Evaluating the Effect of Quality of Service Mechanisms in Power-Constrained Wireless Mesh Networks

A dissertation submitted by

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(B.Tech Hons. Computer Science)

in fulfillment of the requirements for the degree of

Master of Science in Computer Science

to

The Department of Computer Science,

Faculty of Science and Agriculture,

University of Zululand

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2013

DECLARATION

I, O.A. Oki hereby declare that this dissertation is my own original work, conducted under the supervision of Mr. P. Mudali and Prof M.O. Adigun. It is submitted for the degree of Master of Science in Computer Science in the Faculty of Science and Agriculture, at the University of Zululand, South Africa. No part of this research has been submitted in the past, or is being submitted, for a degree or examination at any other University. All sources used in the dissertation have been duly acknowledged. Parts of this work were published and presented at SATNAC 2011 in South Africa, IET ICWCA 2012 in Malaysia, IEEE AFRICON 2013 in Mauritius and at the IEEE ICAST 2013 in South Africa. And a journal publication submitted to *Wireless Networks* is currently under review.

Signature: ______________________________

OKI O.A.

DEDICATION

I dedicate this work to my late father, Elder A.O. Oki, even though I wish he could be alive to receive this, but God knows better and a special dedication to God almighty for given me the privilege to be able to complete the work.

ACKNOWLEDGMENTS

I would like to thank God for the opportunity that he gave me, for providing an intellectually and socially stimulating and well-organized environment for me and for giving me the strength to pull through the difficult times.

My special thanks go to my supervisors Mr. P. Mudali and Professor M.O. Adigun for guidance, support and for making this research work realizable. They also stood by me from the beginning till the end. I would like to also thank Mr. Bethel Mutanga, whose support, advice and guidance got me through the tough times. His work as my unofficial supervisor contributed immensely to the successful completion of this work. Your down-to-earth spirit and passion for helping others are very remarkable.

Special thanks go to Telkom, whose sponsorship of me through their Centre of Excellence program enabled me to meet my financial obligations, thus allowing me to focus on the completion of this project. I would like to thank the Wireless Mesh Network cluster situated at the Department of Computer Science and my other research colleagues in the centre, with whom I had the pleasure to discuss, argue and work, etc. This work would have been impossible without their contributions.

My sincere gratitude also go to my parents, my Brothers (Olayinka Oki & Olalekan Oki) for really acting as the 'father' to me. Also, thanks to my other family members and all my fellow Nigerian 'fathers', 'mothers', 'brothers' and 'sisters' at the University of Zululand for their understanding, advice, support and encouragement.

Finally, I would like to specially express my profound gratitude to Professor M.O. Adigun for taking me as his own son and not just a student, wherever your children goes to in life, the mercy of God shall always speak for their favor.

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ABSTRACT

Wireless Mesh Network (WMN) is a collection of wireless nodes which can dynamically communicate with one another in multi-hop manner. This network has received considerable attention as a means to connectivity in community and commercial entities. The easy deployment and self-management characteristics of WMN, makes it a good choice for rural areas. However, in most developing countries, electricity is scarce or unreliable in the rural areas. A candidate solution to the lack of electricity supply in these areas is the use of solar/battery-powered nodes. Significant efforts have gone into optimization of Quality of Service (QoS) provisioning in WMN; hence, a lot of QoS mechanisms on OSI layer have been proposed. It is, however, not clear how different QoS mechanisms on OSI layer affect the node lifetime and the energy cost per bit of a battery-powered WMN nodes. Different protocols at different layers have varying effects on the energy efficiency of the battery-powered WMN nodes, when those protocols are subjected to various transmission power levels and payload sizes.

The goal of this study is to evaluate how different existing QoS mechanisms affect the operational lifetime of battery-powered WMN nodes. This goal was achieved by evaluating how connection (TCP) and connectionless (UDP) Transport Layer protocols together with Reactive (AODV) and Proactive (OLSR) Routing protocols influence the lifetime of battery-powered nodes when subjected to different transmission power levels and payload sizes. The evaluation was carried out using NS-2 simulation and a fourteen nodes indoor testbed.

The overall results of both the simulation and the testbed experiments show that for a TCP-based scenarios, TCP with OLSR at maximum transmission power level and maximum payload size outperform others in terms of packet delivery ratio, average throughput and average energy cost per bit, while TCP with AODV at minimum transmission power level and maximum payload size outperform others in terms of node lifetime. And for the UDP-based scenarios, UDP with AODV at maximum transmission power level and maximum payload size outperform others in terms of packet delivery ratio, average throughput, node lifetime and average energy cost per bit, while TCP with AODV at minimum transmission power level and maximum payload size outperform others in terms of node lifetime. The results of this study also reveal that simulation results only give a rough estimate of the real world network performance. Hence, whenever it is feasible, validating a simulation result using testbed is highly recommended in order to have clear and better understanding of the protocol performances.

CHAPTER ONE

INTRODUCTION

1.1 Preamble

A Wireless Mesh Network (WMN) is a distributed multi-hop system with self-configuration and self-organization capabilities where each node is able to develop packet forwarding functions toward other neighbouring nodes [Baccarelli *et al,* 2005]. This type of network is implemented over a wireless network system such as wireless LANs. WMNs differ from other networks in that the nodes can communicate with one another in a multi-hop manner. As a result of WMN system dynamism, the system can adapt to both the node entering and exiting of the network, which could be due to node outage, poor connectivity, node failure, etc. The robust nature of wireless mesh networking makes it a perfect technology that can be used in rural areas and where the setting up and installation of a wired network would be very expensive.

The versatility of a WMN can be used to efficiently satisfy the needs of multiple applications. Examples of these applications include: broadband home networking, community and neighbourhood networking, enterprise networking, metropolitan area networks, transportation systems, health and medical systems, security surveillance systems and education. WMNs can also be employed in isolated locations, rugged terrain, cities and municipalities. The deployment of WMNs eliminates the need to bury cables in old buildings and across cities. Dozens of well-placed indoor and outdoor nodes can provide adequate coverage over a variety of areas. Therefore, WMNs have received considerable attention from both the industrial and the academic sectors [Zhang, 2010].

Unfortunately, the power saving of conventional IEEE 802.11b/g nodes used by WMNs has focused mainly on the client stations because the IEEE 802.11b/g standard assumes that, access nodes will always have continuous power supply, which is not the case in some rural part of developing countries [Ntlatlapa, 2007], where power-constraints exist. Provisioning of reliable power supply for the 802.11b/g access nodes is imperative to the deployment of WMNs in various ways. Hence, the nodes power consumption needs to be regulated in order to prevent excessive energy utilisation, to enhance network reliability, and to control the transmission rate.

Power can be supplied through different means, such as via the electrical grid, wind/battery, solar/battery and Power Over Ethernet (POE). Solar/battery energy may however be used as a renewable power source for a power-constrained node especially in rural areas of African countries. One of the reasons for solar/battery energy recommendation and performance in these areas is the ambient sunlight. Before nodes are installed in a solar/battery-powered network, the nodes need to be equipped with a battery and a solar panel that would be sufficient to power the devices on a continuous basis.

Many modern wireless networks comprise nodes that operate based on small and energy-limited batteries. Examples of such networks include mobile cellular systems, wireless local area networks and wireless sensor networks [Hoang, 2005]. In these power-constrained wireless networks, a fundamental design challenge is to achieve an efficient system performance while conserving nodes' energy, using some existing Quality of Service (QoS) mechanisms.

QoS refers to the ability to provide differing priorities to the various applications, users, or data flows. QoS may also be referred to as the resource reservation control mechanism [Marchese, 2007]. QoS comprises requirements on all aspects of a connection and it is affected by various factors which can be divided into “human” and “technical” factors [Xiao, 2008]. Human factors include: stability of service, availability of service and user information. Technical factors include: reliability, scalability, effectiveness, maintainability, grade of service, etc [Xiao, 2008]. QoS support is required at every OSI layer, but in this study, the focus is on two OSI layers (the Network and Transport Layers), which encompass most of the technical factors affecting QoS mechanisms in a power-constrained WMN.

The QoS required at the Network Layer includes: the selection of efficient routes, offering of priorities and resource reservation. On the other end, the QoS required at the Transport Layer includes: end-to-end recovery when possible and defining well-known ports. The Transport Layer Protocols (TLPs) dictates how the data is sent and it also defines well-known services (ports). TLP provides two types of services: connection oriented (TCP) and connectionless oriented (UDP). The various Transport Layer QoS parameters must be supported by the Transport Layer Protocols for the Application Layer. Typical examples include Throughput, Delay, and Packet Delivery Ratio.

The Network Layer (routing protocol) is one of the key communication protocol layers to efficiently use the resources in a WMN, where the available bandwidth is cut down by both internal and external radio interference. This Layer also provides logical addressing and finds the best path to a destination. For WMNs, simple (i.e., low overhead), scalable, distributed, load-balancing and link quality-aware routing protocols would be required for efficient multihop communications. Proactive (OLSR, DSDV) and Reactive (DSR, AODV) Routing Protocols are the two common categories of routing protocols in WMN. Efficient Routing and Transport protocols are needed for non real-time and real-time traffic to satisfy different QoS requirements in energy consumption of battery-powered WMN. Hence, in order to deploy an efficient and cost effective WMNs in power-constrained areas, a system is needed through which the power consumption of the battery-powered access nodes can be regulated using existing QoS mechanisms.

1.2 Statement of the Problem

In most African rural areas, electricity is a scarce commodity; hence, the lack of reliable electricity supply hinders development. ICT infrastructure such as WMNs that have proven to be a solution for Internet access in rural areas and in free local communications is also adversely affected by this problem. Solar/battery technology is one of the best solutions that work in such power-constrained areas. Significant efforts have gone into optimization of QoS provisioning in WMN. Hence, a lot of QoS optimization mechanisms have been proposed, with little focus on Energy Efficiency, because of the assumption that a WMN node does not suffer from power-constraints [Ntatlapa *et al*, 2006], which is not the case in rural areas of Africa. It is thus unclear, how different QoS mechanisms affect the operational lifetime of a battery-powered WMN node.

1.3 Research Question

Pertinent to the study, one research question and two sub-research questions were posed:

What are the *effects* of existing QoS mechanisms on battery-powered wireless mesh nodes *operational lifetime*?

(a) i. What is the effect of reactive routing protocol on the operational lifetime?

ii. What is the effect of proactive routing protocol on the operational lifetime?

(b) i. What is the effect of connection oriented protocol on the operational lifetime?

ii. What is the effect of connectionless oriented protocol on the operational lifetime?

In this study, the *effect* is referred to as the performance and energy consumption level, while the *operational lifetime* is the duration that the nodes remains in proper working order.

1.4 Rationale of the Study

The continuous bridging of the digital divide is being accomplished through the use of various technologies, one of them being WMNs. This WMN technology is eminently suitable because of its easy deployment and self-management characteristics. Despite the social importance of this network, the emphasis in Africa, most especially in rural areas, is usually on provisioning of affordable, efficient and reliable access to the internet.

Providing connectivity to under-serviced rural areas of Africa comes with a unique set of challenges such as the lack of reliable power supply, high cost of equipment, skill shortages and high cost of providing Internet connectivity which is mostly satellite based. One of the main challenges when deploying a WMN in rural areas of Africa is to get a reliable power supply for the network nodes, because a poor power supply will result in node outages with undesirable performance. Hence, the provisioning of reliable power supply to the network nodes will contribute in achieving desirable Quality of Service properties of WMN in rural areas of Africa. It is this vision that inspires us to conduct research on the effect of Routing and Transport Layer Protocols on power-constrained WMNs.

Based on the increasing number of battery-powered WMN deployments in rural areas, evaluating the effect of existing QoS mechanisms on the operational lifetime of battery-powered access nodes will contribute in preventing node outage, improve the network performance and make WMN cost effective for future deployments.

1.5 Research Goal and Objectives

In this section, we present the aim of this research study. The aim is further divided into four objectives:

Research Goal

The goal of this research study is to evaluate how different existing Quality of Service mechanisms affect the operational lifetime of battery-powered WMN nodes.

Research Objectives

i. To evaluate the effect of connection oriented protocol on the operational lifetime of battery-powered WMN nodes.

ii. To evaluate the effect of connectionless oriented protocol on the operational lifetime of battery-powered WMN nodes.

iii. To evaluate the effect of reactive routing protocol on the operational lifetime of battery-powered nodes.

iv. To evaluate the effect of proactive routing protocol on the operational lifetime of battery-powered nodes.

1.6 Overview of Research Methodology

In order to achieve the aforementioned objectives, both the Experimentation and Simulation research methods were used. Experimentation and Simulation research methods were chosen for this study because they complement each other. Whilst Simulation simplifies some parts of real environment in order to understand the impact of other factors, the Testbed experimentation aims at capturing the full interaction between all parts. Studies [Anastasi *et al*, 2006, Gregori *et al*, 2004] have shown that, the Simulation results are not accurate enough to truly model the unpredictable environments that wireless ad hoc networks protocols are subjected to in the real world situation. Hence, there is an increasing demand to complement Simulation results with Testbeds results, in order to improve confidence in the results presented by the researchers.

In Sub-sections 1.6.1 and 1.6.2, a brief explanation of these two research methods are presented, while the comprehensive details of how these methods were implemented in this study are discussed in Chapter Four. The results of this study would be applicable to wireless mesh networks that employ power-constrained and low-cost network nodes.

1.6.1 Primary Research Method: Experimentation

The primary research method consists of an Indoor Experimental Testbed, which provides a real environment for the researchers to be able to produce results and inferences that can be used directly in an actual deployment. The nodes used for this testbed were powered using actual battery (12V8Ah). The major focus here was to experiment, analyze and evaluate the effect of existing QoS mechanisms on battery lifetime and the network performance of WMN nodes, when subjected to various transmission power levels and payload sizes. Both connection (TCP) and connectionless (UDP) Transport Protocols coupled with Proactive (OLSR) and Reactive (AODV) routing protocol were experimented and analyzed. The performance were analyzed and evaluated using five metrics; Packet Delivery Ratio, Average Throughput, End-to-End Delay, Node Lifetime and Average Energy Cost per Bit. This research method helped us to partly achieve the four objectives, since Testbed complements the Simulation studies.

1.6.2 Secondary Research Method: Simulation

The secondary research method involved simulation using Network Simulator (NS2) version 2.34. NS2 is a discrete event simulator for networking research and this simulation tool is based on standard OTcl and C++. The simulation was used to evaluate the effect of connection-oriented (TCP) and connectionless (UDP) Transport protocols, coupled with OLSR as the Proactive Routing Protocol representative and AODV as the Reactive Routing Protocol representative on the operational lifetime of battery powered WMN, when subjected to various payload and network sizes. The simulation evaluation was done using four performance metrics; Packet Delivery Ratio, Average Throughput, End-to-End Delay and Network Lifetime. The results obtained via this research method coupled with the testbed results, helped to fully achieve the four objectives and to convincingly answer the stated main and sub research questions.

1.7 Organization of the Dissertation

The remainder of this dissertation is organized as follows:

- Chapter Two gives a background of this study by introducing the WMN deployment challenges and solutions in rural areas of developing nations.
- In Chapter Three, the energy-efficiency and general performance of Routing and Transport Layer Protocols in wireless ad hoc networks is explored. We discuss OLSR and AODV which represent Proactive and Reactive Routing Protocol respectively, while TCP and UDP represent connection- and connectionless-oriented Transport Layer Protocol respectively.
- Chapter Four presents the Simulation and Indoor Testbed setup, together with the description of the measurement process used to carry out both the simulation and testbed experiments. The Simulation and Testbed coupled with measurement processes form the bases for the next two chapters in which the analysis of both Simulation and Testbed Experiments are presented.
- In Chapters Five and Six, a comprehensive analysis of two Routing Protocols (OLSR and AODV) and two Transport Layer Protocols (TCP and UDP), when subjected to various conditions is carried out. We specifically evaluate packet delivery ratio, throughput, end-to-end delay, lifetime and average energy cost per bit for the mentioned protocols using Simulation and Indoor Testbed platforms.
- Chapter Seven summarizes this work and highlights the contribution of this dissertation. The study limitations are also presented together with the conclusions and future work.

CHAPTER TWO

BACKGROUND

2.1 Introduction

Currently, the world population is approximately seven billion with Africa as the second most populated continent. But it is unfortunate that despite its population, Africa has the lowest Internet penetration rate [see Figure 2.1]. Inadequate Internet access in developing countries shows that the digital divide still exists between them and the developed countries. This Internet inadequacy is hindering both social communication and business advancements in developing nations of the world. Wireless Mesh Networks (WMNs) are often used as a cost-effective means to provide broadband connectivity in those areas without prior network infrastructure as well as in areas where network infrastructure already exists [Akyildiz *et al*, 2009]. Typical WMN usage scenarios include amongst others, community and municipal networking, transportation systems, security surveilance system, enterprise networking, medical and health systems [Akyildiz *et al*, 2009].

In Africa, the primary reason for deploying wireless mesh networks has been to provide affordable access to the Internet as well as allowing free local communications to be in place. Several examples of African WMNs deployments can be found [Johnson, 2007, Johnson *et al*, 2010, WirelessGhana, 2012, Schoolnet Mozambique, 2012]. Many of these deployments are facing very similar challenges; namely:

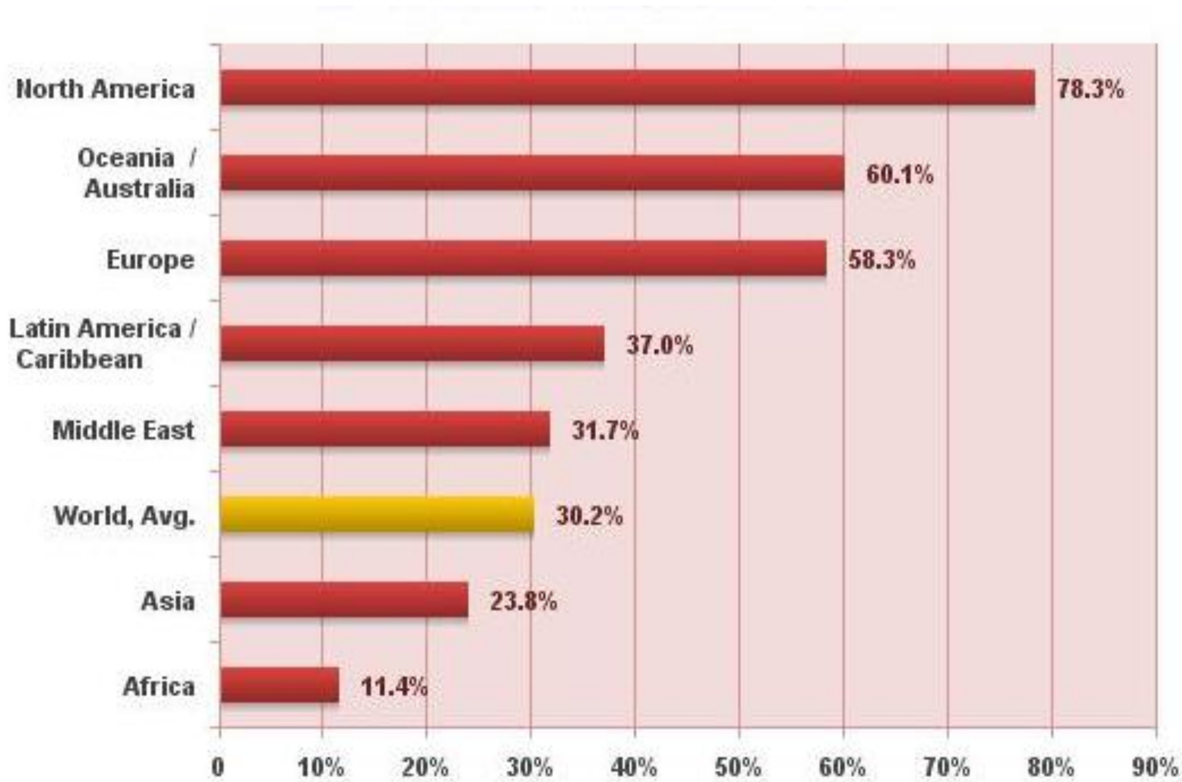

Figure 2.1: World Internet Penetration Rates [Internet world Stat, 2011]

- *Lack of reliable power supplies especially in rural areas*
- *Lack of technical skills to troubleshoot problems*
- *Low levels of disposable income and high ICT costs [*ICT Price Basket, 2011*]*

Thus, WMN deployments in African countries should be easy to setup, possess a low total cost of ownership and should be as energy-efficient as possible. These characteristics are essential in improving the operation of existing WMNs deployments as well as in making WMNs a much more attractive option for providing the networking infrastructure that could be used to bridge the existing digital divide.

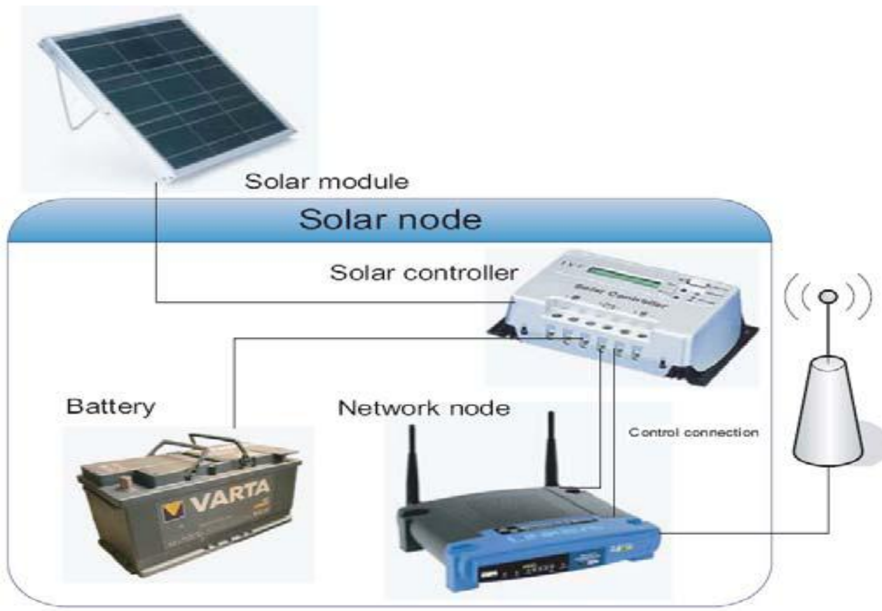

Figure 2.2: Basic Battery-Powered Node

The African continent is well-endowed with solar radiation and the use of solar powered networking infrastructure has been previously explored with the specific aim of deploying base stations for cellular networks [Matsuda, 1999] in remote areas. Solar technology [See Figure. 2.2] is, however, expensive due to the costs associated with the solar panel and the battery. *Figure 2.3* depicts the influence of the battery capacity on the solar/battery technology cost. The depicted costs are for 12V batteries of varying capacities.

One of the more feasible alternatives to lowering the cost of using solar technology is to reduce the capacity of the batteries being employed. The battery is employed to store excess energy in order to power devices even in adverse conditions such as nightfall and periods of heavy cloud cover. Although, the use of smaller-capacity batteries may reduce the cost of solar/battery-powered WMN, the duration for which the battery is able to power the WMN node is lessened.

