traffic_Sent_Soil_NutSensor</b>	<b>Traffic_Sent_Temp_HumSensor</b>
0	0	0	0
6	0	0	0
12	0	0	0
18	0	0	0
24	0	0	0
30	0	0	0
36	0	0	0
42	0	0	0
48	0	0	0
54	0	0	0
60	2.909090909	2.909090909	2.909090909
66	5.333333333	5.333333333	5.333333333
72	7.384615385	7.384615385	7.384615385
78	9.142857143	9.142857143	9.142857143
84	10.66666667	10.66666667	10.66666667
90	12	12	12
96	13.17647059	13.17647059	13.17647059
102	14.22222222	14.22222222	14.22222222
108	15.15789474	15.15789474	15.15789474
114	16	16	16
120	16.76190476	16.76190476	16.76190476
126	17.45454545	17.45454545	17.45454545
132	18.08695652	18.08695652	18.08695652
138	18.66666667	18.66666667	18.66666667
144	19.2	19.2	19.2
150	19.69230769	19.69230769	19.69230769
156	20.14814815	20.14814815	20.14814815
162	20.57142857	20.57142857	20.57142857
168	20.96551724	20.96551724	20.96551724
174	21.33333333	21.33333333	21.33333333
180	21.67741935	21.67741935	21.67741935
186	22	22	22
192	22.3030303	22.3030303	22.3030303
198	22.58823529	22.58823529	22.58823529
204	22.85714286	22.85714286	22.85714286
210	23.11111111	23.11111111	23.11111111
216	23.35135135	23.35135135	23.35135135
222	23.57894737	23.57894737	23.57894737
228	23.79487179	23.79487179	23.79487179
234	24	24	24

240	24.19512195	24.19512195	24.19512195
246	24.38095238	24.38095238	24.38095238
252	24.55813953	24.55813953	24.55813953
258	24.72727273	24.72727273	24.72727273
264	24.88888889	24.88888889	24.88888889
270	25.04347826	25.04347826	25.04347826
276	25.19148936	25.19148936	25.19148936
282	25.33333333	25.33333333	25.33333333
288	25.46938776	25.46938776	25.46938776
294	25.6	25.6	25.6
300	25.7254902	25.7254902	25.7254902
306	25.84615385	25.84615385	25.84615385
312	25.96226415	25.96226415	25.96226415
318	26.07407407	26.07407407	26.07407407
324	26.18181818	26.18181818	26.18181818
330	26.28571429	26.28571429	26.28571429
336	26.38596491	26.38596491	26.38596491
342	26.48275862	26.48275862	26.48275862
348	26.57627119	26.57627119	26.57627119
354	26.66666667	26.66666667	26.66666667
360	26.75409836	26.75409836	26.75409836
366	26.83870968	26.83870968	26.83870968
372	26.92063492	26.92063492	26.92063492
378	27	27	27
384	27.07692308	27.07692308	27.07692308
390	27.15151515	27.15151515	27.15151515
396	27.2238806	27.2238806	27.2238806
402	27.29411765	27.29411765	27.29411765
408	27.36231884	27.36231884	27.36231884
414	27.42857143	27.42857143	27.42857143
420	27.49295775	27.49295775	27.49295775
426	27.55555556	27.55555556	27.55555556
432	27.61643836	27.61643836	27.61643836
438	27.67567568	27.67567568	27.67567568
444	27.73333333	27.73333333	27.73333333
450	27.78947368	27.78947368	27.78947368
456	27.84415584	27.84415584	27.84415584
462	27.8974359	27.8974359	27.8974359
468	27.94936709	27.94936709	27.94936709
474	28	28	28
480	28.04938272	28.04938272	28.04938272
486	28.09756098	28.09756098	28.09756098
492	28.14457831	28.14457831	28.14457831
498	28.19047619	28.19047619	28.19047619
504	28.23529412	28.23529412	28.23529412
510	28.27906977	28.27906977	28.27906977

516	28.32183908	28.32183908	28.32183908
522	28.36363636	28.36363636	28.36363636
528	28.40449438	28.40449438	28.40449438
534	28.44444444	28.44444444	28.44444444
540	28.48351648	28.48351648	28.48351648
546	28.52173913	28.52173913	28.52173913
552	28.55913978	28.55913978	28.55913978
558	28.59574468	28.59574468	28.59574468
564	28.63157895	28.63157895	28.63157895
570	28.66666667	28.66666667	28.66666667
576	28.70103093	28.70103093	28.70103093
582	28.73469388	28.73469388	28.73469388
588	28.76767677	28.76767677	28.76767677
594	28.8	28.8	28.8
600	#N/A	#N/A	#N/A

