End to end delay minimization for zigbee healthcare monitoring system in ambient assisted living

End to End Delay minimization for ZigBee Healthcare Monitoring System in Ambient Assisted Living

by

Bongisizwe Erasmus Buthelezi
(213223569)

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Supervisor: Prof Maredi Mphahlele

Co–Supervisor: Mr Solly Maswikaneng

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DECLARATION

I, Bongisizwe Erasmus Buthelezi, hereby declare that the dissertation titled, *End to end Delay Minimization in ZigBee Wireless Sensor Network for Ambient Assisted Living* is my own original work, conducted under the supervision of Prof Maredi Mphahlele and Mr. Solly Maswikaneng. It is submitted for the Magister Technologiae (MTech) degree: Information Technology in the Faculty of Information and Communication Technology (ICT) at Tshwane University of Technology. There is no part of this research that has been submitted in the past or is being submitted, for a degree or examination at any other institution of higher learning. I further declare that all sources cited or quoted in this dissertation have been duly acknowledged by means of a comprehensive list of references.

Signature……..… Date……..…

Dedication

This study is dedicated to my mother Nokwazi, my farther Bhekisani Buthelezi, my siblings Ndumiso, Andile, Njabulo, and Sibusiso, my nephews Cebo and Solwazi, my extended families, friends and everyone who supported me during the course of this study. I come in front of all of you knowing that you are standing behind me with your prayers and your thoughts, therefore I thank you all for your support. In return, I am sending the following words of gratitude to all of you including everyone who will read this dissertation:

“Where there is focus energy flows, there is nothing impossible in this universe, only if we master our thoughts by taking that one step towards trying continuously, each and every day, every hour, every minute and every second, each and every one of you have greatness within.”

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Publications

Parts of this dissertation that were presented and published in different conferences and Journals are as follows:

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Bongisizwe Buthelezi, Maredi Mphahlele, Deon Du Plessis, and Solly Maswikaneng. "ZigBee Healthcare Monitoring System for Ambient Assisted Living Environments." International Journal of Communication Networks and Information Security (IJCNIS 2018).

Topside E. Mathonsi, Tshimangadzo M. Tshilongamulenzhe, and Bongisizwe Buthelezi. "An Efficient Resource Allocation and Management Algorithm for Heterogeneous Wireless Networks." Information Communication Technology & Society Conference (ICTAS 2019).

"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it"

– Mark Waiser

Abstract

Ambient Assisted Living (AAL) is an emerging multidisciplinary research area where different technologies such as Internet of Things (IoT), Wireless Sensor Networks (WSN), Artificial Intelligence (AI) etc. are integrated. The general goal of AAL is to apply Ambient Intelligence (AmI) technology to elderly and people with disabilities to live a better life in their preferred environment with Information and Communication Technology (ICT). ZigBee is one of the Wireless Sensor Network that can be implemented in AAL as a communication technology for sensory devices. In WSN applications such as homes, hospitals, clinics and other industrial areas, the number of wireless sensor devices continues to increase. End-to-end delay of packets, loss of packets, packets collision and bandwidth are some of the major issues experienced in WSN. In this study, ZigBee routing protocols are studied and analysed. High network latency is identified as one of the shortcomings of ZigBee Tree Routing protocol. This shortcoming is caused by the end-to-end delay of packets as they are routed on a Tree topology. In response to this shortcoming, this study is proposing a New Tree Routing Protocol (NTRP) algorithm that attempts to improve the original ZigBee Tree Routing protocol. NTRP is an output of merging ZigBee Tree Routing algorithm and Kruskal's Minimum Spanning Tree Protocol. NS-2 simulator is used to validate the proposed NTRP. The results are compared to protocols such as and the Velocity Energy efficient and Link Aware Cluster Tree (VELCT). NTRP algorithm reduces end-to-end delay by 11% and the rate of energy consumption is reduced by 10%, average delivery ratio is 94.5%, and the throughput is 86.91%. These results show that the proposed NTRP is better than VELCT and STR.

Keywords**:** *Ambient Intelligent, Ambient Assistive Living, Wireless Sensor Network, ZigBee Protocol, Healthcare Monitoring Systems.*

List of Figures

List of Tables

List of Algorithms

Glossary

AAL	Ambient Assisted Living
AI	Artificial Intelligence
AmI	Ambient Intelligence
AODV	Ad hoc On-Demand Distance Vector
BAN	Body Area Network
CPU	Central Processing Unit
DSDV	Destination Sequenced Distance Vector Routing
DSR	Dynamic Source Routing
ERD	Enable Route Discovery
FaDIS	Fall Detection and Intervention System
FFD	Full Function Device
FRD	Force Route Discovery
GloMoSim	Global Mobile Information System Simulator
GUI	Graphical User Interface
HCI	Human Computer Interaction
HMSs	Healthcare Monitoring Systems
HTAP	Hierarchical Tree Alternative Path
ICT	Information and Communication Technology
IE	Intelligent Environment
IoT	Internet of Things
ISO	International Organization for Standardization
IT	Information Technology
LANs	Local Area Networks
LCR	Link Collision Reduction
LEACH	Low Energy Adaptive Clustering Hierarchy
LQI	Link Quality Indicator
LR-WPAN	Low Rate Wireless Personal Area Network
MAC	Media Access Control
MAS	Multi Agent Systems
MATLAB	MATrix LABoratory
MHMSs	Mobile Healthcare Monitoring Systems
MRL	Message Retransmission List

NAM	Network Animator
NS2	Network Simulator 2
NS3	Network Simulator 3
NTRP	New Tree Routing Protocol
ODS	Open Distributed Systems
OLSR	Optimized Link State Routing
OMNET++	Optical Micro Networks
OPNET	Optimized Network Engineering Tools
OTcl	Object-oriented Tool command language
PAN	Personal Area Network
PHY	Physical Layer
PSO	Particle Swarm Optimization
QoS	Quality of Service
RFD	Reduced Function Device
RFID	Radio Frequency Identification
RHMSs	Remote Healthcare Monitoring Systems
SRD	Suppress Route Discovery
TRP	Tree Routing Protocol
Ubicomp	Ubiquitous Computing
VELT	Velocity Energy efficient and Link Aware cluster Tree
VINT	Virtual Inter-Network Testbed
VLAN	Virtual Local Area Network
VR	Virtual Reality
WAN	Wide Area Network
WANs	Wide Area Networks
WBAN	Wireless Body Area Network
WHMSs	Wearable Healthcare Monitoring Systems
WPAN	Wireless Personal Area Network
WRP	Wireless Routing Protocol
WSN	Wireless Sensor Network
ZC	ZigBee Coordinator
ZED	ZigBee End Device
ZR	ZigBee Router
ZTR	ZigBee Tree Routing

Chapter1: Introduction

1.1. Background

Ageing is taking place almost everywhere, but its extent and speed vary according to different factors. World Health Organization estimated that the portion of the world population aged over 60 years will increase to about two billion by the year 2050 (Organization, 2012). It is also arguable (Finegold et al., 2013) that if this anticipation is realized, there will be 392 million persons aged 80 years or over by 2050, more than three times the present number. This shows that older persons are anticipated to exceed the number of children for the first time in year 2047 to 2050. This increase of elderly population is directly proportional to chronic illnesses of cardio vascular diseases such as falls, stroke, heart attack, Alzheimer and other aging related diseases. This has also raised a huge cost challenge for taking care of elderly people affected by the mentioned diseases.

The American Heart Association (AHA) evaluates and monitors sources of information on stroke and heart disease in order to produce annual statistical updates (Mozaffarian et al., 2016). The statistics report realised in 2016 states that in year 2013, 370213 Americans died of coronary heart disease, and one in nine death certificates mentioned heart failure. Cardiovascular disease study published in European Heart Journal shows that heart attack disease is considered as the most common cause of death with approximately two times as many deaths as cancer across the continent (Townsend et al., 2015). The need for assistance and health care to the elderly is becoming more necessary for social as well as for economic reasons.

In response to the heart, failure disease challenge, the World Health Organisation proposed a strategy of active aging, which focuses on enhancing the quality of life of aging people by providing quality healthcare (Organization, 2012). This attracted ICT industry and researchers to offer health technologies that can provide quality healthcare for elderly people in real time. Ambient Assisted Living (AAL) environment is a home equipped with smart healthcare monitoring systems that are built to bring comfort to the elderly people and quick response to their diseases (Alor-Hernández et al., 2014). The European Union launched Ambient Assisted Living Joint Programme was launched by the European Union in 2008 with the aim of finding an efficient solution to assist elderly people living independently. AAL deals with healthcare-related applications such as assistance to the elderly and

handicapped persons and emergency services (Hilia et al., 2013). AAL environment integrates wireless devices (sensors) and systems with home communications networks to provide quality healthcare to the users. This has also attracted researchers in the field of Engineering and ICT to develop Healthcare Monitoring Systems based on Body Area Network and Personal Area Network using wireless sensors.

IEEE 802 Working Group 15 developed a set of standards for short range for Wireless Personal Area Networks (Siep et al., 2000). Wireless Personal Area Networks (WPANs) are focused around the personal operating space, meaning they operate in a space around a person that can extends up to 10 metres in all directions (Gutierrez et al., 2001). Healthcare Monitoring Systems use wireless body sensors to collect data from a human body. Examples of wireless body sensors that are normally found in healthcare monitoring systems are pressure sensor for blood pressure, thermal sensor for body temperature, ECG for heart pulse, etc. For further processing, collected data is passed to the Personal Area Networks (PANs) such as Bluetooth, ZigBee or Wi-Fi. PANs usually have a gateway device that can allow local data to be sent to a remote server for further processing or to alert a caretaker for an emergency. Research studies were conducted based on developing Healthcare Monitoring Systems. However, among existing development challenges, the communication technology needed for the environment still exists as a challenge (Mshali et al., 2018). Existing communication technologies have their shortcomings. However ZigBee is better than Wi-Fi and Bluetooth because it uses low power to transmit data, which saves energy for the nodes. Therefore, ZigBee network is considered a better communication PAN protocol for Healthcare monitoring Systems in AAL environments.

ZigBee is a specification formalized by the IEEE 802.15.4 standard for low-power, low-cost and low-data-rate wireless personal area networks that has seen more adoption for Healthcare Monitoring Systems (Shih et al., 2013). To route data between the devices in a ZigBee Personal Area Network, ZigBee Tree Routing protocol and Ad hoc On Demand Vector (AODV) protocol are used by default. However, tree routing suffers with high network latency caused by the end-to-end delay of data packets transferred between the devices (Bhatia and Kaushik, 2008). The tree routing protocol uses tree hierarchical topology structure, where ZigBee router called coordinator sits on top of the tree hierarchy to control the network. Other sensor nodes such as routers and end devices on a ZigBee network connects to one another through a coordinator using a mechanism called parent-child

communication. Parent-child communication has devices (routers) connected to the coordinator called children and the coordinator becomes their parent. This pattern is repeated down the hierarchy as more devices join the network, become the children of the parent router they have joined. The fallback of the tree routing is that if an end device at the lowest level sends data, that data has to pass all the children (nodes) of the coordinator before it reaches the coordinator. Then a coordinator can forward the data down the tree hierarchy or outside the network to the intended receiver. This leads to high end-to-end delay caused by hop-to-hop delay of data as it travels towards the coordinator.

Therefore this study aims to enhance a ZigBee Tree Routing protocol through minimizing end-to-end delay of packets from source to destination. This study proposes a New Tree Routing Protocol (NTRP) that improves the traditional ZigBee Tree routing protocol. NTRP merges ZigBee Tree Routing algorithm with Kruskal's Minimum Spanning Tree algorithm to minimize a number of hops between a source and a destination device. Clustering mechanism and neighbor table mechanism are ZigBee standard features defined in (ZigBee Alliance, 2003), that are added to complement our proposed solution of minimizing end-to-end delay on a ZigBee network. This solution also improves the overall performance of a Healthcare Monitoring System as it allows heart rate medical data to be transmitted quicker. This allows an elderly person to get an emergency response from a medical practitioner connected to the health monitoring system, which can minimize the number of heart attacks if medical assistance is offered timeously.

1.2. Motivation

This research is essential as it helped in developing a routing protocol algorithm called NRTP for a ZigBee Personal Area Network. NRTP aims to minimise end-to-end delay of vital medical data such as Heart Pulse signal on a Healthcare Monitoring System. This could pave the way for further work for researchers to enhance network performance for Healthcare Monitoring Systems. In addition, the study contributed to the scientific body of knowledge in the domain of Ambient Assisted Living and Wireless Sensor Network as well as in the society. Elderly people with cardiovascular disease such as heart attack can be remotely assisted using Healthcare Monitoring Systems in real time.

1.3. Premises of the research

To improve the ZigBee Tree Routing protocol, this study complied with the IEEE 802.15.4 standard (ZigBee Alliance, 2003). IEEE 802.15.4 standard is for Wireless Personal Area Network (WPAN). IEEE 802.15.4 standard defines the specifications of wireless communications supporting a physical layer and data link layer, for small devices with low power and 10-100m wireless working boundaries.

1.4. Problem Statement

Healthcare Monitoring Systems uses radio communication technology such as ZigBee network to collect medical data for humans through body sensors. ZigBee standard uses protocols that are not suitable for transmission of large quantity of data; however, it is designed for only low-power and low-speed data transmission (ZigBee Alliance, 2003). By default, ZigBee Tree Routing protocol uses a parent-child relationship to forward the packets towards the destination node. In a parent-child relationship, a source node sends packets up to their parent router (coordinator) on a tree hierarchical topology. Tree hierarchical topologies allow all sending devices to direct their data to the coordinator via parent routers. The coordinator will forward the packets down the tree branches to reach the destination node after receiving it from its child routers.

This implies that data packets may be routed through several hops to the destination node even if the destination node is in a closer range towards the sending node. This is a challenge that causes end-to-end delay which leads to poor network performance as the network will be experiencing high network latency, congestion, data collisions and transmission imbalance. According to Choudhury et al. (2016) the mentioned challenges are caused by the end-to-end delay of packets that traverses through many intermediate nodes before they reach their destination. End-to-end delay is a serious challenge in AAL because cardio vascular diseases such as heart failure require an instant assistance. Therefore, in AAL, the delayed important information may lead to a worse situation of the heart attack to an elderly person monitored by the healthcare system.

1.5. Research Questions

The main research question for this study is; how can end-to-end delay be minimised on a ZigBee network for Healthcare Monitoring Systems that monitors heart condition of elderly people. The rest of the research questions are outlined as follows:

1. What are current Healthcare Monitoring Systems that use ZigBee network to transmit medical data (Heart Rate) about the health status of elderly people in AAL?
2. What are the challenges associated with ZigBee routing protocols in Healthcare Monitoring Systems?
3. How can the ZigBee Tree routing protocol be improved to minimise end-to-end delay in Healthcare Monitoring Systems?
4. How can the improved ZigBee routing protocol be evaluated?

1.6. Technical Objectives

The following are the technical objectives for this study. The main objective is to propose a solution that improves ZigBee protocol through end-to-end delay minimisation on a ZigBee Healthcare Monitoring System for heart monitoring.

The objectives for this study are outlined as follows:

1. To study and identify the existing Healthcare Monitoring Systems that use ZigBee network to transmit heart rate data such as Heart rate.
2. To identify the challenges associated with the ZigBee routing protocols in Healthcare Monitoring Systems.
3. To improve ZigBee Tree routing protocol algorithm in order to minimise the end-to-end delay of data transmission in Healthcare Monitoring System.
4. To test and evaluate the effectiveness of the improved ZigBee routing protocol algorithm.

1.7. Research Methodology

A literature review and an experimental methodology were conducted in this study. Literature was reviewed to get more understanding and to identify gaps in the field of WSNs. This is achieved through reading peer-reviewed papers such as journals and conference proceedings, texts and books and other scientific reviewed internet sources.

1.7.1 Literature Review

Literature review was conducted to support the main contribution of this study, which is to propose a protocol that reduces the end-to-end delay in ZigBee WSNs. Below are the four reasons to conduct the literature review (Webster and Watson, 2002):

- To identify various gaps in the current research.
- To understand an established but fragmented topic.
- To understand new research topics.
- To study how empirical evidences support theories or methods.

Experimental methodology involves computer simulation modelling tool, and evaluation. This is explained in detail in the following sub-sections;

1.7.2 Modelling

Simulation modelling is the process of creating and analysing a digital prototype of physical model to predict its performance in the real world. In this study, NS2 simulation tool was used to understand the performance conditions for the real network environment.

1.7.3 Implementation

To evaluate the effectiveness of the proposed model, the model was implemented on a network simulation tool in order to simulate the settings of a real live environment.

1.7.4 Simulation

The experiments of the proposed model were carried out on NS-2 tool. The network topology and configurations were implemented in C++ and Tool Command Language script. AWK programs were coded to calculate the average of the metrics used in this study. The research questions, technical objectives, and methodology are summarized in Table 1.1 below.

Table 1. 1: Research Questions, Technical Objectives, and Methodologies

Research Questions	Technical Objectives	Methodology
What are current Healthcare Monitoring Systems that use ZigBee network to transmit heart rate data signals for elderly people in AAL?	To study and identify the existing Healthcare Monitoring Systems that use ZigBee network to transmit heart rate	Literature Review

	data signals.	
What are the challenges associated with ZigBee routing protocols in Healthcare Monitoring Systems?	To identify the challenges associated with the ZigBee routing protocols for Healthcare Monitoring Systems.	Literature Review
How can the ZigBee routing protocol algorithm be improved to minimise end-to-end delay in Healthcare Monitoring Systems?	To improve the ZigBee Tree routing protocol algorithm performance in order to minimise the end-to-end delay of data transmission in Healthcare Monitoring Systems.	Modeling and implementation
How can the improved ZigBee routing protocol algorithm be evaluated?	To test and evaluate the effectiveness of the proposed ZigBee routing protocol algorithm.	Simulation

1.8. Expected Results

The expected results of this study were:

1. A model that reduces end-to-end delay on a ZigBee network.
2. Peer reviewed and published conference proceedings, journal papers and book chapters.
3. A comparison of the results of the proposed algorithm with the previous solutions.

1.9. Contributions of the Study

The main contributions of this study are as follows:

1. A New Tree Routing Protocol (NRTP) algorithm that minimises end-to-end delay on a ZigBee network Healthcare Monitoring Systems to monitor elderly people's heart rate.
2. NRTP algorithm allows a network to be subdivided into clusters which saves node's energy, additionally, it finds short paths to the destination node using Kruskal's algorithm that uses neighbour tables to forward packets to the neighbour nodes.

1.10. Structure of the Dissertation

An overview of this dissertation is structured as follows;

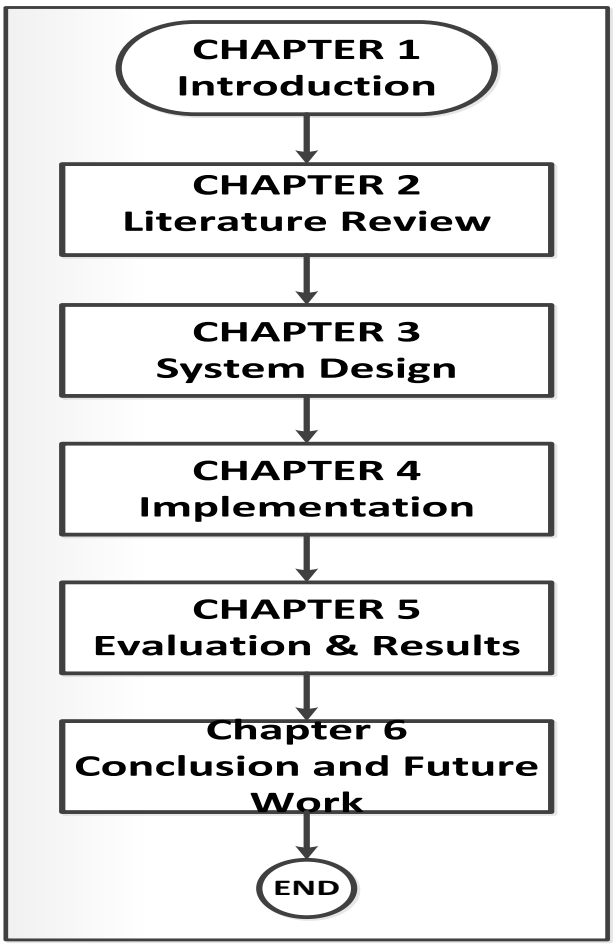

Figure 1.1: Dissertation structure

Chapter 1 is the introduction and the background of the theories that underpin this study**.**

Chapter 2 review the literature studies that are related to the problem our work is attempting to solve. Firstly, the concept of Ambient Assisted Living (AAL) and Healthcare Monitoring Systems (HMSs) are discussed. HMSs are further investigated as they involve body sensor networks and Personal Area Network (PANs). The chapter further discusses PANs, their strengths and shortcoming. ZigBee PAN is chosen as a network of choice of interest to conduct the research study with, however, there are challenges identified in ZigBee Tree Routing algorithm. Studies that have attempted to solve ZigBee Tree Routing algorithm problem are also discussed.

Chapter 3 presents the system design architecture for the proposed New Tree Routing Protocol model. Firstly, ZigBee HMS architecture for AAL environment is discussed. Furthermore, HMS is broken down into 3-Tiers; Body Area Network, Personal Area Network and Wide Area Network. Because the scope of this study is in exhaustive and so limits our focus on ZigBee network, only ZigBee PAN Architecture is discussed. NTRP algorithm is laid in detail and further details on how it operates are provided.

Chapter 4 is an overview of the system implementation where network simulators are studied. NS2 is used to implement the NRTP algorithm.

Chapter 5 presents the results for the NTRP simulations which are based on the metrics such as throughput, delivery ratio, end-to-end delay, and energy consumption.

Chapter 6 concludes the study by addressing those objectives that were and were not met. Furthermore, this chapter also highlights the future research that could be conducted following the study's recommendations

1.11. Summary

This chapter presents the background of the Ambient Assisted Living and the Wireless Sensor Network domains. Various challenges in ZigBee network were identified. The main objective of this study is to minimise the end-to-end delay of packets in ZigBee network. The research questions and objectives supporting the problem statement are provided. The research methodology to be followed in designing and implementing the proposed protocol is also provided in this chapter. In the next Chapter, we present the Literature Review and discuss various works related to this study.

Chapter 2: Literature Review

2.1 Introduction

The purpose of this chapter is to present a detailed literature study based on Healthcare Monitoring Systems, Wireless Sensor Networks, and routing protocols in Wireless Sensor Networks. This literature study is supporting the main contribution of the research study findings. In this chapter, an overview of Ambient Assisted Living (AAL) is provided to link its solution of assisting elderly people through Healthcare Monitoring Systems. The application of Healthcare Monitoring Systems is in AAL and other applicable environments are discussed. Furthermore, ZigBee network communication protocol is introduced and IEEE 802.15.4 specification standard is laid into details. The identified gaps on ZigBee network are addressed. The studies that support our research study are summarised as related works section at the end of this chapter.

The rest of this chapter is structured as follows: **Section 2.1** is the introduction of Ambient Assisted Living domain. This section provides an overview of the various concepts and background theories that underpin this study. **Section 2.2** provides the overall overview of Ambient Assistance Living. **Section 2.3** introduces data communication using Wireless Sensor Networks (WSNs) in Healthcare Monitoring Systems (HMSs). This section provides an overview background of HMSs and WSN linked to IEEE 802.15.4/ZigBee standard. In **Section 2.4** Routing selection in Wireless Sensor Network is introduced. This section explicates what the body of literature says about the routing selection concepts and principles that may subsequently guide our modelling in Chapter 4. **Section 2.5** classify the types of Healthcare Monitoring Systems and their application in AAL. **Section 2.6** Introduces the ZigBee network overview. **Section 2.7** Routing in ZigBee network is laid in details. In **Section 2.8** ZigBee Tree Routing protocol is discussed and its challenges are identified. Finally, a summary of related studies to the end-to-end delay problem is presented.