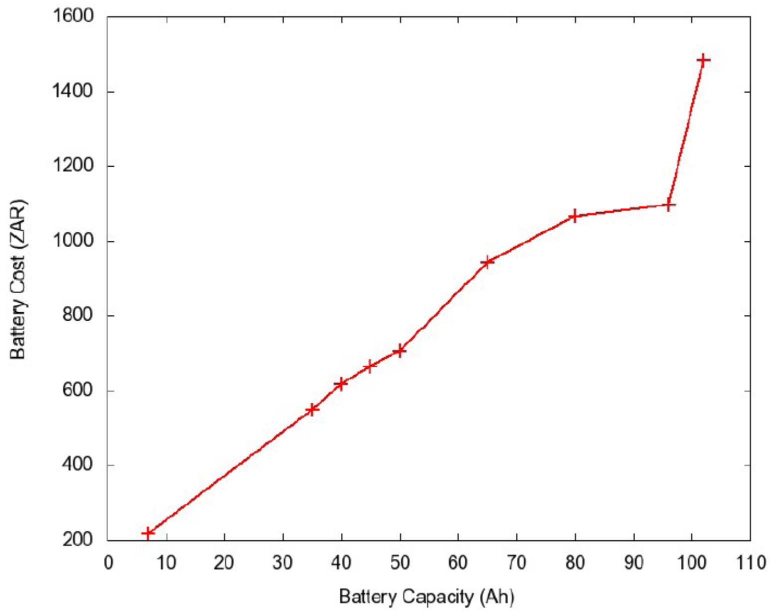

Figure 2.3: Cost vs. Battery Capacity [Green World Solar Solution, 2011]

Thus, the operational lifetime of the node is negatively affected. One of the possible solutions to improve the operational lifetime of the battery-powered node would be to have some resource reservation control mechanisms i.e. to set priority for different users, applications, and to guarantee certain performance level to the data flow. And this concept is referred to as Quality of Service mechanism (QoS).

In section 2.2, Quality of Service is described as it affects the power consumption of OSI layers. The energy efficiency as it relates to different layers of OSI is introduced in section 2.3. Section 2.4 summarizes this chapter.

2.2 Quality of Service (QoS)

QoS encompasses requirements on all the features of a connection and it is requisite at every OSI layer. There are two essential layers (Network and Transport Layer) which control several activities during transmission in any network. These two layers host

Routing protocols (host-to-host communication) and Transport protocols (end-to-end throughput). Transmission power control has a key influence on several performance measures such as Energy Efficiency, Throughput and Delay. The transmission power control, also has a significant influence on both the Transport Protocols and Routing Protocols, because it regulates the interference levels which affect congestion control mechanisms in the Transport layer and determine the set of candidate nodes for next-hop selection in Routing Protocols [Boukerche, 2009]. Thus, in order to achieve Energy-efficiency, high End-to-end Throughput and High Packet Delivery in WMNs, both Congestion Control and Power Control need to be optimally designed and distributedly implemented in the OSI layers.

2.3 Energy Efficiency in Wireless Mesh Networks

Wireless mesh networks are currently being used in a variety of network infrastructure applications in which radio coverage is required over expansive outdoor and rural areas. In rural areas, continuous power supplies are not always available. The unreliable power supply condition in Africa and some rural areas of other developing nations makes energy efficiency in WMNs an important issue. Energy efficiency can be defined as the ratio of the amount of data delivered to the total energy consumed and not just the battery lifetime. One of the solutions to the unreliable power supply problem is the use of solar/battery- powered nodes [Figure 2.2].

Network infrastructure applications require continuously operating networks when battery-powered mesh nodes are used. As a result, it has become an important issue to optimize performance from an energy-awareness point of view [Boukerche, 2009]. All the communication layers are interconnected in power consumption and the alternative strategies to address the energy-efficiency issue include Power-Aware Routing, Low-power Physical Layer Mode and Transmission Power Control [Fotino *et al*, 2007]. *Transmission Power Control* is a key factor to several performance measures such as Delay, Energy-Efficiency and Throughput. The transmission power determines the transmission range, the interference created for other receivers in the network and the signal strength at the receiver. Hence, Transmission Power Control affects the sharing of wireless medium, thereby affecting many aspects of the operation of a WMN [Mudali, 2007]. For example, Transmission Power Control can determine the contention region at the MAC layer, determine the set of candidate nodes for next-hop selection in routing protocols, and affect the operation of congestion control in the transport layer by affecting the congestion level of wireless medium [Mudali, 2007].

Transmission Power Control in conjunction with the MAC, Network and Transport Layer affects the energy efficiency of wireless ad hoc networks and wireless mesh networks. The effect of Transmission Power Control on energy efficiency as it relates to MAC, Network and Transport Layers of OSI are discussed in sub-section 2.3.1, 2.3.2 and 2.3.3 respectively.

2.3.1 The Media Access Control (MAC) layer

At the Media Access Control (MAC) layer, the transmission power determines the transmission and carrier sensing range of the sending node. One of the approaches through which energy efficiency has been addressed in MAC layer of wireless ad hoc network is by Transmission Power Control. The MAC layer Transmission Power Control approaches energy efficiency by trying to send packets at the minimum transmission power such that the Signal-to-Interference-plus-Noise Ratio (SINR) at the receiver's end is above a predefined threshold for successful transmission. This reduction in transmission power leads to the improvement of spatial reuse in wireless nodes and energy saving for the nodes. However, the intended receivers of the transmission are determined by the routing protocols of the Network Layer. One of the major roles of Physical and MAC layers are to send packets to the destinations specified by the Network Layer. Hence, placing power control functionality at the MAC layer only, will not give the routing protocols of the Network Layer the opportunity to choose an optimal next hop node. This means that the MAC layer approach to the Transmission Power Control only leads to local optimization of network performance. Hence, the energy efficiency at the MAC layer can be obtained using a cross-layer design (MAC and network layer) approach like Topology Control. Topology Control addresses the energy efficiency by attempting to reduce the energy consumed per bit transferred. Studies [Mudali *et al,* 2010, Aron *et al,* 2008] have shown that a significant amount of the total power consumed by a node is attributable to the transceiver and Topology Control attempts to minimize the transceiver powers being used by network nodes while maintaining network connectivity.

2.3.2 Routing Protocols

Routing protocols provide logical addressing and find the best path to a destination. These protocols also provide host-to-host communication between a pair of nodes. By incorporating the Transmission Power Control function into the routing protocols, energy can be saved for terminals, which is an important metric to assess the performance of wireless ad hoc networks. At the Network Layer, Routing Protocols may balance power consumption at nodes according to their routing decisions. The MANETs group proposes two kinds of Routing Protocols: Reactive and Proactive, which has been mainly designed for mobile ad hoc networks.

2.3.2.1 Reactive Routing Protocol

A reactive or on-demand routing protocol (DSR, AODV) determines routes only when there is data to be sent. If a route is unknown, the source node initiates a search to find one, and it is primarily interested in finding any route to the destination, not necessarily the optimal route. Mobile nodes do not rely on periodic messages, with a consequently efficient advantage in terms of battery consumption. The node only updates its routes when it needs to react to link mechanisms (Route Discovery and Route Maintenance). Reactive protocols allow multiple routes to any destination and allow each sender to select and control the routes used when performing routing decisions.

2.3.2.2 Proactive Routing Protocol

A proactive routing protocol attempts to continuously maintain routes to all destinations, regardless of whether they are required or not. To support this behavior, the Routing Protocol propagates periodic information updates about the network topology or connectivity throughout the network. Optimised Link State Routing (OLSR) is an optimization of the classical link state algorithm, tailored to the requirements of an ad hoc network. Because of their quick convergence, Link State Algorithms are somewhat less prone to routing loops than Distance Vector Algorithms, but they require more CPU power and memory. Proactive protocols can be more expensive to implement and support but are generally more scalable. The key concept used in OLSR is the Multipoint Relay.

Multipoint Relays are the only nodes which forward broadcast messages during the flooding process. This technique substantially reduces the message overhead when compared to classical flooding mechanisms where every node retransmits each message received. Thus, a mobile node can reduce its energy consumption. OLSR provides optimal routes in terms of number of hops. The protocol is particularly suitable for large and dense networks.

2.3.3 Transport Layer Protocols

The Transport Layer is responsible for providing communications for applications residing in different terminals in the network. One of the main functions at the Transport Layer is congestion control, which mitigates the congestion level in wireless ad hoc networks and thus improves the end-to-end throughput of the networks. Several Transport Layer Protocols exist to date. The most widely used Transport Layer Protocols for Internet-based applications are the Transmission Control Protocol (TCP) and the User Datagram Protocol (UDP); both of which are discussed below.

2.3.3.1 Transmission Control Protocol (TCP)

TCP is a reliable byte-stream connection-oriented, data ordered delivery and bi-directional transport layer protocol, [Postel, 1981]. For battery-powered wireless mesh networks, which operate independently with constrained power supply, one of the main challenges is the energy inefficiency of TCP. One of the main causes of this inefficient use of energy in TCP is the end-to-end retransmission scheme, which requires that lost packets are re-sent by the original sender of the packet. In a WMN, the packets being re-sent must be forwarded by all intermediate nodes from the sender to the receiver, thus consuming a significant amount of energy at every hop and also waste the available bandwidth and limit the throughput.

Different approaches have been considered in the literature to overcome the problem of energy inefficiency of TCP, largely in the area of Wireless Sensor Networks, because of the assumption that wireless mesh networks nodes are not power constrained, which is not the case in rural areas of Africa [Ntlatlapa, 2007]. Some of these approaches are discussed in Chapter Three.

2.3.3.2 User Datagram Protocol (UDP)

UDP is a connectionless, simple, unordered Transport Layer Protocol and is designed for unicast multimedia applications that prefer timeliness of data to reliability [Kohler *et al,* 2006]. UDP does not assure reliability and chronological delivery of packets, but is delay sensitive; hence, it is well suited for delay-sensitive applications (VoIP, teleconferencing, video chat etc).

Most applications that are UDP based do not have good control mechanism and there are no congestion avoidance mechanisms. As a result of the congestion insensitivity of UDP applications, it consumes a significant amount of available bandwidth which in turn consumes more power and lessens the operational lifetime of the battery-powered nodes. One of the approaches to partially resolve this issue is the use of Datagram Congestion Control Protocol [Kohler *et al,* 2006].

One of the advantages of UDP which makes it consumes less energy is that, it does not introduce additional delays due to retransmission as in TCP [Mujica *et al,* 2004]. However, some of the problems to be addressed in Transport Layer Protocols of WMNs comprise the provisioning of energy efficient protocols, congestion control mechanisms and the reliability of the network.

In order to achieve energy-efficient and high end-to-end throughput in wireless ad hoc networks with multihop communications, both congestion control and power control need to be optimally designed and distributedly implemented.

2.4 Summary

This chapter has laid the background for this research work by identifying some challenges facing the deployment of wireless mesh networks where there is a lack of reliable power supplies, which is especially the case in rural areas of Africa. Solar/battery-power usage was discussed as a possible solution to the existing power constraint. Quality of Service (QoS) was also introduced as a cost-effective means of improving the operational lifetime of the solar/battery-powered nodes. The effect of QoS on all layers of OSI was briefly discussed and its effect on energy efficiency of the MAC, Routing and Transport Layer protocols was explained.

Energy is one of the main resources in a battery-powered WMN; hence, in order to keep the network functional for as long as possible, energy efficient mechanisms should be devised. By reducing the transmit power level, the energy consumption for packet transmissions at each node can be reduced. Thus, Transmission Power Control is an important technique to design energy efficient mechanisms for conserving the battery energy of nodes and prolonging the operational lifetime of the nodes.

The next chapter reviews both the energy efficiency and general performance of both the Routing Protocols and Transport Layer Protocols in battery-powered wireless ad hoc networks and wireless mesh networks based on various evaluation methodologies.

CHAPTER THREE

EXPLORING THE PERFORMANCE AND ENERGY-EFFICIENCY OF ROUTING AND TRANSPORT LAYER PROTCOLS IN WIRELESS AD HOC AND MESH NETWORKS

3.1 Overview

The previous chapter introduced our study area and presented the background for energy efficiency of both the Transport Layer and Routing Protocols in battery-powered WMNs. Energy efficient protocols have mostly been proposed for use in wireless ad-hoc networks such as wireless sensor networks (WSNs) and mobile ad hoc networks (MANETs) and the few works dealing with WMNs use mathematical- and simulation-based studies. Some of the results obtained from both mathematical and simulation-based studies are yet to be proven in a real world environment [Anastasi *et al*, 2006].

In this chapter, particular attention has been paid to the different evaluation methodologies employed in the studies of energy-efficiency and the general performance of Routing Protocols and Transport Layer Protocols in wireless ad hoc and mesh networks. Section 3.2 presents the Mathematical-based energy efficiency and general performance studies of Routing and Transport Layer Protocols. Sections 3.3 presents the Simulation-based studies on energy efficiency and general performance of Routing and Transport Layer Protocols in MANETs while Section 3.4 explores the Testbed-based studies on energy efficiency and general performance of Transport Layer and Routing Protocols of wireless ad hoc and mesh networks. The chapter is summarized in Section 3.5.

3.2 Mathematical-based Energy Efficiency and General Performance Studies

In mathematical-based studies, mathematical models were used to evaluate the network performance. The derivation of mathematical equations which illustrate the behavior of wireless ad hoc networks is a useful tool to generate generalised problem estimations. These models are also useful in understanding the theoretical lower or upper performance bounds to problems. This section reviews the mathematical-based energy efficiency and general performance of Routing protocols and Transport Layer protocols in wireless ad hoc and mesh networks.

3.2.1 Energy Efficiency of Routing Protocols

The energy efficiency of routing protocols in WMN has not received sufficient attention due to the assumption that this particular type of network does not suffer from power constraints [Akyildiz *et al*, 2009]. One of the ways by which Routing Protocols can balance the nodes power consumption is through their routing decisions. The next three sub-subsections generally review a number of mathematical-based studies on energy efficiency of routing protocols.

3.2.1.1 Node Energy Resource Assignment [Ghada *et al,* 2008]

In this study [Ghada *et al*, 2008], the node resource provisioning problem for temporarily deployed WMNs was considered and the objective was to minimize the total cost of the battery assigned to each node as an energy source. The assignment of resources to nodes are comprised of a solar panel and a battery that would be sufficient to power the node and prevent the network partitioning which could occur as a result of node outage. The resource assignment problems were studied by characterizing them, using shortest-path and energy-aware routing.

Algorithms and mathematical models were designed to develop a linear programing formulation that considered lower bounds for the network nodes' resource assignment and upper bounds for the network lifetime. In order to compare the effectiveness of different routing algorithms, competitive ratios were employed.

The results of this study show that in a small mesh network, where the real traffic-flow is directly proportional to the design profile, the energy-aware resource saving routing are fairly modest, whereas, in a large mesh network, greater resource assignment improvements can be achieved through energy-aware routing. Theoretical/mathematical method of analysis was used in this study. The theoretical analysis of WMNs remains difficult since the mathematical constructs are very complex for the development of realistic models [Zimmermann *et al,* 2007]. Therefore, there is often significant difference between the results predicted by mathematical models and the results obtained on testbeds. Hence, our study shall investigate the effect of both Routing and the Transport Layer protocols when subjected to various payload sizes and transmission power level using both Simulation and Testbed.

3.2.1.2 Traffic-Oblivious Energy Aware Routing Framework [Li *et al,* 2006]

In [Li *et al,* 2006], the energy aware routing in ad hoc multi-hop wireless networks and the traffic-oblivious problem were studied. Wireless networks with fixed topology were focused on. The objective of the study was to design a routing scheme with minimum energy consumption in a multi-hop wireless network through a weak assumption of the traffic pattern and without the collection of the ongoing network information.

A polynomial size linear programing model was developed to design an energy aware routing framework in multi-hop wireless networks. These linear programing models were generally designed in order to model different kinds of wireless systems (e.g. MIMO). Based on the results of this study; it was concluded that the routing scheme designed, can only perform better in an interference-free wireless network environment.

The routing is fixed; hence, it is unaware of changes both in the traffic and in the current network state such as the present energy level of the wireless ad hoc nodes and their respective network load. The scheme was designed so that it does not need to collect network information except for the fixed topology and the initial energy levels of the nodes.

The performance of the polynomial size linear programing model developed in this work was close to the performance of an oracle in the performance studies. The results for multi-hop wireless networks with a single sink are better than the others. The study discussed and used a theoretical framework method of analysis and the designed framework improves performance in a wireless interference-free environment.

It is almost impossible to have a complete interference-free environment in real life environment; hence, the result of this study may not be completely applicable in real life environment. Also, the theoretical framework/analysis is not an ideal platform for the study and analysis of a wireless mesh network, because the theoretical analysis gets very complex for realistic considerations. Hence, our study shall investigate the performance of Routing and Transport protocols in the context of wireless mesh network using both simulation and an indoor battery-powered WMNs testbed.

3.2.1.3 Resource Allocation and Outage Control [Farbod and Todd, 2007]

In solar powered networks, the cost of battery and the solar panel constitute a significant fraction of the total cost [see Figure 2.3]. Hence, reducing the nodes power consumption shall be of great importance, because it will reduce the size of the battery and in-turn reduces the total cost.

In [Farbod and Todd, 2007], the resource allocation and outage control were considered for solar-powered WMNs. The resource allocation and outage control design involves specifying a capacity profile which depicts the workload that the access point shall be designed to handle. Given an averaged offered capacity profile, both the reliability level required and the system configuration is determined using available meteorological data.

A battery/solar panel configuration methodology was introduced based on the proposed access point energy-aware version of IEEE 802.11. It was assumed that the outage control designed in this work uses the power-saving mechanism proposed by the extensions to IEEE 802.11.

In order to maintain the node outage-free performance, which sometimes introduce an access point capacity deficit, a control algorithm was introduced. The public meteorological data was used to design the load profile which is a function of time at the peak workload.

The result from this study shows that significant resource reductions are possible, using the proposed resource allocation configuration methodology and also shows that the control algorithms can prevent node outage even at high levels of excess loading.

Unfortunately, the proposed energy saving was designed using statistical data which was met for a particular target activity and that make its applicability in real life deployment questionable.

Our study shall investigate the performance of Routing and Transport protocols in the context of wireless mesh network using both simulation and an indoor testbed.

3.2.2 Energy Efficiency and General Performance of Transport Layer Protocols

A number of researchers have proposed improvements on the traditional TLPs (TCP and UDP) while other researchers have proposed new protocols in order to improve the performance of WMNs. These activities have lead to several TLPs being available. However, most of the recently proposed and improved TLPs for wireless mesh networks are based on the connection-oriented Transmission Control Protocol (TCP) and rely mostly on simulation and emulation-based evaluations.

In this section, we review a number of existing mathematical-based research works, which analyzed the energy efficiency and the general performance of transport layer protocols in wireless ad hoc and mesh networks.

3.2.2.1 TCP Performance over Wired/Wireless Links [Balakrishnan *et al,* 1997]

In [Balakrishnan *et al*, 1997], goodput and end-to-end throughput of TCP error control strategies for three implementations of TCP were compared. Only wired/wireless goodput was considered as the metric for the comparison. The authors implemented the three versions of TCP using the x-kernel protocol framework and their focus was to study heterogeneous wired/wireless environments. Theoretical analysis was used as an evaluation method.

Based on the results of this study, it was concluded that a reliable link-layer protocol with some knowledge of TCP will provide better goodput performance. It was also concluded that a good throughput performance can be achieved without splitting the end-to-end connection at the senders' node. In this study [Balakrishnan *et al*, 1997] only throughput was measured to determine the performance of various TCP implemented. Considering only throughput metric, is not enough to determine the best performing scenario. Hence, our study shall investigate the performance of both TCP and UDP by measuring Packet Delivery Ratio, Average End-to-End delay, Throughput, Lifetime and Average Energy Cost per bit using both simulation and testbed.

3.2.2.2 Rate Control for Communication in Wireless Ad hoc Networks [Kelly *et al,* 1998 and Boyd *et al,* 2004]

In [Kelly *et al*, 1998 and Boyd *et al*, 2004], two classes of rate control algorithm for wireless networks were analysed using stability and fairness as the two metrics. The main issue addressed in [Kelly *et al*, 1998], was on how the available bandwidth within a large-scale broadband network can be shared among the competing nodes. A tractable mathematical model was used to analyse both the stability and fairness of the rate control algorithm. In [Boyd *et al*, 2004], it was shown that the transmission power control has a significant influence on transport layer because it determines the interference level in the wireless networks, which creates congestion regions in wireless networks. In both of these studies, a distributed algorithm was used for congestion control to solve the network utility maximization problem. Both studies use mathematical methods of analysis and the developed algorithm was only subjected to various transmission power levels. Our study shall investigate the work further by subjecting both the Routing protocols and Transport Layer protocols to various transmission power levels and payload sizes using simulation and testbed methods.

3.2.2.3 TCP Jointly Optimal Congestion Control and Power Control [Chiang .M, 2005]

Chiang, (2005) proposed a Jointly Optimal Congestion control and Power control (JOCP) algorithm in wireless multihop networks. CDMA-based medium access and fixed single-path routing are assumed in the algorithm, thus avoiding the problem of contention resolution in the MAC layer and routing in the network layer. The objective of the study was to increase the throughput and the energy-efficiency of the network. Theoretical/analytical method was used for the analysis and evaluation of the proposed algorithm. The study combined both the proposed JOCP algorithm and existing TCP algorithm to enhance the end-to-end throughput and energy-efficiency of multihop transmissions in wireless networks.

Based on the results of this study, it was concluded that, the existing TCP algorithm does not need any modification in order to achieve the optimal balancing between data rate regulated through TCP and the data rate regulated through power control. It was further concluded that the proposed JOCP algorithm is robust (scalability, adaptability, manageability and deplorability) to wireless channel variations and path loss estimation errors. The mathematical method of evaluation was used in this study and the energy efficiency was measured using only lifetime. The Lifetime provides a high-level look at the energy efficiency, while the average energy cost per bit provides an indication of the utility of a node, whilst it is alive by assessing the amount of data received within the achieved node lifetime. The general performance of the developed algorithm was measured using only throughput.

Our study shall improve on this work [Chiang, 2005], by considering both the Lifetime and Average energy cost per bit in determining the energy efficiency of both Routing and Transport layer protocols using simulation and battery-powered testbed. Also, we shall measure packet delivery ratio, average end-to-end delay and throughput.

3.3 Simulation-based Energy Efficiency and General Performance Studies

All the studies discussed in the previous Section for both Routing and Transport Layer Protocols used the theoretical/mathematical method of analysis. Unfortunately, theoretical analysis of WMNs is very difficult, since the mathematical constructs get very complex for realistic considerations. In addition, useful mathematical tools do not exist [Zimmermann *et al*, 2007].

A simulation environment offers a high degree of control, scalability and repeatable results to the researcher. This is particularly useful when studying highly distributed networks like wireless mesh networks. Simulation studies are very scalable, flexible and cost effective. In sub-sections 3.3.1 and 3.3.2, we review a number of simulation-based studies on energy efficiency and general performance of Routing and Transport Layer protocols respectively.

3.3.1 Simulation-based Energy Efficiency and General Performance of Routing Protocols

This section reviews a number of existing simulation-based studies on energy efficiency and the general performance of Routing Protocols in wireless ad hoc and mesh networks.

3.3.1.1 Performance Analysis of Routing protocols [Tyagi and Chauhan, 2010]

The performance of a routing protocol in a WMN is an important issue, due to highly dynamic nature of WMNs. Some of the issues affecting the performance of routing protocol include: limited battery back-up, low processing capability and inadequate memory resources of the network nodes. Apart from the efficient utilization of the battery, efficient routing and security are other important areas of concerns for routing protocols.

In this study [Tyagi and Chauhan, 2010], a performance analysis and comparison of three ad hoc networks protocols was performed. The protocols include two reactive protocols (AODV, DSR) and a proactive protocol (DSDV). The performance metrics considered include packet delivery ratio, packet loss, routing overheads and average end-to-end delay. The study was simulation based and the tool that was used for simulation is Network Simulator two (NS2).

The series of simulation results from this study shows that both AODV and DSR outperformed DSDV in terms of packet delivery ratio and packet loss. AODV outperformed the others in dense environment except for packet loss. AODV and DSDV outperformed DSR in terms of average end-to-end delay, while DSR outperformed others in terms of packet loss. Based on the results of this study [Tyagi and Chauhan, 2010], it was concluded that; theoretically, DSDV routing overhead is negligible. Whilst it is not very clear that any one protocol is best for all the scenarios, each protocol possesses its own advantages and disadvantages and may be well suited for certain scenarios. Hence, our study shall improve on this study by investigating the protocols performance using testbed, so as to be able to know which protocol suits best for all the scenarios.

