Towards the Design of an Energy-Aware Path Selection Metric for IEEE 802.11s Wireless Mesh Network

By

Mhlanga MM
(B.Sc. Hons. Computer Science)

Supervisor: Prof MO Adigun
Co-Supervisor: Dr N Ntlatlapa

This dissertation is submitted to the Department of Computer Science at the University of Zululand's Faculty of Science and Agriculture, in fulfilment of the requirements for the degree of Master of Science in Computer Science

2012

Declaration

I declare that this dissertation is my own original work, conducted under the supervision of Prof M.O. Adigun and Dr N. Ntlatlapa. 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, KwaDlangezwa. 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. Part of this work was published and presented at SATNAC 2009 in Swaziland and another publication at the IEEE AFRICON 2011 in Zambia.

Signature: ____________________

MHLANGA M.M

Dedication

I dedicate this work to all my family members and friends and a special dedication to my late brother Thami Mhlanga.

Acknowledgements

I would like to express my appreciation to Dr N. Ntlatlapa and Prof M.O. Adigun for providing dedicated supervision throughout my research. Financial support by employer CSIR Meraka Institute. A special thanks to Telkom, Thrip and Huawei for the support they have shown to the Department of Computer Science at the University of Zululand through the CoE program it is gratefully acknowledged.

I would also like to thank my research colleagues at CSIR and in the Department of Computer Science with whom I had the pleasure to discuss, argue and work, etc. This work would have been impossible without their contributions. The following made explicit and highly valuable input that can be found throughout the dissertation. Their help is gratefully acknowledged:

My gratitude extends to my unofficial supervisor Thulani Nyandeni whose criticisms have made it possible for this work to be finally submitted as a thesis. Many thanks also goes to Dr. Thomas Olwal for mentoring and encouraging me to work hard. Without his help, this work would not have seen light. He helped me to understand the interpretation of mathematical equations. A special thanks to Clemence Kyara for introducing me to NS-2 simulator and for his constructive criticisms.

Many thanks to Bethel Mutanga for encouraging me to work hard and also his valuable suggestions and criticisms to help produce a good thesis. A special thanks also goes to Sihle Sibiya for his contribution in structuring my thesis. My sincere gratitude also goes to my parents and family members. Finally, I would like to thank God for the opportunity that he gave me, for providing an intellectually and socially stimulating and well-organised environment for me and for giving me the strength to pull through difficult times.

TABLE OF CONTENT

List of Figures

List of Tables

Abstract

It is everyone's dream to have network connectivity all the time. This dream can only be realised provided there are feasible solutions that are put in place for the next generation of wireless works. Wireless Mesh Networking (WMN) is therefore seen as a solution to the next generation of wireless networks because of the fact that WMNs configures itself and it is also self healing. A new standard for WMNs called the IEEE 802.11s is still under development. The protocol that is used by the IEEE 802.11s for routing is called Hybrid Wireless Mesh Protocol (HWMP). The main purpose of HWMP is to perform routing at layer-2 of the OSI model also referred to as the data link layer (DLL). Layer-2 routing is also referred to as the mesh path selection and forwarding. Devices that are compliant to the IEEE 802.11s standard will be able to use this path selection protocol. Devices that are manufactured by different vendors will therefore be interoperable.

Even though significant efforts have gone into improving the performance of HWMP, the protocol still faces a lot of limitations and the most limiting factor is the small or restricted energy of the batteries in a wireless network. This is because of the assumption that mesh nodes that are deployed in urban areas tend to have no energy constraints while WMN nodes deployed in rural faces serious energy challenges. The latter relies on batteries and not on electricity supply which powers the WMN nodes in urban areas. This work, therefore, explores further the current trends towards maximising the network lifetime for the energy constrained networks. Hence the goal of this study is to design a path selection algorithm that is energy-aware and optimising for the IEEE 802.11s based HWMP.

The main idea is that paths with enough energy for transmission must be selected when transmitting packets in the network. Therefore, a simulation using NS-2 was carried out to assess the network performance of the proposed EAPM metric with the other metrics that have been analysed in literature including ETX. ETX has been used in WMNs but was not developed specifically for mesh. In conclusion, EAPM conserves more energy than the Multi-metric, airtime link metric and lastly ETX. The simulation experiments show that EAPM optimises the energy used in the network and as a result EAPM has a prolonged network lifespan when comparing it to the rest of the metrics evaluated in this study. The results also revealed that the newly proposed EAPM exhibits superior performance characteristics even with regard to issues like end-to-end delay and packet delivery ratio.