2.2. An Overview of Ambient Assistive Living

This section provides an overview of the various concepts and background theories that underpin Ambient Assisted Living and it addresses how these theories interrelate to each other. This section is guided by the key words and themes in our research topic, research questions, research objectives as well as related studies in Wireless Sensor Networks environments. Ambient Assisted Living is defined (Dohr et al., 2010) as a multidiscipline

research area that includes fields such as Internet of Things (IoT), Artificial Intelligence (AI), Pervasive/Ubiquitous computing, Networks and Middleware, Sensors and Actuators, and Human Computer Interaction (HCI). These technologies encompass technical systems that support elderly people with their daily living.

The number for elderly people population is increasing worldwide. Statistics South Africa has published three censuses reports (1996, 2001 and 2011). These reports prove that the number of elderly persons aged 60 years and above has increased over the period of (1996-2011) compared to those aged 59 years and below (Lehohla, 2011). Additionally, the report further proves that the number has increased from 2, 8 million in 1996 to 4, 1 million in 2011. This number is projected to continue to increase to approximately seven million elderly persons living in South Africa by the year 2030.

In its inception, AAL is the research field aiming at exploiting information and communication technologies in personal healthcare and tele-health systems for countering the effects of aging elderly population. According to (Rodrigues et al., 2015), AAL uses ambient technologies, including data sensing, processing, transmission, and artificial intelligence, to enable new products, services, and processes that help to provide safe, healthy lives for the aged and disabled. It allows an independent and safe lifestyle through the integration of information technologies within homes and residences. The general goal of AAL solutions is to apply ambient intelligence technologies to enable elderly and people with special needs such as disabilities to live longer in their preferred environment (Palumbo, 2016). In this study, Environment refers to any physical space such as home, house, building, classroom, hospital etc. An Intelligent Environment (IE) can be defined as one in which the actions of numerous networked controllers (controlling different aspects of an environment) is orchestrated by self-programming pre-emptive processes (e.g. intelligent software agents) in such a way as to create an interactive holistic functionality that enhances occupants experiences (Augusto et al., 2013).

In computing, Ambient Intelligence (AmI) refers to the electronic environments that are sensitive and responsive to the actions and the presence of people and cater for their needs (Aarts and Wichert, 2009). The emergence of AmI is perceived as the third wave in the evolution of computer technology. It deals with new paradigms where computing devices are spread everywhere to allow intelligent and natural interactions between the human beings and the physical environment. The interaction among different disciplines forms an Intelligent

Environment, which makes the technology to disappear in front of human eyes as this was coined by (Weiser, 1999) in “The computer for the 21st century” where he stated that “The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they become indistinguishable from it”

It is noted on the AAL literature study that many AmI systems are solving real problems in the society; however, there are gaps in terms of interconnecting AmI systems. This literature study looks at the communication protocols and algorithms that are implemented in wireless sensor networks. These AmI systems can be called Healthcare Monitoring Systems as they are designed to monitor humans in environments such as homes, clinics and hospitals. The next section discusses the interaction of different disciplines around Intelligent Environments used to build AmI systems such as Healthcare Monitoring Systems.

2.2.1 Interaction among different Intelligent Environment disciplines

The revolution of Ambient Intelligence program emanates from the integration of numerous related scientific areas, including sensor networking, machine learning, semantic-based knowledge systems and human-computer interaction, artificial intelligence, and ubiquitous computing (Zografistou, 2012). Figure 2.1 below shows the interactions among different disciplines in AmI working towards the improvement of elderly citizen’s quality of life. The interaction among the different disciplines in AmI are all relevant and interrelated, however, none of them covers the full scope of AmI solution (Augusto and McCullagh, 2007). Healthcare Monitoring Systems covered in section 2.4 of this chapter is part of AmI solution that is implemented based on the technologies mentioned in Figure 2.1 below. As part of Healthcare Monitoring Systems, wireless sensor networks are used for data communication among desired devices inside or outside the local network.

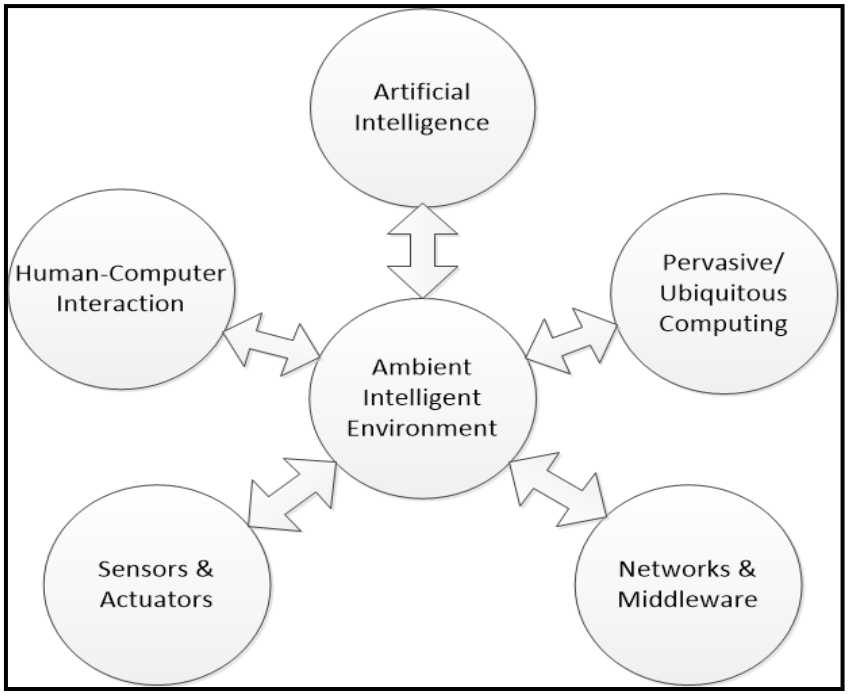

Figure 2.1: Interactions among disciplines in Ambient Intelligent Environments (Augusto and McCullagh, 2007).

Based on the technologies in the AmI disciplines in Figure 2.1 above, this study focuses on data communication for ZigBee wireless sensor networks. Healthcare Monitoring Systems uses ZigBee wireless sensor networks for data transmission within a Personal Area Network. Sensors collect data and send it to the ZigBee PAN and then it will be forwarded to the remote networks via a WAN. However, ZigBee Tree Routing is one of the ZigBee routing protocols that suffers with end-to-end delay of packets as they travel a number of hops before reaching the destination node (Howitt and Gutierrez, 2003a). Therefore, this study attempt to minimise end-to-end problem by proposing a new routing protocol that caters for heart rate data information in Healthcare Monitoring Systems.

- **Pervasive/Ubiquitous computing:** Pervasive computing has strong emphasis on devices, their networking and the processing of data they produce. With Ubiquitous Computing (Ubicomp), computing is profound to disappear into the background of our lives. Ubicomp enhances computer use by making many computers available throughout the physical environment, but making them effectively invisible to the user (Weiser et al., 1999).
- **Networks and Middleware:** The flow of data is channelled to the main system through a wired or a wireless network. However, middleware facilitates interoperability between devices from different manufactures to understand each other

and converge into a presentation that is understood by software at upper levels of the system architecture.

- **Sensors and Actuators:** There is a wide range of sensors with varying capabilities; such as pressure sensors, some sensors can measure the weight of a person, some can identify information including biometric data and others measure distance, motion, temperature and so forth. On the other hand, an actuator is a type of motor that is responsible for controlling a system.
- **Human-Computer Interaction**: The technology should be easy to use. Humans should be able to utilize the technology in a way that does not require them to do advance training before they can use it.
- **Artificial-Intelligence:** Autonomous decision making is one of the expectations about any intelligent environment. To achieve this, systems will usually apply AI techniques, which will allow them to perform: Learning and activity recognition, sensing, reasoning, making decisions, and giving back the feedback.

A combination of these technologies results into a solid Healthcare Monitoring System that can enhance the way humans interact with the smart environments. A Smart Home is one example of the environment where such systems are implemented but the idea can also be applied in relation to hospitals, learning institutions, transport, agriculture and other environments for different purposes (Sabri et al., 2011, Alam et al., 2012). This study uses Ambient Assisted Living as an application of Healthcare Monitoring Systems to monitor the data transmission through wireless sensor networks such as Body and Personal area networks. It examines the loopholes of a Low-Power ZigBee communication protocol and in response to the identified gaps, a better solution is proposed. Extensive research has been conducted in AAL; (Augusto et al., 2010, Ding et al., 2011), however, there is still a lot to be done as there are lots of challenges that arise in this area. The challenges are caused by the complexity of merging the above-mentioned disciplines in Figure 2.1 above. The next section gives an overview discussion on Wireless Sensor Networks communication in Healthcare Monitoring Systems and the challenges associated with Healthcare Monitoring Systems.

2.3 Data communication using Wireless Sensor Networks in Healthcare Monitoring Systems

In recent past years, healthcare monitoring systems have been developed to monitor elderly people and patients' conditions in smart environment. Healthcare Monitoring System is an

integration of ubiquitous computing and communication technologies emerged with a promise to provide e-health services (Mshali et al., 2018). In general, HMSs in Ambient Assisted Living monitor and evaluate any health condition for an elderly person, as well as monitoring their daily activities. This can be achieved by installing sensors that are connected together to collect information, send it to the processing module through radio communication technologies such as (Bluetooth, ZigBee, etc.) and send the processed information to the local database or to the doctor in the case of emergency. The below Figure 2.2, is a typical illustration of how elements of a Healthcare Monitoring System are integrated.

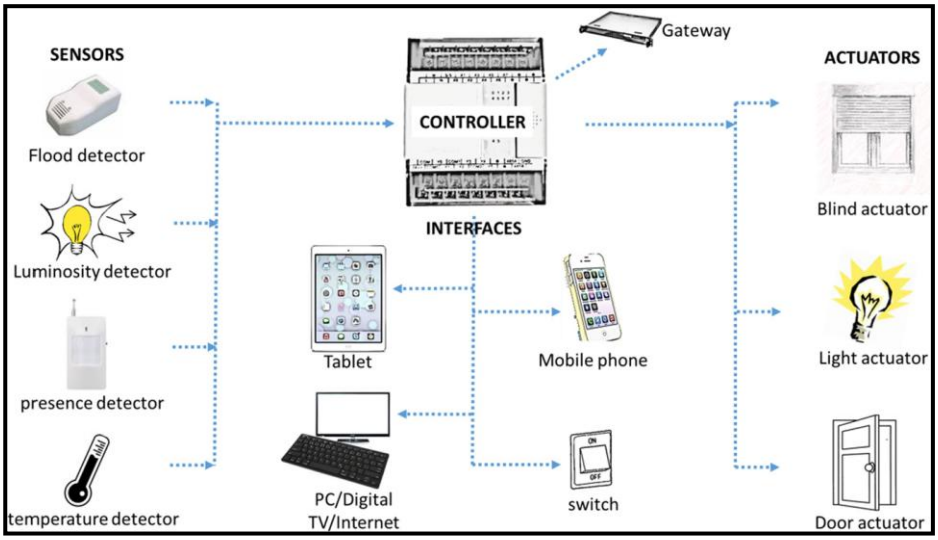

Figure 2.2: Elements of an integrated Healthcare Monitoring System.(Mshali et al., 2018).

2.3.1 Elements of a Healthcare Monitoring System

Information in a monitoring system is collected from the input sensors. This information is sent to the controllers such as Arduino, Raspberry Pie for processing and finally sent to the actuators for output (Kioumars and Tang, 2011). Healthcare Monitoring System's elements are sensors, interfaces, controllers, actuator, residential gateway and protocols as depicted in Figure 2.2 above. The elements of a Healthcare Monitoring Systems are further discussed below.

- **Sensors**: Sensors are small wireless devices that are capable to monitor any environment. They are capable of transforming raw data into digital information and transmit it to a Personal Area Network such as ZigBee. There are different types of sensors such as environmental sensors (water, gas, smoke, temperature, wind,

humidity, rain, lighting, movement, etc.), physiological sensors (measuring pulse, respiration, blood pressure, etc.) or multimedia sensors (microphones, cameras, etc.).

- **Interfaces**: Interfaces are devices such as screens that are capable of displaying information about the system to the end users and can allow them to interact with the system in real time. These interfaces together with wireless sensors, communicate with the controller in order to decide which actuator must perform what action. An example of an interface is a tablet or smart phone that runs an application to interact with the system.
- **Controller**: This device is a heart of the system as it manages the system based on the information received from sensors or interfaces. The system may have a single controller or multiple distributed controllers that processes and manages raw information.
- **Actuator**: It receives the commands from the controller to perform an action on a household component. Usually these are automated devices that controls any electromagnetic motors in a Healthcare Monitoring System based on issued commands. An example of the actuator could be an automated garage door that can be remotely controlled based on given commands.
- **Residential gateway**: A gateway acts as a last resort device on the network that connects the Local Area Network to the internet. In general, sensors, interfaces, actuators and controllers understand a single protocol; however, the gateway allows the interconnection of devices that use different communication protocols to achieve a global system. An example could be a Healthcare Monitoring System that has a gateway to connect ZigBee protocol and Bluetooth protocol.
- **Protocol**: A communication protocol is used to transmit the information between sensors, interfaces, actuators and controllers. The transmission process is carried out by a wireless or wired transmission medium according to a specific protocol. There are many protocols such as ZigBee, Z-Wave, Bluetooth, INSTEON etc. However, this study is focusses on improving the ZigBee communication protocol based on the shortcomings identified in the ZigBee Tree Routing algorithm. Section 2.6.3 discusses the ZigBee topic in detail.

2.3.2 Transmission Media for Healthcare Monitoring Systems

The two types of communication technologies used to transmit information between different Healthcare Monitoring devices are wired and wireless technologies; however, this study is

more focused on routing protocols for PAN wireless sensor networks such as ZigBee. Therefore, the focus in this section is limited to wireless transmission media. The next section discusses the topic of wireless sensor network devices and its application in Healthcare Monitoring Systems.

2.3.3 Application of Wireless Sensor networks in Healthcare Monitoring Systems

A sensor is a physical device capable of detecting physical signals and transforming them into electrical signals (Sharma and Sharma, 2014). These electrical signals are transmitted through a wireless network and are converted into digital signals as they traverse across the network. Wireless Sensor Networks are defined as a group of autonomous sensors and the actuators with wireless infrastructure that is intended to control and monitor any kind of environment (Yang, 2014). Recently, wireless sensor network has gained popularity in research academic field and in industry due to their ability to solve society problems such as assisting elderly people with their daily living and monitoring their health status. Environmental and wearable sensors are two different types of sensors that can be considered for Healthcare Monitoring environment depending on the data that needs to be collected.

- **Environmental sensors** are ubiquitous distributed around the environment such as a home, agricultural field and industrial sector (Hart and Martinez, 2006). Environmental sensors can be used to monitor temperature, fire, smoke, surveillance, etc.
- **Wearable sensors** are small sensor nodes that can be worn by the residents or they can be implanted on humans body to collect medical data about the health status of the human (Pantelopoulos and Bourbakis, 2010). These sensors can be embedded into clothes (sensing textiles), eyeglasses, shoes and wristwatches, or positioned directly on the body. Mostly they are used to collect the physiological data for elderly people or any inhabitants who are monitored.

This study is interested in the transmission of physiological data for elderly people through wireless sensor networks; therefore, a suitable option for this study is the wearable sensors. In the next section, a three-tier wireless sensor network topology for Healthcare Monitoring Systems is discussed.

2.4 Wireless Sensor Network architecture for Healthcare Monitoring Systems

There are different types of wireless technologies, however, the most prominent difference is how much bandwidth they can offer and the distance between the communicating nodes (Tiwari et al., 2015). Traditional Healthcare Monitoring Systems are composed of Body Area Network (BAN) for data collection, Personal Area Network (PAN) for data communication locally and a Wide Area Network (WAN) for remote communication. This study aims to enhance a ZigBee Wireless PAN routing protocol. This is the main reason the study focuses in Wireless Personal Area Network part of the HMS. However, BAN and WAN are discussed to understand their relationship to PANs as well as their impact on HMSs.

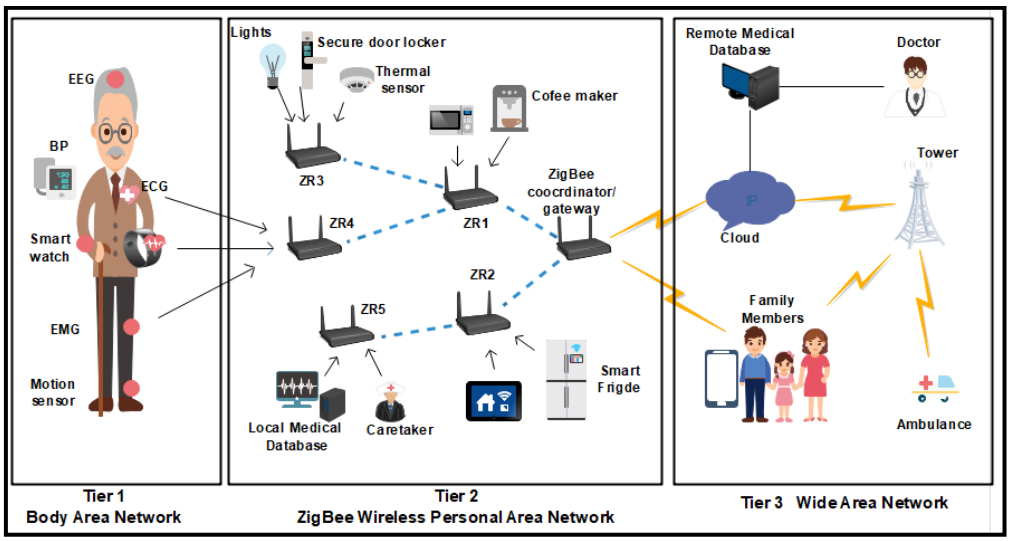

Figure 2.3: A 3-Tier network architecture (Sangwan and Bhattacharya, 2015).

As depicted in Figure 2.4 above, Healthcare Monitoring System is built based on 3-Tier architecture. Tier-1 is responsible for collecting medical data, Tier-2 is responsible to locally transmit the collected data, and lastly, Tier-3 is responsible for communicating local data to the remote sites such as a database stored on cloud. For this study, Body Area Network is Tier-1, Personal Area Network is Tier-2, and Wide Area Network is Tier-3 and our interest is mainly on the ZigBee wireless Personal Area Network.

a) Body Area Network (Tier-1)

With the rise of population number in older people, Wireless Body Sensor Networks proves to be beneficial in providing medical service to people who require continuous monitoring and care (Sangwan and Bhattacharya, 2015). Development in technologies for Wireless Communication has led to sensor nodes, which can be worn over the body or implanted in the body. Body Wireless Sensors are small sized devices, which can perform processing on the

medical signals sensed from the human body. Sensed medical data is communicated to the required destination such as medical-database by using low power communication protocol. Collected medical data can be used for either various research purposes or diagnosis purposes.

In the recent past, much of the research studies based on Body Area Networks deals with the designing of Sensor nodes, miniaturizing the nodes, various protocols related to communication and routing. A Wireless Body Sensor Network (WBSN) defines an autonomous system which is used to monitor the daily life activities of a person (Chen et al., 2009). It consists of intelligent sensor nodes, which do not hamper the daily life activities and are useful in detecting chronic diseases like heart attack, asthma, diabetes etc. A Wireless Body Sensor based monitoring system is capable of warning patients in case of emergency conditions detected in a human.

This study aims to enhance the PAN communication by minimizing the time for a vital data to reach to the third party. As part of wearable or implanted body sensors, the following Table 2.1 summarizes different types of sensor nodes that could be implemented in a Managed Wireless Body Sensor Network.

Table 2.1: Wearable Body Sensors for Healthcare Monitoring Systems.

Sensor	Measurement	Data Rate
Thermal	Body Temperature	Very Low
CO2	Respiration	Very Low
Heart	Heart Rate	Low
Pulse Oximeter	Blood Oxygen Saturation	Low
Pressure	Blood Pressure	Low
Glucometer	Blood Glucose	High
Electrocardiography (ECG)	Cardiac Activity	High
Electroencephalography (EEG)	Brain Activity	High
Electromyography (EMG)	Muscle Activity	Very High

Based on the summarized Table 2.1 above, this study is limited to the heart rate based Healthcare Monitoring Systems, meaning that the BAN is responsible for collecting heart rate signals from an elderly person, and send it to the PAN for communication purposes. One of the reasons to have chosen heart rate signals is that they require low data rate to be transmitted over the network. This qualifies them as a suitable parameter to be transmitted over a Low-Power Rate communication protocol such as in ZigBee network which is

discussed in detail in the sections below. Another reason for why the heart rate signals data are chosen for monitoring is because when an elderly person is having a heart attack, they require real time assistance. In response to this, we propose to merge the ZigBee Tree Routing protocol with Kruskal's Minimum Spanning Tree protocol. This will allow heart rate signals to use the shortest path to the destination, which will prompt a quick response because of the reduced transmission time.

b) Personal Area Network (Tier-2)

Wireless Personal Area Networks (WPANs) are used to convey information over short distances; this allows small, power efficient, inexpensive solutions to be implemented for a wide range of devices. In December 2000 an IEEE 802 WPAN group was founded to define the wireless protocol for WPAN (ZigBee Alliance, 2003). WPANs are used to convey information over short distances among a private group of participant devices. The IEEE 802.15 working group developed a number of Wireless Personal Area Network (WPAN) consensus standards for short distances as demonstrated in the below Figure 2.5 below. However, our study focus scope is limited to IEEE 802.15.4 standard due to its low cost and low energy transmission. Different studies in our literature review section argue that IEEE 805.15.4 is a best suitable standard for Homecare Monitoring Systems.

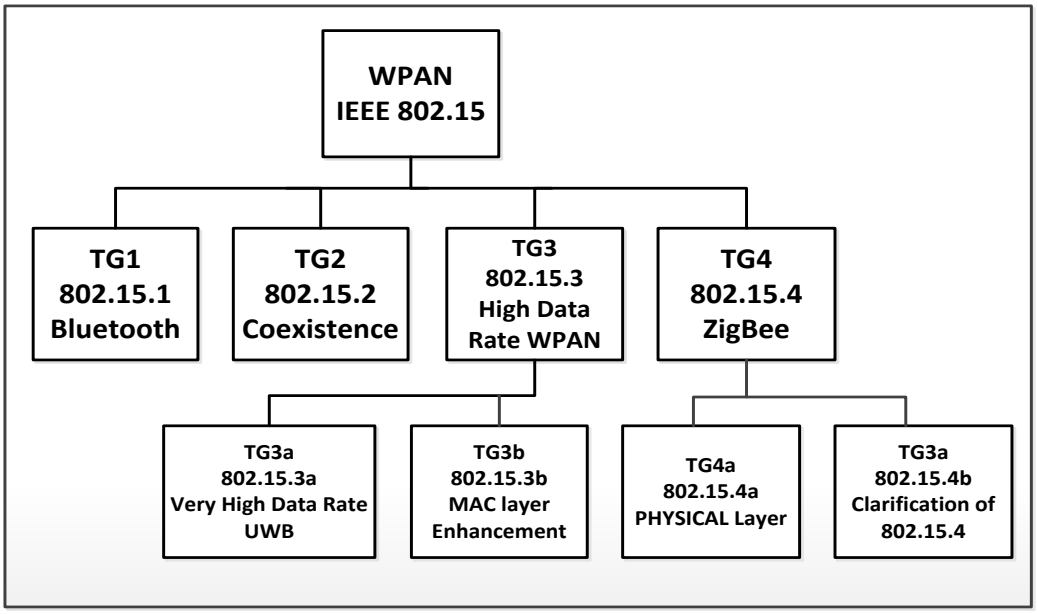

Figure 2.4: IEEE 802.15 Standards.