3.3.1.2 Energy-Flow Model for Self-Powered WMNs [Pejovic *et al,* 2009]

The quality of service (QoS) being delivered by WMNs in the rural areas of developing nations are often bounded by some fundamental issues like the irregular/unavailability of electrical power supply to the nodes. As a result of the nodes' dependency on renewable power sources and variable energy consumption, it becomes difficult to predict the available energy and provide a reliable network communication performance.

In [Pejovic *et al*, 2009], an energy trend was estimated and an energy-flow model was developed, which makes provision for communication and energy reaping hardware equipment specifications (time-varying weather information and high resolution, complex interaction among the nodes). The objective of this study was to design an energy-flow simulation model using NS2 for self-powered wireless mesh networks deployment in rural areas of developing countries, due to their poor electrical power supply. Based on the designed model, a Lifetime Pattern-based Routing (LPR) protocol was developed.

In order to test the validity of the model that was developed, an energy-aware routing protocol and operational LPR (Lifetime Pattern- based Routing) were introduced. And it was specifically designed for a self-powered wireless mesh network. The operational lifetime pattern-based routing decisions were based on the estimated energy level provided by the energy-flow model. The weather sensor traces collected from actual self-powered rural wireless network nodes were used for the LPR protocol simulation.

Based on the series of simulation results from this study, the developed LPR protocol balances the available energy plan for use by all nodes and as a result, power failures were evenly distributed among all participating nodes. It was also shown that the developed LPR performs better than the existing works in wireless network routing.

The simulation method of evaluation was used in this study and the energy efficiency was measured using only operational lifetime. The lifetime only provides a high-level look at the energy efficiency, while the average energy cost per bit provides an indication of the utility of a node whilst it is alive by assessing the amount of data received within the achieved node lifetime. Hence, our study shall improve on this work by considering both the operational Lifetime and Average energy cost per bit in determining the energy efficiency of both Routing and Transport layer protocols using simulation and testbed.

3.3.1.3 Maximizing Network Lifetime in WSNs

[Chang and Tassiulas, 2004]

Power consumption in the wireless networks can be largely categorized into two parts: the communication related and non-communication related such as processing or sensing. In [Chang and Tassiulas, 2004], the objective was to extend the network lifetime of a battery-powered wireless sensor network by reducing the energy consumption at the receiver's node. The lifetime was defined as the time until the network partition occurs due to energy source outage. Chang and Tassiulas formulated a routing problem in the form of a Linear Programming problem. Constant rates and arbitrary information generation rate processing model were considered. Shortest-cost path routing algorithm was proposed, which made use of both the residual energy levels and the communication energy consumption rates at both the receiving and sending nodes. The link cost of the proposed algorithm is a combination of reception energy consumption, transmission energy and the residual energy levels at both end nodes.

The newly formulated problem showed that the minimum total energy routing was not suitable for network-wise optimal consumption of transmission energy. This work showed that, significant improvement can be made by the newly proposed routing algorithm in terms of maximizing the lifetime of the system. A simulation method was used to test the validity of the linear programming algorithm that was formulated. The results for both constant and arbitrary information-generation process models show that the shortest-cost path routing algorithm that was proposed can obtain a network lifetime result that is close to the result obtained by using the linear programing for optimal network lifetime.

3.3.1.4 Energy-Aware Behavior of Routing Protocols

[Fotino *et al,* 2007]

The power source of a node is one of the main factors that determines a node's operational lifetime. In battery-powered MANETs, the efficient utilization of battery powered nodes are important, because it can affect the overall performance of the network by causing network partitioning. Hence, reducing the power consumed by the nodes in MANETs becomes an important issue that needs to be addressed. The routing protocols of a MANETs can consume different amounts of energy and their various routing decisions may be conditional. The energy consumption should be equally distributed on the MANETs nodes and the overall transmission power for each connection should be minimized.

In [Fotino *et al,* 2007], two different routing protocols for Mobile Ad Hoc Networks (MANETs) were modelled. These protocols include Dynamic Source Routing (DSR), which represent reactive protocols and Optimized Link State Routing (OLSR), which represent proactive routing protocols. The two protocols (DSR and OLSR) were analyzed using energy efficiency as the main metric. The study is simulation-based and the tool that was used for simulation is Network Simulator two (NS2).

The two main objectives of [Fotino *et al*, 2007] included the evaluation of how different approaches affect the energy consumption of MANET nodes, using OLSR (proactive) and DSR (reactive) routing protocols. The second objective was to evaluate how some of the proposed energy aware routing in the literature can be effectively utilized to extend the operational lifetime of the IEEE 802.11 technology. The series of simulation results from this study show that, in a static connection pattern scenario, DSR outperformed

OLSR in terms of their energy consumption due to its reactive nature. However, when the traffic load was high and the network was dense, OLSR performed better. It was also observed that DSR was more adaptive to dynamic networks and this made it recover its lost path quickly which led to better average throughput performance.

When the node mobility was low, OLSR can achieve high performance in terms of end-to-end delay and load balancing. However, this advantage was lost when the node mobility was high and when the wireless ad hoc network was dense, the overhearing problem can affect the operational lifetime of the nodes, irrespective of the routing protocol.

In the case of mobile and wireless networks, which have a very intricate and dynamic environment, some of the simulation environments are far from being realistic and this leads to results that most times do not fit with real-world measurement [Zimmermann *et al,* 2007]. Also, the operational lifetime only provides a high-level look at the energy efficiency. Hence, our study shall improve on this study by evaluating the energy efficiency of both routing (AODV and OLSR) and transport layer protocols (TCP and UDP) on a testbed, using both the lifetime and average energy cost per bit metrics.

3.3.2 Simulation-based Energy Efficiency and General Performance of Transport Layer Protocols

This section reviews a number of existing simulation-based studies on energy efficiency and general performance of Transport Layer Protocols in wireless ad hoc and mesh networks.

3.3.2.1 TCP Performance over Routing Protocols [Ahuja *et al,* 2000]

Mobility is one of the causes of link failures in ad hoc networks and TCP cannot distinguish between route failure packet loss and packet loss that occurred as a result of congestion.

In [Ahuja *et al*, 2000], the performance of TCP in ad hoc networks were analyzed over four different ad hoc routing protocols. These routing protocols are: DSDV, SSA, DSR and AODV. This study used simulation method to investigate the performance of TCP over the four routing protocols. Simulations were carried out using network simulator (NS2) with CMU (Carnegie Mellon University) extensions. The only performance metric that was measured is throughput.

This simulation created an ad hoc network, consisting of twenty-five mobile nodes, with variations in movement speeds and node mobility rates. As the mean speeds of nodes increased, the TCP throughputs decreased and the route failure frequency increased.

TCP performance over AODV and DSR outperformed others in terms of their throughput at all levels of mobility and this was due to the fact that AODV and DSR are both on-demand routing protocols, which searches for a route only when the need arises. Whilst the TCP performance over DSDV was the least performing among all the scenarios considered and DSR outperform others at low mobility. Based on the obtained results, it was inferred that the routing overhead, delay in route establishment and route failures were the key factors that are affecting TCP throughput in wireless ad hoc networks.

3.3.2.2 Comparison of TCP Performance over Routing Protocols in Wireless Networks [Dyer & Boppana, 2001]

The literature has shown that as a result of the temporarily broken routes in mobile ad hoc networks, the congestion control mechanisms of TCP react badly to packet loss.

In simulation-based study [Dyer & Boppana 2001], the TCP performance for bulk data transfer in MANETs was considered. The two main goals of this study were to compare the TCP performance over different routing protocols and to also investigate the sender-based heuristic called “fixed RTO”, to distinguish between packet loss as a result of congestion and packet loss as a result of route failures. The TCP connections were varied and the performance of three different routing protocols was compared. The routing protocols considered included AODV, DSR and ADV, where AODV and DSR are reactive routing protocols representative and ADV represents a proactive routing protocol.

The NS2 simulations were conducted to measure the TCP performance for a large volume of data transfers over the three different routing protocols (DSR, AODV and ADV). Based on the series of simulation results presented in this study, ADV outperformed the others in terms of low connection time and higher throughputs, under different conditions. And the proposed fixed RTO techniques enhanced the AODV and DSR performance significantly, because the higher the number of TCP connections, the higher the AODV and DSR packet delivery rates.

3.4 Testbed-based Energy Efficiency and General Performance Studies

In all the studies discussed in the previous section, simulations were used as the evaluation platform. In mobile and wireless networks, which have a very complicated and dynamic environment, some of the simulation environments are far from realistic and this leads to results which in most times do not fit with real-world measurement [Zimmermann *et al,* 2007]. Therefore, in this section, a number of existing testbed-based studies on energy efficiency and the general performance of Routing and Transport Layer Protocols in wireless ad hoc and mesh networks were reviewed.

The testbed is one of the best environments to study WMN protocols performance. Usually, testbed evaluations are conducted by implementing a prototype; hence, the results and conclusions can be easily transferred to real life, since the prototype and the results obtained from a testbed possess a higher-degree of reality than theoretical and Simulation-based counterparts.

Sub-sections 3.4.1 and 3.4.2 reviewed a number of simulation-based studies on energy efficiency and general performance of Routing and Transport Layer protocols respectively.

3.4.1 Testbed-based Energy Efficiency and General Performance of Routing Protocols

The evaluation and design of energy aware routing protocols in wireless networks requires the knowledge of energy consumption behavior of the actual wireless network interface. The practical information that is available concerning the energy consumption behavior of well-recognized wireless network interface and device specifications is little. Hence, lack of enough practical information has affected the swift development of protocols by the protocol developers. The next three sub-subsections generally reviewed testbed-based studies on energy efficiency and general performance of routing protocols in wireless ad hoc and mesh networks.

3.4.1.1 Broadband Wireless Mesh Networks Testbed [Akyildiz *et al,* 2005]

In [Akyildiz *et al,* 2005], an indoor wireless mesh networks testbed called Broadband and Wireless Network (BWN) was set-up at Georgia Institute of Technology. In this wireless mesh network testbed, there are fifteen IEEE 802.11b/g based mesh routers and some of them were connected to the Internet.

The routers were located in various parts of the rooms on the floor where the broadband wireless network indoor testbed were located. Most of the routers used for this testbed were laptops, by using the system NIC which are capable of running in 802.11b/g mode.

The effects of distance in-between the routers and clustering was investigated by changing the network topology and node mobility.

In this study, the existing protocols (IEEE 802.11g as MAC protocol, AODV as routing protocol and TCP as transport layer protocol) were evaluated and the evaluation results show that the performance of these traditional protocols are below the IEEE standard expectations, in terms of throughput and end-to-end delay in wireless mesh networks.

3.4.1.2 Energy Consumption of a Wireless Network Interface [Feeney and Nilsson, 2001]

In [Feeney and Nilsson, 2001], a sequence of experiments was carried out to obtained detailed measurements of the energy consumption of an IEEE 802.11 MANET interface in an ad hoc operating environment.

The measurements of different energy consumed in the course of sending, receiving and discarding of packets at various sizes were presented as collection of linear equations with a visual form which emphasize the general conclusions.

When in ad hoc mode of operation, the idle power consumption is of considerable value, as hosts needs to maintain their network interfaces in idle mode so as to work together in maintaining the ad hoc routing fabric. Particular attention was paid to the partitioning of routing protocols, which dynamically maintain a cluster-based “infrastructure” and may be well-suited to apply some modifications to the management of energy techniques used in a base station environment.

The presented data was a collection of linear equations for calculating the energy consumed in sending, receiving and discarding broadcast and various packet sizes.

The series of experimental results from this study show that the energy consumption of an IEEE 802.11 wireless interface has a complex range of behaviors that are of importance to the design of low energy consumption routing protocols. The evaluation and design of energy-aware routing protocols should consider factors such as the point-to-point traffic, relative proportions of broadcast, packet size and promiscuous reliance on the mode of operation.

3.4.1.3 Energy-Aware Routing Protocol in WSNs [Liu *et al,* 2009]

In [Liu *et al*, 2009], the proposed energy-aware routing protocols take the remaining battery levels of nodes into consideration, when the routing decisions were made. The rationale applied to this type of routing is that nodes with lower battery levels were employed to forward network traffic only as a last resort, thus conserving energy. The resultant energy conservation prolongs the lifetime of the node.

Clustering was used in this study to provide a hierarchical approach to routing in sensor networks. The remaining energy levels of cluster nodes were taken into consideration to determine the cluster head that assumes the routing responsibilities. The proposed energy aware protocol scheme was found, through simulation to improve the network nodes lifetime by controlling the number of active neighbors in each cluster.

Despite showing that the size of the active neighbourhood of the cluster head impacts on the node lifetime, the influence of the sleep state on the node lifetime performance cannot be discounted since wireless mesh networks nodes typically do not employ such a state.

It is believed that the number of hop(s) between the sender and receiver is one of the key factors when considering node lifetime because of the broadcast nature of wireless mesh networks communications, which forces nodes to expend energy in decoding packets even if those packets are not intended for them. Thus, the greater the number of hops between source and destination, the greater the total energy spent in decoding and re-encoding the packets.

In our testbed study, we shall investigate the impact of hop-count on the node lifetime and other performance metrics (throughput, packet delivery ratio and average end-to-end delay), using simulation and indoor testbed.

3.4.2 Testbed-based Energy Efficiency and General Performance of Transport Layer Protocols

Energy is one of the major factors that determine the operational lifetime of an energy constrained ad hoc networks. Hence, it is imperative to reduce the energy consumption of the ad hoc network communication.

Various energy efficiency techniques have been proposed in the Transport Layer to reduce the energy consumption of the network nodes. The next four sub-subsections generally reviewed testbed-based studies on energy efficiency and general performance of transport layer protocols in wireless ad hoc and mesh networks.

3.4.2.1 Analysis of TCP Performance in Ad hoc Networks [Anastasi *et al,* 2006]

In [Anastasi *et al*, 2006], an experimental analysis of TCP over IEEE 802.11b/g in a static multi hop wireless ad hoc network was presented. Two different routing protocols (AODV and OLSR) were used for the performance analysis.

An indoor testbed was used to test the validity of some of the previous simulation results that have been presented in the literature. However, for the sake of equal and better comparison with simulation results, TCP was investigated using a static chain topology along with different hop counts. This indoor testbed comprises of five nodes, which were made up of IBM R-50 laptops, equipped with IEEE 802.11b compatible wireless cards and running Linux kernel 2.6.12 with ipw2200 driver.

The transmission power of the wireless cards was set to the minimum value allowed by the manufacturer (-12dbm) in order to reduce the transmission range and to force a multi hop network. Four different scenarios were considered with various hop counts that range from 1 to 4. Whilst two performance metrics were measured: throughput and retransmission index ("the percentage of segments re-transmitted by the sender TCP").

The results of this study were presented alongside with simulation results. Some of these experimental results are in contrast with that of simulation and such discrepancies were largely due to different kinds of protocol implementations; where the one in real practice differs from that of simulation tools.

Another reason for the discrepancies in the results was the existence of several wireless access points within the vicinity which lead to some interference in the transmission.

Based on the results of this study, it was shown that a small value for the re-transmission index is important in order to achieve a better energy-efficiency in a power-constrained wireless network.

3.4.2.2 TCP Energy Consumption in Ad hoc Networks [Singh and Agrawal, 2001]

In [Singh and Agrawal, 2001], the energy efficiency (communication cost and protocol processing) of four different TCP variants in ad hoc networks was investigated, in order to reduce their various energy consumption. The four TCP variants studied are: Selective ACKnowledgement (SACK), Reno, Newreno and TCP-ECN-ELFN.

This study utilized a testbed and three metrics were measured: idealised energy consumption, total energy consumed and the protocol goodput for data transfer. The idealised energy consumption is the energy consumed by the sender when receiving or transmitting the data which does not include the node idle energy.

The results of this study show that in all of the scenarios considered, TCP-ECN-ELFN outperformed Reno, Newreno and TCP-SACK in terms of lower energy consumption and it delivers higher goodput depending on the conditions of the network.

3.4.2.3 TCP Energy Computational Cost in MANETs [Wang and Singh, 2004]

In [Wang and Singh, 2004], the node-level cost of TCP and the breakdown of the energy consumption for different TCP functions were studied. The aim of the study was to evaluate and analyze the energy consumed by different operations of TCP. Laptops and an iPAQ equipped with IEEE 802.11b network card together with three different operating systems (Linux 2.4.7, FreeBSD 4.2 and FreeBSD 5.0) were used as the platforms for the evaluation. The processing cost of major TCP functions (triple duplicate ACKs and timeouts) was determined. Some measurement techniques were developed to measure the energy consumption of TCP for different functions performed by the sender and the receiver.

The energy consumption measurement results showed that 60-70% of the transmission or reception energy is accounted for by the kernel network interface card copy operation. The remaining 30 - 40% was accounted for by the TCP processing cost. Based on these results analysis, an energy saving (20-30%) technique for computational cost of TCP was presented.

3.4.2.4 Experimental Investigation of TCP Performance [Kawadia and Kumar, 2005]

In [Kawadia and Kumar, 2005], a detailed experimental study of TCP performance over wireless networks was presented. In investigating the performance of TCP, three parameters were varied and these include congestion window size, RTS/CTS mechanism (enabled/disabled) and selective ACK (enabled/disabled).

This study was investigated using an indoor testbed and three metrics that were measured, which include throughput, average end-to-end delay and jitter experienced by TCP segments.

Laptops equipped with IEEE 802.11b Aironet 350 series wireless network cards together with Linux kernel 2.4.19 version of operating system were used as the platforms for the evaluation. The cards has six various levels of transmission power and in order to reduce the cards communication and transmission range so as to be able to create different topologies, the cards antenna were partly covered with copper tape.

The major concern of this study was to investigate the factors that affect the TCP performance over a multihop wireless network, even when the network is not mobile.

In all the previous studies discussed, no routing protocols were used and this would have impact on the results, because the routing protocols also contribute to the energy consumption of the node and some of the other performance metrics in a real wireless networks environment. Laptops and iPAQ were used as the nodes in all the studies, and this would affect some of the obtained results, because of the processing cost and the transceiver power level of a laptop network card, which would affect the throughput and the energy consumption of the network.

In our study, we shall investigate the energy efficiency and the general performance of both TCP and UDP using AODV and OLSR routing protocols in an indoor testbed. The IEEE 802.11b/g Linksys WRT54GL router, which is a popular and realistic WMN node, will be employed and the study shall measure the node lifetime, average energy cost per bit, packet delivery ratio, average end-to-end delay and throughput.

3.5 Summary

This chapter has reviewed three different evaluation methodologies (mathematical-based, simulation-based and testbed-based) that are commonly employed in the studies of energy efficiency and some other performance metrics of Routing Protocols and Transport Layer Protocols in wireless ad hoc and mesh networks.

Mathematical-based analysis of Wireless Mesh Networks has limitations, since the mathematical constructs get very complex for realistic considerations. Currently, useful mathematical tools do not exist [Zimmermann *et al,* 2007] and in the case of mobile and wireless networks, which have a very complicated and dynamic environment, most of the simulation environments are far from being realistic and this leads to results that do not fit with real-world measurement [Zimmermann *et al,* 2007]. Table 3.1 summarizes the three prominent evaluation methodologies in wireless ad hoc networks, which were reviewed in this chapter.

Table 3.1: Summary of Evaluation Methodology Behavior in Wireless Ad hoc Network

Characteristics	**Environments**		
	Mathematical Analysis	**Simulation**	**Real Testbed**
Transport	——	Low	High
Network/Routing	——	Low	High
Datalink	——	High	High
Applicability	Poor	Low	High
Controllability	high	High	Low
Scalability	——	High	Low
Scenario Creation	——	Simple	Complex
Duration	——	Varies	Real
Cost	——	Low	High

In the case of routing protocols, many protocols have mostly been proposed for use in sensor network and mobile ad hoc networks and this is due to the assumption that WMN nodes do not suffer from power supply constraints. The majority of the proposed protocols were evaluated via theoretical- and simulation-based evaluations. Whilst very few used a testbed [Akyildiz *et al*, 2005 and Liu *et al*, 2009], the nodes used for these testbed were laptops [Wang and Singh, 2004 and Anastasi *et al*, 2006], which would affect the results because of the laptop network card processing and transceiver power level.

In transport layer protocols, all the analysis was based on TCP's performance and none of them focused on UDP. Similarly, most of the analyzed work that are under static conditions did not consider any specific routing protocol in their evaluation. This would have an impact on the results, because the routing protocols also contribute to the energy consumption and the general performance of the wireless networks.

In this study, we shall investigate the performance of both TCP and UDP using both AODV and OLSR routing protocols on a testbed. The IEEE 802.11b/g Linksys WRT54GL router, which is a common hardware platform for wireless mesh networks deployments, will be used as the testbed nodes. The following metrics will be measured on the testbed; node lifetime, average energy cost per bit, packet delivery ratio, throughput and average end-to-end delay.

In the next chapter, details of the evaluation methodologies being employed in this study and the various performance metrics measured are described. Details of the measurement methodologies employed are also given in the next chapter.

CHAPTER FOUR

SETUP OF EXPERIMENTAL AND SIMULATION ENVIRONMENT

4.1 Introduction

One of the main challenges for researchers of wireless networks is the ability to carry-out reliable evaluations and performance analysis of different protocols. In the previous chapter, three different evaluation methods (mathematical, simulation and testbed) were explored, which researchers use for the evaluation and validation of their results in wireless ad hoc and mesh networking. The limitations of mathematical method of evaluation were also highlighted in the previous chapter.

This study employs both simulation and testbed evaluation platforms for reasons previously discussed. This chapter describes the setup and construction of an indoor wireless mesh network testbed and the simulation setup used for this study, so as to assist other researchers to create a similar facility. In addition, a description is given of the measurement methodology used to carry out the different experiments and simulations, which help to evaluate the effect of existing QoS mechanisms on battery-powered wireless mesh networks.

4.2 The Wireless Mesh Testbed Setup

The mesh testbed comprises of fourteen nodes, which were arbitrarily placed in an 8m by 12m room and for the purpose of clarity, the nodes were labeled from N1 to N14 as depicted in *Figure 4.1*.