CHAPTER ONE

INTRODUCTION

1.1 Preamble

It has always been a dream for everyone to have a network connection at all times whenever the connection is needed. It is, therefore, for that reason we believe that in order to achieve this dream, feasible results to the next generation wireless networking should be realised and implemented. Extensive and remarkable investigation has been conducted in the field of wireless networks that has produced important research contributions. These research advances include but not limited to routing algorithms, protocols and metrics for wireless networks and theoretical capacity bounds. However, there are still some problems in the field of routing that have not been taken care of, such as: scalability, network capacity, security and energy awareness.

The centre of attention for this research is, therefore, towards ensuring that the network is made aware and efficient about the energy usage. This is more essential especially when the network is designed to be deployed in rural areas. The current research and developments in WMNs have not invested much in ensuring that the routing protocol developed for WMN is energy efficient. The reason being that the backbone routers for WMNs have been alleged to be using electric power supply and are stationary, as a result, are alleged not to have energy constraints (Aron et al, 2008 and Ntlatlapa, 2007). But when considering a situation where the mesh network is deployed in rural areas, the wireless mesh nodes would run out of energy in-spite of being stationery. As a multi hop network, a WMN uses intermediate nodes to relay packets to its neighbours until the packet reaches the intended destination and that reduces the chances of a network's operation being hampered. The energy exhaustion of nodes when routing packets is the biggest intimidation to the necessary survivability of the network. The newly proposed protocol for WMNs performs routing in layer-2, which is also called mesh path selection and forwarding at the data link layer (Aoki, 2005). The Hybrid Wireless Mesh Protocol (HWMP) is the protocol that is explicitly designed for layer-2 routing and also regarded as a default mandatory protocol for WMNs.

However, HWMP does not regard energy optimisation as a priority in wireless mesh networks. A routing protocol that does not consider energy issues when choosing a path has a tendency of using the same path for a longer period. The effect of using the same path for a longer period is that the energy that is being used by the nodes along the frequently used path may be quickly exhausted, causing network partitioning. In order to try and avoid such problems, we therefore, suggest that energy should always be well thought-out when a WMN is designed. This is mainly because the amount of energy the network consumes determines how long the network can work (Aron et al, 2008). Therefore, we think that the most valuable metric for routing protocol performance under the IEEE 802.11s is network survivability especially when the network is deployed in rural areas (Ntlatlapa, 2007).

1.2 Statement of the Problem

The IEEE 802.11 wireless standards have received a considerable attention in the literature towards the study of energy-awareness and optimisation issues, especially in the field of wireless sensor and wireless ad hoc networks in general. However, not much has been reported regarding the optimisation of energy in WMNs. Two facts are established from this. The first one is the assumption that a WMN deployment in rural areas tend to have no energy constraints (Aron et al, 2008). The second one is that WMNs faces serious energy challenges when it is deployed in rural areas. The latter relies on batteries and not on electricity power supply which powers WMN nodes in urban areas. As a result, the WMN nodes deployed in rural areas would run out of energy in-spite of being stationery (Ntlatlapa, 2007).

Therefore due to the above mentioned constraints, a huge interest in developing energy optimizing routing protocols for WMNs that will help save energy and by so doing prolong the network's operational time has emerged. The main challenge with the existing routing protocols that are currently used in wireless networks is that they tend to discover the shortest path with no consideration of energy and use that particular path for every communication, which is really bad for the network's life's span. For this problem to be addressed, this research therefore, proposes an energy-aware path selection metric (EAPM) for IEEE 802.11s WMNs.

1.3 Motivation for the Study

The research conducted by the CSIR Meraka Institute in Ntlatlapa, (2007) reveals that energy efficiency in (WMNs) is the best possible solution to the problem of digital divide in Africa. This research is motivated by the ambition to connect more or less than 450 million rural Africans that have no access to broadband ICT infrastructure and services. Without access to broadband these rural communities are not able to access a lot of these new ICT applications that are available for use, such as e-learning, e-government, e-health and e-commerce. The research presented by Aron et al, (2008) also motivated us to look at the outstanding energy issues in WMNs that needs serious attention especially for the benefit of the rural community in Africa.