As depicted in Figure 2.5 above, the efforts of IEEE 802.15 are divided up into four main areas (Patel and Kulkarni, 2014) :

1. Task Group 1 (TG1) is creating a WPAN standard based on Bluetooth to operate in the 2.4 GHz ISM band.
2. TG2 is concerned with the coexistence of unlicensed spectrum devices.
3. TG3 is responsible for high data rate (in excess of 20 Mbps) WPAN standards
4. TG4 is creating a low data rate, low power WPAN standard.

An additional group, TG3a, was created to investigate physical layer alternatives for high data rate WPAN systems. In Table 2.2 below, a summary of Bluetooth/IEEE 802.15.1, Wi-Fi/IEEE 802.11, and ZigBee/IEEE 802.15.4 is provided.

Table 2.2: Summary of WPAN communication protocols.

Protocol	**Network Definition**	**IEEE Standard**	**ISM frequency bands**	**Max. Data Rate**
Bluetooth	Wireless Personal Area Network (WPAN)	IEEE 802.15.1	900 MHz	1Mbt/s (v1.2) 3Mbit/ (v2.0)
Wi-Fi	Wireless Local Area Network (WLAN)	IEEE 802.11	5.8 GHz	11Mbt/s (802.11b) 54Mbt/s (802.11g)
ZigBee	Low Rate WPAN (LR-WPAN)	IEEE 802.15.4	2.4 Ghz	250 Kbt/s

c) Wide Area Network (Tier 3)

These types of networks cover a large area such as a city, country, continent and the entire planet through multiple satellite systems that are monitored by Internet Service Providers (ISPs) (Sharma and Dhir, 2014). Data at WAN level can be stored on servers and databases for diagnosis and analysis by a third party such as a doctor or a researcher. WAN is not part of the scope for our study, however, it is part of the Health Monitoring System therefore, different types of WAN technologies such as 2G, 3G, 4G, and 5G are discussed to clarify how data travels outside the BAN and PAN tiers. Studies have been conducted such as (Abidoye et al., 2011), where medical sensors are used to collect physiological data from the patients and transmit it to the Intelligent Personal Digital Assistance (IPDA). 3G communication technology is used to send data to the remote servers and databases. Stored

data can be easily accessed via a computer or a mobile device such as a smart phone, which can allow the doctor to diagnose a patient remotely.

Projects and research studies have been conducted based on Healthcare Monitoring Systems, The following Table 2.3, summarises some of the studied projects based on the system's target audience, the type of BANs, PANs, WANs and sensors used in each system.

Table 2.3: Summary of the projects conducted for HMSs

PROJECT	TARGERT	BAN	PAN	WAN	SENSORS
MobiHealth	Patient Monitoring	Manually	ZigBee/Blueto oth	GPRS/UMTS	Egg, Heart Rate, Blood Pressure
CodeBlue	Medical care	Wired	ZigBee/Mesh	N/A	Motion, EKG, Pulse, Oximeter
Health Service	Mobile Health	Wired	UMTS/GPRS	UMTS/GPRS	ECG, Pulse Rate EMG, SpO2
ASNET	Remote Health Monitoring	Wired/Wi-Fi	Wi-Fi/Ethernet	GSM/Internet	Blood Pressure, Temperature
UbiMon	Healthcare	ZigBee	Wi-Fi/GPRS	Wi-Fi/GPRS	SpO2,3 leads ECG, 2leads ECG strip
AID-N	Mass Casualty	Wired	Mesh/ZigBee	Wi-Fi/Internet/Cellular Networks	Blood, Heart Pulse, ECG, Temperature
Tele-medicine	Home Based Care & Medical Treatment	Bluetooth	Internet	Internet	Blood Pressure, Temperature, ECG

2.5 Types of Healthcare Monitoring Systems and their application in AAL

Healthcare Monitoring Systems can be classified as Traditional Healthcare Monitoring Systems and Smart Healthcare Monitoring Systems. Smart Healthcare Monitoring Systems (SHMS) are traditional HMS with advanced smart technologies or new smart approaches to address health related issues. Based on the Figure 2.6 below, (Pramanik et al., 2017) classify Smart Healthcare Monitoring Systems into three categories such as Remote Healthcare Monitoring Systems (RHMSs), Mobile Healthcare Monitoring Systems (MHMS) and Wearable Health Monitoring Systems are classified as Smart Health Monitoring Systems (SHMS).

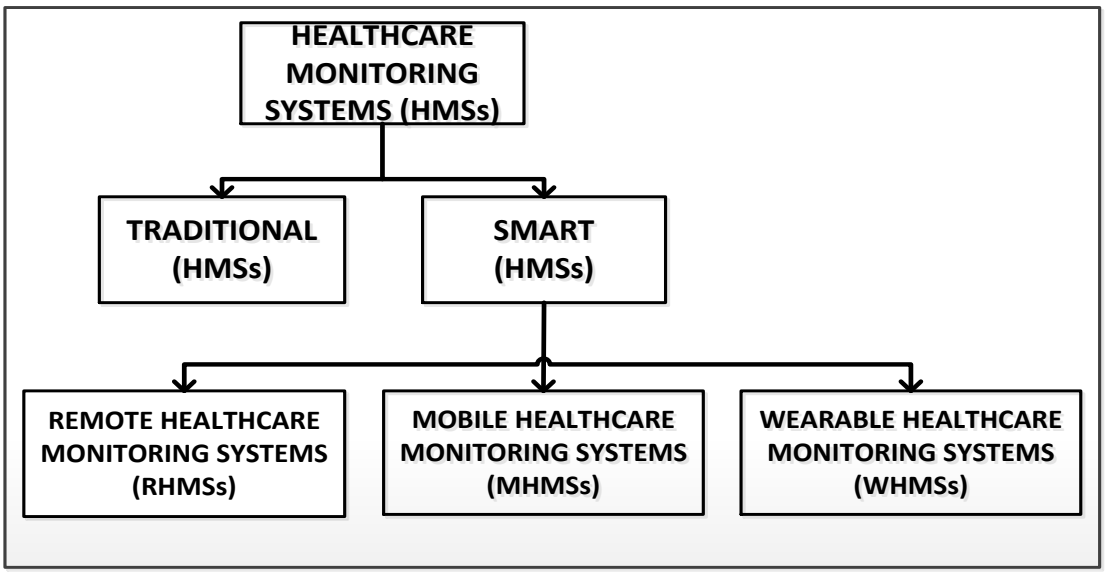

Figure 2.5: Healthcare Monitoring Systems classification.

a) Remote Healthcare Monitoring Systems (RHMS)

RHMSs are systems that are able to send and receive data from a remote location where distance separates patients or elderly people from the healthcare professionals with electronic information and telecommunication technologies such as sensor networks. These systems are implemented in hospitals as well as in homes by using advanced mobile radio communication technologies to transmit vital bio-data from a remote location in real time. RHMSs are merged with wearable monitoring technologies and mobile communication systems.

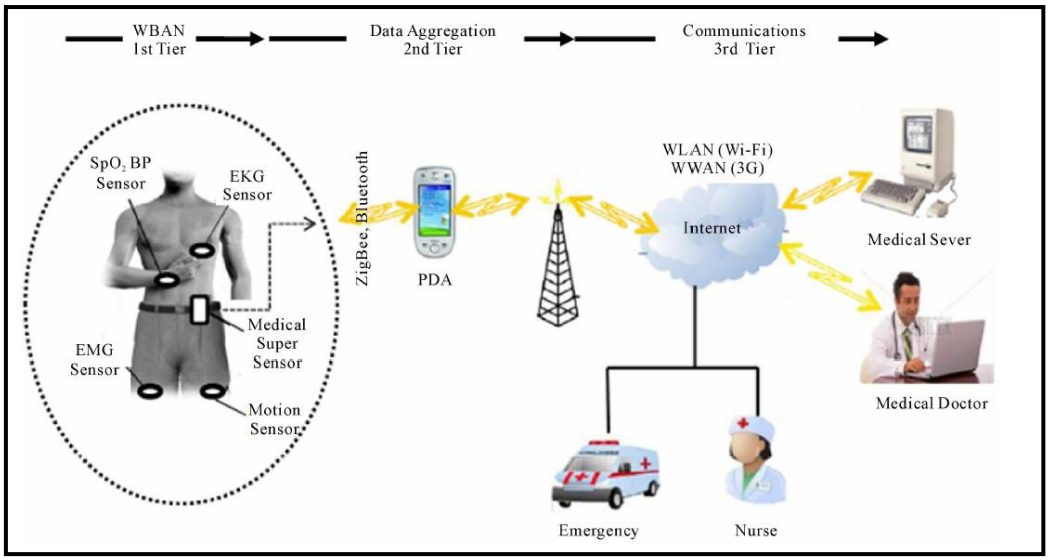

Figure 2.6: Remote Healthcare Monitoring Systems (Abidoye et al., 2011)

The above architecture for a remote healthcare monitoring system has been adopted by (Abidoye et al., 2011) to improve the communication of physiological vital signs by using ZigBee/IEEE 802.15.4 standard. Their system use ZigBee WPAN standard to collect data wearable sensors to the Intelligent Personal Digital Assistant (IPDA). From there IPDA, data is sent to the medical server by using 3G communication. However, end-to-end delay is one of the challenges for the healthcare systems. A study based on end-to-end delay, where a reliable, intelligent monitoring system developed based on efficient communication, effective management of wearable medical devices energy shows the improvement of reliability of data communication on a network (Ren et al., 2010). Another study proposed an embedded mobile ECG monitoring system that focuses on a client-server architecture that stores ECG signals for patients that are geographically located (Shih et al., 2010). To minimise end-to-end delay challenge in Personal Area Networks, priority scheduling and data compression mechanism is implemented increase the rate of transmission for critical physiological signals in mobile ECG monitoring system.

b) Mobile Healthcare Monitoring Systems (MHMS)

MHMSs use mobile devices such as smart phones, personal computers, assistive mobile robots to collect and distribute across the network (Qing-hua and Jian-ye, 2011). A study based on self-powered wireless sensor network was undertaken to monitor ECG, pulse-oximeters and BP for elderly people residing in a remote location (Hande et al., 2006). Their system use low power sensor network and tri-axis accelerometers to display graphical charts. A call from a mobile phone to a server computer initiates transition of graphical chart via the mobile phone.

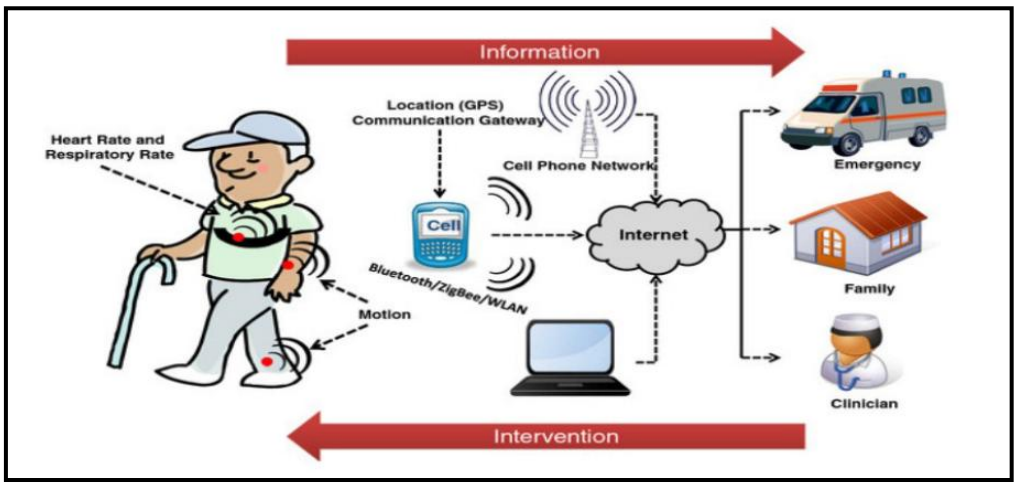

Figure 2.7: Mobile Healthcare Monitoring Systems (Patel et al., 2012)

A Mobile Healthcare Monitoring Systems in Figure 2.8 above is proposed by (Bakar et al., 2016). The system uses mobile devices such as smart phones to access medical data. Arduino microcontroller is a programmable hardware device used to process data from sensors such as heart rate pulse and body temperature. Arduino connects to the GSM device, which provides connection to mobile devices. Finally, the system can send automated alerts to the doctor, nurse or care-taker in charge.

However, the limitations for their systems are the high-energy consumption and the continuous transmission of messages that lead to network latency. Our study focus area is to enhance ZigBee Tree Routing (ZTR) protocol. In response to the network latency problem identified in (Bakar et al., 2016), our proposed solution is to merge ZigBee Tree routing protocol to find the shortest path to the destination device.

c) Wearable Health Monitoring Systems (WHMS)

WHMS consists of wearable clothes with sensors embedded on them or biosensors implanted on a human body and form a network connection. A Smart-Vest is a wearable physiological monitoring system proposed by (Pandian et al., 2008). Smart-Vests are wearable physiological monitoring systems used to measure parameters such as ECG, PhotoPlethysmoGraphy (PPG), HR, BP, Body temperature, and Galvanic Skin Response (GSR) in a human body. Figure 2.8 below depict the flow of data in a typical Wearable Health Monitoring System.

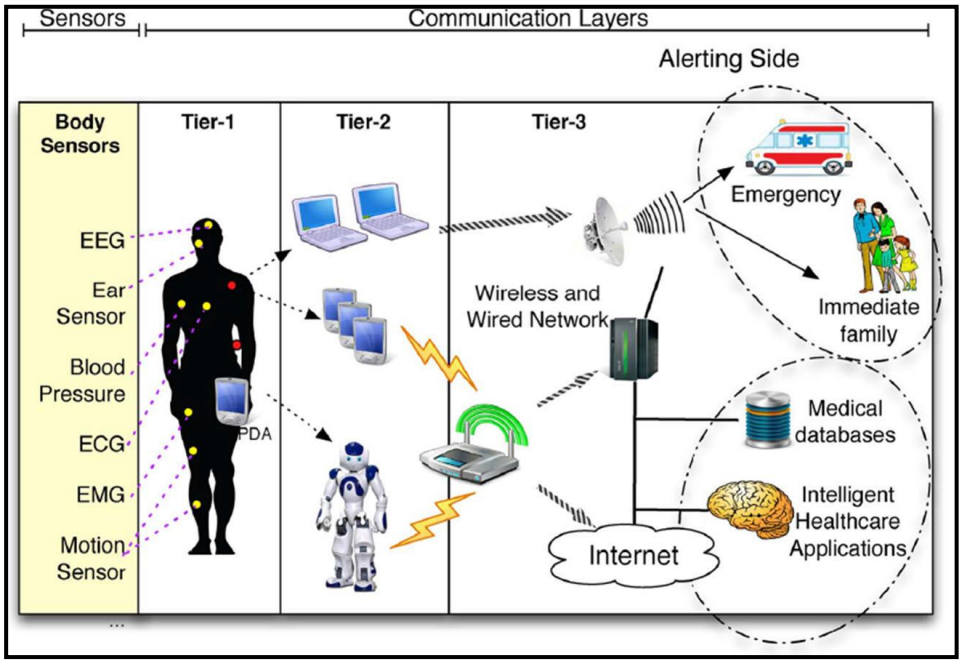

Figure 2.9: Wearable Health Monitoring Systems

This study chose a Remote Healthcare Monitoring System, however, ZigBee Personal Area Network is the centre of focus for our research work as it aims to propose an improved ZigBee routing protocol. Improving how data is routed on PAN level in HMSs can reduce network latency, which in turn reduces the end-to-end delay of vital physiological data of a monitored elderly citizen. The overview of ZigBee communication technology is laid in detail in the next section.

2.6 ZigBee network overview

ZigBee is the Low-Rate Personal Wireless Area Network (LR-WPAN) protocol that supports more network nodes, consumes less power, costs less and is easy to expand (ZigBee, 2009). ZigBee technology is simpler and is less expensive than Bluetooth. The main objectives of LR-WPAN protocols such as ZigBee are ease of installation, reliable data transfer, short-range operation, extremely low cost, and a reasonable battery life, while maintaining a simple and flexible protocol.

2.6.1 ZigBee Protocol Stack Architecture ZigBee Devices and topologies

ZigBee defines three types of devices: ZigBee Coordinator (ZC), ZigBee Router (ZR) and ZigBee End Device (ZED) (ZigBee Alliance, 2003). The mentioned devices can be classified as Full Function Device (FFD) or Reduced Function Devices (RFD). ZigBee Coordinator (ZC) and ZigBee Router (ZR) are classified as Full Function Devices (FFD) and ZigBee End Devices are classified as Reduced Function Devices (RFD). FFD are devices that can operate as ZigBee coordinator, ZigBee router and a ZigBee end device while RFDs can only operate as end devices. An FFD can talk to other FFDs as well RFDs whereas RFD can only talk to FFDs.

ZC is the most capable device on a ZigBee network. It forms the root of the network tree and might bridge to other networks. There is only one ZC in each network. ZC stores information about the entire network. ZR can act as an intermediate router that allows data from other devices to pass through it. ZED is the device that communicates with the parent node, which could be ZC or ZR. However, it cannot relay data from other devices. Therefore, it can be on a sleep mode for a significant amount of time and that allows it to save more power. Lastly, ZED requires the least amount of memory, therefore, it is less expensive to manufacture compared to ZC or ZR. Compared to Bluetooth and Wi-Fi, ZigBee network layer has an advantage to support three types of topologies such as Star, Mesh and Tree respectively (Habib et al., 2015):

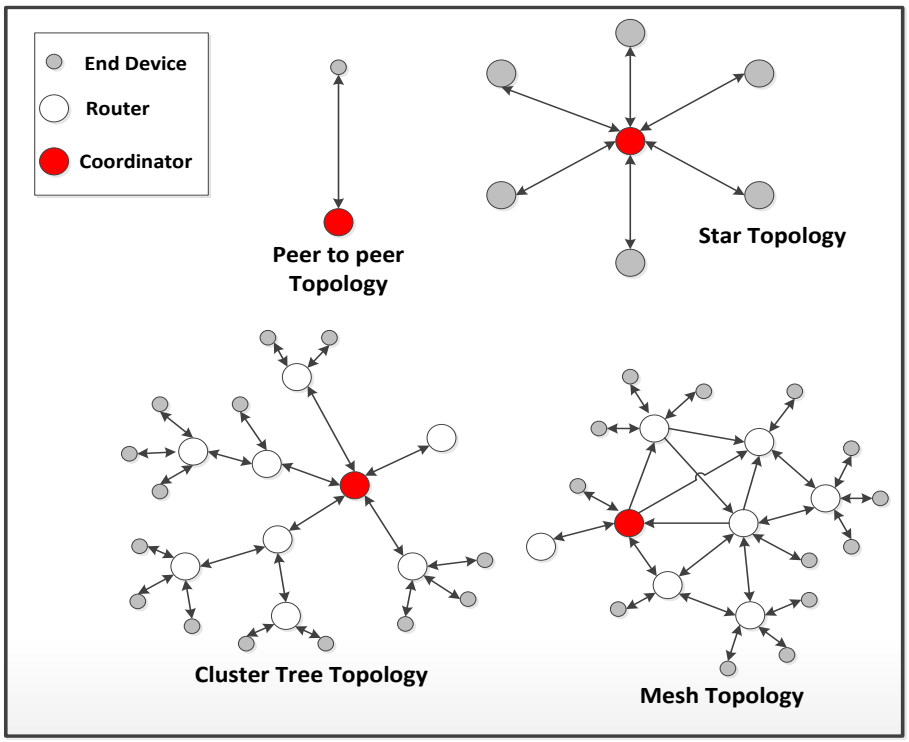

Figure 2.10: ZigBee Peer to peer, star, cluster, and mesh network topologies

ZigBee networks can connect togather in different topologies. These topologies demonstrate how network nodes are logically connected to one another. As demonstrated in Figure 2.10 above, a peer to peer topology has one node directly connecting to another node. One node becomes a coordinator and the other node becomes a router or an end device. In a star topology, a coordinator acts as a central device where all other ZigBee nodes connect. This simply means that when two nodes are communicating to each other, their messages pass through the coordinator, which routes them according to the specified destination of choice. In this topology end, devices cannot communicate directly to each other. In a ZigBee network, a star topology is composed of two devices namely; a ZigBee coordinator and end device (some end devices are routers). This is a simple topology to implement, though its shortcoming is a central point of failure. When a coordinator is down, the whole network will be down. Cluster tree network topologies have nodes grouped into clusters. Each cluster has a cluster head (usually a router) selected and the end nodes rely on the cluster head for communication. Mesh topologies have all nodes connected and can participate in sending and receiving messages. A network coordinator is responsible to manage the network in this kind of topology. Typical common applications of IEEE 802.15.4 devices are (Zhang et al., 2010):

1. Home automation
2. Health care and environmental monitoring

3. Emergency and disaster response
4. Security, location and asset tracking
5. Industrial control

This study aims to simulate a ZigBee network implemented to transmit data collected by wireless sensors that are ubiquitous installed in Ambient Assisted Living (AAL) space. In this study AAL is defined as an environment such as a home, small clinic, old age home or any kind of a building where elderly people stay and have assistive technology tools such as sensors installed in their living space.

2.6.2 ZigBee Network Architecture

ZigBee is an IEEE 802.15.4 standard for Wireless Personal Area Network (WPAN) developed for low power consumption, low data rate and low cost. IEEE 802.15.4 is the standard that is generally used by most of the indoor applications for home automation and industrial monitoring. The following diagram demonstrates the ZigBee network architecture. The diagram demonstrates how the devices are logically connected on a network based on the ZigBee Tree Routing protocol. ZigBee network is composed of wireless sensor devices such as bio-medical sensors for healthcare monitoring, kitchen appliances that use IP addresses, environmental sensors such as temperature as well as other intermediary devices such as routers. ZigBee is defined (Choudhury et al., 2016) as a networking standard for resource constrained networks that use low powered devices to transmit low data rate signals.

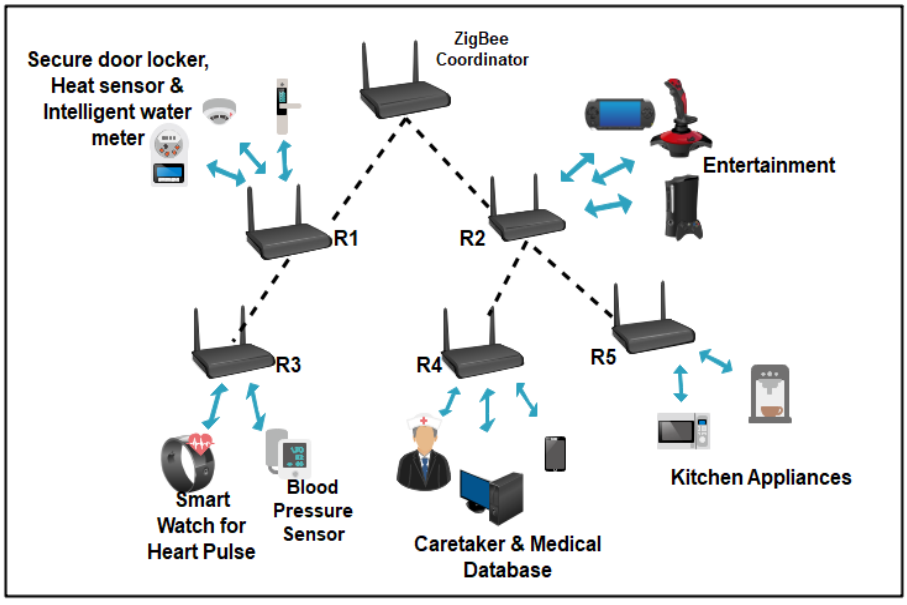

Figure 2.11: ZigBee Network Architecture (adopted from: http://www.emwhiz.com/solutions-wireless-mesh-networking.php)

2.6.3 ZigBee Network Stack Protocol

The ZigBee Protocol stack architecture is composed of four layers (ZigBee Alliance, 2003): Application layer, Network layer, Media Access Control layer, and Physical layer. Each layer uniquely performs specific function. Based on ZigBee specification, in December 2003 a new protocol called IEEE 802.15.4 for domestic and industrial environments was released for low power and low cost wireless network (Howitt and Gutierrez, 2003b). According to ZigBee standard (ZigBee Alliance, 2003), ZigBee stack architecture is based on the ISO/IEC 7498-1 (Commission, 1994) standard well known as Open Systems Interconnection (OSI) seven layer model but it defines only those layers relevant to achieving functionality in the intended market. Therefore, the IEEE 802.15.4 standard defines the lower layers: the physical (PHY) layer and the Medium Access Control (MAC) sub-layer. The ZigBee Alliance builds on top of this foundation by providing the Network (NWK) layer and the framework for the application layer. Based on the Physical (PHY) and Medium Access Control (MAC) layer, the ZigBee Alliance released its first specification in December 2004. The design of ZigBee low rate Wireless Personal Area Network (LR-WPAN)/IEEE 802.15.4 ensure reliability, low power and cost-effective communication.