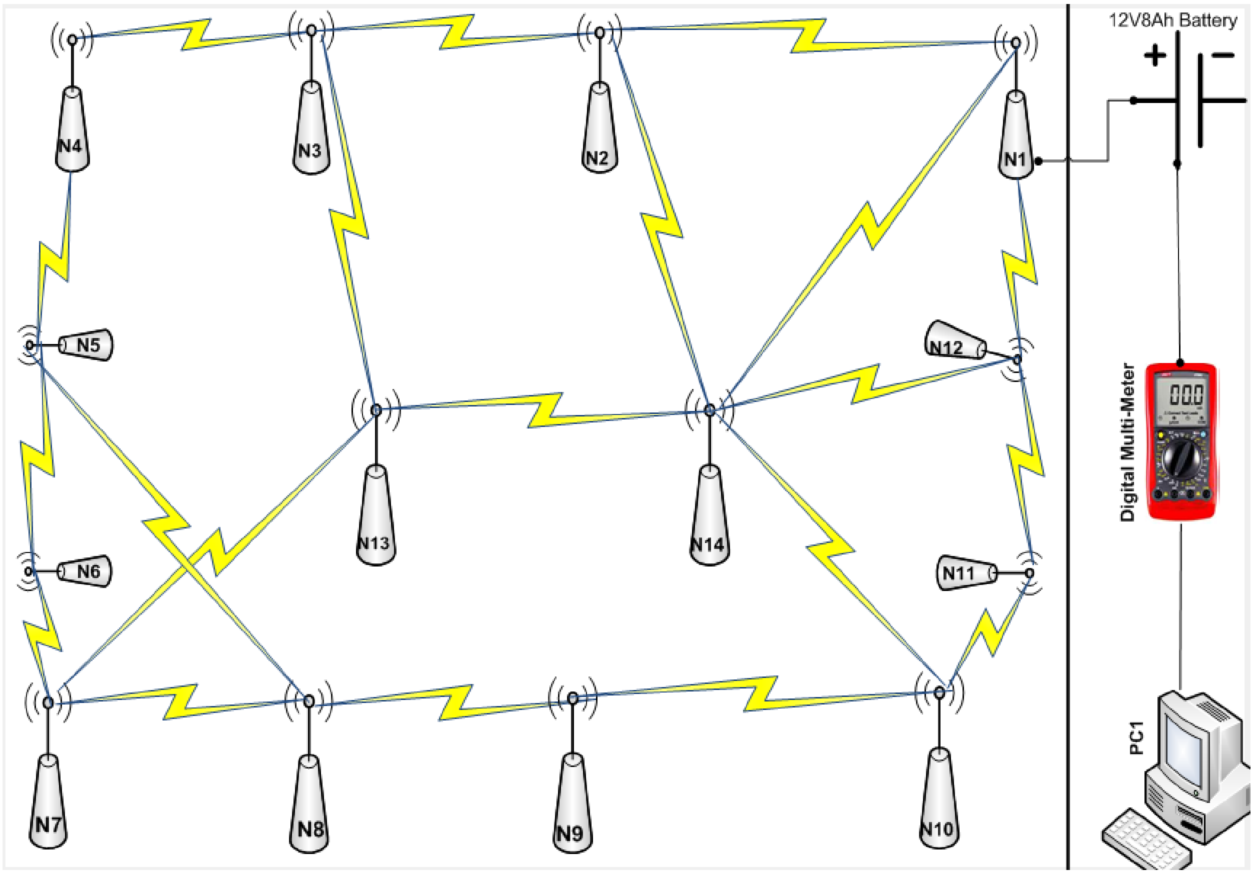

Figure 4.1: The architecture of the Mesh Testbed

The node N1 was powered using 12V8Ah battery connected with a Digital Multi-meter (DMM) and the Digital Multi-meter was connected with a central data collection PC1 as also depicted in *Figure 4.1*, while the remaining nodes were mains powered. Cisco Linksys WRT54GL version 1.1 routers with OpenWRT Freifunk v1.7.4 firmware were installed to provide mesh functionality. WRT54GL routers were chosen for this study, because they are popular choice for WMN deployments such as in [Lundgren *et al*, 2006, Ismael *et al*, 2008], due to their cost effectiveness and easy availability. The Linksys WRT54GL v1.1 routers possess a CPU speed of 200MHz, a Broadcom 802.11b/g radio chipset, 16MB of RAM and 4MB flash memory. The wireless chipset allows transmission power output levels to be set between 0 and 19dBm, which is the maximum output power recommended by the manufacturer.

This testbed is located within a faculty building with laboratories and offices. Hence, there are several other wireless LANs that are operational within the proximity. This mesh testbed was operated in 802.11g mode at 2.4GHz with channel 6 so as to reduce the interference caused by other wireless LANs that are operational within the building.

Each of the testbed nodes is equipped with a pair of 5dBi gain antenna and these antennas were disconnected in order to reduce the radio signal and the transmission range so as to be able to force a real multi-hop wireless network within an indoor environment.

One of the key challenges in setting up a testbed using actual routers is getting implementations of the routing protocols that are well written and are RFC compliant [Johnson and Lysko, 2008]. There are currently more than 100 known Mobile Ad hoc networks routing protocols which can run in a simulation environment such as NS2. Unfortunately, approximately 16 have an implementation which can execute on both the simulation and testbed platforms. Optimised Link State Routing (OLSR) has seven implementations, Ad hoc On-Demand Distance Vector (AODV) has ten, Dynamic Source Routing (DSR) has four, Topology Broadcast based on Reverse-Path Forwarding (TBRPF) has one and Dynamic MANET On-demand (DYMO) has two, at the time of this write-up.

The selection of AODV-UU [Nordstrom, 2008] and Tonnesen OLSR [Tonnesen, 2004] routing protocol for this study (among several implementations of these protocols) was based on the fact that they are RFC compliant (AODV RFC3561, OLSR RFC3626) and the same code base can be used for both simulation and testbed evaluations.

There were a series of challenges in installing AODV on the Linksys WRT54GL v1.1 and actual routers generally [Johnson and Lysko, 2008, Brolin and Hedegren, 2008], which was also experienced during the setup of this study testbed. Some of these challenges include:

1. Lack of multi-hop (2-hops and above) functionalities among the nodes
2. Automatic restart of the nodes after every 1500secs
3. The iptables forwarding conflicts
4. Frequent Link failure
5. Lack of support from OpenWRT support team

These challenges are not encountered during the simulations and the first two were not encountered when using laptop/desktop equipped with NIC as the routers/nodes. As a result of some of these challenges, most WMN researchers [Johnson and Lysko, 2008, Brolin and Hedegren, 2008] are not interested in using AODV for their evaluations, despite some of its advantages.

In this study, the first three challenges were resolved and the fourth one was partially resolved. These challenges were resolved by editing the Freifunk Firmware version 1.7.4 as briefly explained below.

Freifunk (http://start.freifunk.net/) is a firmware designed based on openWRT technology and it is OLSR-based. OLSR is disabled using Linux "killall" function; thereafter, AODV-UU 0.9.3.ipk was installed using "ipkg install" function. And lastly, the "insmod" and "use_dev" functions were used to activate the AODV routing protocol. The installation details and the script employed to get AODV up and running are contained in Appendix C.

The OLSR protocol is a proactive protocol where all nodes maintain routing table entries for all the remaining network nodes. Control messages are propagated via a smart broadcasting system that relies on nodes called Multi-Point Relays to disseminate these messages. The OLSR-based OpenWRT Freifunk firmware version 1.7.4, which is the current version as at the time this testbed setup was installed. OLSR was configured to use the default settings specified in RFC3626 and comes packaged with the OpenWRT Freifunk firmware (v1.7.4). The OLSR visualization package enables easy assessment of the network connectivity.

In this study, TCP was used as the transport layer protocol for the connection oriented applications, while UDP was used as the transport layer protocol for the connectionless oriented applications. The NetScanTool Pro version 11.0 was utilized to generate both the TCP and the UDP traffic. The TCP window size was set to 16384, the packet timeout was 3000ms, while the source and destination port were set to 49724 and 80 respectively. In addition, the UDP source and destination ports were set to 890 and 14685 respectively. These settings represented the default settings used by the NetScanTool application except for the packet data length (either 32 or 512 bytes) and the number of packets sent (dependent upon the node lifetime achieved).

The transmission power levels used by the testbed nodes were varied by using either the minimum or maximum level (1dBm or 19dBm). By varying the transmission power levels, the change in power level on the energy efficiency of the existing QoS can be studied. The NetScan basic settings for both TCP and UDP is depicted in Figure 4.2. Table 4.1 summarizes the testbed configuration that was used in this research work.

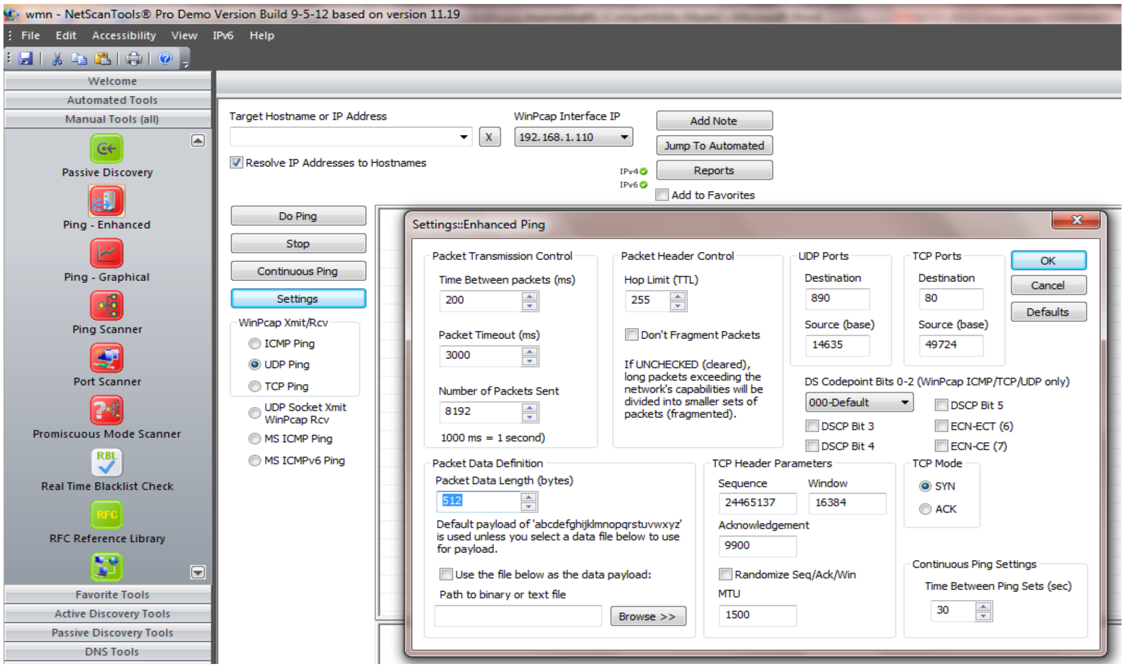

Figure 4.2: NetScanTool Basic settings

Table 4.1: Testbed Configuration

Power Supplies	Rechargeable 12V8Ah battery and mains supply
Transmission Power	1 dBm and 19 dBm
Channel/Frequency	6/2.34 GHz
Mac protocol	IEEE 802.11g
Data Rate	1 Mb/s
Packet Size	32 bytes and 512 bytes
Traffic Generation Tool	NetScanToolPro 11.0
OLSR based Firmware AODV based Firmware/version	OpenWRT freifunk v1.7.4 OpenWRT freifunk v1.7.4 /AODV-UU 0.9.3.ipk
Routing Protocols	OLSR, AODV
Transport layer Protocols	TCP, UDP

4.3 The Simulation Setup

The simulation environment used for this research work is made of a set of extensions designed for static wireless networks. Other researchers have widely used these extensions and the release of the standard VINT which lead to the release of NS-2, was as a result of the adoption of this version for the wireless networks extensions.

The Network Simulator version 2.34 (NS2) software running on Ubuntu 9.10 operating system was used to conduct an extensive simulation for this study. NS2 is an open-source event-driven simulator tool that was designed particularly for research in computer communication networks [Fall and Varadhan, 2008]. NS2 can be used to simulate both wired and wireless networks and it is primarily Linux based which also contains modules for numerous network components such as application, MAC, routing and transport layer protocols. NS2 uses two languages, namely: an object oriented simulator (written in C++), and an OTcl (an object oriented extension of Tcl language) interpreter, used to execute user's command scripts [www.isi.edu/nanam/ns].

The wireless nodes in this simulation study were modelled on a Cisco Linksys WRT54GL v1.1 router [Linksys Inc, 2007] using NS2.34.

Appendix A shows the simulation script that was used for WRT54GL router modeling. This particular router model was used for our simulation in order to approximate the testbed, so as to be able to compare the testbed results with that of simulation.

The simulation version of AODV designed by Uppsala University (AODV-UU 0.9.3) together with UM-OLSR version 0.8.8 were used as the routing protocols, while the NS2 default TCP and UDP were used as the transport layer protocols for the simulation. All the protocols (Routing and Transport) used were the ones implemented according to the corresponding RFC standard.

Various network sizes, ranging from 20 to 120 wireless nodes were statically spread over a rectangular 400m x 400m flat space for 100s of simulated time.

The "*setdest*" utility of ns-2.34 was used to generate Scenario files for varying number of nodes (20-120) and keeping pause time and simulation time constant. While the *"cbrgen.tcl"* utility of ns-2.34 was also used to generate both TCP and UDP Constant Bit Rate (CBR) traffic files. The maximum number of connections (mc) was set to be equal to the number of the nodes for each experiment, while the data communication rate was set to four packets per second and two different packet sizes (32 bytes and 512 bytes) were used. These packet sizes are mutually exclusive (only one of the two sizes is active at any single time during our simulation). *tTcl* scripts were run over in order to generate the trace files for various protocols OLSR, AODV, TCP and UDP.

The detailed trace files generated from the various simulation experiments were stored and analyzed using an AWK script [see Appendix B], while Microsoft Excel and gnuplot were used to plot the graphs.

Table 4.2 summarizes the simulation setup details that were used in this research work.

Table 4.2: Simulation Setup Details

Simulation Time	100 Seconds
Number of Nodes	20-120 nodes
Network Area	400m x 400m
Routing Protocols	AODV, OLSR
Transport Layer Protocols	TCP, UDP
Traffic type	CBR
Packet Size	32 bytes, 512 bytes
Rate	4 kb/s
Nodes movement	Static
Initial Energy	1.0 Joule
Transmit Energy	o.6W
Receive Energy	0.3W

4.4 Measurement Process

This section present the evaluation parameters used to evaluate the effect of routing and transport layer protocols on the operational lifetime of a battery-powered WMN node. The following measurement procedures were used for each of the metrics being measured:

4.4.1 Packet Delivery Ratio (PDR)

PDR is defined as the fraction of all the data packets from the sender node that reaches the destination node at the application layer. Different payload sizes (32 and 512 bytes) were specified using NetScanTool 10.0 application. An optimal route needs to have high packet delivery ratio, hence, the higher the value the better the network performance. This metric will give us an idea of how effective different combinations of routing and transport layer protocols perform in terms of packet delivery at different transmission power level using different payload sizes. PDR was calculated using the formula below:

$$pktdeliveryratio = \frac{num_{sent}}{num_{received}} * 100$$

The total number of packets sent is denoted by num_{sent}, while the total number of packets received is represented by $num_{received}$.

4.4.2 Average Throughput

Throughput is determined by the number of data packets that were processed over a period of time. The throughput is measured at the application layer and the data traffic is generated between the source node (N1) and the destination node (N7) as depicted in *Figure 4.1*. Both the number and size of the data packets could be varied. Payload size of 512 and 32 bytes were employed in this study and the higher the throughput value, the better the network performance. The throughput is calculated using the formula below:

$$throughput = \frac{num_{reveived} * payload\_size}{sim\ \_time}$$

Where the total number of packets received is represented by $num_{received}$ and $sim\ \_time$ is the total simulation time.

4.4.3 Average End-to-End Delay

The average end-to-end delay is the time taken to successfully transmit a packet from the source node to the intended destination node. This time ends after the source node have received the acknowledgement from the destination node to confirm that the packet was successfully received. This metric is calculated by subtracting "time at which first data packet was transmitted by source" from "time at which first data packet arrived at destination". And this includes all possible delays caused by queuing at the interface queue, buffering during route discovery, retransmission and propagation delays at the MAC and transfer times. The lower the delay value, the better the performance.

4.4.4 The Node Lifetime

The node lifetime is defined as the length of time for which the node remains powered by its power source. This metric was determined by measuring the elapsed time until the battery discharges from a fully-charged 12.5V to a pre-defined threshold voltage of 10.5V. The threshold voltage value was derived based on initial experimentation with the battery. This threshold value is considered a safe value for ensuring that the battery is not damaged during the discharge process.

The nodes used in this testbed are capable of adjusting their transmitting power levels between 1-19dBm. The *wl* utility was employed to adjust the transceiver power levels while the Digital Multi-meter (DMM) data capture was used to capture the real-time node operational lifetime voltage. Data packets were sent from the source node (N1) to the destination node (N7), until the battery threshold voltage was reached. This metric will record the duration for which a 12V8Ah battery can effectively power the WMN nodes when subjected to different scenarios.

4.4.5 Average Energy Cost per Bit

This metric is defined as the average energy it takes to successfully transmit one bit of data packet from the source node to the destination node. The average energy cost per bit is calculated using the formula below:

$$Avg\_Energy\_Cost = \frac{Total\ Energy\ in\ Joules}{Total\ packet\ delivered * Payload\ Size}$$

The Total Energy in Joules was calculated as follows:

$$Total\ Energy\ in\ Joules = P_{(w)} * t_{(s)}$$

$t_{(s)}$ is described as the node lifetime and $P_{(w)}$ was calculated using the formula:

$$P_{(w)} = I_{(A)} * V_{(v)}$$

Where $P_{(w)}$ is Power measured in watts, $I_{(A)}$ is the Current measured in amps and $V_{(v)}$ is the Voltage measured in volts.

The fully charged battery that was used for the testbed experiments is 12.5V8Ah (V=12.5V and I=8A). Hence, the power in watts is equal to 100W.

The value of the total packet delivered varies for each of the scenarios that were considered. Two different payload sizes were considered, the maximum payload size is 4096 bits and the minimum payload size is 256 bits.

4.5 Summary

This chapter has presented both the experimental testbed setup details and the simulation setup details that were used to conduct the experiments. These experiments will be analyzed and discussed in the next chapter. Both the simulation and testbed setups were homogeneous, so as to be able to compare the simulation and testbed results. The evaluation metrics used to evaluate the effect of routing and transport layer protocols on the operational lifetime of battery-powered WMN nodes were presented. The performance metrics considered include: packet delivery ratio, throughput, average end-to-end delay, node lifetime (the length of time for which the node remains in proper working order) and average energy cost per bit (average energy it takes to successfully transmit one bit of data packet from the source node to the destination node).

The next chapter presents the experimental results obtained from both the simulation setup and the testbed setup, using the evaluation metrics described in this chapter.

CHAPTER FIVE

SIMULATION-BASED PERFORMANCE ANALYSIS

5.1 Introduction

The previous chapter presented both the simulation setup and the testbed setup alongside the performance metrics used in this study. The goal of this evaluation is to determine the effect of TLPs and Routing Protocols on the operational lifetime of a battery-powered WMN node. In order to achieve this goal, we analyze the performance of Reactive (AODV) and Proactive (OLSR) Routing protocols together with connection (TCP) and connectionless (UDP) Transport Layer protocols when subjected to various payload and network sizes. Apart from PDR, Average Throughput and Average End-to-End delay; the Network Lifetime presented in sub-section 5.2.4 is the main metric studied with the objective of measuring the energy efficiency of both Routing and Transport layer protocols transmission mechanisms. The Network Lifetime provides a high-level look at the energy efficiency.

The next section presents the results that were obtained from the Simulation-based study. Section 5.3 summarizes the obtained results, while the simulator and experimental limitations and assumptions are outlined in Section 5.4.

5.2 Simulation Experiments and Results

This section present results of the experiments that were carried out. The simulation parameters used for various experiments are given in Table 4.2. Each of the reported results is the average of seven experiments for each scenario that was considered, which spanned an average of 19 hours, especially when considering the OLSR with higher number of nodes. The use of a combination of TCP, UDP, AODV, OLSR, various network sizes and packet sizes resulted in forty-eight evaluation scenarios. Table 5.1 summarizes the 48 evaluation scenarios that were considered in this study.

Table 5.1: Simulation-based Evaluation Scenarios

Number of Nodes	Transport Layer Protocols	Routing Protocols	Payload Sizes (Bytes)
20	TCP/UDP	OLSR/AODV	32/512
40	TCP/UDP	OLSR/AODV	32/512
60	TCP/UDP	OLSR/AODV	32/512
80	TCP/UDP	OLSR/AODV	32/512
100	TCP/UDP	OLSR/AODV	32/512
120	TCP/UDP	OLSR/AODV	32/512

5.2.1 Experiment I: Packet Delivery Ratio (PDR)

The purpose of this experiment was to determine the effect of OLSR and AODV together with TCP and UDP on the packet delivery ratio of the network, when subjected to different payload and network sizes. Packet Delivery Ratio is achieved by measuring the overall percentage of the packets that arrives at the intended destination node successfully.

Figures 5.1a and 5.1b depict the results of the OLSR and AODV performance on TCP when respectively subjected to the maximum and minimum payload sizes, whilst Figures 5.2a and 5.2b depict the results of the OLSR and AODV performance on UDP with maximum and minimum payload sizes. It can be observed from these experiments that both AODV and OLSR perform better with TCP than with UDP in terms of Packet Delivery Ratio, while AODV outperforms OLSR for both TCP and UDP at both maximum and minimum payload sizes.

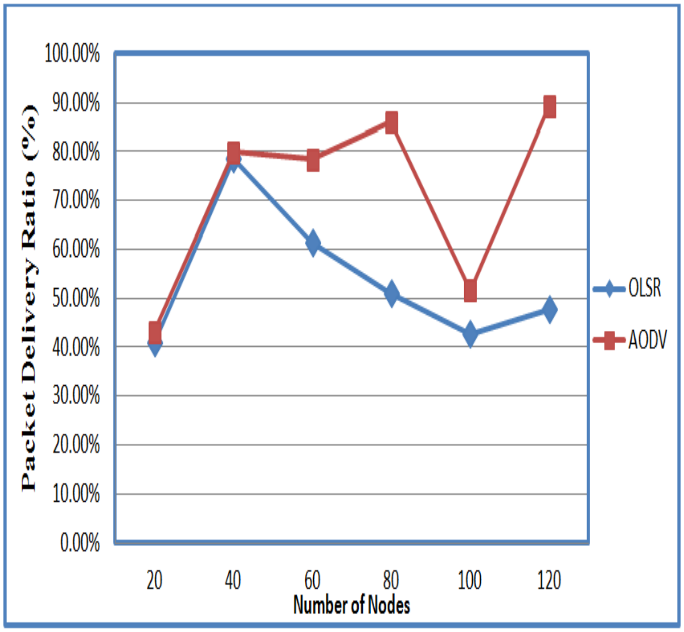

Figure 5.1a: TCP Packet Delivery Ratio at Maximum Payload

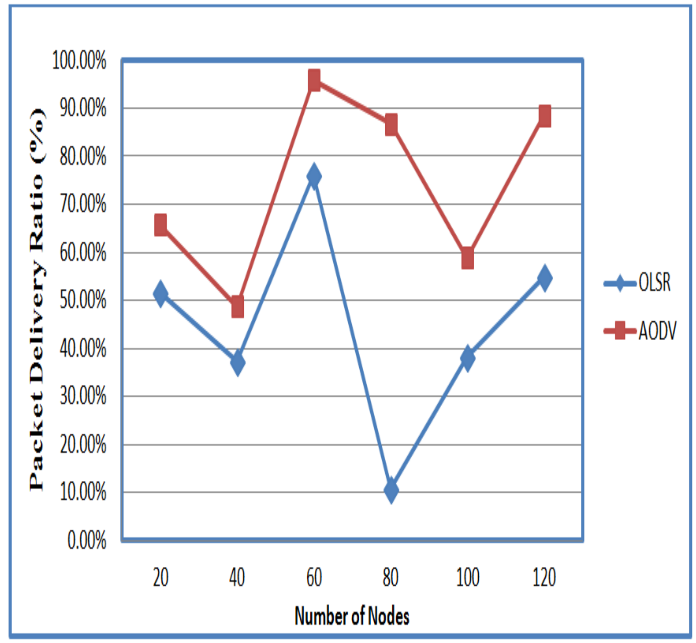

Figure 5.1b: TCP Packet Delivery Ratio at Minimum Payload

The better performance of AODV can be attributed to the on-demand route discovery mechanisms of AODV. AODV is better equipped to discover broken links and changes in the network topology most especially in a static network, where the source and destination pairs are relatively small for each node.

It can also be observed from Figure 5.2a and 5.2b that AODV outperforms OLSR for all the UDP-based scenarios. The low performance of OLSR can be attributed to buffering during the route discoveries, which could lead to additional delays in packet transmission and in turn lessen the number of packets delivered.