This research, therefore, considers the use of WMNs in remote or inaccessible areas of the African continent where nodes operate on batteries. Our aim is to minimise energy consumption at the same time achieving throughput and low delay. The study embraces a community network based philosophy and visualises the practical deployment of WMNs in energy constrained rural areas. It is, therefore, essential for the WMN to be energy efficient by introducing energy efficient routing protocols for WMNs. Hence this prompted us to direct our research focal point on the design of a metric that helps to choose paths that are energy-aware and optimising for the IEEE 802.11s WMN.

1.4 Goals and Objectives.

1.4.1 Goal

The goal of this study is to design an energy-aware and optimising path selection metric for the IEEE 802.11s based HWMP.

1.4.2 Objectives

The goal of this research is broken down into the following measurable objectives:

i. To identify and investigate existing energy aware routing protocols with their metrics and algorithms in wireless ad hoc networks.

ii. To develop an energy-aware and optimising path selection metric for HWMP to help choose a path that will help conserve energy.

iii. To conduct a performance assessment of the newly proposed energy-aware and optimising path selection metric in comparison with the already existing metrics through simulation.

1.5 Research Methodology

The most essential thing about the results obtained from this study is that they should be applicable to the IEEE 802.11s extensibility framework; using the following methodology:

1. *Literature survey.* This method entails surveying the background of the area of interest and the theoretical part of this research involves analysing previous work in the field energy efficient routing in wireless ad hoc networks. This kind of an investigation is done based on the theoretical framework that is specifically developed for this task. Surveying the field of study, identification of a problem, literature review in the area of

interest, problem analysis and initial solution to the problem.

2. *Metric Design*. Designing the EAPM for IEEE 802.11s WMNs requires a constructive engineering approach hence the above analysis is used to formulate the processes/ methods/ algorithms that will contribute towards the development of our metric.

3. *Simulation of proposed metric using NS2 simulator*. A design criterion is formulated before the proposed metric is simulated in NS2.

4. *Metric Analysis and Evaluation*. A performance analysis of the proposed EAPM with the other evaluated metrics was done using both graphical and theoretical techniques. The following experimental metric components were utilised for the performance assessment of the proposed path selection metric:

    i. The amount of energy consumed in a unit flow transmission over the path.

    ii. The initial energy of a node.

    iii. The remaining energy (residual energy) at the transmitting node.

1.6 Organisation of the Dissertation

The rest of this dissertation is structured as follows: The first chapter is introductory, which outlines the: statement of the problem, motivation of the study, goals and objectives and the research methodology. Chapter two gives a background of this study by introducing some basic concepts in WMNs, the IEEE 802.11s standard and HWMP. In Chapter three we make analysis of what other scholars have proposed in the literature. The taxonomy of the energy efficient routing protocols is presented in this chapter. The chapter concludes by listing common deficiencies among the energy conserving protocols in the literature which is a characteristic that is common among the previously cited studies. The min-max cost function is also applied. Chapter four discusses the proposed energy-aware path selection metric. The introduction of flow argument routing is also discussed in chapter four. Chapter five details the simulation and performance evaluation of the proposed metric. It discusses simulation environment and parameters that are utilized in the simulation. The same chapter furthermore presents the analysis of the results. Chapter six provides a conclusion of the study. It gives a synopsis of the achievements made and challenges. The chapter concludes by suggesting some views and possible future directions.

CHAPTER TWO

BACKGROUND

2.1 Introduction

The design of the IEEE 802.11s standard for WMNs can be applicable to quite a number of usage scenarios. Below is a group of four imperative usage scenarios that have been identified (Conner, 2004).

i. Home networks for residential areas,
ii. Wireless networks for office environments,
iii. Large scale wireless Internet for campus, communities, and public access.
iv. An ad hoc wireless communication network setup designed for emergency staff which is flexible for public safety.

The IEEE 802.11s standard is divided into four main components – general topics, MAC enhancements, routing and security (Aoki, 2005). Our research, therefore, pays attention only to the data link layer (DLL) which is routing in layer-2 also referred to as the path selection and forwarding. The protocol that is used in layer-2 as a default and mandatory protocol for WMNs is called a Hybrid Wireless Mesh Protocol (HWMP) which is defined by the IEEE 802.11s draft standard. HWMP uses a hierarchical routing method to make use of a tree-like logical structure (Aoki, 2005). To assure the full functioning of the mesh, all wireless mesh points (MPs) should implement the HWMP as a mandatory algorithm. On the other hand, other proprietary protocols could also be employed. It is also imperative to have a forwarding algorithm with a determination to assist in building paths that can, therefore, build the Mesh backbone. Instead of using some of the frequently used layer three routing algorithms or protocol, 802.11s brings this feature at layer-2 of the TCP/IP protocol suite. The good thing about this method is that it makes the mesh visible to upper layer protocols (e.g network/IP), where any anticipated destination within the mesh is seen to be only one hop away (Bahr, 2006). HWMP is the mixture of AODV and tree-based routing. AODV is designed to work by means of IP addresses on the network layer. AODV also make use of hop count as a routing metric. Instead of hop count, HWMP uses RM-AODV which is specifically designed to work on layer-2 with MAC addresses and it makes use of a routing metric that is radio aware for path selection (Bahr, 2006). Another optional protocol has been proposed which is a layer-2 adaptation of OLSR called RA-OLSR.