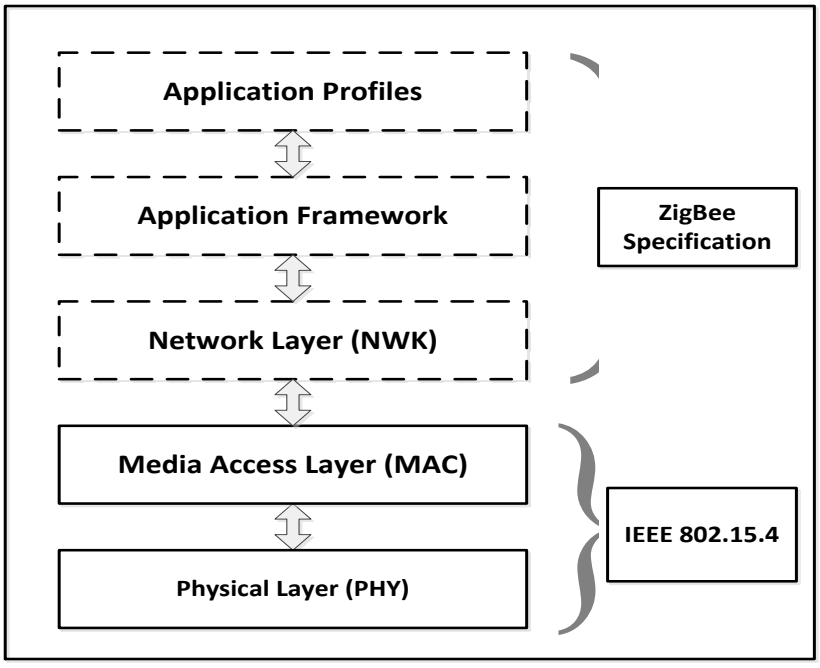

Figure 2.12: ZigBee Protocol Stack Architechture

- IEEE 802.15.4 PHY (Callaway et al., 2002) operates in two separate frequency ranges where there is lower frequency of 868/915 and a higher frequency of 2.4 GHz. The lower frequency of 868 MHz for European band and the 915 MHz covers United

States of America and Australia. The higher frequency of 2.4 GHz is virtually used across the globe.

- IEEE 802.15.4 MAC (Lu et al., 2004) sub-layer uses Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism to control access to the radio channel. MAC sub-layer is responsible for beacon frame transmission, synchronizing and providing reliable transmission mechanism.

- Application layer (ZigBee Alliance, 2003) consists of the APS sub-layer, the Application Framework (AF), the ZDO and the manufacturer defined application objects. APS sub-layer maintains tables for binding. Binding is the ability to match two devices together based on their services and their needs, and forwarding messages between bound devices. ZDO defines the role of the device within the network such as ZigBee coordinator or the end device. It is also responsible for discovering devices on the network and determines which application services they provide. The application framework in ZigBee is the environment in which application objects are hosted on ZigBee devices. Application objects send and receive data inside the application framework through the Application support Sub-layer Data Entity (APSDE-SAP).

- Network layer (NWK) deals with forwarding packets and routing them to the preferred destination on a network, depending on the routing protocol used. Network (NWK) layer responsibilities include mechanisms used to join and leave the network, to route frames from source node to the intended destination node, and to apply security to frames before they are sent over the network (ZigBee Alliance, 2003). NWK layer also plays a role in the discovering and the maintenance of routes between the ZigBee nodes.

Our study aims to improve a Tree routing protocol for a ZigBee network. We aim to achieve reduced end-to-end delay mechanism for packets travelling on the ZigBee network, which will minimize network latency in Healthcare Monitoring Systems. ZigBee Network layer is laid in detail in the next section, which gives clarity and understanding on what routing mechanisms are used for in ZigBee network.

2.7 Routing in ZigBee network

Routing is the process of transmitting a data packet from one device to another by deciding the best path for a packet to take in a network. Routing algorithms plays a vital role in selecting the best path and moving packets from the source to destination node. Routing has the following three elements (routing database, routing protocol and routing algorithm) that are discussed further in the next section.

2.7.1 Routing Database

A routing database acts as storage of routing information in a network. A routing table is contained within the routing database; it has information needed to transfer a packet to the most appropriate route to its destination node. A data packet contains information about the source and the destination nodes such as IP addresses. When an intermediary device receives a packet, it first examines a routing table to match the source and destination IP addresses and it selects the perfect path for the packet. A routing table database will therefore, provide commands for the device to forward the packet to the selected path.

2.7.2 Routing protocol

Routing protocol is defined as a mechanism used by the routers to decide the end-to-end best route from the source node to the destination node (Karia et al., 2013). Generally, routing protocol objectives are delay minimization, network throughput maximization, energy consumption minimization, distribution of traffic load equality, and data-delivery-ratio maximization.

Generally, routing protocols are grouped according to position and topology. Routing protocols based on the position utilizes position information to locate the exact position of the destination node (Purnima and Umashankar, 2014). Position based routing protocol uses position location information such as Global Positioning System (GPS) to provide more reliable routing of packets. Routing protocol based on the topology can be classified into hybrid, reactive, and proactive routing protocols. This study interest is on topology routing protocols.

- Reactive routing protocols (Patel et al., 2014) can route information only when there is a need. This allows minimization of control overhead. However, one of the challenges with the reactive routing protocols is the delay caused by the first packet to be delivered.

- Proactive routing protocols (Alubady et al., 2015) have a node that can recognize a route to other node all the time. The advantage is the absence of delay; however, its shortcoming is the increase of control overhead.
- Hybrid routing protocol (Cheun et al., 2015) is a combination of the advantages of both reactive and proactive routing protocols .

2.7.3 Routing algorithms

Routing algorithms often plays an important role in routing protocol design on a network (Yao et al., 2015). Routing algorithms are used to select the shortest optimal path to the destination node on a network. An ideal routing algorithm should have the following attributes:

- Optimality; a proposed algorithm should be capable of providing optimal path to the destination node with decreased end-to-end delay.
- Fairness; the selection for a proposed algorithm should be fair and reasonable to other nodes on a network.
- Stability; a proposed algorithm should have enough strength to support any changes such as network scalability.

There are a number of routing algorithms in wireless networks; the following algorithms provide shortest path selection for data communication on a network.

1. Kruskal's algorithm; uses the greedy mechanism to find the minimum spanning tree on a network. This algorithm connects one node to another only if the node has the lowest cost, compared to other available options.
2. Prim's algorithm; is another algorithm that finds the minimum spanning trees using greedy mechanism.
3. Dijkstra's algorithm; finds the shortest path from a source to a destination using hop count.
4. Bellman-Ford algorithm computes shortest paths from a single source vertex to all of the other vertices in a Weighted Graph.
5. Weighted Graph algorithm is a graph in which each branch is given a numerical weight.

2.8 ZigBee Tree Routing (ZTR) protocol

ZTR protocol is the basic routing protocol used in ZigBee network, which is also known as the hierarchical routing protocol (ZigBee Alliance, 2003). ZTR transmit data packets without incurring route discovery overhead. This is achieved by using parent-child links in a hierarchical tree topology. ZigBee Tree routing uses the distributed block addressing scheme to prevent the route discovery overhead for both bandwidth and memory. This allows any source node to transmit a packet to the destination. Due to route discovery capability, ZTR is considered a better protocol for resource constrained devices that require low network latency. However, the shortcoming for ZTR protocol is that, devices forward packets to the parent or child node only along the Tree topology towards the destination node. This parent-child mechanism is followed even if the destination node is located nearby the sending device. This results to high network latency caused by the end-to-end delay of packets. As the packets follow a tree path towards the destination, they are routed through a number of intermediary devices.

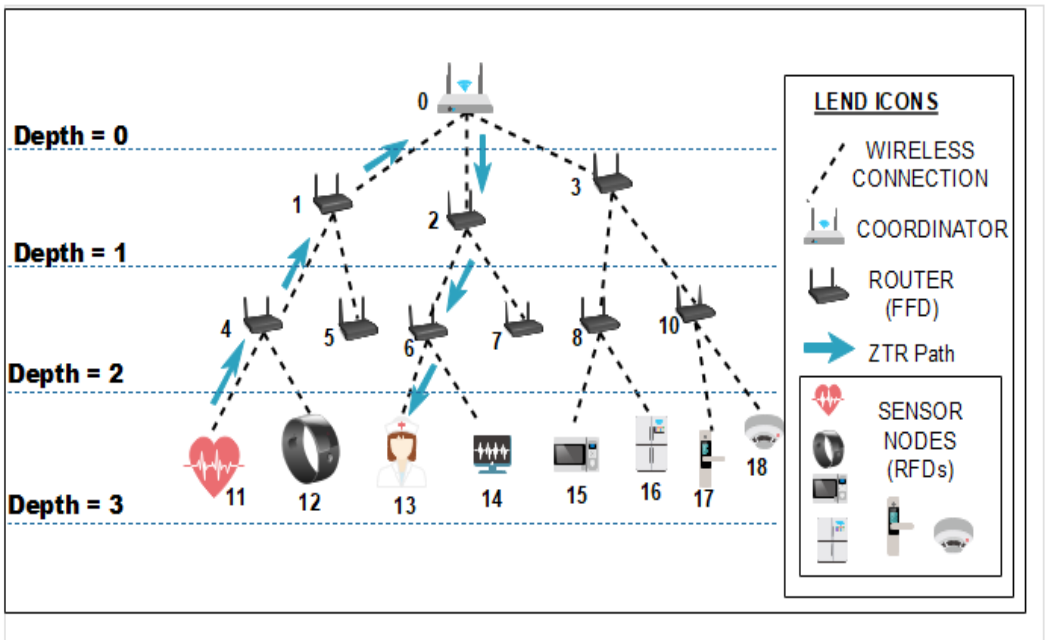

Figure 2.13: Route Path for a parent child mechanism

Thus, the main goal of the proposed NRTP is to improve the traditional ZTR routing algorithm in order to reduce the end-to-end delay for real time traffic Healthcare Monitoring Systems in Assisted Living environments.

2.8.1 Routing table and Neighbor table for a ZigBee Tree

A routing table is that which a ZigBee coordinator or ZigBee router stores temporary information used during route discovery (Kim et al., 2014). A ZigBee router or ZigBee coordinator maintains a routing table. During route discovery, the information that a ZigBee router is required to maintain in order to participate in the discovery of a particular route is distributed between a routing table entry and a route discovery table entry. Once discovery has been completed, only the routing table entry needs to be maintained in order for the NWK layer to perform routing along the discovered route.

Neighbor table is that which is used by ZigBee devices to keep track of other devices as it contains information about every device within the transmission range (Gawande and Sahu, 2014). There are two useful contexts for a neighbor table. The first one is used during network discovery or rejoining to store information about routers within Radio Frequency (RF) reception range that may be candidate parents. The second one is that which after the device has joined a network is used to store relationship and link-state information about neighboring devices in that network. A table entry is updated every time a device receives any frame from the corresponding neighbor.

2.8.2 Address assignment mechanism in ZigBee network

According to ZigBee specification (ZigBee, 2004), Full Function Devices (routers) that have not taken any part in any network formation are the potential candidates for ZigBee network coordinator. With a distributed addressing scheme for network address assignment in ZigBee network, a default value for a network address allocation ($nwkAddrAlloc$) is $0*00$ where address 0 is allocated to the coordinator. The coordinator gives out 64-bit addresses to new devices that are joining the network. This mechanism is designed to provide every potential parent (router) with a finite sub-block of a network address. A parent will then give out unique network addresses to its children. The ZigBee coordinator manages a number of children that are joining a network. As these children join the network, the coordinator chooses (C_m, R_m, and L_m) parameters before joining the network. R_m is the maximum number of child routers that can be associated with a router ($nwkAddrAlloc$). C_m is the maximum number of children a router can have including both the child routers and the end devices ($nwkMaxChildren$). L_m is the maximum depth ($nwkMaxDepth$) of the ZigBee

network that indicates a minimum number of hops a message can travel by using only the parent child links to reach the ZigBee coordinator.

Full Function Device (FFD) can act as both a router and an end device whereas Reduced Function Device (RFD) can be an end device only. Therefore, only the FFD can participate as a PAN coordinator. When given values for the maximum number of children, maximum number of routers, and the maximum depth of the network, $C_{skip(d)}$ function may be computed. Address space can be logically partitioned into Rm+1 block. If a parent (coordinator) has a child (router), that child router is assigned the first Rm block and the end devices are assigned the last block. In short, $C_{skip(d)}$ is the size of the address sub-block being distributed by each parent at that depth to its router capable child devices for a given network depth. The offset $C_{skip(d)}$ for the PAN coordinator or any other router is given by:

$$Cskip(d) = \begin{cases} 1 + C_m \cdot (L_m - d - 1), & \text{if } R_m = 1 \\ \dfrac{1 + C_m - R_m - C_m \cdot R_m^{L_m - d - 1}}{1 - R_m}, & \text{otherwise} \end{cases} \quad (1)$$

According to the ZigBee specification, (Mshali et al., 2018) the coordinator is always at depth 0, therefore if a parent is at depth d, its child is at $d+1$. A parent assigns address that is greater than its own to its first router capable child device. This also implies that the network addresses shall be assigned to router capable child devices using the value of $C_{skip(d)}$ as an offset. A ZigBee network has a maximum of 65536 address spaces, so if a parent node has an address A_{parent} at depth d, the $n-th$ child router is assigned to address $A_{parent} + (n-1)\ C_{skip(d)} + 1$, and the $n-th$ child end device is assigned to address $A_{parent} + R_m \,.\, C_{skip(d)} + n$. (2)

2.9 A summary of related studies to end-to-end delay problem

ZigBee is a low-power network that uses a classical Tree routing algorithm as one of its routing protocols. The main advantage of ZigBee Tree Routing is its ability to operate without route discovery overload. This is the result of its application to low-cost, low-power, and low-rate communication. However, ZigBee Tree Routing suffers a problem of hop redundancy and traffic concentration (Feng et al., 2015). ZTR algorithm utilizes the parent-child relationship mechanism to establish possible routes between the nodes. A parent-child

mechanism has an end-to-end delay problem due to a number of hops a packet has to pass through before reaching the destination node.

In response to this problem, (Feng et al., 2015) proposed an Enhanced Neighbour Tree Routing (ENTR) and the Neighbour Hierarchical Tree Routing (NHTR) as a two Tree Routing strategy. This strategy takes into account the neighbour relationship among tree nodes when forwarding the packets to the destination device. ENTR gets the shortcut by establishing the 2-hop neighbour table and the virtual destination neighbour group, while the NHTR focuses on the path efficiency of ZigBee Tree Routing by inserting the initial exploration in the neighbour table.

A number of studies were conducted in response to the identified above problem of end-to-end delay in the ZigBee Tree Routing protocol. A study proposed an improved Tree Routing algorithm which utilizes the information of the neighbours within two hops (Yao et al., 2012). Their proposed solution allows nodes to use the Distributed Address Assignment Mechanism (DAAM) to calculate their depth. For a node to receive the 2-hop neighbour information easily, the routing nodes broadcast beacon messages with local neighbour information. The 2-hop neighbour information mechanism determines the optimal path to the destination node. However, if all nodes broadcast their neighbour's address, many packets can be broadcasted to ensure that all nodes could receive the packets. This increases the cost overhead and the end-to-end delay as the packets are broadcasted to many intermediary devices before reaching the destination device.

ZBR-M is an improvement of ZigBee Tree Routing protocol to reduce end-to-end delay (Kasraoui et al., 2013). ZBR-M protocol allows a horizontal exploration of the tree and more vertical exploration of the links between parent and child nodes. It increases the likelihood of finding an alternate path from the destination without achieving a common parent node. However, this algorithm introduces an additional energy cost compared to the basic hierarchical routing. A hybrid routing protocol for wireless sensor networks is proposed to improve the efficiency of a Tree Routing protocol in ZigBee network. In addition to parent-child links, a hybrid protocol uses links to other one hop neighbour if they are identified to be able to provide a route shorter than the tree path (Qui et al., 2007). The address assignment scheme of ZigBee networks is exploited to make such identification possible.

An Improved Tree Routing (ImpTR) protocol is proposed to enhance the classical Tree Routing protocol (Al-Harbawi et al., 2009). The proposed ImpTR protocol determines the

shortest path to the sink node depending on the neighbour table instead of following the tree topology. The packets are forwarded to the neighbour node if the path to the destination through neighbour node is shorter than the path through PAN coordinator. To find a shortest path to the destination node in ZigBee network, a Shortcut Tree Routing (Kim et al., 2007) protocol is proposed to reduce the routing cost of ZigBee Tree Routing by using the neighbour table that is originally defined in the ZigBee standard. Neighbour table is used to find the optimal next hop node that has the smallest remaining hop count to the destination. While following the ZigBee Tree Routing Algorithm, the Shortcut Tree Routing (STR) suggests forwarding a packet to the neighbour node if it can reduce the routing cost to the destination. However, ImpTR and STR mechanisms are not cluster based they consume more energy and incur more control overhead than cluster based mechanisms.

A study was conducted to improve Tree Routing protocol by implementing a Cluster-Tree algorithm (Li et al., 2010). The proposed solution is a control overhead based on ZigBee cluster tree architecture. It uses Cluster-Tree parameter of ZigBee network and network address of destination nodes to restrict its transmission direction and control transmission range. Z-MHTR (ZigBee Multipath Hierarchical Tree Routing) is proposed by (Bidai et al., 2012) to enhance the performance of the ZTR protocol. Z-MHTR uses simultaneous multipath routing as a solution. The proposed Z-MHTR is a node disjoint multipath routing extension for the ZigBee Tree Routing protocol in Cluster-Tree wireless sensor networks. To make its forwarding decisions, Z-MHTR relies on a ZigBee Tree structure based on parent child established relationships.

Another study conducted based on Cluster-Tree algorithm (Meng et al., 2012) proposed to improve the ZigBee Tree Routing protocol by introducing a neighbour table forwarding mechanism. It is claimed that the proposed algorithm finds better paths to forward data packets to the destination. A mesh routing protocol for a ZigBee network called ZigBee-Cluster-Label (ZiCL) is proposed (Lee et al., 2006). ZiCL routing protocol aims to reduce end-to-end delay and packet delivery ratio. ZiCL divides the ZigBee network into one or more logical clusters. To identify each cluster, a cluster head in each logical cluster assigns a unique Cluster Label to cluster numbers. Clustering encourages nodes to share routing information and reduces numerical potential route discoveries. To exploit the logical network effectively, ZiCL provides an algorithm to calculate the cluster label of a node and encourage nodes within each cluster to share routing information.

The problem of finding a minimum spanning tree of an edge of the least possible weight that connects any two trees in the forest was first solved by (Kruskal, 1956). A problem of determining multicast trees that guarantee certain bounds on the overall cost, and end-to-end delays from the source to each of the destination nodes was considered (Aissa et al., 2009). Based on the conducted studies, a number of possible solutions are proposed to improve the ZigBee Tree Routing protocols by minimising end-to-end delay that has been identified as a major concern to be addressed in this research study. The proposed solutions use different methodologies to address the end-to-end delay. The proposed solutions improve the overall performance for the ZigBee network, however, additional challenges arises. The end-to-end delay problem then remains unsolved. Our study aims to combine some of the above mechanism to fully address the end-to-end delay problem.

A Velocity Energy-efficient and Link-aware Cluster-Tree (VELCT) scheme for data collection in WSNs is proposed, which would effectively mitigate the problems of coverage distance, mobility, delay, traffic, tree intensity, and end-to-end connection (Velmani and Kaarthick, 2015). The designed VELCT scheme minimizes the energy exploitation, reduces the end-to-end delay and traffic in cluster head in WSNs by effective usage of the DCT. The strength of the VELCT algorithm is to construct a simple tree structure, thereby reducing the energy consumption of the cluster head and avoids frequent cluster formation.

Shortcut Tree Routing (STR) has been proposed to provide a near optimal routing path (Salmu and James, 2015). It also maintains the advantages of the classical ZigBee Tree Routing protocol such as no route discovery overhead and low memory consumption. SRT uses 1-hop neighbour information. Source node selects the next node having the smallest remaining tree hops to the destination regardless of whether it is a parent, child, or neighbour node. The individual node decides routing path selection in STR in a distributed manner by calculating the remaining hops from a source to the destination using the hierarchical addressing scheme. Instead of calculating route dynamically by using control packets, a set of predefined paths can be used for forwarding packets. Each source forwards a packet to the neighbour node with the smallest remaining hops in its neighbour table.

The related studies above have attempted to solve end-to-end delay problem in ZigBee network using different methods. However, this is a continuous challenge as more and more devices are becoming smarter and connected on the internet. The above-related studies used NS-2 network simulation tool to evaluate their proposed algorithms. In response to the

network latency challenge identified in ZigBee Tree Routing protocol, we propose to minimise the end-to-end delay by implementing the following mechanisms;

- ZigBee Tree Routing protocol is merged with Kruskal's Minimum Spanning Tree protocol to find the minimal shortest path to the destination.
- Clustering mechanism is implemented in our proposed solution to group devices in clusters according to their functionality; an example will be grouping physiological sensors together, home appliances in their own cluster, and security surveillance sensors in their own cluster. This can allow clusters with vital medical data to get high priority for emergency purposes.
- Neighbour tables are used to find if the destination device is not near the sending device.

2.10 Summary

This chapter laid the detailed discussions on the concepts of Ambient Assisted Living, Healthcare Monitoring Systems, Wireless Sensor Networks and Ambient Intelligence. It also linked the implementation of Wireless Sensor Networks to Healthcare Monitoring Systems. Challenges and problems facing WSN when implemented in Healthcare Monitoring Systems were also addressed. The High Network Latency caused by the end-to-end delay based on a Parent-Child communication mechanism is identified as a major challenge this study intends to address. Metrics such as end-to-end delay, throughput, congestion, and loss of packets were identified as the significant factors to minimize the end-to-end delay problem in ZigBee network. However, there is a need to develop a suitable methodology to reduce end-to-end delay of packets. The next chapter focuses on developing an algorithm to minimize end-to-end delay of packets in ZigBee Tree Routing protocol.