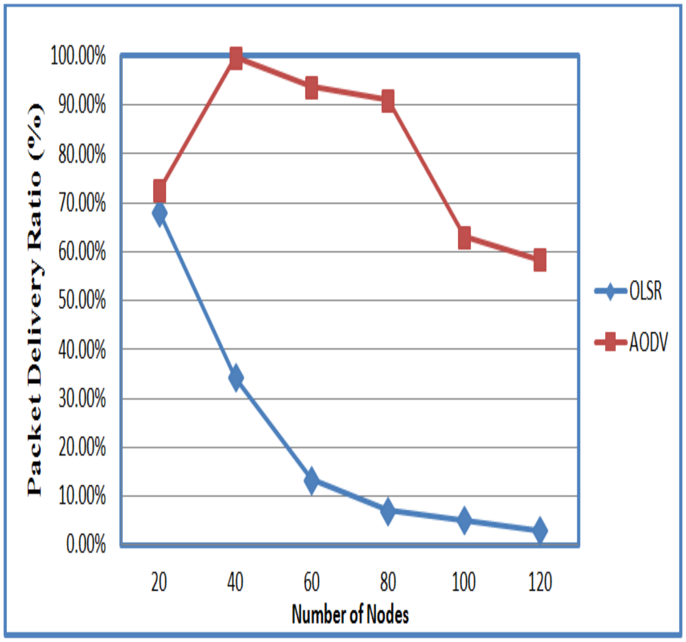

Figure 5.2a: UDP Packet Delivery Ratio at Maximum Payload

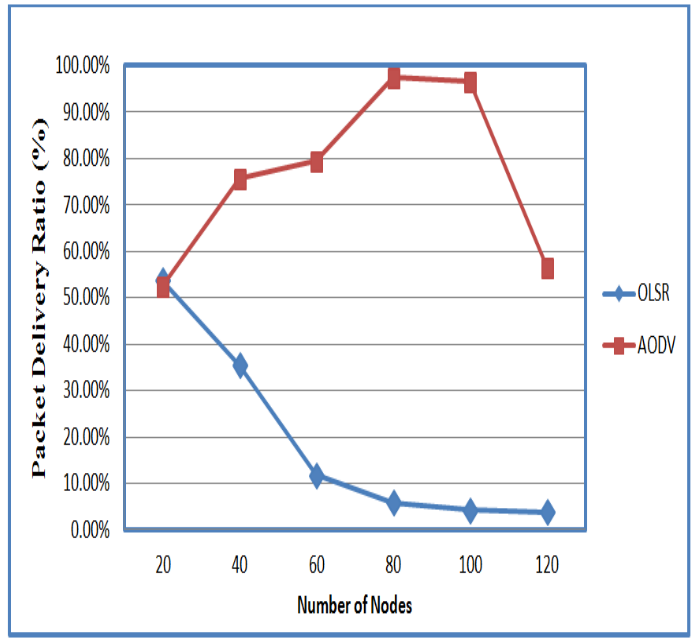

Figure 5.2b: UDP Packet Delivery Ratio at Minimum Payload

5.2.2 Experiment II: Average Throughput

The purpose of this experiment was to determine the effect of OLSR and AODV together with TCP and UDP on the average throughput of the network when subjected to different payload and network sizes.

Figure 5.3a and 5.3b depict the results of the OLSR and AODV performance on TCP when subjected to the maximum and minimum payload size, while Figure 5.4a and 5.4b depict the results of the OLSR and AODV performance on UDP with maximum and minimum payload size. It can be observed from these experiments that both OLSR and AODV perform better on TCP than with UDP at both maximum and minimum payload size. The higher throughput value achieved by OLSR and AODV on TCP can be attributed to the “Automatic Repeat-reQuest” (ARQ) mechanism and the connection-oriented based of TCP, which makes its data delivery guarantee.

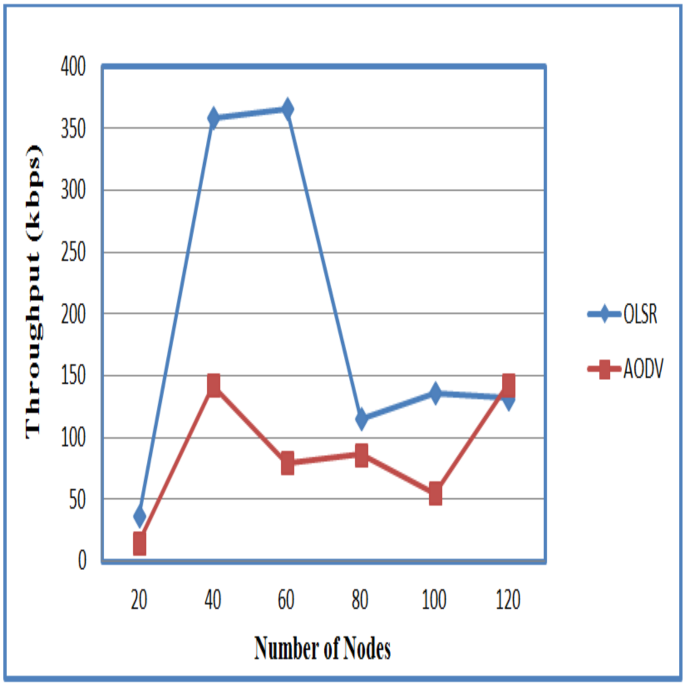

Figure 5.3a: TCP Throughput at Maximum Payload

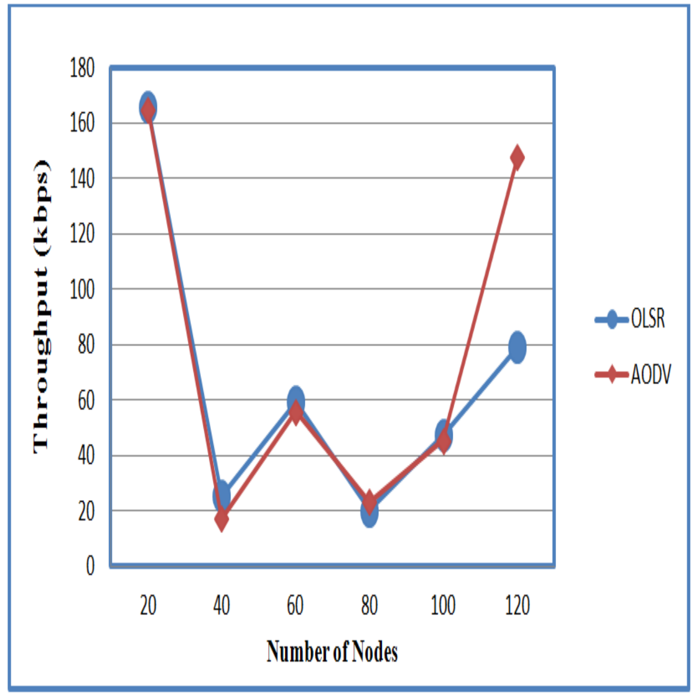

Figure 5.3b: TCP Throughput at Minimum Payload

Figure 5.3a indicates that OLSR outperforms AODV; however, in Figure 5.3b none of the two protocols (OLSR and AODV) considered shows better performance over the other.

In Figure 5.4a and 5.4b, AODV outperforms OLSR for both maximum and minimum payload size. The better performance of AODV on UDP can be attributed to both the on-demand characteristic of AODV and the connectionless characteristic of UDP. It can be inferred from Figures 5.3a, 5.3b, 5.4a and 5.4b that throughput of OLSR at maximum payload is better with TCP traffic, while AODV at maximum payload is better with UDP traffic.

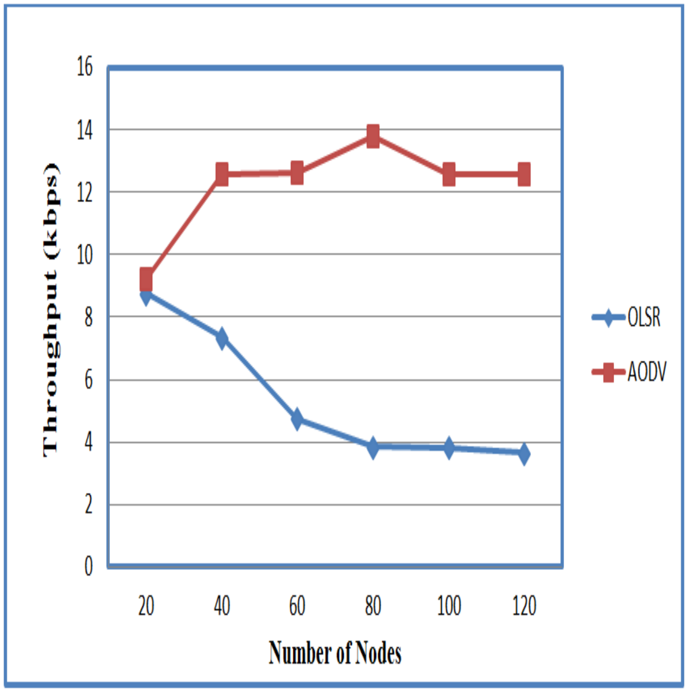

Figure 5.4a: UDP Throughput at Maximum Payload

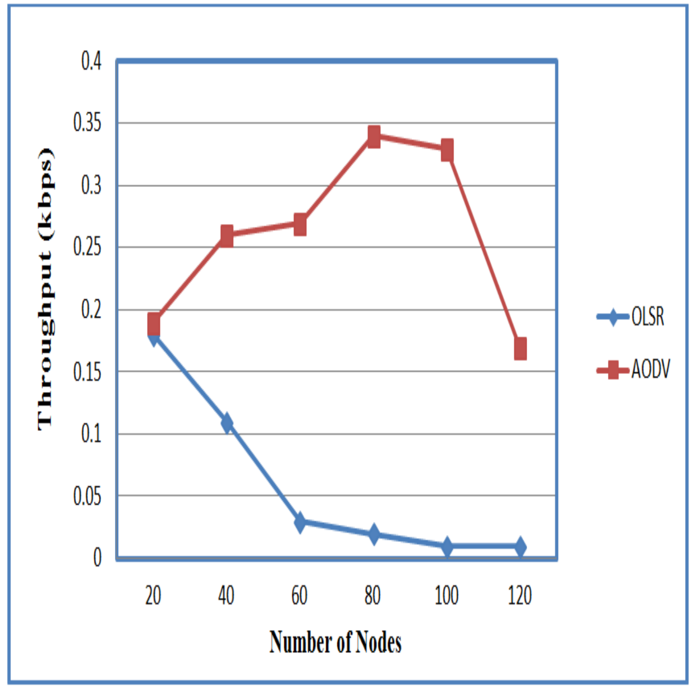

Figure 5.4b: UDP Throughput at Minimum Payload

5.2.3 Experiment III: Average End-to-End Delay

The purpose of this experiment was to determine the effect of OLSR and AODV together with TCP and UDP on the average time taken by the network layer packets to reach their destination, when subjected to different payload and network sizes.

In this experiment, the focus was on network layer packets, because routing is normally done at the network layer of the OSI model. High delay decreases the overall network performance; hence, the lower the delay value, the better the protocol performance. The average end-to-end delay was measured in milliseconds (ms). Figure 5.5a and 5.5b depict the results of the OLSR and AODV performance on TCP with maximum and minimum payload size.

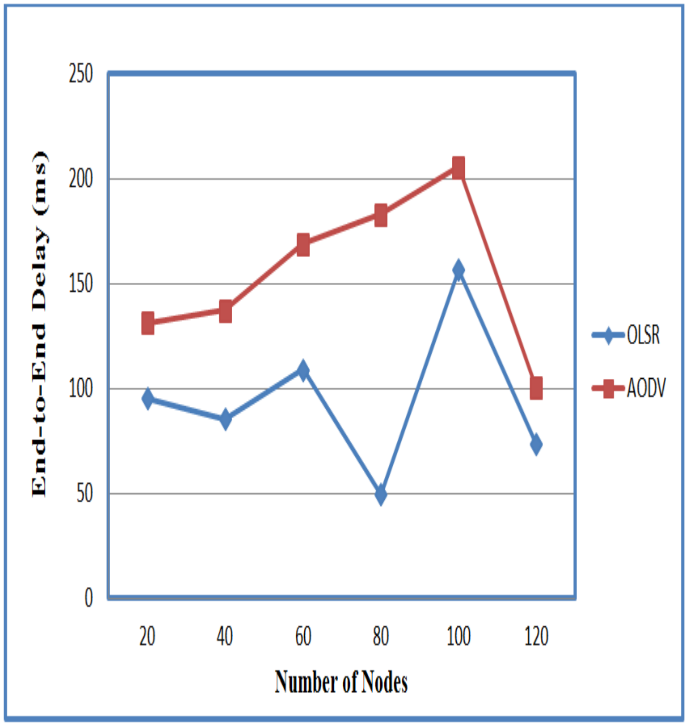

Figure 5.5a: TCP End-to-End Delay at Maximum Payload

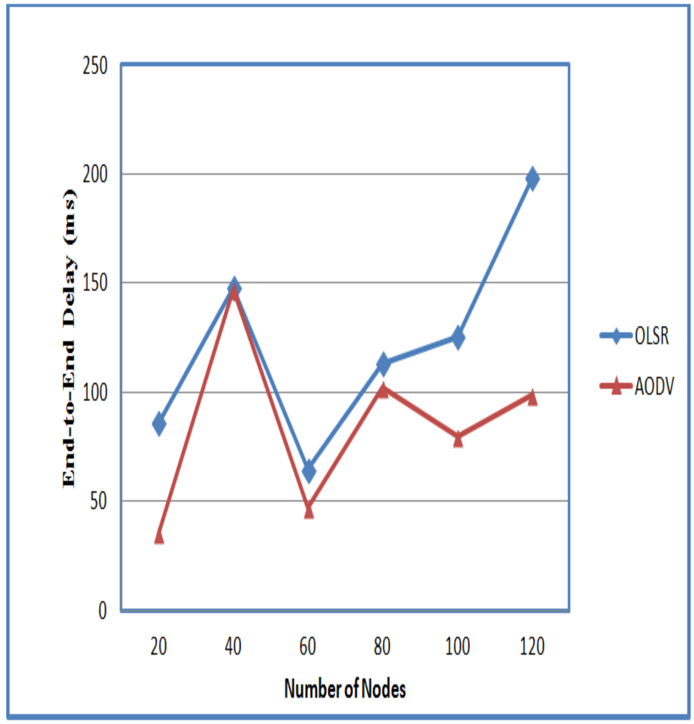

Figure 5.5b: TCP End-to-End Delay at Minimum Payload

Figure 5.5a shows that AODV has higher delay values than that of OLSR, and since the lower the value the better the performance in terms of delay, hence, OLSR outperform AODV at maximum payload.

The better performance of OLSR can be attributed to the table-driven characteristic of OLSR, in which all the routing information are always stored in the table. Hence, it takes a lesser time for the packets to reach their destination node, unlike the AODV (on-demand) which needs more time in route discovery and this will lead to more delay between the source and the destination node.

In Figure 5.5b, it was observed that AODV outperforms OLSR, and this performance can be attributed to the routing policy of reactive protocol (AODV), which performs better at low traffic load, while a proactive protocol (OLSR) performs better at high traffic load.

Another reason for OLSR performance could be retransmission delay and buffering during route discoveries.

Figure 5.6a and 5.6b depict the results of the OLSR and AODV performance on UDP with maximum and minimum payload size.

It can be observed from Figure 5.6a and 5.6b that, OLSR outperform AODV at both maximum and minimum payload. Also, it was observed that both OLSR and AODV perform better with UDP than with TCP in terms of average end-to-end delay. This performance can be attributed to the delay sensitivity and the connectionless characteristics of UDP as against packet retransmission and packet delivery reliability characteristics of TCP, which introduces additional delays in TCP packets transmission.

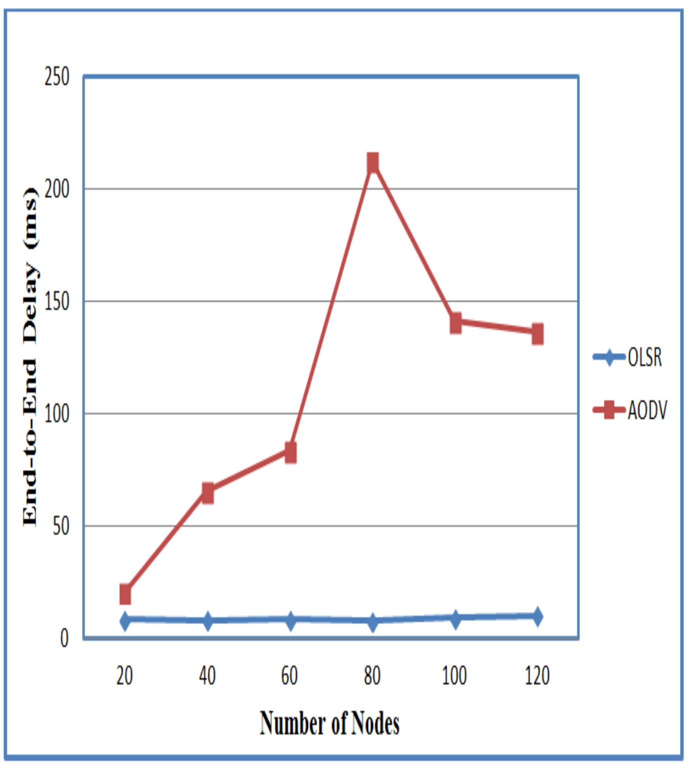

Figure 5.6a: UDP End-to-End Delay at Maximum Payload

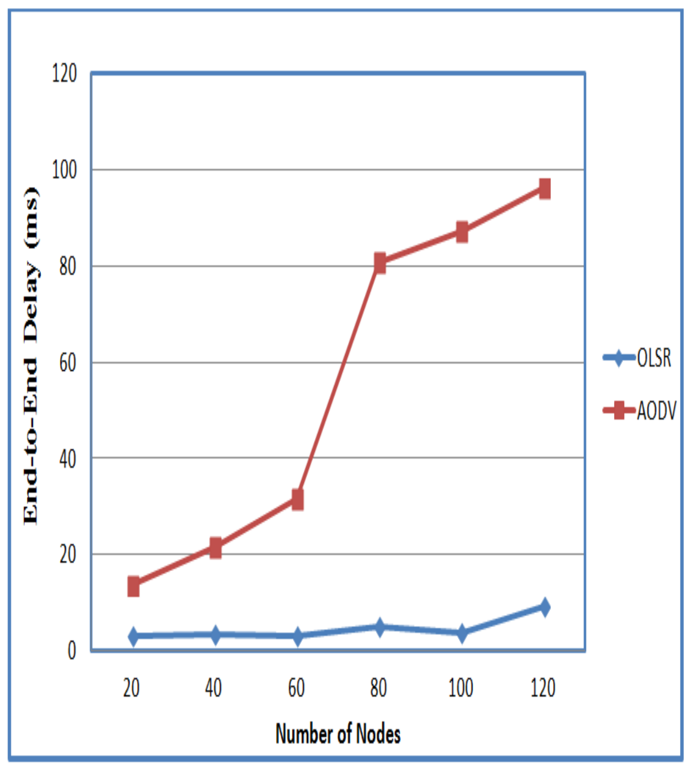

Figure 5.6b: UDP End-to-End Delay at Minimum Payload

5.2.4 Experiment IV: Network Lifetime

The network lifetime is defined as the length of time in which the network remains in proper working order before the first node exhausts its energy allocation.

The purpose of this experiment was to determine the effect of OLSR and AODV together with TCP and UDP on the operational lifetime of a battery-powered wireless mesh network when subjected to different payload sizes. The number of surviving nodes and their respective time were determined by using a *Perl script* to analyze the trace files that were generated. The number of surviving nodes was plotted against the simulation time.

Figure 5.7 depicts the effect of AODV and OLSR on the network lifetime of a 120 nodes network, when subjected to different payload sizes using TCP as the transport layer protocol. It can be observed from this Figure that AODV at maximum payload outperform others. However, the energy efficiency of both OLSR and AODV on TCP were below average. The poor performance of both AODV and OLSR on TCP in terms of energy efficiency can be attributed to the Automatic Repeat-reQuest mechanism and the connection oriented based of TCP. These two mechanisms make TCP draw more bandwidth, while trying to resend lost packets and this in-turn draws more energy, which lessens the network lifetime. Another reason for the poor performance of AODV and OLSR could be attributed to overhearing effect. Overhearing activities can cause reduction in the network lifetime, because all the neighboring nodes of a transmitting node also consume energy while trying to overhear data packets addressed to other nodes.

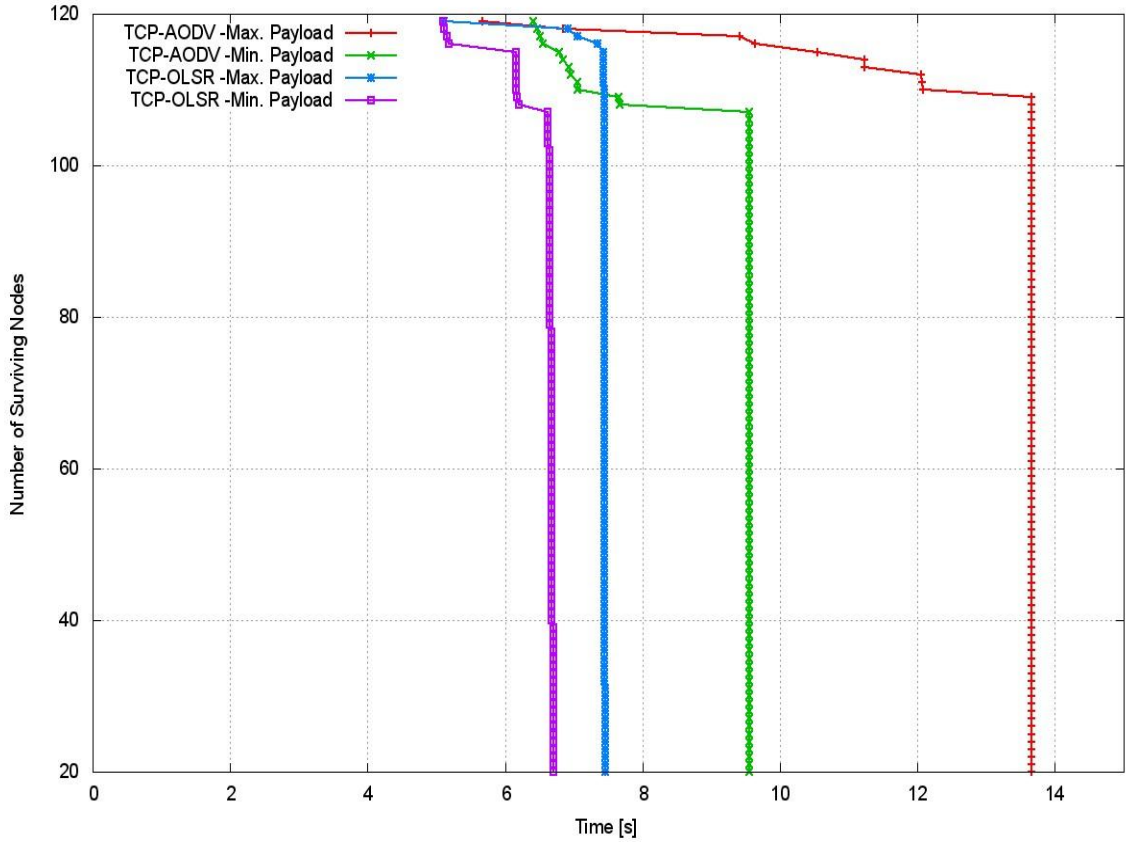

Figure 5.7: TCP-based Network Lifetime

Figure 5.8 depicts the effect of AODV and OLSR on the network lifetime of a 120 nodes network, when subjected to different payload sizes using UDP as the transport layer protocol. It can be observed from this Figure that AODV at minimum payload outperform others. Both AODV at minimum and maximum payload size performs above average. However, the performance of OLSR in terms of energy efficiency on UDP was below average. The poor performance of OLSR in terms of energy efficiency can be attributed to its routing policy, which introduces additional delays in packet transmission while trying to build and update the routing table during the transmission.