## APPENDIX B: Simulation Data for Received Traffic (bits/sec)

Time (sec)	Received Traffic_Cordinator	Received Traffic_Motion_Cordinator	Received Traffic_SoilNut_Cordinator
0	0	0	0
6	0	0	0
12	0	0	0
18	0	0	0
24	0	0	0
30	0	0	0
36	0	0	0
42	0	0	0
48	0	0	0
54	0	0	0
60	64	64	96
66	64	64	96
72	64	64	96
78	64	64	96
84	64	64	96
90	64	64	96
96	64	64	96
102	64	64	96
108	64	64	96
114	64	64	96
120	64	64	96
126	64	64	96
132	64	64	96
138	64	64	96
144	64	64	96
150	64	64	96
156	64	64	96
162	64	64	96
168	64	64	96
174	64	64	96
180	64	64	96
186	64	64	96
192	64	64	96
198	64	64	96
204	64	64	96
210	64	64	96
216	64	64	96
222	64	64	96
228	64	64	96
234	64	64	96
240	64	64	96
246	64	64	96
252	64	64	96
258	64	64	96
264	64	64	96
270	64	64	96

276	64	64	96
282	64	64	96
288	64	64	96
294	64	64	96
300	64	64	96
306	64	64	96
312	64	64	96
318	64	64	96
324	64	64	96
330	64	64	96
336	64	64	96
342	64	64	96
348	64	64	96
354	64	64	96
360	64	64	96
366	64	64	96
372	64	64	96
378	64	64	96
384	64	64	96
390	64	64	96
396	64	64	96
402	64	64	96
408	64	64	96
414	64	64	96
420	64	64	96
426	64	64	96
432	64	64	96
438	64	64	96
444	64	64	96
450	64	64	96
456	64	64	96
462	64	64	96
468	64	64	96
474	64	64	96
480	64	64	96
486	64	64	96
492	64	64	96
498	64	64	96
504	64	64	96
510	64	64	96
516	64	64	96
522	64	64	96
528	64	64	96
534	64	64	96
540	64	64	96
546	64	64	96
552	64	64	96
558	64	64	96
564	64	64	96

570	64	64	96
576	64	64	96
582	64	64	96
588	64	64	96
594	64	64	96
600	#N/A	#N/A	#N/A

### APPENDIX C: Simulation Data for End-to-End Delay (second)

Time (sec)	PAN0	PAN1	PAN2
0	#N/A	#N/A	#N/A
6	#N/A	#N/A	#N/A
12	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A
24	#N/A	#N/A	#N/A
30	#N/A	#N/A	#N/A
36	#N/A	#N/A	#N/A
42	#N/A	#N/A	#N/A
48	#N/A	#N/A	#N/A
54	#N/A	#N/A	#N/A
60	0.007103284	0.002810759	0.00519625
66	0.005799531	0.002784093	0.005168368
72	0.006830642	0.002890759	0.006626146
78	0.006483975	0.002917426	0.006732813
84	0.008092864	0.002917426	0.008261701
90	0.010830642	0.002757426	0.007257257
96	0.010812864	0.002650759	0.007355035
102	0.010486245	0.002570759	0.006937257
108	0.01092842	0.003024093	0.007195035
114	0.008519531	0.002597426	0.007132813
120	0.009935134	0.002517426	0.00723059
126	0.010670642	0.002490759	0.007266146
132	0.009221753	0.002224093	0.006786146
138	0.010243975	0.002810759	0.007141701
144	0.011152912	0.002944093	0.006928368
150	0.011186198	0.002810759	0.00731059
156	0.011636221	0.002597426	0.007763924
162	0.009375777	0.003024093	0.007968368
168	0.011467333	0.002464093	0.007861701
174	0.009502888	0.002517426	0.007132813
180	0.008818444	0.001744093	0.007399479
186	0.009523975	0.003050759	0.007639479
192	0.009949602	0.002650759	0.006546146
198	0.009612864	0.002570759	0.006759479
204	0.010400666	0.002784093	0.007763924
210	0.009826198	0.002837426	0.006679479
216	0.008747333	0.003450759	0.007595035
222	0.009526245	0.002784093	0.007728368
228	0.009446245	0.002677426	0.007523924
234	0.010137309	0.002997426	0.007879479
240	0.010676221	0.002304093	0.007043924
246	0.01156738	0.002837426	0.00763059
252	0.009781753	0.003237426	0.007612813
258	0.010681801	0.002517426	0.006492813
264	0.010821753	0.003264093	0.007701701
270	0.009526245	0.002837426	0.007426146
276	0.009843975	0.003184093	0.00763059
282	0.011111777	0.002917426	0.006839479
288	0.010990642	0.003157426	0.007328368