Chapter 3: System Design and Architecture

3.1 Introduction

In order to facilitate communication within the wireless sensory network, a routing protocol is used to discover routes between nodes. By default, a classical ZigBee network uses ZigBee Tree Routing (ZTR) to forward packets on a network. Based on a Graph Theory, this study proposes to enhance the ZigBee Tree Routing (ZTR) protocol by merging ZTR it with the Kruskral's Minimum Spanning Tree Protocol (MSTP) algorithm. This allows nodes to choose a path with minimal number of hopes towards the destination device. Clustering technique introduced in is implemented to divide the network into clusters where parent-routers selects cluster head for each cluster (Li et al., 2010). Additionally, neighbour table mechanism also discussed in ZigBee specification is implemented to retain a table that contain information of all the neighbour nodes within the 1-hop transmission.

This chapter presents the architecture and the design of the proposed New Tree Routing Protocol (NTRP) algorithm with the aim of minimising end-to-end delay in a ZigBee network. In this chapter the sections are arranged as follows: **Section 3.2**, provides the details of the proposed NTRP. Lastly, **Section 3.3** provides a summary of the whole chapter. The next section will introduce us to the architecture of the ZigBee network.

3.2 Proposed Routing algorithm

In wireless sensor networks the spanning tree is usually used as a routing structure to collect data. Kruskal's algorithm (Wen et al., 2017) is an algorithm in graph theory that finds a minimum spanning tree for a connected weighted graph. This means it finds a subset of the edges that forms a tree that includes every vertex, where the total weight of all the edges in the tree is minimized. It uses greedy forwarding decisions using only information about a router's immediate neighbours in the network topology. This study is proposing to integrate the ZigBee Tree Protocol with Kruskal's MSTP algorithm (Kruskal, 1956), which will allow the nodes to be clustered, in order to reduce end-to-end delay, and the neighbour table is utilized to find the shortest route to the destination node. NTRP proposes to implement neighbour table based on a spanning tree protocol to reduce end-to-end delay. By default ZigBee devices transit to sleeping mode to save energy when they are inactive for a long period of time.

With NTRP algorithm, nodes are divided into multiple clusters. For each cluster, one special node named cluster head which also acts a bridge to other clusters. This is demonstrated in Figure 3.3 below that illustrate a ZigBee network divided into four clusters with cluster heads labelled 1, 2, 3, and 4. Cluster head is the node that has the smallest hop account to the coordinator. However, we consider the coordinator as a cluster head for the entire ZigBee network as it controls the whole network. To comply with the ZigBee specification standard, the 16-bit network address is divided into two parts, cluster ID and the node ID. The network address of a node n is thus expressed as (Cl_n, Nd_n) where Cl_n and Nd_n are n's cluster ID and node ID respectively.

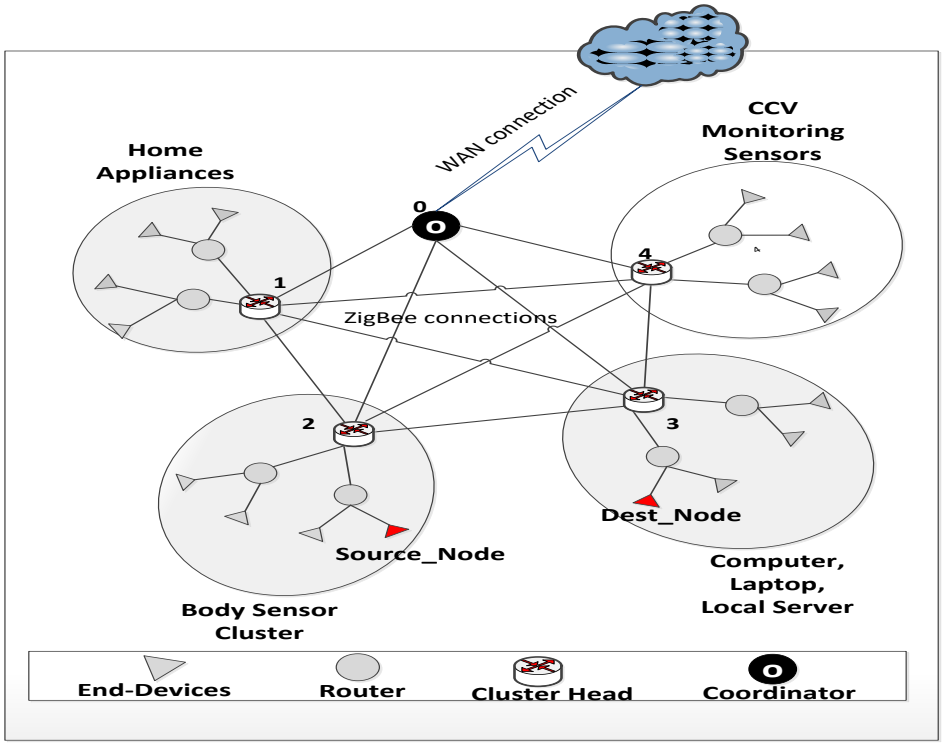

Figure 3.1: Route Path for the proposed NRTP algorithm

The ZigBee topology depicted in figure 3.3 above is suitable to demonstrate the difference between the proposed NTRP algorithm and the original ZTR algorithm. As it is discussed in chapter two, ZTR uses a parent-child mechanism to forward packets in a tree hierarchical topology. It is discussed that parent-child mechanism forwards packets to the coordinator first before they are relayed to the destination. Using ZTR to forward a packet from the source node to destination node in figure 3.3 above, the packets will take the following path: source node $\rightarrow 2 \rightarrow 1 \rightarrow 0 \rightarrow 4 \rightarrow 3 \rightarrow$ destination node. Based on our problem statement in section 1.4 of chapter one, ZTR suffers from end-to-end delay due to parent-child that allow packets to pass through many hops before reaching the destination. In response to this challenge, the

proposed NTRP minimises end-to-end delay by reducing a number of hops a packet can pass through. NTRP uses neighbour communication and clustering mechanism to pass messages between neighbour cluster heads. An example of a route path a packet can take from source to destination node using NTRP algorithm will be: source node $\rightarrow 2 \rightarrow 3 \rightarrow$ destination node.

In this proposed routing algorithm, a graph is formed by vertices and edges connecting the vertices which create the short cut from source to destination device. Formally, a graph is a pair of sets $({}_1V, E_1)$, where V_1 is the set of vertices and E is the set of edges, formed by pairs of vertices (Ruohonen, 2013). In graph theory, a graph is an ordered pair $G_1 = (V_1; E_1)$ comprising a set of vertices or nodes together with a set of edges (Ramalingam and Reps, 1996). Edges are 2-element subsets of V_1 which represent a connection between two vertices. Edges can either be directed or undirected and they can also have a weight attribute.

The graph $G_1 = (V_1, E_1)$, *where* $V_1 = \{v_1, ..., v_n\}$ & $E_1 = \{e_1, ..., e_m\}$, satisfies

$$\sum_{i=1}^{n} d(v_i) = 2m. \tag{2}$$

Therefore, for a graph $G_1 = (V_1, E_1)$, the spanning tree is $E_1' \subseteq E_1$ such that:

$$\exists u \in V_1 : (u, v) \in E_1' \vee (v, u) \in E_1' \forall v \in V_1 \tag{3}$$

In other words, the subset of edges spans all vertices. On a cluster tree topology after an association request and association response, the parents of the clusters form a tree structure and act as intermediate routers. The maximum number of children in each cluster head and the maximum depth of the tree have to be fixed in order to better control the ZigBee network topology.

3.2.1 Address Assignment

The network manager (coordinator) first assigns a cluster ID to all the nodes on the network. The cluster ID of a coordinator is 0. After network deployment, node ID's are assigned to each node using distributed address assignment method. $rC_{skip}(d)$ denotes the address size space for the network, represent the maximum number of nodes that can be associated with a router. rC_m is the maximum number of children a router can have including both the child routers and the end devices. rL_m is the maximum depth of the ZigBee network that indicates a minimum number of hops a message can travel using only the parent child links to reach

the ZigBee coordinator. Once the devices have joined the network, the coordinator assigns cluster ID's to all clusters as follows:

- Firstly $rC_{skip}(d)$ looks for rC_m, if $rC_m = 1$ the branch is not formed.
- If $rC_m = 1$, then the cluster ID assignment is insignificant because there is no branch formed in the network.
- If $rC_m \geq 2$, then the cluster ID' are assigned in a recursive manner following NTRP style.

For all nodes at depth d at any given graph, if their cluster ID is T, therefore $i-^{th}$ child is assigned a cluster ID of

$$T + (i-1) \times rC_{skip}(d) + 1 \qquad where$$

$$rC_{skip}(d) = \frac{1 - rC_m^{\,rL_m - d}}{1 - rC_m} \tag{4}$$

Each node can periodically send broadcast "HELLO" messages after node deployment and cluster ID assignment mechanism is completed. Broadcasted HELLO messages include IEEE 64-bit MAC address of each node and, a 16-bit network address. All nodes maintain their cluster ID neighbour tables to record and keep their neighbours information. Therefore the coordinator starts the process of node ID assignment by sending a broadcast address with its node ID of 0.

$$rCskip(d) = \begin{cases} \dfrac{1 + rC_m - rR_m - rC_m \cdot rR_m^{\,rL_m - d - 1}}{1 - rR_m} \text{ where,} \end{cases} \tag{5}$$

d is network depth of the parent node. A parent device that has a $rCskip(d)$ value greater than 0 shall accept child devices and shall assign addresses to them differently depending on whether or not the child devices are using the value of $rCskip(d)$ as an offset. A parent assigns an address that is +1 greater than its own first router capable child device. Subsequently assigned addresses to router capable child devices are separated from each other by $rCskip(d)$:

$$A_k = A_{parent} + rC_{skip}(d) \cdot (k-1) + 1 (1 \leq k \leq rRm) \tag{6}$$

Network addresses shall be assigned to end devices in a sequential manner with the n^{th} address. If the child node is a RFD, the assigned address given by its parent node is:

$$A_n = A_p + rC_{skip}(d) \cdot rR_m + n, 1 \le n \le C_m - R_m \quad (7)$$

If the child node is an FFD, the address of FFD is:

$$A_n = A_p + 1 + rC_{skip}(d) \cdot (n-1), \qquad 1 \le n \le rR_m, \quad (8)$$

where A_n is an assigned address for the child node, A_p is address of the parent node. Fig. 3.3 shows address assignment mechanism with $rC_m = 4$, $rR_m = 3$, $rL_m = 4$. The address and depth of coordinator node in ZigBee network are 0. The number on the right of circle is node network address.

3.2.2 Neighbor Discovery Mechanism

A coordinator is responsible to perform the neighbour discovery procedure. The aim of using neighbour discovery in this study is to establish the neighbour tables for the neighbouring cluster heads. The coordinator scans neighbour by sending hello broadcast message. The aim is to establish a neighbour table to store the information of the neighbours.

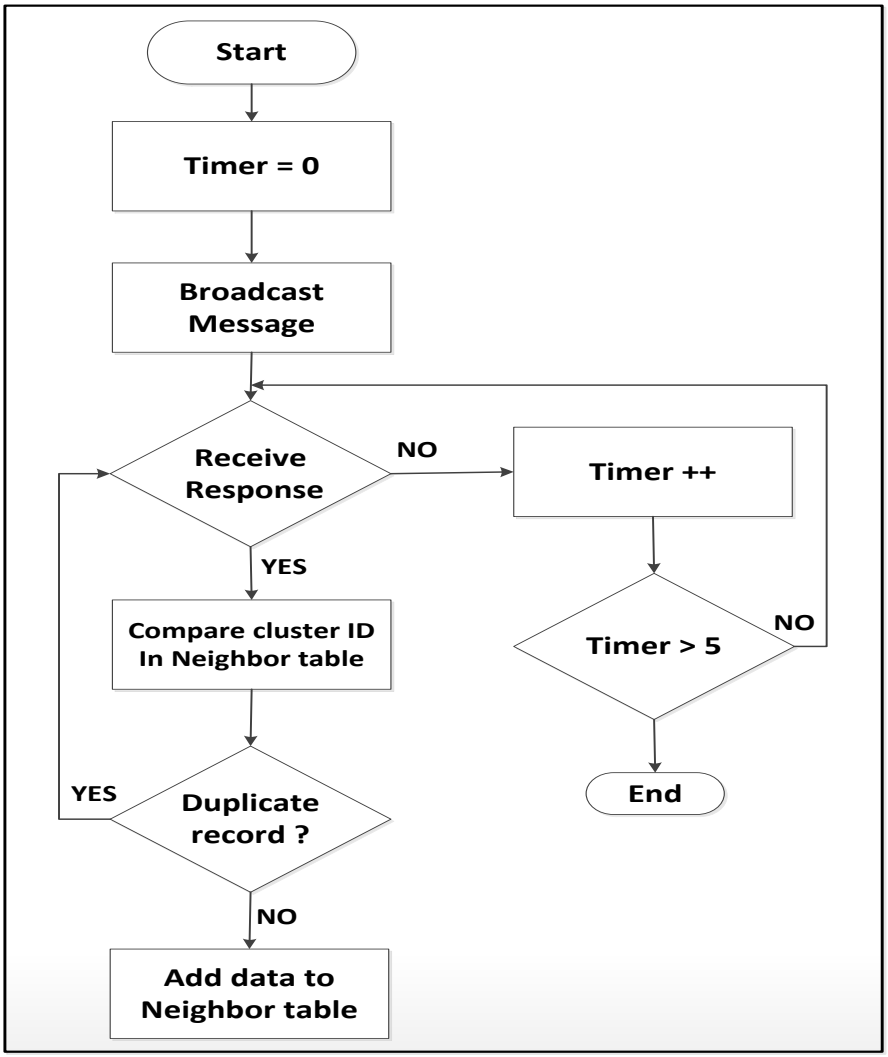

Figure 3.2: Neighbour discovery flow chart.

As depicted in Figure 3.4 above, at the beginning of the neighbour discovery, the coordinator establishes a neighbour table to store the information of the neighbour cluster heads. Firstly, the timer is set to 0, and then a broadcast message is sent to find the neighbours. A neighbour cluster head that receives this hello message responds with an acknowledgement message. An acknowledgement message contains the information of the responding node such as cluster ID, and the cluster head ID. If the coordinator receives an acknowledge message from a neighbour cluster head, it checks for duplicate data. If there are no data duplicates, data is added to the neighbour table and the timer is increased to 5. After completing the neighbour discovery procedure, neighbour cluster heads have the information with a minimum delay to reach other neighbour cluster heads as well as their child end devices.

3.2.3 New Tree Routing Protocol (NTRP) algorithm and its routing rules.

1. #include< iostream >
2. #include< vector >
3. #include< utility >
4. #include< algorithm >
5. using namespace std;
6. const int MAX = 1e4 + 5;
7. int Nd_n[MAX], nodes, Src_Node, Dest_Node, HR_pulse, NTR_Addr;
8. Max_Depth_Dest_Node = Find_maxParAddr (Dest_Node,0,0);
9 { if (min_HR ≥ 60 && max_HR ≤ 100);
10. Status_condition = normal;
11. else if (min_HR≥0 && max_HR ≤ 60);
12. Status_condition = abnormal;
13. else if (min_HR≥100 && max_HR ≥ 100);
14. Status_condition = abnormal;
15. end if }
16. { if Nd_n is an FFD && Dept(Y)< $rL_m - 1$ && $Nd_n(Y) < rR_m$ then
17. $Nd_p(Y) \leftarrow Nd_p(Y) + 1$ // accomodating node as a ZigBee parent router, allocate the following address
18. $Addr(Y) + rC_{skip}(Dep(Y)) \times (Nd_p(Y) - 1) + 1$;
19. else if $Dep(Y) \leq rL_m - 1$ && $Nd_c(Y).rC_m$ then;
20. $Nd_c(Y) \leftarrow Nd_c(Y) + 1$ // accomodating node as a child node, allocate the following address
21. $Addr(Y) + rC_{skip} Nd_p(Y)) \times rR_m + Nd_c(Y)$;
22. else // node cannot be accomodated
23. $rC_{Skip(d)} = \frac{1 + rC_m - rR_m . rR_m^{rL_m - d - 1}}{1 - R_m}$ then;
24. } void initialize ()
25. { for int x = 0; x < MAX ++x);
26. $Nd_n[x] = x$;
27. } int root (int i);
28. { while($Nd_n[i]$!= i);
29. { $Nd_n[i] = Nd_n[Nd_n[i]]$;
30. i = $Nd_n[i]$;
31. }
32. return i;
33. }

```
34. void union A(int i,int d);
35. {  int q = root(i);
36.    int p = root(d);
37.    Nd_n[q] = Nd_n[p];
38.  }
39. long kruskal (pair < long, pair < int,int >> q[]);
40. {  int i,d;
41.    long cost, minCost = 0;
42.    for (int x = 0;  x < edges ; ++x;
43. {       //Selecting edges one at a time in an increasing order
              from the beggining
44.   i = q[x].second.first;
45.   d = q[x].second.second;
46.  cost = q[x].first;
      //  check if the selected edge is creating a cycle or not
47. if (root (i) ! = root(d);
48.     {   minCost = + cost ;
49.         union A(i, d);
50.     }
51.  }   return minCost;
52. }
53. int main();
54.  { int (i,d);
55.    long weight,cost minCost;
56.    initialize();
57.    cin >> inodes >> edges;
58.       for(int x = 0; x < edges; ++ x)
59.       {
60.         cin >> i >> d >> weight;
61.         q[x] = make_pair(weight,make_pair(i,d));
62.       }      // sort the edges in the ascending order
63.      sort (p, p + edges );
64.       minCost = kruskal (p);
65.      cout << minCost << endl;
66. return 0;
67. }
```

Algorithm 3.1: New Routing Tree Protocol (NRTP) algorithm

In the above algorithm, if the packet is intended for N_d , then N_d simply accepts the packet, otherwise it performs the following steps:

- If the destination node is a neighbour of N_d, then N_d directly send the packet to the destination node.
- If $N_{src} = Cl_n$, then the destination node is within the same cluster.
- If $Cl_n = N_{src}$ and the value of $|Nd_n - N_{dst}|$ is summarized, node N_d can find its descendent node in its neighbour table and forward a packet to N_d.
- If N_{src} is an ancestor cluster of Cl_n such that $Cl_n < dest \leq Cl_n + rC_m - 1) \times rC_{skip}(d) + 1$, then N_d looks if it has a neighbour N_d that meets the conditions of $Cl_n \leq N_{src} \leq Cl_n + (rC_m - 1) \times rC_{skip}(d+1) + 1.$ In a circumstance where multiple candidates satisfy the above condition, the one with the smallest $|Nd_n - N_{dst}|$ is selected. Otherwise N_d looks for a neighbour node in the same cluster that has a maximum node address and the packets are forwarded to that node.
- For other cases N_{src} must be a parent cluster of N_d. Then N_d checks its neighbour table to check if it has a neighbour that satisfy $(Cl_n \leq Cl_n + (rC_m - 1) \times rC_{skip}(d-1) + 1.$
- Otherwise N_d finds local neighbour in the same cluster that has a minimum nodes and forwards packets to N_d.

Hello messages allow nodes on a network to collect their neighbour information such as addresses. Assuming that node N_d at a logical depth (d) receives a packet with a source and a destination address of (N_{src}, N_{dst}). NTRP is a routing method that constructs short paths along the linear paths using clustering and neighbour tables and Kruskal's minimum spanning tree algorithm. NTRP algorithm minimises the end-to-end delay of Heart rate signal packets carried along Healthcare Monitoring Systems.

3.3 Summary

In this chapter, we propose a routing protocol mechanism that attempt to enhance Tree based ZigBee routing algorithm. The proposed solution is a combination of a ZigBee Tree Routing and Kruskral's Minimum Spanning Tree Protocol (MSTP) algorithms. The main objective for the proposed algorithm is to reduce end-to-end delay by avoiding a parent child relationship that has a number of hops a packet can pass through before reaching the destination. The proposed solution adds the neighbor table forwarding mechanism and clustering mechanism

to forward the packets to the neighbor nodes that are cluster heads on the network. This minimizes the network latency by reducing the number of hops a packet can travel over a network. The next chapter discusses more about different simulation tools that are available and we select a suitable tool for this study.

Chapter 4: System Implementation

4.1 Introduction

In the previous chapter, a New Tree Routing Protocol (NTRP) is proposed. NTRP algorithm is designed to minimize the end-to-end delay of packets over the wireless ZigBee network. Therefore this chapter presents the implementation of the proposed NTRP algorithm for the ZigBee Low Power Sensor Network. Different network simulation tools are discussed in this chapter. The proposed New Tree Routing Protocol is implemented using Network Simulator-2 (NS-2) based on IEEE 11.15.4 standard specification. NS2 network simulator was installed and running on Linux Operating System, 2.6/3.x, and 64-bit on a Virtual Box Manager (VM) V4.3.20. TCL scripts and C++ source code were used for network confirmations. The simulations were performed for the duration of 100s. The obtained results were analyzed and stored in trace files. The next chapter will present the results of evaluating the proposed NTRP through the simulations.

The overall layout structure for this Chapter is as follows: **Section 4.2** provides the overview of network simulators. **Section 4.3** presents the types of network simulators that can be used in Wireless Networks. **Section 4.4** provides a detailed comparison of network simulator. **Section 4.5** provides the overview for network simulator (NS2). **Section 4.6** presents the full details about simulation environment for NS2 and NTRP. Lastly, **Section 4.7** provides the summary for the whole chapter. The next section gives the overview of the network simulation tools.

4.2 An Overview of Network Simulation tools

In computer networks, network simulators are a suitable methodology used to evaluate and test the network behavior for different topologies without a real live implementation. This can be achieved through using different conditions presented by different environment setups and models. Setting up a real live network is very expensive and time consuming. Therefore simulators are widely used by research community to evaluate new theories and hypothesis in a lab or using computers. This methodology saves cost and time by sampling the real world environment behavior into computer software. However, it is very challenging to select the correct level of detail for a simulation (Heidemann et al., 2000). Insufficient information may lead to incorrect results output, but too much detail requires time to implement. Therefore, it is a crucial task for researchers to select a network simulator that is suitable for their study.

Depending on the nature of the study conducted, there are a number of network simulators that can be used, however this chapter discusses the following simulation tools; MATLAB, OMNET, NS2, and NS3. The main reason to study and discuss the above mentioned tools is that they are open source by nature. This means that they are freely downloadable and easily accessible on the internet.

4.3 Types of Network Simulators

In this section different types of simulators are discussed. The discussion follows criteria where network simulators are labeled as complex or simple, and if they are commercial or open source.

1. Simple and Complex simulators

Network simulators can be ranged from simple to complex based on certain capabilities and their characteristics (Breslau et al., 2000). Primarily, a simple network simulator allows researchers to define different scenarios and present a network topology. Additionally, it should specify the nodes to be used on the network, connection links between the nodes, and the traffic between the nodes. Graphical applications enable the researchers to easily visualize their work from the simulated environment. On the other hand, complex simulators need more advance technical level of understanding as this allow researchers to specify in details the protocols used on the network. Programming-oriented network simulators are complex as they provide a programming framework that allows the researchers to customize the networking environment for testing. Others can be text-based simulators which provide a less visual interface, but may allow more advanced forms of customization.

2. Commercial and open source simulators

With commercial simulators researchers have to pay for the software and acquire the license in order to use the software. This means that the source code for commercial simulators is not available for free. OPNET simulator is one of the widely used examples of this type of simulator.

In contrast, the open source network simulator is free and open to all the users. This allows the researchers to also contribute to the future improvements as its interface is also open. Open source network simulators are flexible to new technologies and developments which also allow them to be chosen by the researchers for their studies. Therefore in this study, an open source simulator is used. The next section discusses some of the well-known open source network simulators such as MATLAB, OMNET++, Qualnet, NS2 and NS3.