2.2 Overview of Routing Protocols in Wireless Mesh Networking.

A routing protocol's most significant rationale is to supply the nodes with information about which nodes can be used to reach which destinations. Different requirements may be imposed by different routing protocols on the design of their routing metrics. For effective routing to be supported in wireless mesh networks it is essential to first be aware of the crucial properties of routing metrics. Depending on the time of calculating the routes, WMNs can possible use the following categories of routing protocols to calculate routes, namely: reactive, proactive and hybrid routing protocols.

Proactive routing is divided into two subcategories which is based on the manner in which packets are routed along the paths,:

i. source routing

ii. hop-by-hop routing.

All of the above mentioned types of routing methods cost differently in terms of message overhead and complexity management.

2.2.1 Reactive Routing Protocols (Mukhija and Bose, 2001)

Reactive routing protocols calculate and create routes if and only if there is data to send from source to the intended destination node. Network-wide flooding is the method that is used to discover the routes. Therefore, the process of route search is triggered by the need for a route, which makes it to be reactive. Network flooding technique provides superior network connectivity with a moderately minimal overhead for messages when measured up against proactive routing protocols. As pointed out in the literature that HWMP is taken from the original reactive Ad hoc On-demand Distance Vector routing protocol (AODV) presented by Perkins et al, (2003) which is then referred to as the *Radio-Metric AODV (RM-AODV)*. In the next section we, therefore, concentrate on AODV.

2.2.1.1 Ad hoc On Demand Distance Vector (AODV) Routing Protocol (Perkins et al, 2003)

The MANET working group in IETF presented by Perkins et al, (2003) defines AODV as a reactive also referred to as on demand routing protocol for reactive ad-hoc networks. AODV as a routing protocol plays a big role among participating nodes that intends to create and sustain an ad hoc network by enabling self-starting, dynamic and multi-hop routing. AODV makes it possible for nodes to discover routes quick for new destinations, and if the communication is not active the nodes do not maintain routes to destinations. AODV has a mechanism that makes it possible for the wireless nodes to quickly react to link breakages and when there is change in the network topology. The problem of counting to infinity is avoided in AODV because it uses the loop-free operation. The count to infinity problem by Bellman-Ford provides a speedy convergence as soon as the nodes are moving in the network causing changes in the network topology.

When the wireless links that are used for communication in the network break because of nodes that are affected, AODV notifies the affected nodes to use the broken links to invalidate the routes. Destination sequence numbers as a distinctive feature of AODV are used for every route entry. Whenever any route information about a certain destination is sent to requesting nodes, destination sequence numbers are created. It is easy to program destination sequence numbers and the advantage of using them is that they warrant loop freedom. When there are multiple routes to choose from to route from source to destination, the requesting node therefore chooses the route with the maximum sequence number (Perkins et al, 2003). As shown in figure 2.1 below, AODV has three messaging that it defines which are: Route Requests (RREQs), Route Replies (RREPs), and Route Errors (RERRs).