294	0.010146198	0.003530759	0.007461701
300	0.010975134	0.002757426	0.00683059
306	0.01148511	0.002890759	0.007443924
312	0.010249555	0.003077426	0.007532813
318	0.010279531	0.003104093	0.006963924
324	0.010670642	0.002810759	0.00715059
330	0.011224023	0.003130759	0.007497257
336	0.011760666	0.002677426	0.006875035
342	0.010456269	0.003130759	0.007586146
348	0.010705158	0.002490759	0.007106146
354	0.011295134	0.002944093	0.007381701
360	0.010110642	0.003264093	0.007061701
366	0.010584023	0.003077426	0.007861701
372	0.010599531	0.003264093	0.007435035
378	0.009538444	0.002677426	0.006537257
384	0.009831777	0.002410759	0.007301701
390	0.009923975	0.002224093	0.006732813
396	0.011627333	0.003317426	0.007399479
402	0.009549602	0.002730759	0.007417257
408	0.010267333	0.002384093	0.007168368
414	0.01012511	0.002730759	0.00763059
420	0.012424023	0.003130759	0.006866146
426	0.011742888	0.002730759	0.007035035
432	0.010853999	0.002570759	0.007559479
438	0.010519531	0.002944093	0.006741701
444	0.011360666	0.003077426	0.007435035
450	0.010083975	0.002837426	0.007808368
456	0.010777309	0.002944093	0.007897257
462	0.01053069	0.002837426	0.007408368
468	0.011437356	0.002890759	0.007328368
474	0.010747333	0.002864093	0.007737257
480	0.011337309	0.002544093	0.007106146
486	0.008966245	0.002970759	0.00715059
492	0.010507333	0.002304093	0.007603924
498	0.011351777	0.002837426	0.007728368
504	0.01012842	0.003264093	0.007372813
510	0.00940738	0.002464093	0.007701701
516	0.010937309	0.002677426	0.007986146
522	0.010729555	0.002437426	0.006572813
528	0.011221753	0.002944093	0.007203924
534	0.010293999	0.003050759	0.007275035
540	0.00988842	0.002410759	0.007283924
546	0.011636221	0.003104093	0.007319479
552	0.010395087	0.003344093	0.006819831
558	0.010533999	0.003264093	0.006832821
564	0.010457309	0.002570759	0.007319479
570	0.010160666	0.003130759	0.007132813
576	0.011013999	0.002277426	0.007586146
582	0.01151469	0.003344093	0.007159479
588	0.010664023	0.002410759	0.006883924
594	0.010089555	0.003210759	0.007452813
600	#N/A	#N/A	#N/A

### APPENDIX D: Simulation Data for MAC Throughput (bits/sec)

Time (sec)	MAC Throughput of One Sensor Type(bits/sec)	MAC Throughput of Two Sensor Types(bits/sec)	MAC Throughput of Three Sensor Types(bits/sec)
0	0	0	0
6	360	720	1200
12	0	0	0
18	0	0	0
24	0	0	0
30	0	0	0
36	0	0	0
42	0	0	0
48	0	0	0
54	0	0	0
60	2972	3558.666667	7593.333333
66	1536	3726.666667	6824
72	1368	3192	3952
78	1902.666667	3360	5525.333333
84	1368	3192	3952
90	1368	3192	3952
96	1368	3192	3952
102	1368	3192	3952
108	1368	3192	3952
114	1368	3192	3952
120	1368	3192	3952
126	1368	3192	3977.333333
132	1368	3192	3926.666667
138	1368	3192	3952
144	1368	3192	3952
150	1368	3192	3977.333333
156	1368	3192	3926.666667
162	1368	3192	3952
168	1368	3192	3977.333333
174	1368	3192	3926.666667
180	1368	3192	3952

186	1368	3192	3977.333333
192	1368	3192	3926.666667
198	1368	3192	3977.333333
204	1368	3192	3952
210	1368	3192	3926.666667
216	1368	3192	3952
222	1368	3192	3952
228	1368	3192	3952
234	1368	3192	3977.333333
240	1368	3192	3926.666667
246	1368	3192	3952
252	1368	3192	3952
258	1368	3192	3952
264	1368	3192	3952
270	1368	3192	3952
276	1368	3192	3952
282	1368	3192	3977.333333
288	1368	3192	3926.666667
294	1368	3192	3952
300	1368	3192	3952
306	1368	3192	3952
312	1368	3192	3977.333333
318	1368	3192	3926.666667
324	1368	3192	3977.333333
330	1368	3192	3926.666667
336	1368	3192	3952
342	1368	3192	3952
348	1368	3192	3952
354	1368	3192	3977.333333
360	1368	3192	3926.666667
366	1368	3192	3952
372	1368	3192	3952
378	1368	3192	3977.333333
384	1368	3192	3926.666667
390	1368	3192	3952
396	1368	3192	3952
402	1368	3192	3977.333333