4.3.1 MATLAB

MATrix LABoratory (MATLAB) is described as a mathematical software programming package specifically designed for scientific calculations. MATLAB is extensively used in all areas such as applied mathematics, education, research at university levels, and in industry.

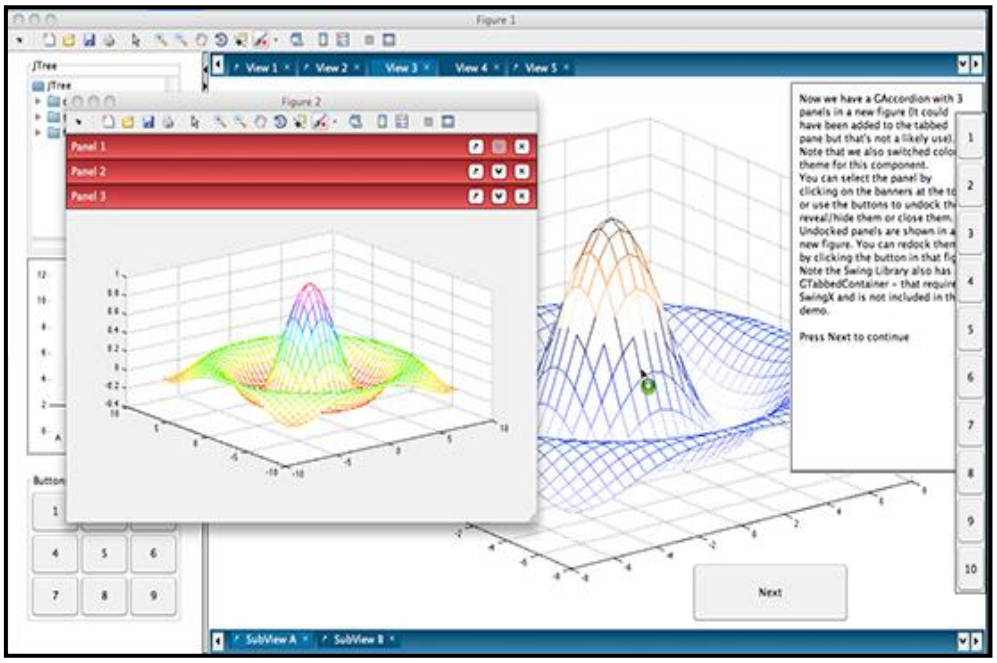

Figure 4.1: MATLAB Simulator Interface

This simulator is useful for linear algebra as it solves algebraic equations, differential equations and it is useful for numerical integration. It has a powerful graphic tool that enables it to produce quality pictures in both 2 Dimension (2D) & 3 Dimension (3D). MATLAB has some tool boxes designed for specific research disciplines such as signal processing, statistics, solution of partial differential equations, image processing, data analysis and optimization. MATLAB is a high-performance language for computing that uses multi-programming languages such as C++, C, Java, Python and FORTRAIN. It has MuPAD symbolic engine that enables it to access computing capabilities. It runs on cross-platforms such as Linux, Microsoft Windows, and Mac OS. The main challenge with MATLAB is that it requires a solid knowledge of basic MATLAB commands. Additionally, it requires more advanced knowledge for features such as 2D and 3D graphics, algebraic and differential equations, calculations with matrices and linear systems of equations.

4.3.2 OMNET++

Objective Modular Network Test bed (OMNET++) is an open source discrete-event simulation tool written in C++ language(Varga, 2003). Unlike other simulators, OMNET++ is object-oriented modular therefore it is not only used for network simulations, but it can be also utilized for complex software systems performance evaluation and multiprocessor modelling. Modules can have parameters which are used for three main purposes: to customize module behavior; to create flexible model topologies (where parameters can specify the number of modules, connection structure etc.); and for module communication, as shared variables. Based on the OMNET++ user manual (Varga, 2003), the simulator can be used for modeling the following:

- communication protocols
- computer networks and traffic modeling
- multi-processor and distributed systems
- administrative systems
- Any other system where the discrete event approach is suitable.

In addition, OMNET++ provides intelligence support and extensive Graphical User Interface (GUI) and it can be accessed in both UNIX and Microsoft Windows systems. The below Figure 4.2 illustrate the OMNET++ simulator interface.

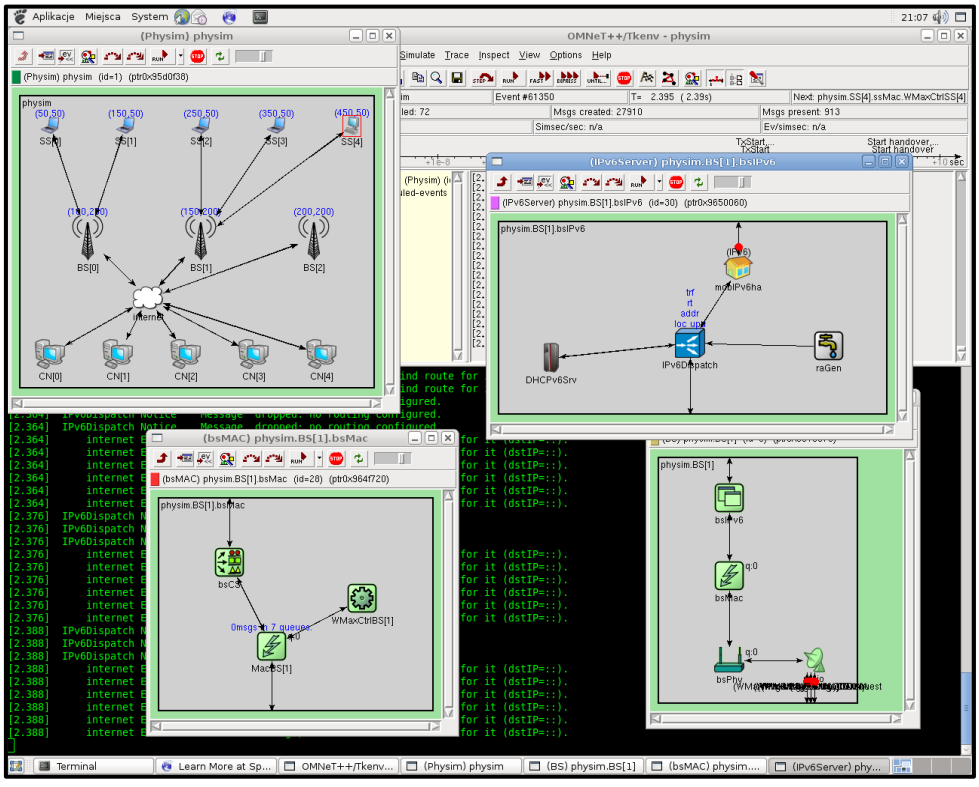

Figure 4.2: OMNET++ Simulator Interface

4.3.3 Qualnet Network Simulator

Qualnet network simulator is a discrete event simulator for large, heterogeneous networks and the distributed applications that execute on those networks. It is a set of comprehensive tools with all the components for custom network modeling and simulation projects QualNet's unmatched speed, scalability, and fidelity make it easy for researchers to optimize existing networks through quick model setup and in-depth analysis tools. Qualnet simulator has extensive library from wired LANs and WANs, to cellular, satellite, WLANs and mobile ad hoc networks, for VoIP, telnet, ftp, http, etc. However, QualNet simulator is not an open source code but it is a commercial simulator. The below Figure 4.3 illustrate the Qualnet simulator interface.

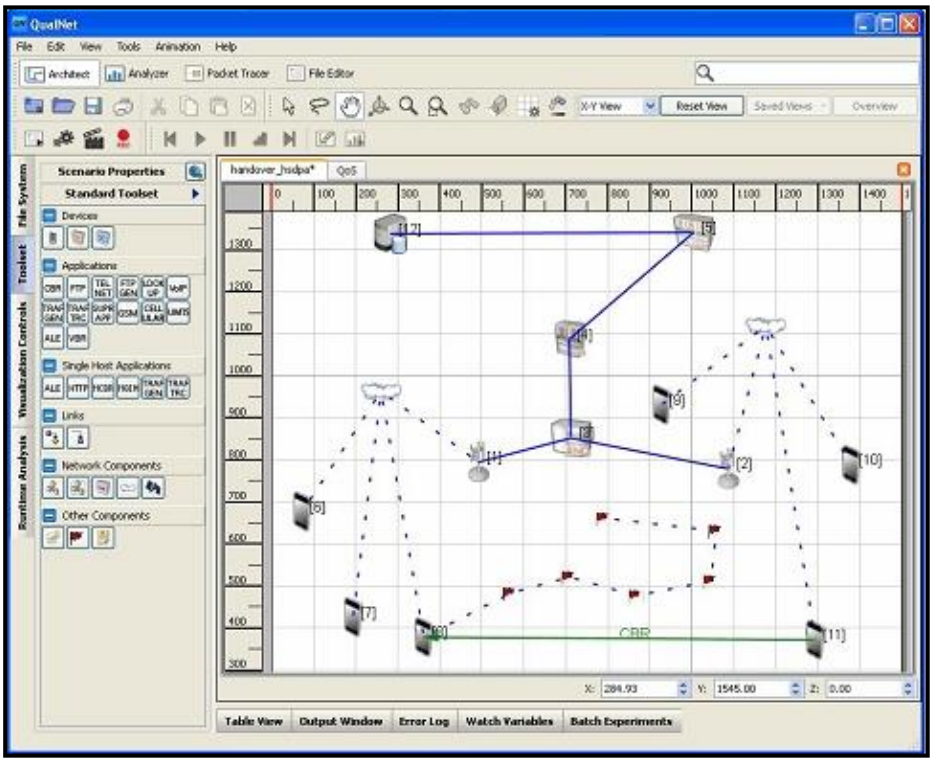

Figure 4.3: QualNet Simulator Interface

4.3.4 Qualnet Components

QualNet Scenario Designer: A model setup tool that allows users to set up geographical distribution, physical connections, protocols, traffic and functional parameters, using intuitive click and drag operations.

QualNet Animator: A graphical experiment animation tool that allows users to watch traffic flowing and critical performance metrics while a simulation is running.

QualNet Analyzer: A statistical graphing tool to display customized graphs of simulation statistics, including multi-experiment reports, exportable to spreadsheets.

QualNet Packet Tracer: A packet-level visualization tool for viewing the contents of a packet as it goes up and down the network stack.

4.3.5 NS2 Network Simulator

In NS2 simulator C++ code is used to model the behavior of the simulation nodes, and oTcl scripts (Siraj et al., 2012). NS2 is the second version of NS (Network Simulator). NS2 is widely used in academic research and it also allow different non benefit group to make contribution on the future improvements. It uses Object-oriented Tool command language (OTcl) to create simulation interface and it uses C++ programming language to both new and existing algorithms. The advantage of NS2 is the network animator (NAM) that has the interface with control features that allow researchers to play, pause, fast forward, and to stop the simulation during the evaluation process. For the output purposes, NS2 uses NAM package which is a Tcl based animation system that produces a visual representation of the network defined. NS2 supports the simulation of both wired and wireless networks. A typical illustration for NS2 simulator interface can be seen on the Figure 4.4 below.

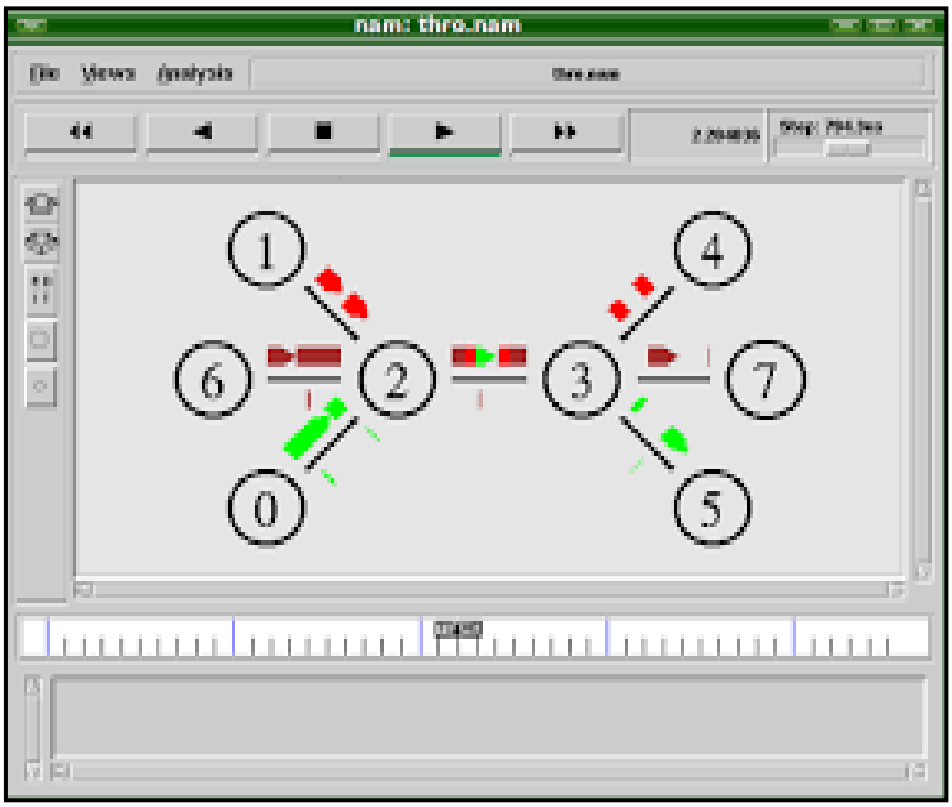

Figure 4.4: NS2 Simulator Interface

4.3.6 NS3 Network Simulator

NS3 is implemented using C++ programming language. With modern hardware capabilities in NS3 compilation time was not an issue like for NS2. However, NS3 no longer uses oTcl scripts to control the simulation therefore; it can be entirely developed with C++. Moreover, a simulation script can be written as a C++ program, which is not possible in NS2. NS3 have the advantage that it has a limited support for Python in scripting as well as visualization. In terms of memory management functions such as new, delete, malloc, and free is still available on NS3 as it is implemented in C++ code.

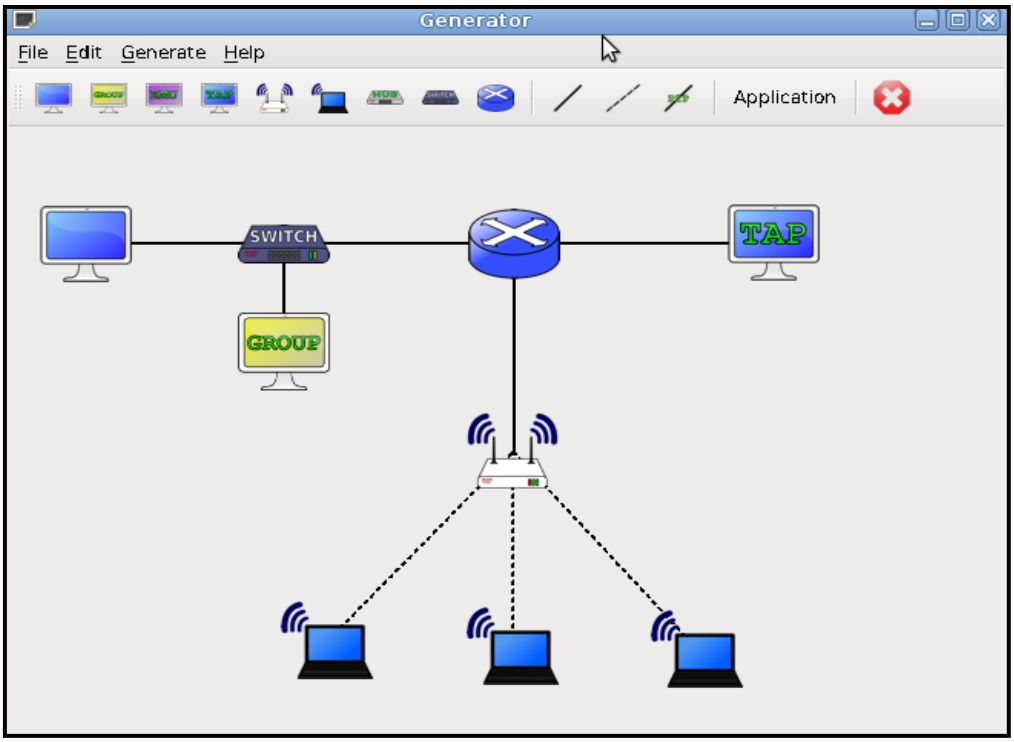

Figure 4.5: NS3 Simulator Interface

In NS3 a packet consists of a single buffer of bytes that corresponds to the stream of bits that would be sent over the real network. Additionally, information is added to the packet by using subclasses and a header which adds information to the beginning of the buffer, and a trailer which adds information at the end. In terms simulation output, NS3 employs a package known as PyViz which is a python based real-time visualization package. NS3 was developed to enhance NS2 but it does not support simulation projects written on NS2 and it does not support the Wireless Sensor Networks.

4.4 Comparison of Network Simulator

In this section, network simulators are compared and summarised in Table 4.1 below.

Table 4.1: Comparison of Network Simulators

FEATURES	MATLAB	OMNET++	QualNet	NS2	NS3
Programming Language	C++, C, Java, Python, & Fortain	C++	C	C++	C++
Graphical User Interface (GUI)	Yes	Yes	Yes	Yes	Yes
Accessibility	Yes	Yes	Yes	Yes	Yes
Scalability	High	High	High	Poor	Poor
Ease of Use	Moderate	Hard	Hard	Moderate	Hard
Ease to Setup	Moderate	Moderate	Hard	Easy	Easy
Larger Networks	Yes	Yes	Yes	No	No

In the above Table 4.1 it is recognised that NS2 is a better tool to be utilised for small networks such as Personal Area Networks (PANs), therefore, this study adopts NS2 simulator tool to evaluate the performance of the proposed NTRP algorithm. Additionally, NS2 is widely adopted in the research community as there is online community where new researchers can get guidance on how to use the simulator. Therefore the literature study in chapter 2 has compared research works that used NS2 tool to evaluate their proposed solutions. This gives the proposed NTRP results a fair comparison when it is compared to the studies that utilised NS-2 for their performance evaluation.

NS2 is a GUI that supports the simulations of all IEEE 802.15.4 models and other IEEE 802.11standards. Different routing protocols for both wired and wireless networks are also supported by NS2. In this study, all the simulations were conducted on the network simulator version 2 (NS-2.34). This is mainly due to the variety of ad-hoc routing protocols, the large number of available models (mobility model, energy model, traffic and movement patterns) and wireless network interfaces that it offers. It also includes the capability of creating custom applications and protocols as well as modifying several parameters at different layers. These are the reasons this study used NS2 to simulate NTRP algorithm.

4.5 An Overview of Network Simulator (NS2)

The NS-2 is an objective oriented, discrete event network simulator widely used in the networking research community. It was originally developed at the University of California, Berkeley (Siraj et al., 2012) as a part of the Virtual Internet Test bed (VINT). NS2 is an object-oriented, discrete event driven network simulator. It uses is C++ programming language and OTcl (Tcl script language developed at MIT). It separates control path implementations from the data path implementation in order enforce efficiency. To minimize packet and event processing time, the event scheduler and the basic network component objects in the data path are written and compiled using C++. OTcl is the missing puzzle C++ as it happens to have the feature that C++ lacks. Therefore the combination of these two languages proves to be very valuable. The reason behind this effectiveness is that C++ is used to implement the detailed protocol while the OTcl is used for users to control the simulation scenario and schedule the events.

The OTcl script is used to initiate the event scheduler, set up the network topology, and tell traffic source when to start and stop sending packets through event scheduler. The scenes can be changed easily by programming in the OTcl script. When a user wants to make a new network object, he can either write the new object or assemble a compound object from the existing object library, and plumb the data path through the object. This plumbing makes NS2 very powerful.

4.5.1 NS2 Architecture

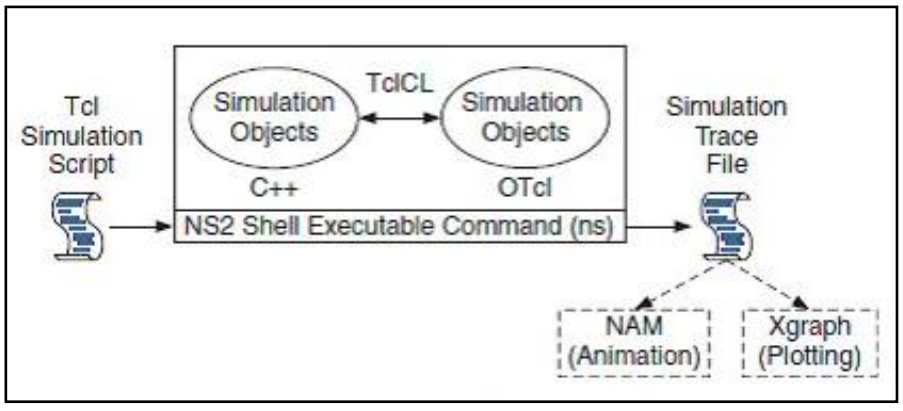

Figure 4.6: NS2 Architecture

As it was mentioned in Section 4.3.4 above, NS2 is an object oriented simulator, written in C++, with an OTcl interpreter as a frontend. It supports a class hierarchy in C++, and a similar class hierarchy within the OTcl interpreter. At packet level, a packet consists of 2 distinct regions; one for headers, and the second stores payload data. NS2 never frees

memory used to store packets until the simulation terminates. It repeatedly reuses the allocated packets; therefore, the header region of any packet includes all headers defined as part of the used protocol even if that particular packet won't use that particular header, but just to be available when this packet allocation is reused. With NS2 a number of protocols such as TCP, UDP, FTP, HTTP and DSR can simulated.

4.5.2 NS2 Class Hierarchy

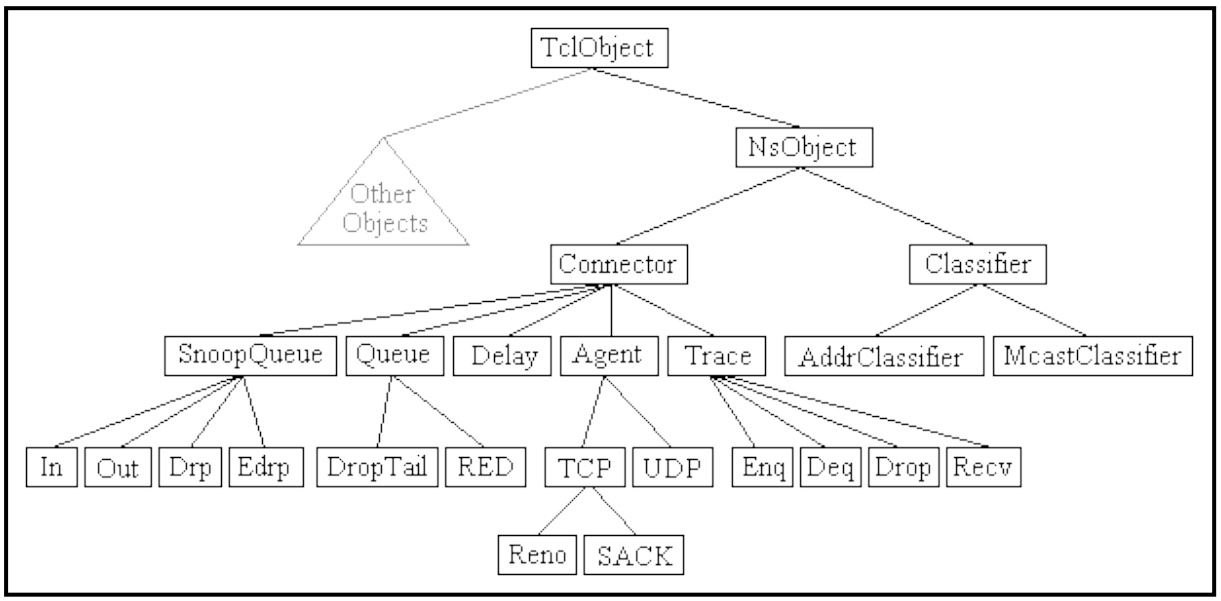

Figure 4.7: NS2 Class Hierarchy

TclObject class is the root of the hierarchy. TclObject is also a super class of all OTcl library objects such as network components, timers, scheduler and other objects including NAM related objects. NsObject class is the super class of all basic network component objects that handle packets such as nodes and links. Based on the number of possible output data paths, the network components are broken down into two sub-classes, Connector and Classifier. The network objects with only one output data path are under the connector class. The switching objects with multiple output data paths are under the Classifier class.