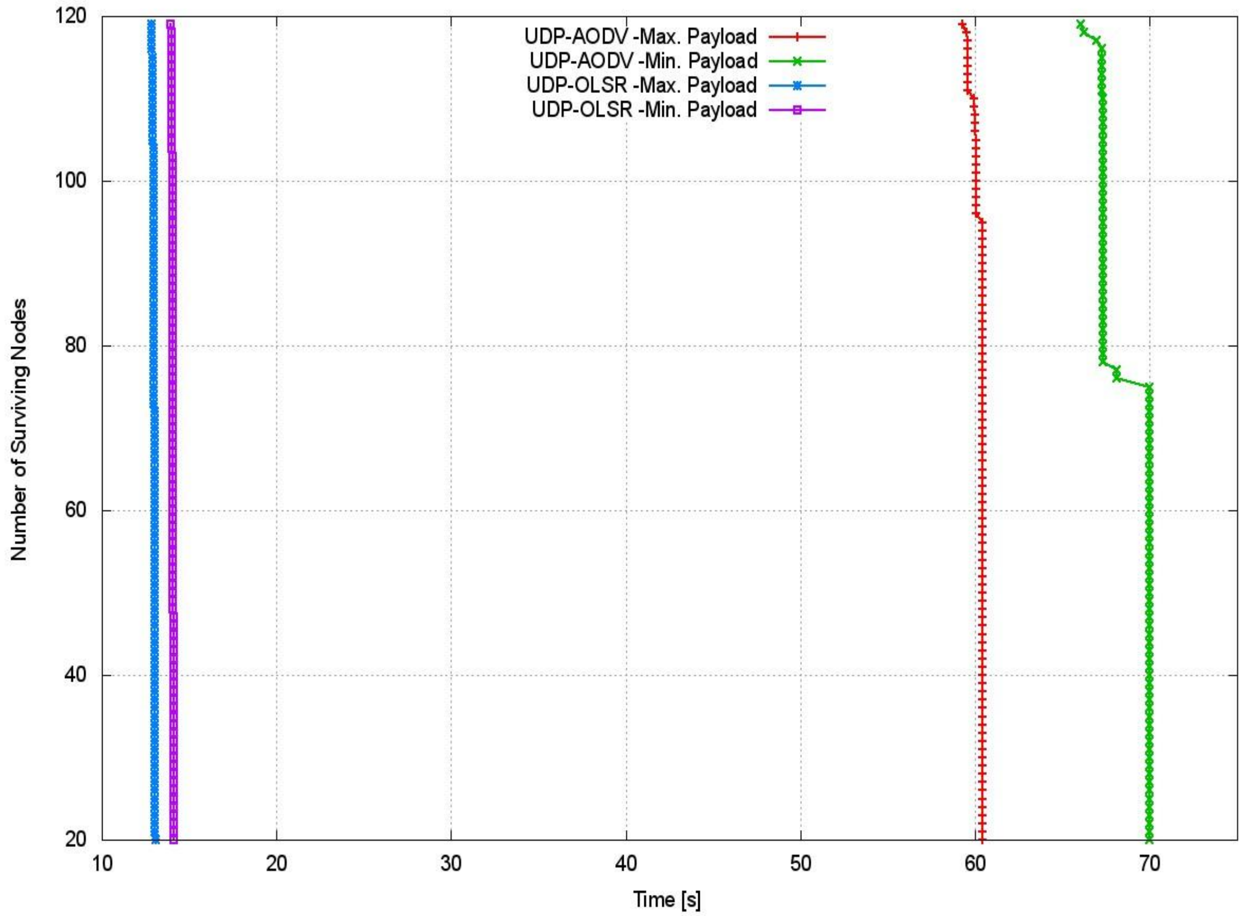

Figure 5.8: UDP-Based Network Lifetime

Another reason for the poor performance of OLSR can be attributed to buffering during the route discoveries, which could lead to the consumption of more bandwidth and in-turn lessen the network lifetime. It can be observed from Figure 5.7 and Figure 5.8 that, as a result of early exhaustion of the batteries in OLSR forwarding nodes, network partitioning occurs, which in turn badly affects the Packet Delivery Ratio of OLSR using both UDP and TCP.

5.3 Summary

Table 5.2 summarizes the best performing scenarios for both TCP and UDP-based results for the Packet Delivery Ratio, Average Throughput, Average End-to-End Delay and Network Lifetime. In this chapter, the Network Lifetime was studied with the objective of measuring the energy efficiency of both Routing and Transport layer protocols transmission mechanisms. This metric helped us to know the duration for which each of the considered scenarios can effectively power the network, when subjected to various conditions. Based on the results obtained from the simulation experiments [See Table 5.2], it is not very clear that any one protocol is best for all the scenarios, each protocol possesses its own advantages and disadvantages and may be well-suited for certain scenarios. Previous studies [Anastasi *et al*, 2006, Tyagi and Chauhan, 2010] also confirm that most of the simulation results do not give clear understanding of the protocols performance in real-world environment. However, for the purpose of clarity and better understanding of these protocols (Transport and Routing) performance in battery-powered WMN, the simulation results are validated using an indoor testbed.

Table 5.2: Best Performing Scenarios for Simulation Experiments

Metrics	Best Performing Scenarios
Packet Delivery Ratio	TCP-based scenarios: AODV at minimum payload
	UDP-based scenarios: AODV at minimum payload
Average Throughput	TCP-based scenarios: OLSR at maximum payload
	UDP-based scenarios: AODV at maximum payload
Average End-to-End Delay	TCP-based scenarios: OLSR at maximum payload
	UDP-based scenarios: OLSR at minimum payload
Network Lifetime	TCP-based scenarios: AODV at maximum payload
	UDP-based scenarios: AODV at minimum payload

5.4 Simulation Assumptions and Limitations

Simulation experiments are at best an abstraction of the real world. Hence, there are bound to be assumptions made in an effort to prototype the environment being considered. It is acknowledged that one or more of the assumptions made and the limitations of the simulation tool could affect the results presented.

The limitations and assumptions made are listed below:

i. All the nodes employed the same transmission power level

ii. An idealized initial energy of one Joule were used to power the nodes

iii. The IEEE 802.11 RTS/CTS mechanisms were disabled, because it does not improve the performance of the wireless mesh networks. Similar findings have been reported by other researchers [Johnson and Lysko, 2008]

iv. The terrain was assumed to be flat with no obstacles, whereas, real world deployments consider the elevation of the nodes as well as objects, such as trees, pole

v. Lack of realistic Application layer modeling; a constant bit rate was used, whereas real application layer traffic uses varying traffic rate.

vi. The network was assumed to be completely interference free, which is relatively impossible in the real world deployment.

vii. There are inconsistencies in the results of the same protocol being run on different simulation tools (NS2, GloMoSim, Qualnet and Opnet) and this is due to the differences in the way each simulator developer model their physical/real world.

In view of some of the limitations identified with both the NS2 and other available simulation tools, hence, in order to understand and to test the validity of the relationship between the simulation research results and reality, an indoor testbed was setup. The results of the indoor testbed experiments presented in the next chapter assist us to check the validity of the simulation results in relation to real world environment and to be able to present a result that can fit into the real-world measurements.

CHAPTER SIX

TESTBED-BASED PERFORMANCE ANALYSIS

6.1 Introduction

In the previous chapter, we presented the performance analysis of simulation experiments. However, due to some limitations associated with simulation tools, it is imperative to validate the simulation results using testbed, so as to be able to have a clear and better understanding of the protocols performance in battery-powered WMN.

The goal of this evaluation is to determine the effect of TLPs and Routing Protocols on the operational lifetime of a battery-powered WMN node. In order to achieve this goal, we analyze the performance of Reactive (AODV) and Proactive (OLSR) Routing protocols together with connection (TCP) and connectionless (UDP) Transport Layer protocols when subjected to various transmission power levels and payload sizes. Apart from PDR, Average Throughput and Average End-to-End delay; the Node Lifetime and the Average Energy Cost per bit presented in sub-section 6.2.4 and 6.2.5 respectively, are the two main metrics studied with the objective of measuring the energy efficiency of both Routing and Transport layer protocols. The Node Lifetime provides a high-level look at the energy efficiency of both Routing and Transport Layer protocols when subjected to different transmission power levels and payload sizes. Energy-efficiency, however, can also be viewed from a data transfer perspective where we either want to receive the same amount of data with lower energy costs or receive more data for the same energy cost. The average energy cost per bit thus provides an indication of the utility of a node, whilst it is alive by assessing the amount of data received within the achieved node lifetime.

The next section presents the results that were obtained from Testbed-based study. Section 6.3 compares the simulation and the testbed results, while the experimental limitations and assumptions are outlined in Section 6.4.

6.2 Testbed Experiments and Results

This section present result obtained from the Testbed experiments that were carried out. The configuration that was used for various experiments scenarios were given in Section 4.2. Each of the reported graphs is the average of five experiments of each scenario that was considered and each experiment spanned a minimum of 31 hours. All evaluation data was collected at PC1 via an Ethernet link to Node N1 and a USB connection to Digital Multi-Meter [see Figure 4.1]. The data collected via Ethernet and USB had no effect on the communications via the wireless interface of the testbed nodes. The use of a combination of TCP, UDP, AODV, OLSR, packet sizes and transmission power levels resulted in the sixteen evaluation scenarios recorded in Table 6.1 and Table 6.2. In Table 6.1 scenarios, only TCP were used as the transport layer protocol for the performance evaluation of OLSR and AODV, while Table 6.2 depicts the UDP-based scenarios that were considered.

Table 6.1: TCP based Evaluation Scenarios

S/N	TCP-Based Scenarios
1	OLSR at maximum transmission power with maximum payload
2	OLSR at maximum transmission power with minimum payload
3	OLSR at minimum transmission power with maximum payload
4	OLSR at minimum transmission power with minimum payload
5	AODV at maximum transmission power with maximum payload
6	AODV at maximum transmission power with minimum payload
7	AODV at minimum transmission power with maximum payload
8	AODV at minimum transmission power with minimum payload

Table 6.2: UDP-based Evaluation Scenarios

S/N	UDP-Based Scenarios
1	OLSR at maximum transmission power with maximum payload
2	OLSR at maximum transmission power with minimum payload
3	OLSR at minimum transmission power with maximum payload
4	OLSR at minimum transmission power with minimum payload
5	AODV at maximum transmission power with maximum payload
6	AODV at maximum transmission power with minimum payload
7	AODV at minimum transmission power with maximum payload
8	AODV at minimum transmission power with minimum payload

6.2.1 Experiment I: Packet Delivery Ratio (PDR)

The purpose of this experiment was to determine the effect of OLSR and AODV together with TCP and UDP on the Packet Delivery Ratio of the network when subjected to different transmission power levels and payload sizes. Packet Delivery Ratio is achieved by measuring the overall percentage of the packets that arrives at the intended destination node successfully. The higher the value of Packet Delivery Ratio, the better the network performance. Figure 6.1a and Figure 6.1b respectively depicts the results of the OLSR and AODV performance on TCP with various payload sizes and different transmission power levels. Figure 6.2a and Figure 6.2b respectively depicts the results of the OLSR and AODV performance on UDP with various payload sizes and different transmission power levels. It can be observed from these experiments that both AODV and OLSR performed better with TCP than with UDP in terms of Packet Delivery Ratio.

In Figure 6.1a and Figure 6.1b, it can be observed that OLSR at maximum transmission power level with maximum payload size outperform others, while AODV at minimum transmission power level with minimum payload size was the least performing TCP-based scenarios in terms of PDR. The general poor performance of AODV can be attributed to high route failure experienced by AODV during the packet transmission. Some other previous testbed studies [Johnson & Lysko, 2008, Brolin & Hedegren, 2008] had reported that, AODV experience more than 80% route failure on the testbed at both maximum and minimum transmission power level. In this study, we edited some AODV and Freifunk firmware parameters values, as explained in Chapter four. And this led to a reduction in the level of AODV route failure, especially at the maximum transmission power level.

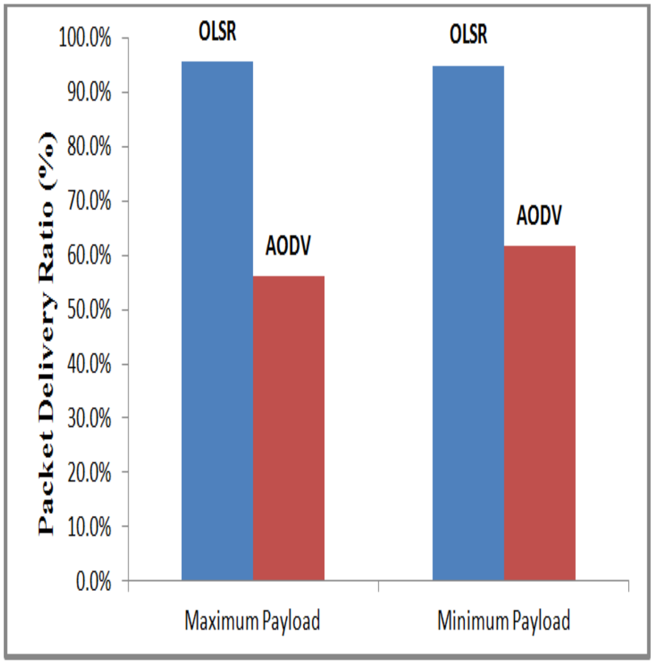

Figure 6.1a: TCP Packet Delivery Ratio at Maximum Transmission Power

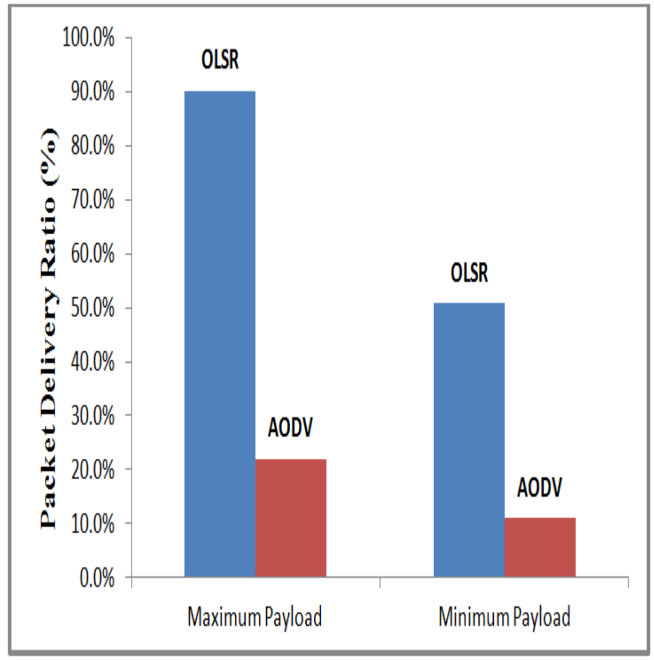

Figure 6.1b: TCP Packet Delivery Ratio at Minimum Transmission Power

In Figure 6.1b, it can be observed that AODV at both maximum and minimum payload size perform very low and also, OLSR at minimum payload size with minimum transmission power level performs low. This performance can be attributed to the reduction in the nodes transmission power level. The lower transmission power will lead to an increase in the number of hops that a data packet will traverse between the sender and the receiver node and this would increase packet drop which in-turn decreases the packet delivery ratio as experienced in Figure 6.1b.

In Figure 6.2a, it can be observed that both AODV and OLSR perform below average, while in Figure 6.2b the performance was very poor for both AODV and OLSR. The poor performance of AODV and OLSR in both cases can be attributed to the wireless channel error experienced by UDP. Wireless channel error occurs due to interference from other wireless LAN that are operational within the building where the testbed is located and since UDP has no control mechanism to recover the packet loss during this error period, a significant amount of packet loss was experienced. Although, we tried to reduce the interference level as described in chapter four, but it is almost impossible to remove the interference completely. In the real-world deployment, it is almost impossible to have complete interference free environment, hence, it makes our result conform to the real deployment situation.

Another reason that could be attributed to the poor performance of AODV and OLSR in UDP-based scenarios is network congestion, which happens as a result of buffer overflow. From our investigation of UDP low performance in terms of PDR, it was observed that NetScanTool and Windows OS offers only 8192bytes as the maximum buffer size, which is low for UDP during the high-volume traffic flow. Hence, when the

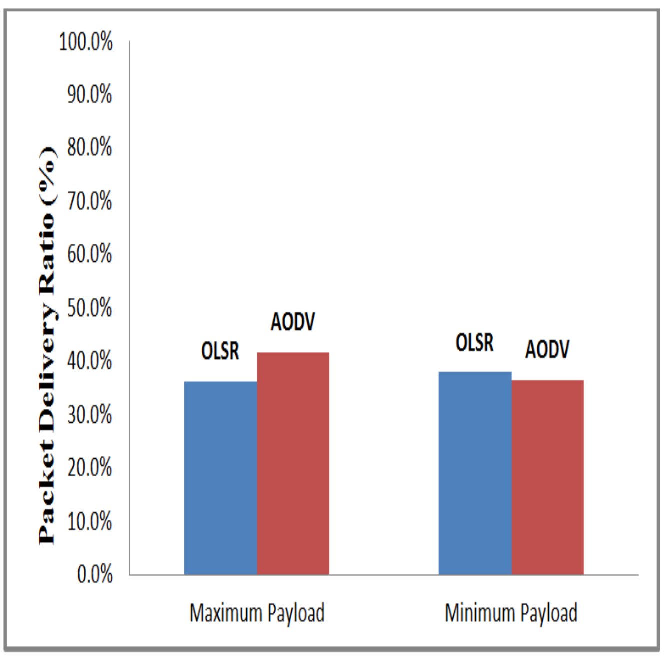

Figure 6.2a: UDP Packet Delivery Ratio at Maximum Transmission Power

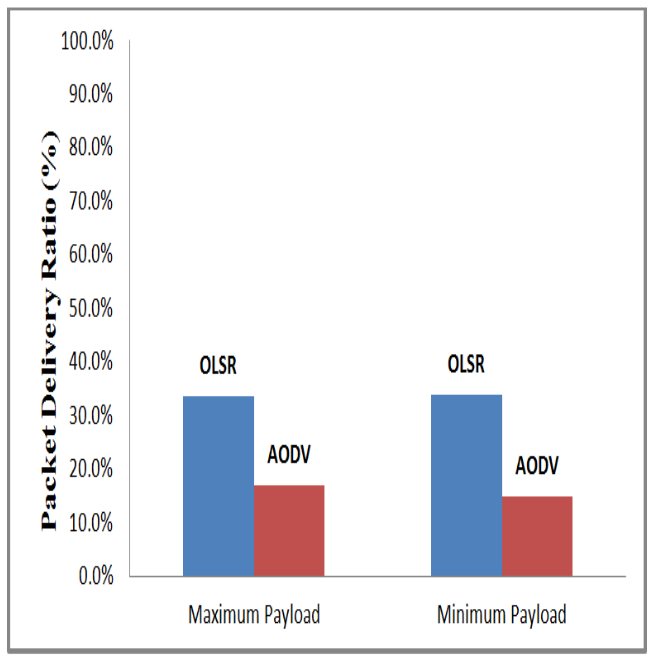

Figure 6.2b: UDP Packet Delivery Ratio at Minimum Transmission Power

packets at the receivers' end are beyond the buffer size, it drops the remaining packets and since there is no scope for recovering packet loss in UDP, it results in lowered Packet Delivery Ratio.

In Figure 6.2b, it can be observed that, even though both AODV and OLSR perform below average (< 50%); AODV at the maximum and minimum payload sizes performs very poorly. Apart from the reasons discussed above (wireless channel error, network congestion and buffer overflow), the poor performance of AODV can also be attributed to the reduction in the nodes transmission power level, which led to an increase in the rate of route failure. And since there is no retransmission mechanism in UDP, hence, it leads to an increase in packet loss which in-turn decreases the packet delivery ratio of AODV.

6.2.2 Experiment II: Average Throughput

The purpose of this experiment was to determine the effect of OLSR and AODV together with TCP and UDP on the average throughput of the network when subjected to various payload sizes and transmission power levels. The network throughput is achieved by measuring the total number of data packets that reaches the destination from the source over a period of time. A high throughput is desired in any network, hence, the higher the throughput value, the better the network performance.

Figure 6.3a and 6.3b depict the results of the OLSR and AODV performance on TCP with maximum and minimum payload size together with maximum and minimum transmission power levels. It can be observed from these experiments that OLSR at maximum payload size and maximum transmission power level outperform other TCP-based scenarios, while AODV at minimum payload size and minimum transmission power is the least performing among all the TCP-based scenarios. However, both OLSR and AODV at minimum payload size for both maximum and minimum transmission power perform very poor. The general poor performance of AODV can be attributed to the time delay during the route discovery experienced by AODV and also, due to high link failure of AODV which was initially explained in Section 6.2.1. In an attempt by AODV to re-establish the route, lots of delay were been experienced and this in turn reduces the average throughput value.

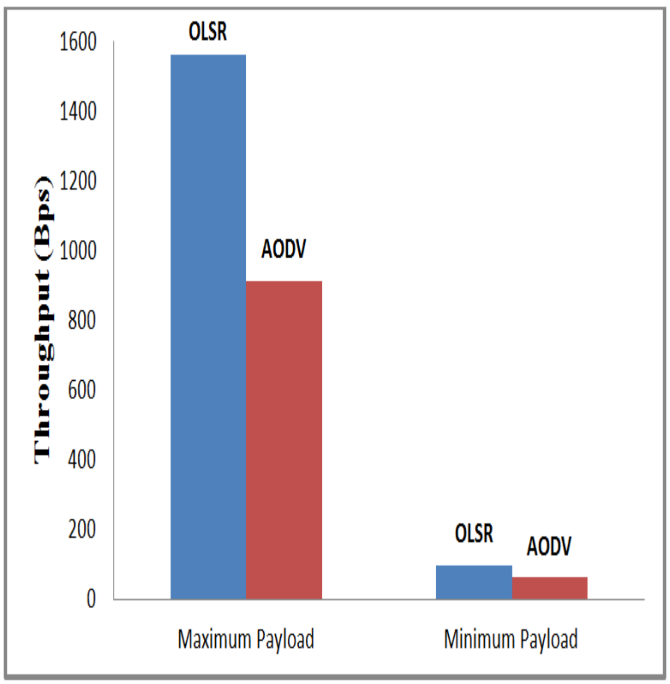

Figure 6.3a: TCP Throughput at Maximum Transmission Power

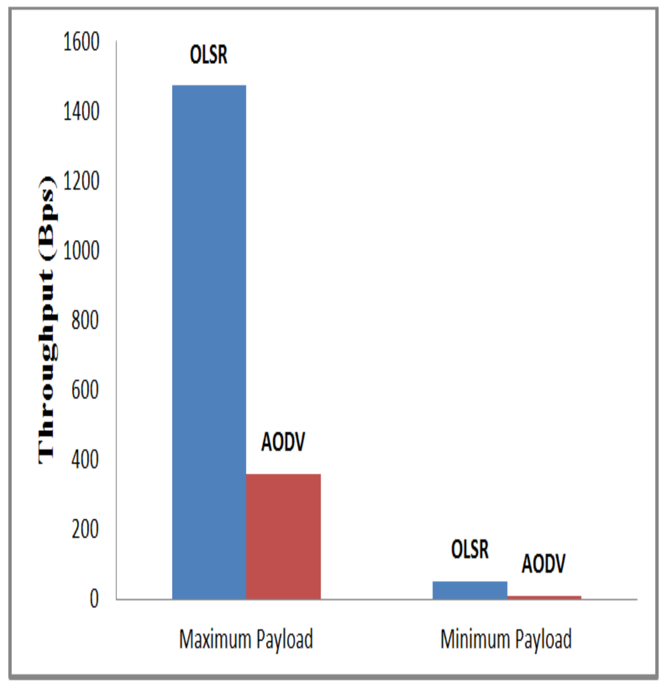

Figure 6.3b:TCP Throughput at Minimum Transmission Power

Also, in Figure 6.3b, it can be observed that AODV at maximum and minimum payload size performs very poorly. Apart from the route discovery delay and link failure, the poor performance of AODV can also be attributed to the reduction in the nodes transmission power level, which led to an increase in the number of hops between the source and the destination node. And the increase in hop count causes more delay in terms of route discovery and re-establishment, which in turn decreases the average throughput value of AODV.