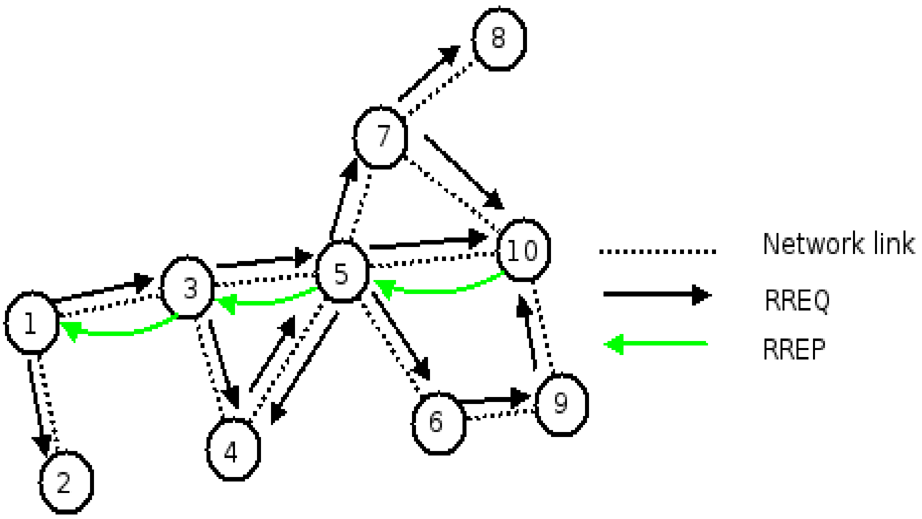

Figure 2. 1 A route discovery process shown by the AODV routing protocol (Johnson, 2008)

UDP is responsible for handling these message types which uses normal IP header processing. An IP address is used by the node that sent the request and the messages uses it as a source IP address. In order to show the range of distribution of broadcast RREQs, the IP header which contains the time to live (TTL) can make of the TTL. The research conducted by Perkins et al, (2003) states that AODV does not apply any role if and only if the connection between the endpoints of a communication have legitimate routes from one point to the other.

For a route to be determined from the source node to the intended destination, the RREQ must have either reached the destination and came back as a RREP or only if there is a neighbour node with a route that is fresh enough to the destination. If a sequence number (SN) for a route is as great as a SN that is found in the RREQ then the route associated with that sequence number is regarded a route that is fresh enough. A route that has not expired to be used to reach the destination is called an unexpired route entry. Upon receiving the RREQ the destination node will then send back a RREP as a unicast to create the route back to the source. The main reason for this is that that all the nodes that receive the RREQ towards the destination takes a route that is heading back to the source node which initiated the request. Any neighbouring node that is able to send the RREP back to the source node can send it at a unicast. In active routes, information about the status of the link to the next hop node is always monitored by the nodes. A RERR message is broadcasted to the entire network to notify the nodes about the link failures when a link failure is detected in a route that is active. The main purpose of a RERR message type is to indicate which destinations nodes are no longer unreachable due to the link failure.

2.2.2 Proactive (Table-Driven) Routing Protocols

These protocols tries to ensure that routing information is kept consistent and fresh from one node to the next node in the network (Johnson, 2008). In proactive routing, the protocol knows about all the paths that are broadcast to the rest of the nodes in the network. With this kind of routing technique each node makes an effort to retain information obtained during routing. Proactive routing protocols, such as the Destination-Sequenced Distance-Vector (Usop et al, 2009) and (Perkins and Bhagwat, 1994), Optimized Link State Routing by Tonnesen, (2004) and Clausen et al, (2002), the Topology Broadcast Based on Reverse-Path Forwarding Ogier et al, (2002) routing protocols and Open Shortest Path First with Minimum Connected Dominating Sets presented by Lin, (2004) all use periodic control messages to maintain up-to-date routing information.

Due to the above mentioned reasons, table-driven routing protocols always exchange packets periodically. One or more routing tables are maintained by each node that uses a proactive routing algorithm. These routing tables are for storing routing information as well as responding to topology changes in the network. For the network view to be consistently maintained, updates are propagated. This research uses two routing tables, the first one is the proactive routing scheme and the other one is the reactive routing scheme. The proactive routing scheme forms the tree like structure and it is adopted from the well-known Optimized Link State Routing (OLSR) (Clausen et al, 2002). OLSR is, therefore, introduced below as a proactive routing protocol.

2.2.2.1 Optimized Link State Routing Protocol (OLSR)

OLSR optimises the classical link-state routing protocol that is developed for mobile networks. In this protocol routes are always available whenever needed due to its proactive nature. OLSR uses multipoint relays (MPRs) to minimise flooding overhead of control traffic to retransmit control messages, which is a subset of nodes in the network. The size of retransmissions that is required in order to flood a message to all the nodes in the network is reduced when this kind of a technique is used. Secondly, OLSR can only provide shortest path routes if and only if there is a partial link state that is flooded.