4.5.3 NS2 Directory Structure

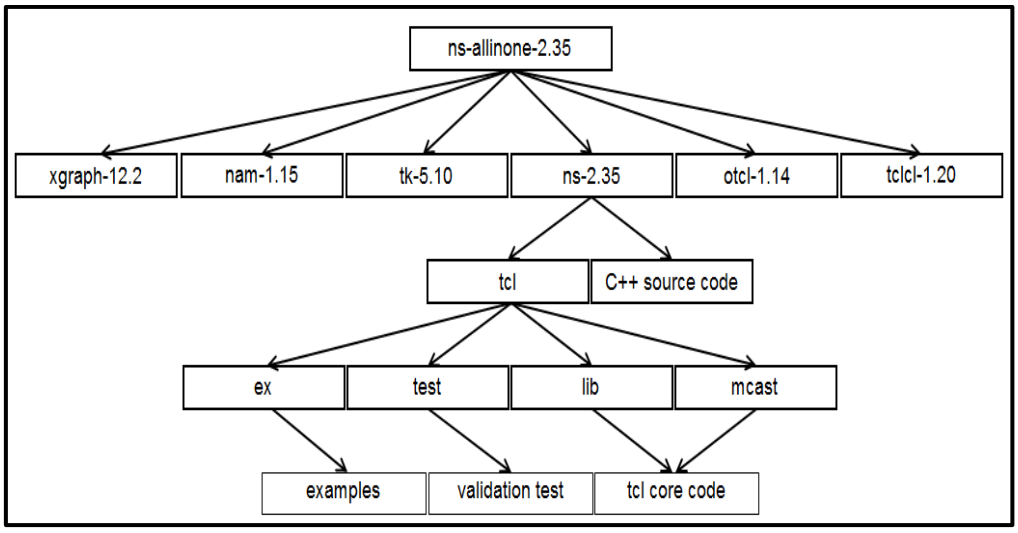

Figure 4.8: NS2 Directory Structure

Normally, NS2 is installed in the directory nsallinone-2.35. The Figure 4.8 above illustrates the NS2 directory structure under directory nsallinone-2.35. C++ classes in NS2 network components are implemented in the subdirectory and the subdirectory of tcl.

4.5.4 Trace File Output

Trace file in NS2 contains details about the information transferred between the nodes on a network. Trace files are automatically generated by the NS2 simulator during the process of simulation. The Trace::format () method defines the trace file format used in trace files produced by the Trace class. It is constructed to maintain backward compatibility with output files in earlier versions of the simulator so that post-processing scripts continue to operate.

Table 4.1: Basic trace file output format

Type Identifier	Time	Source Node	Dest Node	Name	Size	Flags	ID	Source Address	Dest Address	Seq Number	Uniq ID

4.6 Simulation of New Tree Routing Protocol (NTRP) model

NTRP model was proposed in this study to minimise end-to-end delay in a ZigBee network. The simulation was conducted to validate and test the NRTP model. This section presents the details on how to configure NS2 simulator software in Linux operating system. Additionally, the NS2 simulation environment is discussed.

4.6.1 NS2 Configuration

NS2 simulator can be installed in different operating systems such as UNIX/Linux, Mac OS and Windows operating systems. In this study NS2 simulator was installed on Ubuntu Linux operating system. The main reason to use Ubuntu for this study is mainly because Ubuntu is free to use and it is the most widely adopted Linux OS. Below are the configuration steps for setting up the NS2 simulator on Ubuntu OS that were followed in this study.

- Download ns-allinone-2.34.tar from www.isi.edu
- Place ns-allinone-2.34.tar in your desired directory; like /home/student. Then extract ns-allinone-2.34 using the following command. $ cd /home/student $ tar -xvf ns-allinone-2.34.tar
- Go to /home/student/ ns-allinone-2.34. Then install ns2 using this command $./install
- PATH SETTING $ gedit ~/.bashrc this command will open a existing file in editor. This path can be changed according to ns-allinone folder's path] # LD_LIBRARY_PATH OTCL_LIB=/home/student/ns-allinone-2.34/otcl-1.13 NS2_LIB=/home/student/ns-allinone-2.34/lib X11_LIB=/usr/X11R6/lib USR_LOCAL_LIB=/usr/local/lib export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:$OTCL_LIB:$NS2_LIB:$X11_LIB :$USR_LOCAL_LIB # TCL_LIBRARY TCL_LIB=/home/student/ns-allinone-2.34/tcl8.4.18/library USR_LIB=/usr/lib export TCL_LIBRARY=$TCL_LIB:$USR_LIB # PATH XGRAPH=/home/student/ns-allinone-2.34/bin:/home/student/ns-allinone-2.34/tcl8.4.18/unix:/home/student/ns-allinone- 2.34/tk8.4.18/unix #

  Note: the above two lines starting from XGRAPH should come in the same line NS=/home/student/ns-allinone-2.34/ns-2.34/ NAM=/home/student/ns-allinone-2.34/nam-1.14/ PATH=$PATH:$XGRAPH:$NS:$NAM then save and exit.

  to take the effect immediately $source ~/.bashrc
- Perform the validation test using this command. ./validate
- Run ns2 using this command $ns you will get % prompt in your terminal... now ns2 has been installed.
- Finally, when the installation is successfully completed, the NAM Console button will pop up.

NAM is a simple Tcl/TK tool for viewing network simulation traces and real world packet traces. Trace data is normally derived as output from a network simulator or from real network measurements. NAM supports the network topology layout, packet level animation, and various data inspection tool. In the next simulation environment section, Figure 4.9 illustrates the wireless sensor network simulation output for this study through NAM console button.

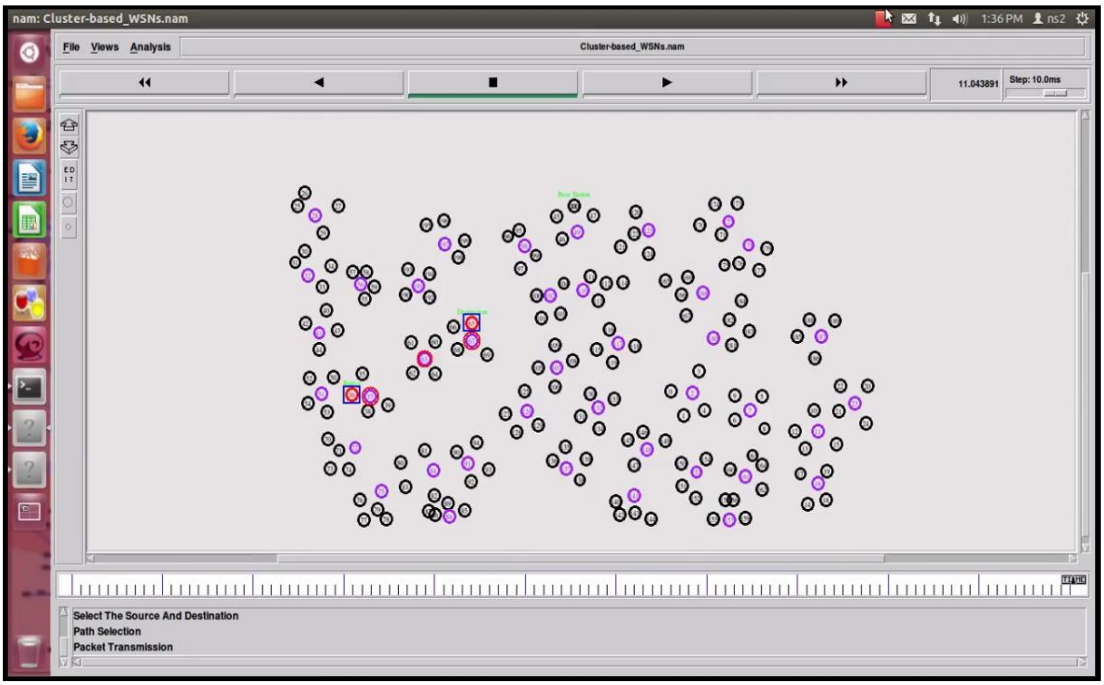

Figure 4.9: NAM simulation output for a ZigBee network

The above Figure 4 illustrates the output for the NTRP algorithm. NTRP use Kruskal's Minimum Spanning Tree Protocol to find shortest paths from source to destination node. Additionally, NTRP implements the neighbour table mechanism that also assists in reducing the delay of finding the destination node. The next section gives an overview of the simulation environment for the proposed NTRP algorithm.

Table 4.3: System Parameters

Parameters	**Values**
Routing Protocol	ZTR
MAC Protocol	IEEE 802.1.4
Channel Type	Wireless Channel
Network Interface Type	Wireless
Propagation Model	Two Ray Ground

Antenna model	Omni Antenna
Queue Type	Queue/Drop Tail/PriQueue
Link Layer Type	LL
Number of nodes	50
Transmission range	100 m
Network Bandwidth	10240 Mb
Message Size	64 bytes
Packet Size	127 byte
Traffic CBR	0.2 interval time
Frequency	2.4 GHz
Simulation Area	1800m X 840m
Simulation Time	100 seconds
Agent Trace	ON
Router Trace	ON
Mac Trace	OFF
Movement Trace	ON

4.7 Conclusion

In this Chapter, the overview of the network simulation tools for computer networks is provided. The background of the simulation tools and the types of software tools that can be used in Wireless Sensor Networks is fully discussed. Some of the open source code simulators were studied and compared to identify a simulation tool that is best for this study. Finally, Network Simulator (NS2) is chosen for this study as it matched our simulation requirements. The simulation environment and the NS2 architecture were presented. In the next chapter, the proposed NTRP algorithm is evaluated and tested on NS2 software.

Chapter 5: Results and Discussion

5.1. Introduction

In computer networks, network simulation software is used in a lab environment to model the behaviour of a real network. Simulation evaluates the proposed product before it is finally implemented as an end product. Simulating a proposed algorithm allows a researcher to study and analyse the results of the proposed model's performance. This is achieved by calculating the network metrics for communication between the different network devices such as links, routers, access points, switches, nodes etc. Performing a simulation in a lab environment saves the costs and time to set-up a real network. This chapter presents the analyses of the results from the software simulations to evaluate the performance of the proposed New Tree Routing Protocol (NTRP) algorithm for a ZigBee network.

In this study, the simulations are conducted in respect to the four following performance metrics: end-to-end delay, delivery ratio, energy and throughput. The results obtained during simulations are recorded on trace files. The recorded results are used to calculate the above mentioned performance metrics. Several simulations were conducted and the results obtained are graphically displayed using R Programming Language.

The remainder of this Chapter is organized as follows: In **Section 5.2,** the simulation environment is evaluated. In **Section 5.3**, discussions of simulations are presented. **Section 5.4** presents the simulation results and the summary is provided in **Section 5.5**.

5.2. Simulation Environment Evaluation

In order to measure the impact of combining ZigBee Tree Routing algorithm and Kruskral's Minimum Spanning Tree Protocol, the simulation topology is created using TCL script. NAM interface is used to observe packet losses, nodes movement, as well as the routing of packets during the simulations. The simulations are performed using Network Simulator2 (NS2) V2.35 based on IEEE 802.15.4 standard specification. NS2 network simulator is installed on a Linux Operating System, 2.6/3.x, 64-bit, on a Virtual Box Manager (VM) V4.3.20. The TCL scripts and C++ source code are used to implement the proposed NTRP network configurations. The simulations were run for 300 seconds. To obtain reliable and satisfactory results, simulation process was repeated six times for each metric. The obtained results were analyzed and stored in trace files. Finally, R Programming is used to graphically

display the analyzed results. At the transport layer of the ZigBee network the traffic source transmit Constant Bit Rate with User Datagram. All wireless links are provided with the bandwidth of 6Mbps. The following Table 5.1 summarizes the topology and traffic parameters respectively.

Table 5.1: Topology and Traffic parameters

Parameters	Values
1. Network Area	100m * 100m
2. Number of nodes	20, 40, 60, 80, 100, 120
3. Packet Rate	2, 4, 6, 8, 10, 12, 14, 16
4. Packet Size	512 and 1024 bytes
5. Traffic Type	CBR
6. Transport Protocol	UDP
7. Data Rate	6Mbps
8. Simulation Time	100s, 200s, 300s

5.3. Simulation Discussions

This section provides the analysis of the results obtained from the simulations performed to evaluate the proposed NTRP model against STR and VELCT algorithms that are discussed in the literature study in chapter 2.

5.3.1 Network, MAC and Physical layer

Depending on the distance of the node from the Base Station (coordinator) and its radio range, a node can calculate its minimum depth. Firstly, it is assumed that the network depth of coordinator is 0. Each of the RFDs and FFDs periodically send a request to join the network if they have not yet joined any. Periodically, each of the FFD nodes advertises itself as the Cluster Head and waits for the join request from the other FFDs or RFDs. If the FFD node does not have NETWORK DEPTH equal to 0 then it will also send the join request to

other FFDs. Decision to choose parent for a FFD is based on received signal strength from the advertising FFD as well as the NETWORK DEPTH of the advertising FFD. Node will always join the cluster head whose NETWORK DEPTH is less than or equal to the depth of the node, i.e. node will never join the cluster whose cluster head has depth more than the node itself. For the performance evaluation at the network, physical and MAC layers, the simulation parameters were summarized in the below table.

Table 5.2: Parameter Values

Parameters	**Values**
Routing Protocol	ZigBee Tree Protocol
MAC protocol	IEEE 802.15.4
Physical layer	Wireless
Frequency	2.4GHz
Antenna	Omni-directional

There are different performance metrics that represents different network performance in order to evaluate the overall network performance. In this study four metrics were used. These metrics are End-to-end delay, Energy saving, Packet Delivery Ratio, and Network Throughput.

5.3.2 Metric Performance

To evaluate the proposed NTRP algorithm against Shortest Tree Routing (STR) and Velocity Energy-efficient & Link-aware Cluster-Tree (VELCT) algorithms, the following performance metrics were used:

1. Average End-to-end delay is used to calculate a period of time a packet takes to move from source node to destination node.
2. Energy consumption is calculated as the amount of energy a battery sensor can consume in a given lifetime.
3. Packet Delivery Ratio is calculated as a percentage of successful packets sent over a network on a given time.

4. Network Throughput is calculated as the total amount of data successfully delivered from the sender to a receiver over a communication channel in a given time.

5.4. Simulations and the results

The NTRP performance is compared with the two algorithms based on shortest path selection. The two algorithms are Shortest Tree Routing (STR) and Velocity Energy-efficiency and Link-aware Cluster Tree (VELCT) discussed in Section 2.9 of Chapter 2. STR overcomes the overheard problem occurred when ZigBee packets follow the tree topology. It reduces routing cost of ZigBee tree routing by using neighbor table. STR follows ZigBee tree routing algorithm but it chooses neighbor nodes as next hop nodes. NS-2 network simulator is used to evaluate the performance results of STR algorithm. On the other hand, VELCT constructs Data Collection Data (DCT) based on cluster head location. Data collection node collects data packet from the cluster head and delivers it to the sink node. The usage of DCT minimizes energy consumption, end-to-end delay and network traffic. NS-2 tool was used to test the performance overall of the proposed VELCT.

5.4.1 End-to-end delay

In this study end-to-end delay is calculated as time taken by a packet to move from a source to a destination node on a network.

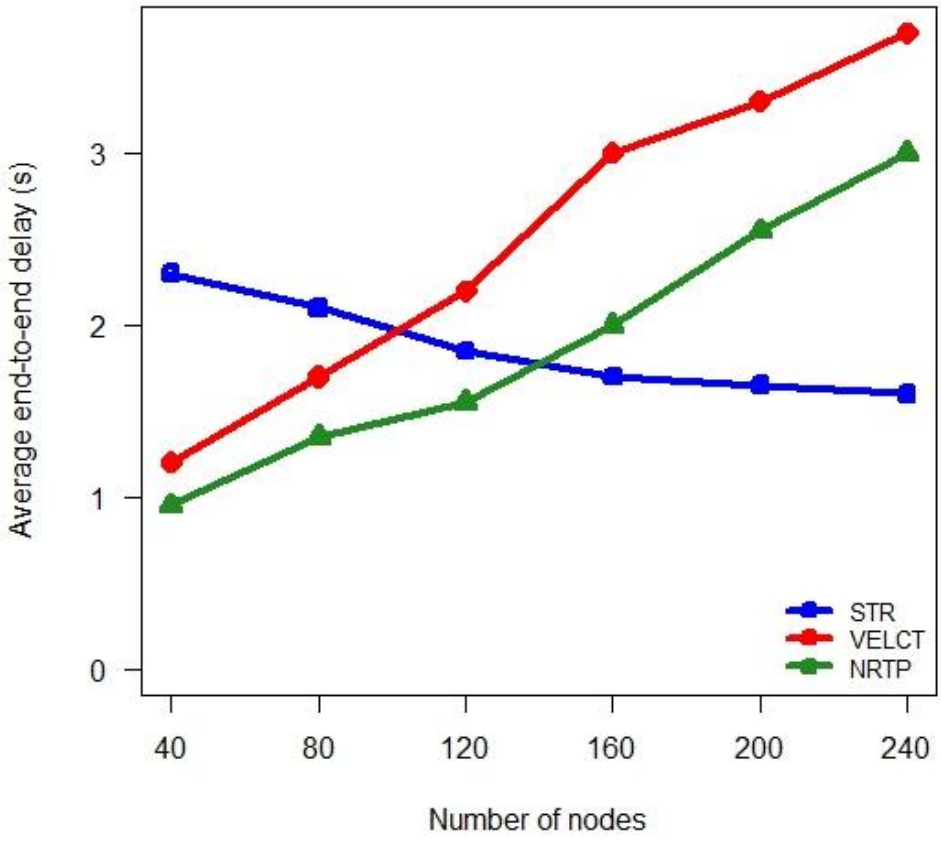

Figure 5.1: Average End-to-end delay

Average end-to-end delay is measured in seconds. The results shows that the total average end-to-end delay for NTRP is minimal compared to STR and VELCT. NTRP has a total average of 1.5%, STR has an average of 1.8% and VELCT has an average of 2.5%. Even though NTRP has a minimal average end-to-end delay, however, when more devices are added on a network end-to-end delay also increases. The results show that if the number of nodes is < 40, end-to-end delay is less than 1s. Adding 40 nodes increase end-to-end delay to 1.2s and another 40 additional nodes increases end-to-end delay to 1.5s. Both VELCT and NTRP follow the same pattern of increased delay as more nodes are added on a network. For VELTC with 40 nodes and below, delay is 1.1s. Adding 40 nodes increase the delay to 1.7s. On the other hand STR's delay decreases as more nodes are added on the network. If the number of nodes are 40 or below the delay is 2.2s. Adding 40 nodes drops the delay to 2s and an additional 40 nodes drops the delay to 1.7s. This shows that NTRP is good for a number of nodes that are equal to 100 or below and STR is good for a network with a number of nodes greater 100.

5.4.2 Packet Delivery Ratio

Packet delivery ratio is defined as the ratio of data packets received by the destinations to those generated by the sources.

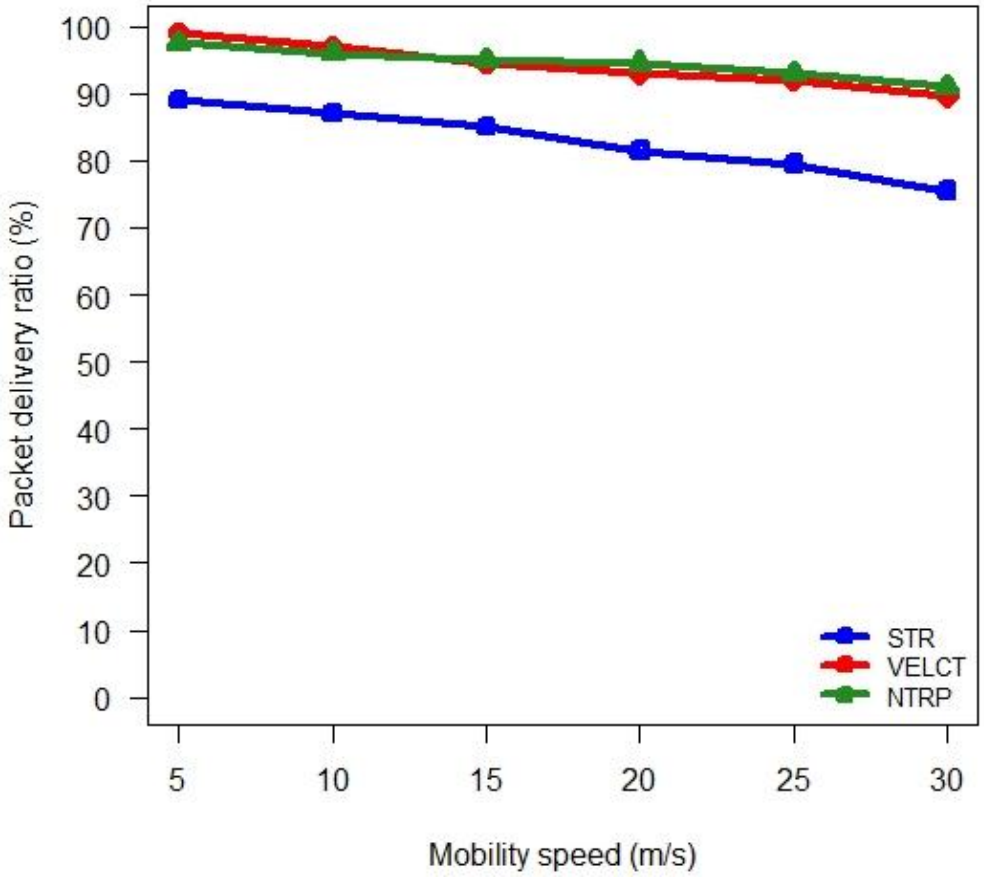

Figure 5.2: Packet Delivery Ratio

Packet delivery ratio percentage is calculated based on mobility speed in m/s. The average percentage of packet delivery ratio is 94.5% for NTRP, 94% for VELCT and 82.9% for STR. The packet delivery ratio also shows that when the mobility speed is increased, percentage packet delivery ratio decreases. For a mobility speed of 5ms in NTRP, packet delivery ratio is 98% but when mobility speed is increased 15ms, packet delivery ratio drops to 95% and an additional mobility speed of 15ms drops the packet delivery ratio to 93%. This pattern continues as long as the mobility speed is increased. With the initial mobility speed of 5ms in VELTC, packet delivery ratio is 100% however, with the mobility speed of 15ms delivery ratio drops to 95% and the mobility speed of 30ms drops the delivery to 90%. STR is better than both NTRP and VELCT in terms of packet delivery ratio. With a mobility speed of 5ms, delivery is 90%, additional 10ms drops delivery ratio to 95% and when the speed is 30ms delivery ratio drops to 75%.

5.4.3 Energy consumption

To measure energy consumption, energy is calculated in joules and the time is measured in seconds.