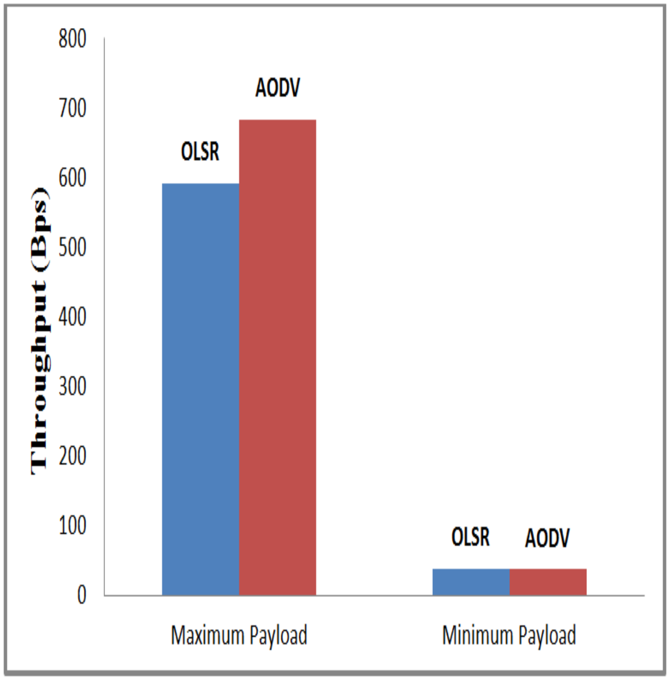

Figure 6.4a: UDP Throughput at Maximum Transmission Power

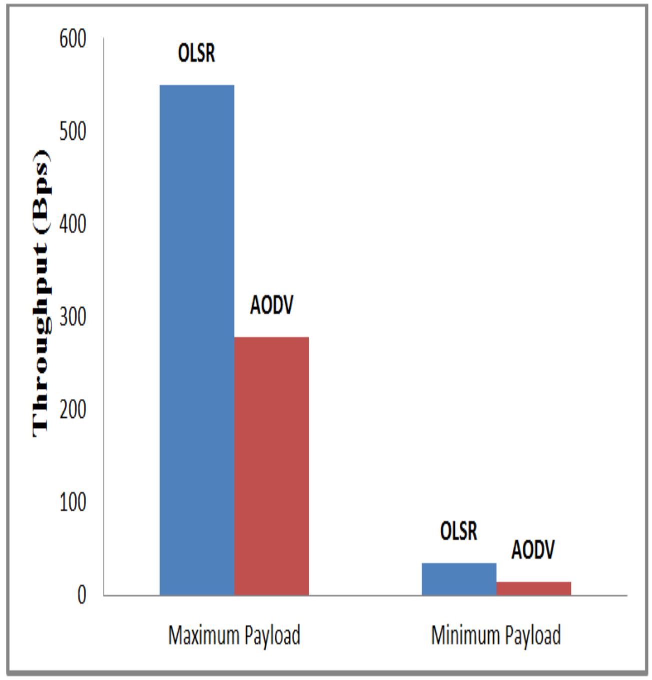

Figure 6.4b: UDP Throughput at Minimum Transmission Power

Figure 6.4a and 6.4b depict the results of the OLSR and AODV performance on UDP with various payload sizes and different transmission power levels. It can be observed from these experiments that AODV at maximum payload size and maximum transmission power outperform other UDP-based scenarios, while AODV at minimum payload size and minimum transmission power is the least performing among all the UDP-based scenarios. The better performance of AODV at maximum payload size with maximum transmission power on UDP can be attributed to both the on-demand characteristic of AODV and the connectionless characteristic of UDP.

However, the performance of OLSR and AODV at minimum payload size with both maximum and minimum transmission power was very poor.

In Figure 6.4a, it can be observed that, at minimum payload size, none of the two protocols (OLSR and AODV) considered, shows better performance over the other.

In Figure 6.4b, it can be observed that OLSR at maximum payload with minimum transmission power outperform other minimum transmission power UDP-based scenarios. From average throughput experiments, both OLSR and AODV perform better on TCP than with UDP at maximum and minimum payload with maximum and minimum transmission power levels.

The higher throughput value achieved by OLSR and AODV on TCP can be attributed to the connection oriented based and “Automatic Repeat-reQuest” (ARQ) mechanism of TCP, which makes its data delivery guarantee and in-turn improves the average throughput.

From Figures 6.3a, 6.3b, 6.4a and 6.4b, it can be inferred that, the average throughput of OLSR at maximum payload size with maximum transmission power level is better with TCP traffic, while AODV at maximum payload size with maximum transmission power level is better with UDP traffic.

6.2.3 Experiment III: Average End-to-End Delay

The purpose of this experiment was to determine the effect of OLSR and AODV together with TCP and UDP on the average time taken by the network layer packets to reach their destination, when subjected to various payload sizes and transmission power levels.

In this experiment, the focus was on network layer packets, because routing is normally done at the network layer of the OSI model. High delay decreases the overall network performance; hence, the lower the delay value, the better the network performance. The average end-to-end delay was measured in milliseconds (ms).

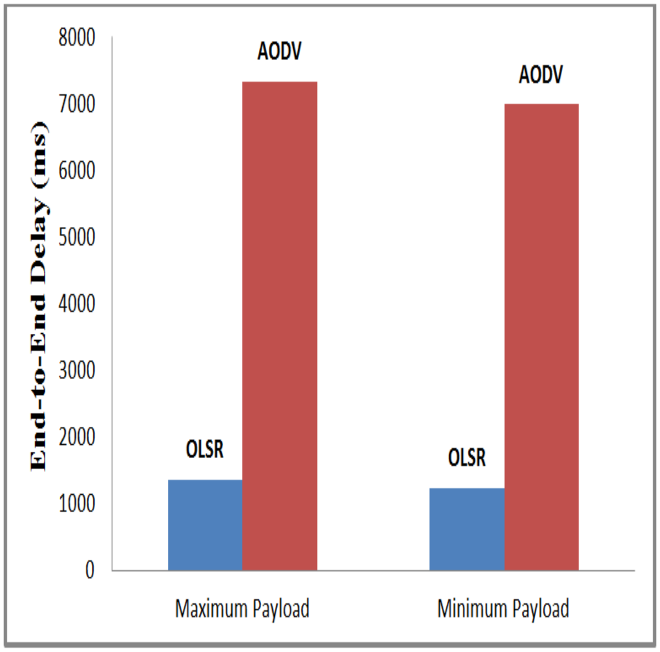

Figure 6.5a: TCP End-to-End Delay at Maximum Transmission Power

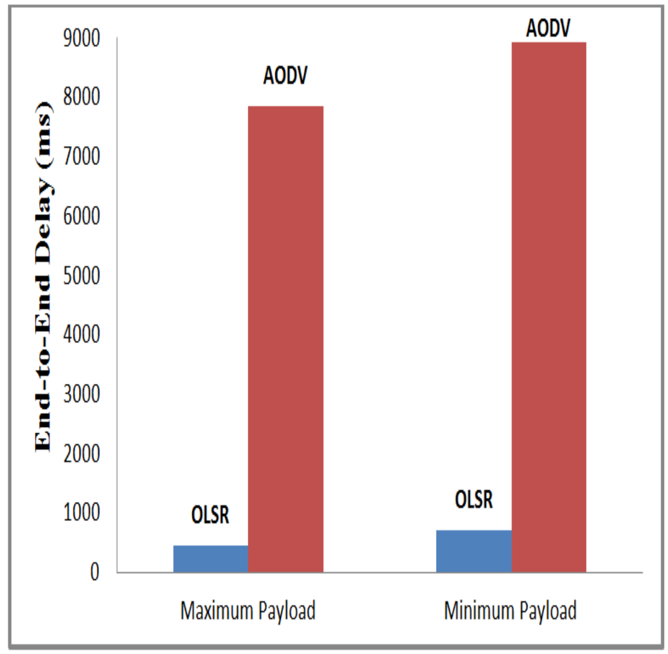

Figure 6.5b: TCP End-to-End Delay at Minimum Transmission Power

Figure 6.5a and Figure 6.5b depict the results of the OLSR and AODV performance on TCP with maximum and minimum payload size together with maximum and minimum transmission power levels.

It can be observed from the TCP-based experiments that OLSR at maximum payload size and minimum transmission power level outperform other TCP-based scenarios, while AODV at minimum payload size and minimum transmission power is the least performing among all the TCP-based scenarios.

The high end-to-end delay value of AODV in all the TCP-based scenarios can be attributed to the on-demand characteristic of AODV, which makes it need some time for the route discovery; in an attempt by AODV to re-establish the route, lots of delay were been experienced and this in-turn increases the average end-to-end delay. Another reason that can also be attributed to the AODV high end-to-end delay performance on TCP is the buffering, which occurs during the route discovery latency.

The better performance of OLSR can be attributed to the table-driven characteristic of OLSR, in which all the routing information is always stored in the table. Hence, it takes a lesser time for the packets to reach their destination node, unlike the AODV (on-demand) which needs more time in route discovery.

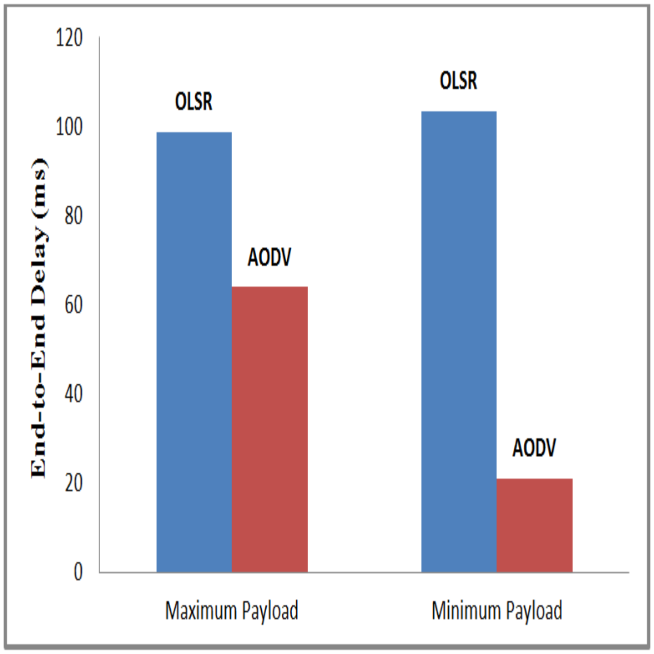

Figure 6.6a: UDP End-to-End Delay at Maximum Transmission Power

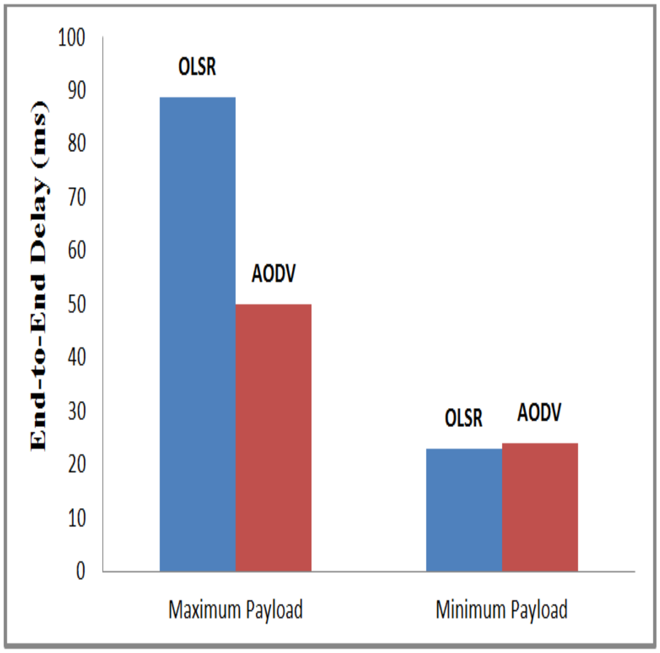

Figure 6.6b: UDP End-to-End Delay at Minimum Transmission Power

Figure 6.6a and 6.6b depict the results of the OLSR and AODV performance on UDP with maximum and minimum payload size together with maximum and minimum transmission power levels.

It can be observed from the UDP-based experiments that AODV at minimum payload size and maximum transmission power level outperform other UDP-based scenarios, while OLSR at minimum payload size and maximum transmission power is the least performing among all the UDP-based scenarios in terms of average end-to-end delay.

In Figure 6.6b, it can be observed that, at minimum payload size with minimum transmission power level, none of the two protocols (OLSR and AODV) considered, shows better performance over the other.

From the above experiments on average end-to-end delay, OLSR and AODV perform better with UDP than with TCP in terms of average end-to-end delay. This performance can be attributed to the delay sensitivity and the connectionless characteristics of UDP as against packet retransmission and packet delivery reliability characteristics of TCP, which introduces additional delays in TCP packets transmission.

6.2.4 Experiment IV: Node Lifetime

The purpose of this experiment was to determine the influence of OLSR and AODV together with TCP and UDP on the operational lifetime of a battery-powered WMN node, when subjected to various payload sizes and transmission power levels.

Figure 6.7 depicts the effect of AODV and OLSR on the operational lifetime of the node, when subjected to various payload sizes and transmission power levels, using TCP as the transport layer protocol. It can be observed from Figure 6.7 that the scenario in which

AODV was used as the routing protocol couples with maximum payload size and minimum transmission power level outperform other TCP-based scenarios in terms of node lifetime, as this scenario caused the battery to power the node for approximately 37.67 hours (136,205secs). Whilst the scenario in which AODV was used as the routing protocol couples with minimum payload size and maximum transmission power level is the weakest among all the TCP-based scenarios considered in terms of node lifetime, as this scenario caused the battery to power the node for approximately 29.33 hours (105,099secs).

Figure 6.8 depicts the influence of AODV and OLSR on the operational lifetime of the WMN node, when subjected to various payload sizes and transmission power levels, using UDP as the transport layer protocol.

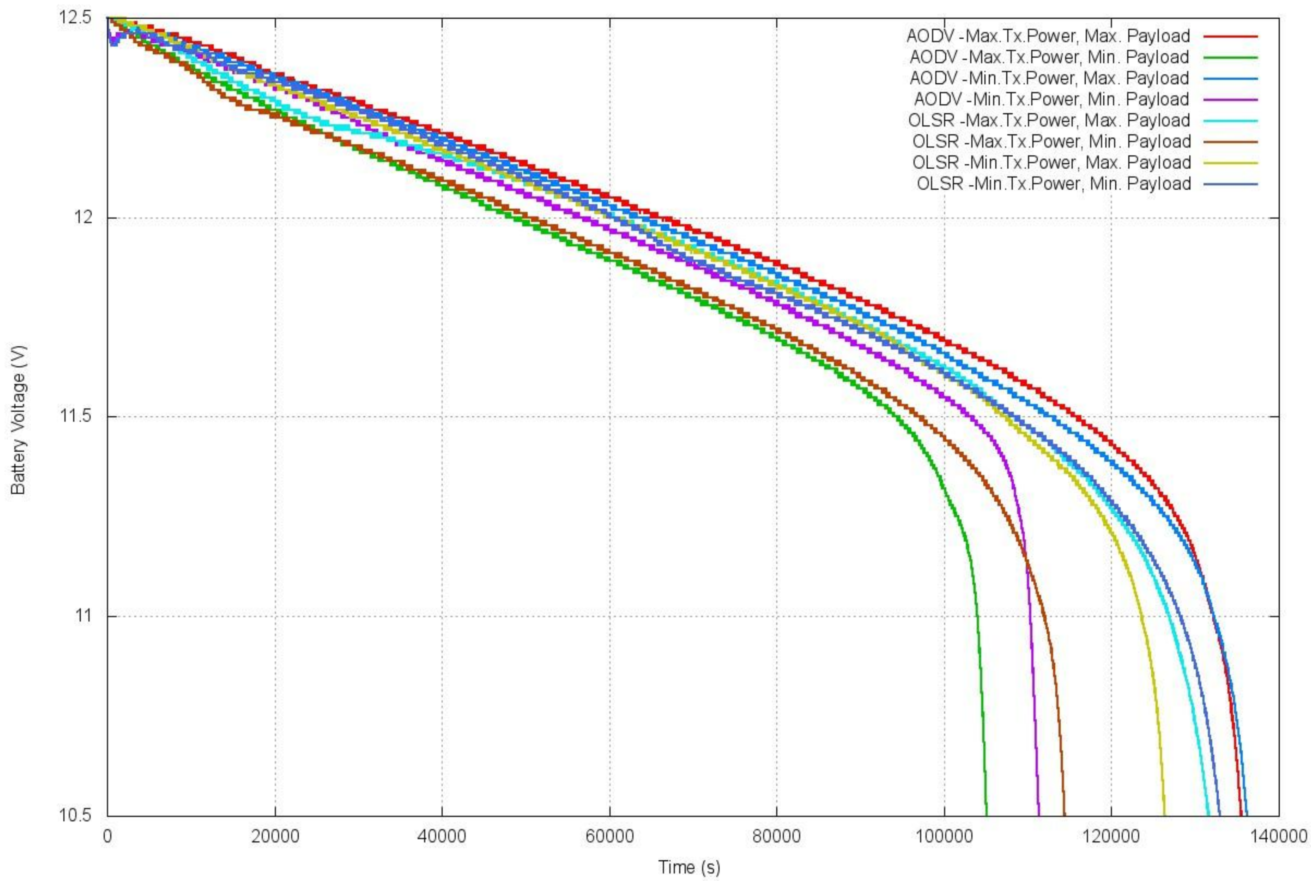

Figure 6.7: TCP-based Node Lifetime

It can be observed from Figure 6.8 that the scenario in which AODV was used as the routing protocol couples with maximum payload size and maximum transmission power level outperform other UDP-based scenarios in terms of node lifetime, as this scenario caused the battery to power the node for approximately 38.50 hours (138,758secs). Whilst the scenario in which AODV was used as the routing protocol couples with maximum payload size and minimum transmission power level is the weakest among all the UDP-based scenarios considered in terms of node lifetime, as this scenario caused the battery to power the node for approximately 32 hours (115,287secs). The best performing scenario can be attributed to the energy saves through the use of maximum transmission power, which caused the packets to traverse shorter routes to reach their destination.

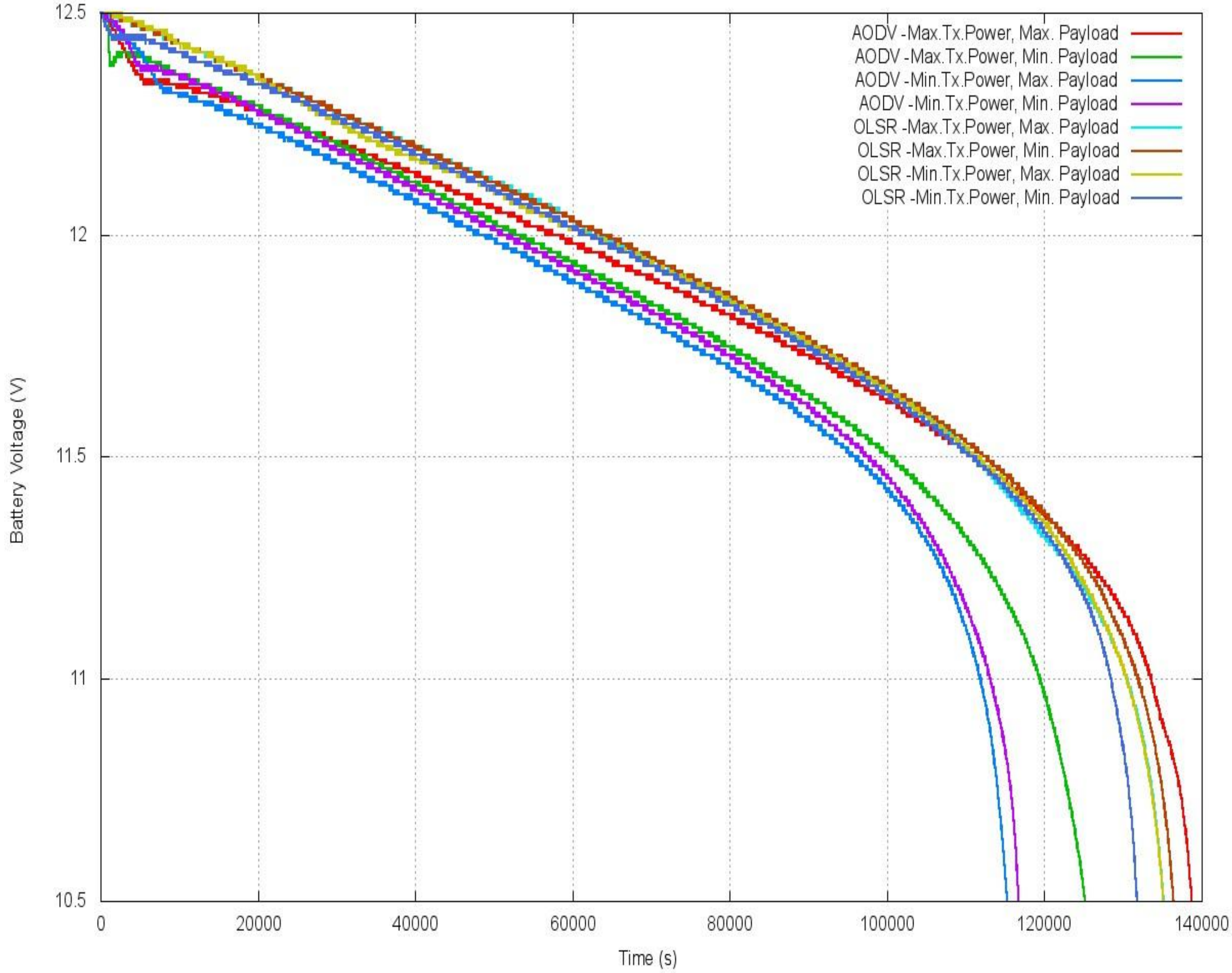

Figure 6.8: UDP-based Node Lifetime

From the above experiments on node lifetime, OLSR and AODV perform better with UDP than with TCP in terms of their operational lifetime. This TCP performance can be attributed to the Automatic Repeat-reQuest mechanism and the connection oriented based of TCP. These two mechanisms make TCP to draw more bandwidth, while trying to resend lost packets and this in-turn draws more energy, which lessen the node lifetime.

6.2.5 Experiment V: Average Energy Cost per bit

The purpose of this metric was to determine the average energy it takes to successfully transmit one bit of data packet from the source to the destination node. In order to obtain this metric, the equation discussed in Section 4.4.5 was used and Table 6.2 depicts the summary of the average energy cost per bit results and various scenarios that were considered. The lower the average energy consumed in transmitting a bit of data packet, the better the performance of that protocol in terms of energy-efficiency.

From the results obtained, it can be observed that OLSR at maximum payload and maximum transmission power level consumes the least value of energy (0.16J) in transmitting one bit of data packet for both the TCP-based and UDP based scenarios, while AODV at maximum payload and maximum transmission power level outperform other UDP-based scenarios. However, AODV at minimum payload and minimum transmission power for TCP-based scenario consumes the highest value of energy (19.28J) in transmitting one bit of data packet.

The lower energy consumption of OLSR can be attributed to the low routing overhead of OLSR compared with that of AODV, which makes OLSR conserves more energy.