408	1368	3192	3926.666667
414	1368	3192	3952
420	1368	3192	3952
426	1368	3192	3952
432	1368	3192	3952
438	1368	3192	3952
444	1368	3192	3952
450	1368	3192	3977.333333
456	1368	3192	3926.666667
462	1368	3192	3952
468	1368	3192	3977.333333
474	1368	3192	3926.666667
480	1368	3192	3977.333333
486	1368	3192	3926.666667
492	1368	3192	3952
498	1368	3192	3977.333333
504	1368	3192	3926.666667
510	1368	3192	3952
516	1368	3192	3952
522	1368	3192	3952
528	1368	3192	3952
534	1368	3192	3952
540	1368	3192	3952
546	1368	3192	3977.333333
552	1368	3192	3977.333333
558	1368	3192	3901.333333
564	1368	3192	3977.333333
570	1368	3192	3926.666667
576	1368	3192	3952
582	1368	3192	3952
588	1368	3192	3952
594	1368	3192	3977.333333
600	#N/A	#N/A	#N/A

### APPENDIX D: Simulation Data for MAC Load per PAN (bits/sec)

Time (sec)	PAN 0	PAN1	PAN2
0	0	0	0
6	280	280	240
12	0	0	0
18	0	0	0
24	0	0	0
30	0	0	0
36	0	0	0
42	0	0	0
48	0	0	0
54	0	0	0
60	2434.666667	477.3333333	2058.666667
66	2320	304	2112
72	1976	304	1824
78	2118.666667	304	1994.666667
84	1976	304	1824
90	1976	304	1824
96	1976	304	1824
102	1976	304	1824
108	1976	304	1824
114	1976	304	1824
120	1976	304	1824
126	1976	304	1849.333333
132	1976	304	1798.666667
138	1976	304	1824
144	1976	304	1824
150	1976	304	1849.333333
156	1976	304	1798.666667
162	1976	304	1824
168	1976	304	1849.333333
174	1976	304	1798.666667
180	1976	304	1824
186	1976	304	1849.333333
192	1976	304	1798.666667
198	1976	304	1849.333333
204	1976	304	1824
210	1976	304	1798.666667
216	1976	304	1824
222	1976	304	1824
228	1976	304	1824
234	1976	304	1849.333333
240	1976	304	1798.666667
246	1976	304	1824
252	1976	304	1824
258	1976	304	1824
264	1976	304	1824
270	1976	304	1824
276	1976	304	1824
282	1976	304	1849.333333
288	1976	304	1798.666667
294	1976	304	1824
300	1976	304	1824
306	1976	304	1824

312	1976	304	1849.333333
318	1976	304	1798.666667
324	1976	304	1849.333333
330	1976	304	1798.666667
336	1976	304	1824
342	1976	304	1824
348	1976	304	1824
354	1976	304	1849.333333
360	1976	304	1798.666667
366	1976	304	1824
372	1976	304	1824
378	1976	304	1849.333333
384	1976	304	1798.666667
390	1976	304	1824
396	1976	304	1824
402	1976	304	1849.333333
408	1976	304	1798.666667
414	1976	304	1824
420	1976	304	1824
426	1976	304	1824
432	1976	304	1824
438	1976	304	1824
444	1976	304	1824
450	1976	304	1849.333333
456	1976	304	1798.666667
462	1976	304	1824
468	1976	304	1849.333333
474	1976	304	1798.666667
480	1976	304	1849.333333
486	1976	304	1798.666667
492	1976	304	1824
498	1976	304	1849.333333
504	1976	304	1798.666667
510	1976	304	1824
516	1976	304	1824
522	1976	304	1824
528	1976	304	1824
534	1976	304	1824
540	1976	304	1824
546	1976	304	1849.333333
552	1976	304	1824
558	1976	304	1798.666667
564	1976	304	1849.333333
570	1976	304	1798.666667
576	1976	304	1824
582	1976	304	1824
588	1976	304	1824
594	1976	304	1849.333333
600	#N/A	#N/A	#N/A