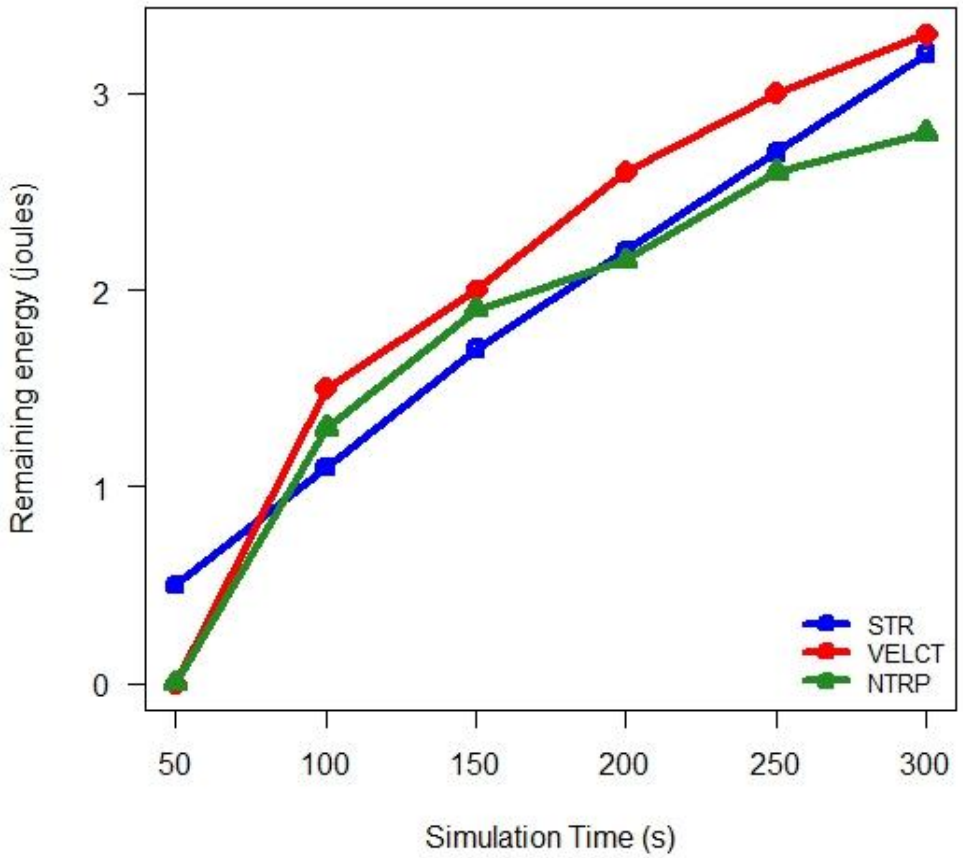

Figure 5.3: Energy consumption

NTRP shows strength with an average of 1.79% followed by the STR with an average of 1.9% and VELCT has an average of 2%. All protocols have low energy consumption initially and the more time added for the simulation, more energy is consumed. With 50s of time, NTRP has energy consumption less than 0.5 joules however, with 300s of time NTRP has energy conservation of 2.6 joules. VELTC has also the same amount of less than 0.5 joules with the 50s time but with the 300s it goes as high as 3.2 joules. STR has slightly higher energy consumption 0.5 joules during the initial stage of 50s. With simulation time of 300s STR can consume above 3 joules of energy.

5.4.4 Network Throughput

This is the amount of data successfully transferred from one place to another in a given time period, and it is measured in bits per second (bps), megabits per second (Mbps) or gigabits per second (Gbps).

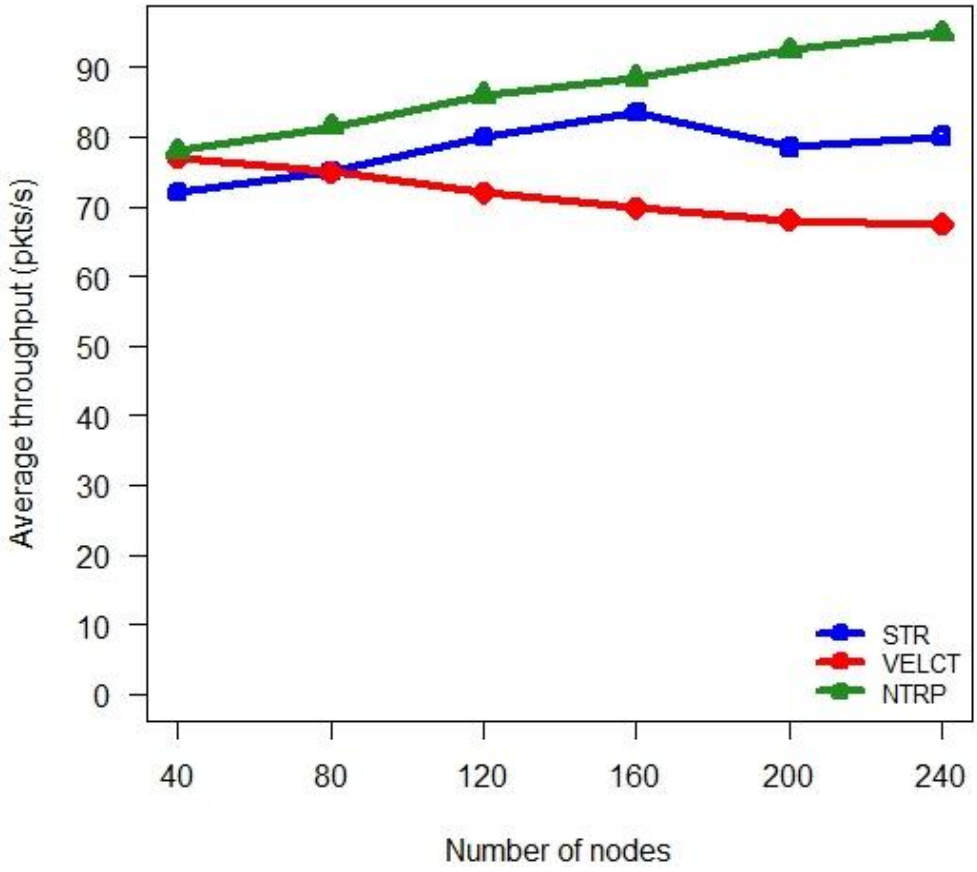

Figure 5.4: Average Network Throughput

Average throughput is measured based on the number of packets transmitted in comparison to the number of nodes. NTRP has an average network throughput of 86.91%, followed by the STR with 78.1% and the VELCT has network throughput of 71.55 %.

Based on the results presented above, it is observed that NTRP outperforms VELCT and STR.

5.5 Summary

In this Chapter, we discussed the experimental evaluation and results analysis of the proposed NTRP algorithm based on the results obtained from the simulations. The effectiveness of the NTRP in reducing network latency by minimising the end-to-end of packets sent from source to destination node was discussed. The results obtained were analyzed and discussed with respect to four performance metrics considered in this study, which include network throughput, end-to-end delay, energy consumption and packet delivery ratio.

Chapter 6: Conclusion and Future Work

6.1.Introduction

The main purpose of this study was to design and implement New Tree Routing Protocol (NTRP) algorithm to minimise end-to-end delay of packets on a ZigBee wireless sensor network. In this study, ZigBee Tree Routing algorithm and Kruskal's Minimum Spanning Tree Protocol algorithm were merged to design a NTRP algorithm. Kruskal's Minimum Spanning Tree Protocol ensures that packets take the best shortest path to the destination node which also minimises the end-to-end delay. Additionally, NRTP algorithm also uses the clustering mechanism and a neighbour table mechanism. The neighbour table mechanism ensures that packets do not follow a hierarchical routing method to the coordinator before packets are forwarded to the destination node. However, with neighbour table mechanism, packets use neighbour tables to find the destination node within its neighbours. This mechanism minimizes the end-to-end delay as packets take minimal time to reach the destination node. The above mentioned characteristics for NRTP algorithm gives it a better advantage over other routing protocols in a ZigBee Wireless Sensor Network environment.

The remainder of this Chapter is organized as follows: In **Section 6.2**, the details on how the objectives of this study were achieved were discussed. In **Section 6.3**, the summary of this study is provided. We discuss the challenges that were encountered during the study in **Section 6.4**. The future work is discussed in **Section 6.5**. Finally, the summary of this chapter is provided in **Section 6.6**.

6.2.Objectives Achievements

In Chapter 1, research questions and technical objectives were presented as a road map for this study. However, all technical objectives addressed in Section 1.6 were achieved during our study. Therefore, this section re-addresses the technical objectives and links the discussions on how these technical objectives were achieved.

1. **To study and identify the existing Healthcare Monitoring Systems that uses ZigBee network protocol to transmit heart rate data.**

In Section 2.5 Healthcare Monitoring Systems are presented. They are classified as Traditional Healthcare Monitoring Systems and Smart Healthcare Monitoring Systems. Smart Healthcare Monitoring Systems are further classified as Remote Healthcare Monitoring

Systems, Mobile Healthcare Systems, and Wearable Healthcare Monitoring Systems. However, it is identified from the literature that most of the Healthcare Monitoring Systems cater for a number of medical data such as heart rate, high blood pressure, stroke, falls and other cardio vascular diseases. It has been a challenge to find studies that were only focusing on heart rate only. Never the less, we selected a Remote Healthcare System as it suits our need of remotely assisting elderly people.

2. **To identify the challenges associated with the ZigBee routing protocols in Healthcare Monitoring Systems.**

Section 2.7 of Chapter 2 presents the background of routing in a ZigBee network. In Section 2.2.3, routing challenges in wireless sensor network were discussed. It was identified that wireless sensor networks have unique characteristics from other traditional wireless networks. These characteristics are associated with the challenges such as incapability of nodes to use the classical IP based protocols. Secondly, data redundancy which leads to network congestion and the end-to-end delay of packet as they take longer time to arrive at the destination node. It was also taken into account that network engineers need to be aware of the challenges during the routing design stage. Design challenges involve energy efficiency, complexity, scalability, delay, and data transmission. However, Section 2.8 discusses the ZigBee Tree Routing protocol and the challenges associated with it. One of the challenges identified is a parent-child mechanism a ZigBee Tree Routing uses to forward packets to the coordinator. This method is identified as the source of end-to-end delay of packets in a ZigBee network as packets are relayed to pass through a number of nodes before reaching the destination node.

3. **To improve the ZigBee Tree routing algorithm performance in order to minimise the end-to-end delay of data transmission in Healthcare Monitoring System.**

The main aim of this study is to propose a routing protocol algorithm that minimizes the end-to-end delay of transmitted packets on a ZigBee network that uses ZigBee Tree Routing protocol. In Section 2.7.3 and Section 2.9 of Chapter 2, shortcut routing algorithms have been presented and we opt for Kruskal's algorithm part of our proposed solution. In Chapter 3, the proposed New Tree Routing Protocol (NTRP) is introduced. NTRP is an enhanced ZigBee routing algorithm that minimizes end-to-end delay while saving routing energy consumption for the devices. NRTP is a blend of the original ZigBee Tree Routing and Kruskal's Minimum Spanning Tree Protocol (MSTP) algorithms. Kruskal's MSTP finds the best

shortest path to the destination. Additionally, neighbour table mechanism is implemented so that destination nodes could be discovered through neighbour tables.

4. To test and evaluate the effectiveness of the proposed ZigBee routing algorithm.

Section 2.9 presented related ZigBee studies that have the results of their proposed solutions tested and verified through NS-2 tool. To test the effectiveness of our proposed solution, NRTP algorithm is evaluated on NS2 network simulator tool. It is identified on the literature study in Section 2.9 that NS-2 is a software network simulator that is very popular in a research community. Researchers use NS2 to evaluate and test their new theories and algorithms. In this study performance metrics such as packet delivery ratio, energy consumption, end-to-end delay, and network through put were used. Chapter 5 presented the results of the simulations for NRTP algorithm. NRTP simulation results were compared to other algorithms such as Velocity Energy efficient and Link aware cluster Tree (VELT), and Shortest Tree Routing (STR). The simulation results for NRTP algorithm in Chapter 5 shows that NRTP is better than the three above mentioned algorithms in terms of minimizing the end-to-end delay and acceptable energy consumption. Therefore, it is concluded that all the objectives of this study achieved successfully.

6.3.Research Summary

The proposed algorithm in this study attempted to minimize end-to-end delay of packets. End-to-end delay is associated with a larger number of hops a packet traverses to reach its destination. Graph theory was introduced to create links; clustering technique and neighbour table mechanism defined in the ZigBee specification are added into New Tree Routing Protocol (NTRP) solution of reducing end-to-end delay. ZigBee algorithms are introduced, chapter 2 where shortcoming and their strengths were identified. Therefore, NTRP merged the strengths characteristics of the original ZigBee Tree Routing algorithm and the strength characteristics of Kruskal's algorithm. NS-2 was used to verify the new proposed algorithm called New Tree Routing Protocol. NTRP average end-to-end delay results shows that it outweighs other algorithm with 11%. Average delivery ratio for NTRP is 94.5%, energy consumption is 1.79 joules and the throughput is 86.91%. These results show that the proposed NTRP is better than VELCT and STR.

6.4.Challenges Encountered

Healthcare Monitoring Systems based on personal networks such as ZigBee is part of the emerging technologies that are still new to the research community. Therefore it was a challenge to find the Healthcare Monitoring Systems studies that are focusing on enhancing routing protocols for communication technologies such as ZigBee. It was also a challenge to learn how to simulate Wireless Sensor Networks using NS-2 as a simulation software tool.

6.5.Future Work

It has been a challenging but interesting journey to study wireless sensor network communication protocols. Based on the information gathered from conducting this study we would like to see more security enhancement on a ZigBee network. Data security and privacy is a significant threat to Healthcare Monitoring Systems. Protection of medical data for elderly people and patients monitored by Healthcare Monitoring Systems needs to be enforced. Security measures such as standards and frameworks needs to be implemented to comply with the medical and ethical standards. Our future work will look at security mechanisms to protect medical data in Healthcare Monitoring Systems. Cyber security is one of the security sector that promise to deal with cyber-attacks. However, Blockchain technologies could play a significant role in protecting medical data as they use open and immutable ledgers to store data. Therefore our future work will look at how we can apply security technologies such as Blockchain in Healthcare Monitoring Systems.

6.6 Summary

In Chapter 1 our problem statement was clearly stated that, in a ZigBee network the ZigBee Tree Routing protocol uses a parent-child relationship to forward the packets to the coordinator first before they are forwarded to the destination node. The coordinator will then forward the packets down the tree branches to reach the destination node. This implies that data packets may be routed through several hops to the destination even if destination node is nearby sender node. ZigBee Tree Routing experiences end-to-end delay due to this mechanism. Literature study was conducted to learn more about other mechanisms that could solve this problem. NRTP was proposed as a better solution to this problem. Therefore we argue that the objectives of this study were successfully met.

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Appendix A: Table of Notations

Notations	Meaning
V	Set of nodes
E	Set of edges
pl	Probability of packet delivery
$C(l)$	Link Cost
T_x	Transmitters
R_x	Receivers
R	Service receiver
$Cskip(d)$	Address Size Space
C_m	nwkMaxChildren
R_m	nwtMaxRouter
L_m	nwkMaxDepth
d	Depth of parent node
A_n	Assigned address for the child
Q	Constant path
A_p	Address of the parent node

Appendix B: TCL Script

```
#===================================================================
#        Copyright © Tshwane University of Technology
#        Department of Information Technology
#        Author: Bongisizwe Erasmus Buthelezi
#        A TCL script to evaluate the performance of routing protocol in WSN.
#===================================================================

set val (node_num)      101
set val(duration)       10
set val(packetsize)     16
set val(repeatTx)       10
set val(interval)       0.02
set val(dimx)           50
set val(dimy)           50
set val(nam_file)       "wireless.nam"
set val(trace_file)     "wireless.tr"
set val(stats_file)     "wireless.stats"
set val(node_size)      5
#===================================================================
# Node options
#===================================================================

set val(chan)           Channel/WirelessChannel;        # channel type
set val(prop)           Propagation/TwoRayGround;   # radio-propagation model
```

```
set val(netif)        Phy/WirelessPhy;                  # network interface type
set val(mac)          Mac/RMAC;                         # MAC type
#set val(mac)         Mac/802_11;                       # MAC type
set val(ifq)          Queue/DropTail/PriQueue;          # interface queue type
set val(ll)           LL;                               # link layer type
set val(ant)          Antenna/OmniAntenna;              # antenna model
set val(ifqlen)       5;                                # max packet in ifq
set val(nn)           $val(node_num);                   # number of mobilenodes
set val(rp)           LINKSTATE;                        # routing protocol
================================================================
# Global variables
================================================================
set ns                [new Simulator]
set tracefd           [open $val(trace_file) w]
set nam               [open $val(nam_file) w]
set stats             [open $val(stats_file) w]
$ns namtrace-all-wireless   $nam $val(dimx) $val(dimy)
$ns trace-all         $tracefd
set topo              [new Topography]
$topo load_flatgrid       $val(dimx) $val(dimy)
#Mac/RMAC set repeatTx_ $val(repeatTx)
#Mac/RMAC set interval_ $val(interval)
$ns node-config \
```

```
        -adhocRouting $val(rp) \
        -llType $val(ll) \
        -macType $val(mac) \
        -ifqType $val(ifq) \
        -ifqLen $val(ifqlen) \
        -antType $val(ant) \
        -propType $val(prop) \
        -phyType $val(netif) \
        -channelType $val(chan) \
        -topoInstance $topo \
        -agentTrace ON \
        -routerTrace ON \
        -macTrace ON \
        -movementTrace OFF
# The only sink node
set sink_node [$ns node]
$sink_node random-motion 0
$sink_node set X_ [expr $val(dimx)/2]
$sink_node set Y_ [expr $val(dimy)/2]
$sink_node set Z_ 0
$ns initial_node_pos $sink_node $val(node_size)
set sink [new Agent/LossMonitor]
$ns attach-agent $sink_node $sink
```

```
# Set up random number generator, to scatter the source nodes

#set rng [new RNG]

$rng seed 0

set xrand [new RandomVariable/Uniform]

$xrand use-rng $rng

$xrand set min_ [expr -$val(dimx)/2]

$xrand set max_ [expr $val(dimx)/2]

set yrand [new RandomVariable/Uniform]

$yrand use-rng $rng

$yrand set min_ [expr -$val(dimy)/2]

$yrand set max_ [expr $val(dimy)/2]

set trand [new RandomVariable/Uniform]

$trand use-rng $rng

$trand set min_ 0

$trand set max_ $val(interval)

# Create all the source nodes

for {set i 0} {$i < $val(nn)-1 } {incr i} {

    set src_node($i) [$ns node]

    $src_node($i) random-motion 0

    set x [expr $val(dimx)/2 + [$xrand value]]

    set y [expr $val(dimx)/2 + [$xrand value]]

    $src_node($i) set X_ $x

    $src_node($i) set Y_ $y
```

```
    $src_node($i) set Z_ 0

    $ns initial_node_pos $src_node($i) $val(node_size)

    set udp($i) [new Agent/UDP]

    $udp($i) set class_ $i

    $ns attach-agent $src_node($i) $udp($i)

    $ns connect $udp($i) $sink

    set cbr($i) [new Application/Traffic/CBR]

    $cbr($i) set packet_size_ $val(packetsize)

    $cbr($i) set interval_ $val(interval)

    $cbr($i) attach-agent $udp($i)

    set start [$trand value]

    $ns at $start "$cbr($i) start"

    $ns at $val(duration) "$cbr($i) stop"

}

proc stop {} {

    global ns tracefd nam stats val sink

    set bytes [$sink set bytes_]

    set losts  [$sink set nlost_]

    set pkts [$sink set npkts_]

    puts $stats "bytes losts pkts"

    puts $stats "$bytes $losts $pkts"

    $ns flush-trace

    close $nam
```

```
    close $tracefd

    close $stats

}

puts "Starting Simulation..."

$ns run
```

Appendix C: Scripting Code

As mention in Section 5.1, in order to analyse/interpret the trace files' data to get useful information such as the number of packets received dropped and throughput of the network, NS2 facilitates the use of *AWK* and *GREP* scripts. The *AWK* program code is given by A_throughput.awk file below.

```
#=============================================================
#        AWK script to calculate the average end-to-end delay
#=============================================================
#read STR, VELCT, and NTRP values from tab-delimited SD_end-to-end delay.dat
autos_data <- read.table("C:\\R\\Delay.dat", header=T, sep="\t")

max_y <- max(autos_data)
#define colours to be used for STR, VELCT, and NTRP lines
plot_colors <- c("blue","red","forestgreen", "orange")

#graph autos using y axis that ranges from 0 to max_y.
#turn off axes and annotations (axis labels) so we can specify them ourselves
plot(autos_data$STR, type="o", pch=22, lwd=4, col=plot_colors[1], ylim=c(0, max_y), axes=FALSE, ann=FALSE)
#make x axis using 1-6 labels, which was the percentage of throughput
axis(1, at=1:6, lab=c(40, 80, 120, 160, 200, 240))
#making the y axis with horizontal labels that display ticks at every 10 seconds. 10*0:max_y is equivalent to c(0, 10, 20, 30, …).
axis(2, las=1, at=1*0:max_y)
#create box around plot
box()
#graph VELCT with red dashed line and square points
lines(autos_data$VELCT, type="o", pch=23, lwd=4, col=plot_colors[2])
#graph NRTP with green dotted line and diamond points
lines(autos_data$NRTP, type="o", pch=24, lwd=4, col=plot_colors[3])
#label the x and y axes with black text
title(xlab= "Number of nodes", col.lab=rgb(0,0.0,0))
```

```
title(ylab= "Average end-to-end delay (s)", col.lab=rgb(0,0.0,0))
#create a legend in the top-left corner that is slightly smaller and has no border
legend("bottomright", names(autos_data), cex=0.8, col=plot_colors, lwd=4, pch=22, bty="n");
#turn off device driver (to flush output to PDF)
dev.on()
```

Appendix D: R Programming Code

Below we provide the sample code, which was used to plot the end-to-end delay, throughput and energy efficiency obtained by our proposed algorithm.

```
#=================================================================
#   R code to graphically display end-to-end delay, throughput and energy efficiency.
#=================================================================

#read STR, VELCT, and NTRP values from tab-delimited SD_throughput.dat

autos_data <- read.table ("C:\\R\\Delay.dat", header=T, sep="\t")

max_y <- max (autos_data)

#define colours to be used for STR, VELCT, and NTRP lines

plot_colors <- c ("blue","red","forestgreen", "orange")

#graph autos using y axis that ranges from 0 to max_y.

#turn off axes and annotations (axis labels) so we can specify them ourselves

plot (autos_data$STR, type="o", pch=22, lwd=4, col=plot_colors[1], ylim=c(0, max_y), axes=FALSE, ann=FALSE)

#make x axis using 1-6 labels, which was the percentage of throughput

axis (1, at=1:6, lab=c(40, 80, 120, 160, 200, 240))

#making the y axis with horizontal labels that display ticks at every 10 seconds. 10*0:max_y is equivalent to c (0, 10, 20, 30, …).

axis (2, las=1, at=1*0:max_y)

#create box around plot

box ()

#graph VELCT with red dashed line and square points

lines (autos_data$VELCT, type="o", pch=23, lwd=4, col=plot_colors[2])
```

```
#graph NRTP with green dotted line and diamond points

lines (autos_data$NRTP, type="o", pch=24, lwd=4, col=plot_colors[3])

#label the x and y axes with black text

title (xlab= "Number of nodes", col.lab=rgb(0,0.0,0))

title (ylab= "Average end-to-end delay (s)", col.lab=rgb(0,0.0,0))

#create a legend in the top-left corner that is slightly smaller and has no border

legend ("bottomright", names(autos_data), cex=0.8, col=plot_colors, lwd=4, pch=22, bty="n");

#turn off device driver (to flush output to PDF)

dev.on()
```