From the above experiments of average energy cost per bit, the use of maximum payload size is recommended, since the value of the average energy cost per bit for maximum payload size is low compare with that of minimum payload size.

Table 6.3 summarizes the testbed results for the PDR, Throughput (TP), Average End-to-End Delay, Node Lifetime and Average Energy Cost per bit.

Table 6.3: Summary of the Results for the Testbed Experiments

Scenarios	PDR (%)	TP (Bps)	Delay (ms)	Lifetime (s)	Average Energy cost per bit (J)
TCP- OLSR at maximum transmission power with maximum payload	95.60	1561.63	1360.85	131,635	0.16
TCP- OLSR at maximum transmission power with minimum payload	94.86	96.88	1234.25	114,429	2.31
TCP- OLSR at minimum transmission power with maximum payload	90.16	1473.2	455.04	126,396	0.17
TCP- OLSR at minimum transmission power with minimum payload	50.86	51.94	720.57	132,958	5.01
TCP- AODV at maximum transmission power with maximum payload	56.00	56.0	7327.0	135,526	0.29
TCP- AODV at maximum transmission power with minimum payload	61.57	61.57	6990.0	105,099	3.27
TCP- AODV at minimum transmission power with maximum payload	22.00	22.0	7854.0	136,205	0.74
TCP- AODV at minimum transmission power with minimum payload	11.06	11.06	8915.0	111,350	19.28
UDP- OLSR at maximum transmission power with maximum payload	36.20	592.10	98.86	135,182	0.45
UDP- OLSR at maximum transmission power with minimum payload	38.00	38.77	103.51	136,422	6.88
UDP- OLSR at minimum transmission power with maximum payload	33.69	550.45	88.76	135,136	0.48
UDP- OLSR at minimum transmission power with minimum payload	33.96	34.68	22.97	131,791	7.43
UDP- AODV at maximum transmission power with maximum payload	41.80	683.09	64	138,758	0.40
UDP- AODV at maximum transmission power with minimum payload	36.60	37.37	21	125,180	6.55
UDP- AODV at minimum transmission power with maximum payload	17.00	278.10	50	115,287	0.81
UDP- AODV at minimum transmission power with minimum payload	15.00	15.30	24	116,734	14.92

6.3 Comparison between Simulation and Testbed Results

Previous studies [Anastasi *et al,* 2006, Gregori *et al,* 2004] have shown that certain aspects of real Wireless Mesh Networks are often not effectively captured in simulation environment. For example, interference caused by other wireless LAN within the proximity is unavoidable in real practice.

In this section, we compare the similarities between the simulation results and the testbed results. For the sake of simplicity and better comparison, both the simulation setup and the testbed setup were homogenous, as explained in Section 4.3.

Table 6.4 summarizes the best performing scenarios for both simulation and the testbed results for the PDR, throughput (TP), average end-to-end delay and lifetime.

It can be observed from these results, that most of our simulation results aligned with the testbed results. However, the magnitude of the difference between those simulation and testbed results are wide. For example, in lifetime experiment, it was observed that, for both simulation and testbed results, AODV performs better than OLSR for both TCP and UDP-based scenarios; however, the magnitude of the difference between simulation result and testbed result is wide. The same magnitude applies to the remaining metrics results where the simulation and testbed results aligned with each another. Hence, it can be assumed that simulation results only give a rough estimate of the network performance. However, it was also observed that, two of our simulation results are in contrast with that of testbed results. These discrepancies in the simulation and testbed results can be attributed to different assumptions in the protocol implementations used in real practice and that of the simulation tool [Anastasi *et al,* 2006]. Another reason that can be attributed to this discrepancy is the variation in the available hardware and software parameter settings used in real practice compared to the assumed ones, used in simulation tools.

Table 6.4: Comparison between Simulation and Testbed Results

Metrics	Simulation Best Performing Scenario	Testbed Best Performing Scenario
Packet Delivery Ratio	TCP-based scenarios: AODV at minimum payload	TCP-based scenarios: OLSR at maximum payload
	UDP-based scenarios: AODV at minimum payload	UDP-based scenarios: AODV at maximum payload
Average Throughput	TCP-based scenarios: OLSR at maximum payload	TCP-based scenarios: OLSR at maximum payload
	UDP-based scenarios: AODV at maximum payload	UDP-based scenarios: AODV at maximum payload
Average End-to-End Delay	TCP-based scenarios: OLSR at maximum payload	TCP-based scenarios: OLSR at maximum payload
	UDP-based scenarios: OLSR at minimum payload	UDP-based scenarios: AODV at minimum payload
Lifetime	TCP-based scenarios: AODV at maximum payload	TCP-based scenarios: AODV at maximum payload
	UDP-based scenarios: AODV at minimum payload	UDP-based scenarios: AODV at maximum payload

6.4 Testbed Experiments Limitations and Assumptions

This section highlights the limitations on the experiments conducted, as well as inherent limitations for the testbed setup that was used for this study.

The following limitations need to be thoroughly considered when setting up and performing experiments on an indoor testbed:

i. The testbed experiments were highly time consuming. Each of the experiment lasted for minimum of 30 hours; hence, it reduces the number of metrics that was considered due to the time frame for this research work.

ii. Finding an interference free channel in 2.4GHz frequency band was not easy. The building where the testbed is located has other wireless LANs operating on 2.4GHz, hence, with the channel that we used, we were only able to reduce the interference level to a bearable minimal.

iii. Debugging of routing protocol implementation: in order to get AODV working properly on WRT54GL routers, some AODV and firmware parameters like interface to use and timeout period in order for the node not to restart need to be reset.

iv. The IEEE 802.11 RTS/CTS mechanisms were disabled, because it does not improve the performance of the wireless mesh networks. Similar findings have been reported by other researchers [Johnson and Lysko, 2008]

v. Due to the size of the laboratory and the number of nodes used for the testbed setup, it was initially difficult to get a multihop environment, which is one of the cores for this study. In order to resolve this issue, the nodes antennae were disconnected and different nodes positioning were tried before we could be able to have a well established multihop environment.

CHAPTER SEVEN

CONCLUSION AND FUTURE WORK

7.1 Summary and Conclusion

This study is a successful attempt to investigate the effects of existing QoS mechanisms on battery-powered wireless mesh networks. After surveying the literature, transport and network layer protocols were selected as existing QoS to evaluate. The performance of transport layer protocols and routing protocols on battery powered nodes were evaluated using NS2 with Wireless Mesh Network simulation environment and an indoor testbed. The main aim of this study was to evaluate how different existing QoS affect the operational lifetime of a battery powered WMNs. It was important to first evaluate the energy-efficiency performance of existing routing protocols and transport layer protocols for WMNs, although they were designed with the assumption that, WMNs are not power constrained, which is not the case in most rural areas of developing nations.

This study answered the following research questions: (1) what are the effects of existing QoS mechanisms on the operational lifetime of battery-powered WMNs? (a) What is the effect of routing protocols on operational lifetime of battery-powered WMNs? (b) What is the effect of transport layer protocols on operational lifetime of battery-powered WMNs?

The goal of this study was divided into four objectives that needed to be fulfilled in order to complete the study. Achieving the set objectives also provide answers to the research questions defined in Chapter One. In order to answer the set objectives, five performance metrics were considered, which include: packet delivery ratio, throughput, average end-to-end delay, node lifetime and average energy cost per bit. This study had the following objectives: (i) to evaluate the effect of connection oriented protocol on the operational lifetime of battery-powered WMNs nodes. (ii) To evaluate the effect of connectionless oriented protocol on the operational lifetime of battery-powered WMNs nodes. (iii) To evaluate the effect of reactive protocol on the operational lifetime of battery-powered WMNs nodes. (iv) To evaluate the effect of proactive protocol on the operational lifetime of battery-powered WMNs nodes.

The first objective was fulfilled by evaluating the performance of TCP on battery-powered WMNs, based on the aforementioned five metrics, using both simulation and an indoor testbed.

In order to fulfill the second objective, UDP was chosen as the existing connectionless oriented protocol to be evaluated, and the UDP performance on battery-powered WMNs was evaluated based on the aforementioned five metrics, using both simulation and an indoor testbed. By successfully evaluating the performance of connection (TCP) and connectionless (UDP) oriented transport layer protocol; we answered the second sub research question (b i & ii).

The third research objective was fulfilled by evaluating the performance of AODV both on TCP and UDP transport layer protocol in battery-powered WMNs node. The evaluation was conducted using both simulation and indoor testbed.

In order to fulfill the fourth objective, OLSR was chosen as the existing proactive routing protocol to be evaluated, and the OLSR performance on battery-powered WMNs nodes were evaluated, using both TCP and UDP as the transport layer protocols. The evaluation was conducted using both NS2 simulation and indoor testbed. By successfully evaluating the performance of reactive (AODV) and proactive (OLSR) routing protocol; we answered the first sub research question (a i & ii). By successfully answered the four sub questions (a & b), the main research question is answered.

Based on the results that were presented in this study, we recommend that when deploying a battery-powered wireless mesh networks for connection-based applications (e.g. FTP, HTTP, VoD), using TCP with OLSR as routing protocol together with maximum payload size and maximum transmission power level will produce a better result in terms of packet delivery ratio, average throughput and average energy cost to transmit one bit of data [see Table 6.3]. Although, TCP plus OLSR with maximum payload size and maximum transmission power level was not the best performing TCP-based scenarios in terms of node lifetime, however, the energy-efficiency of a protocol/network is not determined only by their lifetime, but also by other metrics like PDR, throughput and the average energy it cost to transmit a bit of data.

And while deploying a battery-powered wireless mesh network for connectionless-based applications (DNS, SNMP, Video conferencing) or multimedia traffic based applications, using UDP with AODV as routing protocol together with maximum payload size and maximum transmission power level will produce a better result in terms of packet delivery ratio, average throughput, node lifetime and average energy cost in transmitting one bit of data [see Table 6.3].

Also, based on the results of this study, we can argue that simulation results only give a rough estimate of the real world network performance. Hence, whenever it is feasible, validating a simulation result using testbed is highly recommended in order to have clear and better understanding of the protocol performances.

7.2 Future Work

This study forms a baseline for future experimental research where the performance of new or improved WMNs protocols on the testbed can be studied and analyzed. Although the field of Wireless Mesh Networks is rapidly growing and new developments are coming day by day, there are many challenges to be met in the area of WMNs routing and transport layer protocols. Future work would focus on the following:

- The study results would be improved by migrating from the current indoor testbed to an outdoor testbed, so as to be able to study the effect of atmospheric weather on the battery lifetime and also to have real-world deployment results, which can help to compare the outdoor testbed results with that of indoor testbed.
- The testbed laboratory would be improved by migrating to 5.0GHz frequency band, in order to avoid the current interference challenges on the 2.43GHz frequency band.
- Two layer protocols (transport and routing protocol) were used in all the simulation and the testbed experiments that were conducted in this study. The use of more protocols instead of two should be considered to also run the same set of experiments, in order to have more understanding of their effects on node lifetime
- It emerges from this study that AODV-based simulation results are often differ from that of real-world environment. One of the reasons for this is the link/route failure rate of AODV on real testbed and that of the simulation. Hence, further work on refining the AODV source code in order to completely address the route failure issue will be considered.

7.3 Contribution to Knowledge

The aim of this study was to evaluate how the existing Transport Layer Protocols and Routing Protocols affect the operational lifetime of battery-powered WMNs nodes. Even though the energy-efficiency of routing protocol and TCP has been widely studied, but to the best of our knowledge, the evaluation platforms and setup do not closely resemble an actual WMN deployment. The evaluation presented in this study differs from previous studies in several respects.

In contrast to the use of laptops and PDAs as the nodes in WMNs testbed, this study employs battery-powered Linksys WRT54GL routers, which are popular nodes used for real-world deployments. Also, previous testbed studies only considered TCP as the Transport Layer Protocols, but both TCP and UDP were considered in this study. Both minimum and maximum transceiver power levels were used, whereas power levels were not previously considered in a testbed evaluation. And the energy efficiency of routing and transport layer protocols was evaluated using both the Node Lifetime and Average Energy Cost per Bit metrics.

However, based on the setup and the kind of devices that were used for this study, it is hoped that the obtained results will undoubtedly help in accelerating the research advancement and uptake of wireless mesh network deployments in rural areas of developing nations in order to bridge the existing digital divide between them and the developed nations.

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APPENDIX A – NS-2 Simulation Script for "AODV with UDP at Maximum Payload Size" Scenario

```
# ================================================================
# Define options
# ================================================================
set opt(chan)           Channel/WirelessChannel
set opt(prop)           Propagation/TwoRayGround
set opt(netif)          Phy/WirelessPhy
set opt(mac)            Mac/802_11
set opt(ifq)            Queue/DropTail/PriQueue
set opt(ll)             LL
set opt(ant)        Antenna/OmniAntenna

set opt(x)              400     ;# X dimension of the topography
set opt(y)              400     ;# Y dimension of the topography
set opt(sc)             "scen-udp-120"
set opt(cp)             "traffic-120-udp"

set opt(ifqlen)         50              ;# max packet in ifq
set opt(nn)             120             ;# number of nodes
set opt(seed)           1.0
set opt(stop)           100.0           ;# simulation time
set opt(tr)             120-udp-aodv.tr ;# trace file
set opt(rp)         aodv          ;# routing protocol script
set opt(lm)          "off"        ;# log movement
set opt(agent)        Agent/AODV
set opt(energymodel)    EnergyModel     ;
set opt(initialenergy)  1.0          ;# Initial energy in Joules
set opt(logenergy)      "on"         ;# log energy every 150 seconds

# ================================================================
# needs to be fixed later
set AgentTrace                  ON
set RouterTrace                 ON
set MacTrace            ON

LL set mindelay_        50us
LL set delay_           25us
LL set bandwidth_       0       ; # not used

Agent/Null set sport_   0
Agent/Null set dport_   0

Agent/CBR set sport_    0
```

```
Agent/CBR set dport_        0

Agent/UDP set sport_        0
Agent/UDP set dport_        0

Agent/UDP set packetSize_   512


Queue/DropTail/PriQueue set Prefer_Routing_Protocols    1

# unity gain, omni-directional antennas
# set up the antennas to be centered in the node and 1.5 meters above it
Antenna/OmniAntenna set X_ 0
Antenna/OmniAntenna set Y_ 0
Antenna/OmniAntenna set Z_ 1.5
Antenna/OmniAntenna set Gt_ 1.0
Antenna/OmniAntenna set Gr_ 1.0

# Initialize the SharedMedia interface with parameters to make
# it work like the 914MHz Lucent WaveLAN DSSS radio interface
Phy/WirelessPhy set CPThresh_ 10.0
Phy/WirelessPhy set CSThresh_ 1.559e-11
Phy/WirelessPhy set RXThresh_ 3.652e-10
Phy/WirelessPhy set Rb_ 2*1e6
#Phy/WirelessPhy set Pt_ 0.2818
Phy/WirelessPhy set freq_ 914e+6
Phy/WirelessPhy set L_ 1.0

# ======================================================================

proc usage { argv0 }  {
	puts "Usage: $argv0"
	puts "\tmandatory arguments:"
	puts "\t\t\[-x MAXX\] \[-y MAXY\]"
	puts "\toptional arguments:"
	puts "\t\t\[-cp conn pattern\] \[-sc scenario\] \[-nn nodes\]"
	puts "\t\t\[-seed seed\] \[-stop sec\] \[-tr tracefile\]\n"
}


proc getopt {argc argv} {
	global opt
	lappend optlist cp nn seed sc stop tr x y

	for {set i 0} {$i < $argc} {incr i} {
		set arg [lindex $argv $i]
```

```
			if {[string range $arg 0 0] != "-"} continue

			set name [string range $arg 1 end]
			set opt($name) [lindex $argv [expr $i+1]]
		}
}

# ==================================================================
# Main Program
# ==================================================================
getopt $argc $argv

#source ../lib/ns-bsnode.tcl
#source ../mobility/com.tcl

# do the get opt again incase the routing protocol file added some more
# options to look for
getopt $argc $argv

if { $opt(x) == 0 || $opt(y) == 0 } {
		usage $argv0
		exit 1
}

if {$opt(seed) > 0} {
		puts "Seeding Random number generator with $opt(seed)\n"
		ns-random $opt(seed)
}

#
# Initialize Global Variables
#
set ns_		[new Simulator]
set topo			[new Topography]

set tracefd	[open $opt(tr) w]

$topo load_flatgrid $opt(x) $opt(y)

$ns_ trace-all $tracefd
$ns_ use-newtrace

#
# Create God
#
create-god $opt (nn)
```

```
#
# Create the specified number of nodes $opt(nn) and "attach" them
# the channel.
# Each routing protocol script is expected to have defined a proc
# create-mobile-node that builds a mobile node and inserts it
# into the
# array global $node_($i)
#

        #global node setting

    $ns_ node-config -adhocRouting AODV \
                     -llType $opt(ll) \
                     -macType $opt(mac) \
                     -ifqType $opt(ifq) \
                     -ifqLen $opt(ifqlen) \
                     -antType $opt(ant) \
                     -propType $opt(prop) \
                     -phyType $opt(netif) \
                     -channelType $opt(chan) \
                     -topoInstance $topo \
                     -agentTrace ON \
                     -routerTrace ON \
                     -macTrace OFF \
                     -movementTrace OFF \
                     -energyModel $opt(energymodel) \
                     -rxPower 0.3 \
                     -txPower 0.6 \
                     -initialEnergy $opt(initialenergy)

        for {set i 0} {$i < $opt(nn) } {incr i} {
                set node_($i) [$ns_ node]
                $node_($i) random-motion 0    ;# disable random motion
        }


#
# Source the Connection and Movement scripts
#
if { $opt(cp) == "" } {
        puts "*** NOTE: no connection pattern specified."
    set opt(cp) "none"
} else {
        puts "Loading connection pattern..."
        source $opt(cp)
}
```

```
#
# Tell all the nodes when the simulation ends
#
for {set i 0} {$i < $opt(nn) } {incr i} {
   $ns_ at $opt(stop).000000001 "$node_($i) reset";
}
$ns_ at $opt(stop).00000001 "puts \"NS EXITING...\" ; $ns_ halt"


if { $opt(sc) == "" } {
         puts "*** NOTE: no scenario file specified."
      set opt(sc) "none"
} else {
         puts "Loading scenario file..."
         source $opt(sc)
         puts "Load complete..."
}

puts $tracefd "M 0.0 nn $opt(nn) x $opt(x) y $opt(y) rp $opt(rp)"
puts $tracefd "M 0.0 sc $opt(sc) cp $opt(cp) seed $opt(seed)"
puts $tracefd "M 0.0 prop $opt(prop) ant $opt(ant)"

puts "Starting Simulation..."
$ns_ run
```

APPENDIX B – AWK/PERL Script for Analyzing the Trace files

```
# ==============================================================
 # AWK Script for calculating:
 #     => Packet Delivery Ratio,
 #     => Average Throughput,
 #     => Average End-to-End Delay, and
 #     => Network Lifetime.
# ==============================================================


 BEGIN {
     seqno = -1;
     droppedPackets = 0;
     receivedPackets = 0;
     count = 0;
 }
 {
     #packet delivery ratio
     If ($4 == "AGT" && $1 == "s" && seqno < $6) {
           seqno = $6;
     } else if (($4 == "AGT") && ($1 == "r") && ($7 == "tcp")) {
             receivedPackets++;
     } else if ($1 == "D" && $7 == "tcp"){
             droppedPackets++;
```

```
  }
   #end-to-end delay
   {
  If ($4 == "AGT" && $1 == "s" && seqno < $6) {
       seqno = $6;
  }
         else if(($4 == "AGT") && ($1 == "r")) {
         receivedPackets++;
  } else if ($1 == "D" && $7 == "cbr" && $8 > 512){
         droppedPackets++;
 }
}

END {
  for(i=0; i<=seqno; i++) {
       if(end_time[i] > 0) {
           delay[i] = end_time[i] - start_time[i];
               count++;
      }
         else
         {
               delay[i] = -1;
         }
  }
```

```
  for (i=0; i<=seqno; i++) {

       if (delay[i] > 0) {

           n_to_n_delay = n_to_n_delay + delay[i];

       }

  }

 n_to_n_delay = n_to_n_delay/count;



  print "\n";

#    print "GeneratedPackets            = " seqno+1;

#    print "ReceivedPackets             = " receivedPackets;

#    print "Packet Delivery Ratio      = " receivedPackets/(seqno+1)*100
#"%";

#    print "Total Dropped Packets = " droppedPackets;

  print "Average End-to-End Delay    = " n_to_n_delay * 1000 " ms";

  print "\n";

}

# Average Throughput

BEGIN {
      recvdSize = 0
      startTime = 400
      stopTime = 0
  }

  {
           event = $1
           time = $2
           node_id = $3
           pkt_size = $8
           level = $4
```

```
  # Store start time
  if (level == "AGT" && event == "s" && pkt_size >= 32) {
    if (time < startTime) {
            startTime = time
            }
      }

  # Update total received packets' size and store packets
  # arrival time
  if (level == "AGT" && event == "r" && pkt_size >= 32) {
      if (time > stopTime) {
            stopTime = time
            }
      # Rip off the header
      hdr_size = pkt_size % 32
      pkt_size -= hdr_size
      # Store received packet's size
      recvdSize += pkt_size
      }
  }

  END {
      printf("Average                    Throughput[kbps]                    =                    %.2f\t\t
StartTime=%.2f\tStopTime=%.2f\n",(recvdSize/(stopTime-
startTime))*(8/1000),startTime,stopTime)
  }


# Network Lifetime

#!/usr/bin/perl
#Script to calculate network lifetime
#Created by Pragasen Mudali Tue Nov 02 15:51:43 2010
#Wireless Mesh Networks Group, Centre for Mobile e-Services for Development
#Dept. Computer Science
#University of Zululand
use strict;

# to check the command line option
          If ($#ARGV<0) {

Printf ("Invalid Usage: no trace file found: perl lifetime.pl <no. nodes> <trace file>\n");
    exit 1;
}
open (Trace, $ARGV [1])or die "Cannot open trace file";
my $network_size = $ARGV [0];
```

```
my $current_time = 0;
my $no_surviving_nodes = $network_size;

printf("Time\t\tNode ID\tNo. Surviving Nodes\n");

#for (my $count = 0; $count > $network_size; $count++) {
	while (<Trace>){
		my @line = split;
		if ($line[0] eq "N") {
			#if ($line[4] == $count){
				if ($line[6] eq "0"){
					$current_time = $line[2];
					$no_surviving_nodes--;

		printf("%f\t%d\t%d\n", $current_time, $line[4], $no_surviving_nodes);

				}
		}

	}
```

APPENDIX C – Script for Node Firmware and AODV Installation

```
$ cd /home/WRT54Gfirmware

$ ls

OpenWRT-g-freifunk-1.7.4-en

$ tftp 192.168.1.1

tftp > bin

tftp > put OpenWRT-g-freifunk-1.7.4-en.bin

$ reboot

$ telnet 192.168.1.1

$ passwd

$ reboot

root@openwrt:/# ipkg install libpcap_0.9.4-1_mipsel.ipk

root@openwrt:/# ipkg install libgcc_3.4.4-5_mipsel.ipk

root@openwrt:/# ipkg install rccdcgi1_mipsel.ipk

root@openwrt:/# ipkg install wl-adv_1.1_mipsel.ipk

root@openwrt:/# ipkg install rrdcollect_0.2.3_mipsel.ipk

root@openwrt:/# ipkg install tcpdump_3.9.4-1_mipsel.ipk

root@openwrt:/# ipkg install aodv-uu_0.9.3-1_mipsel.ipk

root@openwrt:/# ipkg install kmod-ipt-queue_2.4.30-brcm-5_mipsel.ipk

root@openwrt:/# killall olsrd

root@openwrt:/# insmod ip_queue

root@openwrt:/# insmod kaodv

root@openwrt:/# aodvd use_dev=eth1
```