OLSR can also help in optimising the reactivity to topological changes. To achieve this, there has to be a reduction in the maximum time interval given for periodic control message transmissions. When there is a substantial amount of subsets of nodes that exchange messages to each other, OLSR always provide a better-quality for traffic patterns. In OLSR all the routes to their respective destinations are maintained at all times. They are also maintained especially where the source node varies with destination node over time. OLSR is an excellent protocol that is designed for big and crowded networks; this is for the reason that the optimisation made by means of MPRs does wonders in this context. OLSR can achieve more optimisation if the network is larger and denser than the classic link-state algorithm (11-05/0563, 2005). Due to the fact that OLSR works perfectly in a distributed approach, therefore, any central approach won't perform well. As a result there is no need of any reliable transmission of control messages. In OLSR to control messages there are no reliable transmissions needed. Control messages are sent at regular intervals in order to sustain a reasonable loss of some form of such messages.

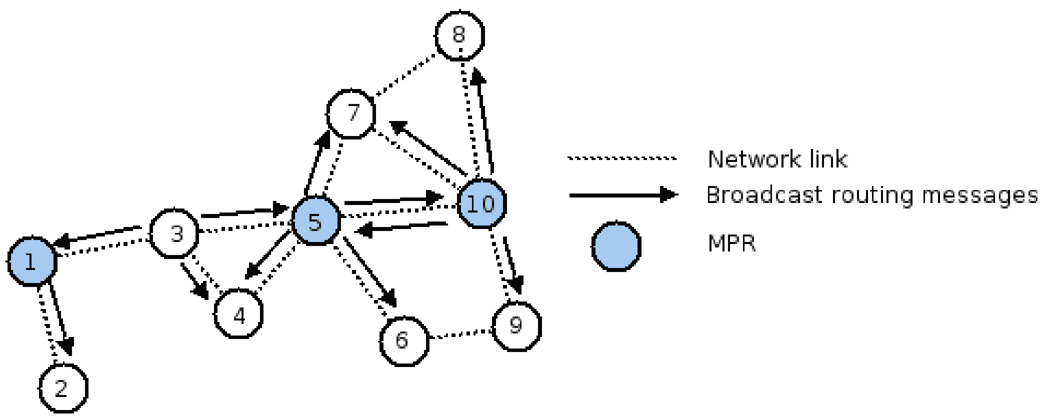

Figure 2.2 OLSR routing protocol showing selection of MPRs (Johnson, 2008)

Transmission problems such as collisions occur a lot in radio networks causing a loss of some messages in the network. There is no need for sequence delivery messages in OLSR. For every control message that is generated a sequence number is incremented. For that reason the recipient of a control message has the potential to simply recognise the most recent information and this applies to even messages that have been re-ordered while in transmission. In addition, protocol extensions like the sleep mode operation and the multicast-routing etc are offered support by the OLSR. The protocol may have these extensions introduced as add-ons without breaking any backward compatibility. The proactive approach does not apply global route discovery broadcasts but it still has challenges, for example its two main advantages are:

- Proactive protocols demonstrate a certain amount of control message overhead even if the network is idle.
- Proactive protocols consume a lot of time to adjust to topology changes.

The attractive characteristics of both proactive and reactive routing protocols resulted in the development of the Hybrid Wireless Mesh Protocol (HWMP) for the IEEE 802.11s standard (Bahr, 2006 and 11-05/0563, 2005). Hybrid protocols are designed such that they use proactive algorithms when they are within local clusters of nodes and then reactive algorithm between clusters.

2.2.3 Hybrid Wireless Mesh Protocol (HWMP)

HWMP is specifically designed as the default routing protocol for the IEEE 802.11s wireless mesh networking (11-05/0563, 2005, and Bahr, 2006). Every device that is compliant to the IEEE 802.11s will be able to use the HWMP protocol. The advantage of IEEE 802.11s compliant devices is that devices of diverse vendors will be interoperable. HWMP is a combination of reactive routing capabilities and proactive routing capabilities (11-05/0563, 2005). The most part of HWMP is basically adapted from AODV to radio-aware link metrics and MAC addresses which is called the Radio-Metric AODV. This section gives explanation of two examples of protocols for path selection that can be applied in the extensible 802.11s structure. The reactive component of HWMP uses a method for discovering paths that is very much alike to the one used in AODV.

AODV is designed to work in the network layer (layer 3) with the use of IP addresses and it uses hop count as its routing metric. On the other hand, RM-AODV works in the data link layer (DLL) with the use of MAC addresses and for path selection it uses a radio-aware routing metric. An optional protocol from the IEEE 802.11s draft (11-05/0563, 2005) is described. The work presented in Bahr, (2006) states that this hybrid mechanism and the manner in which HWMP has been configured as shown in Figure 2.3; offers a first-class performance in all anticipated usage scenarios.

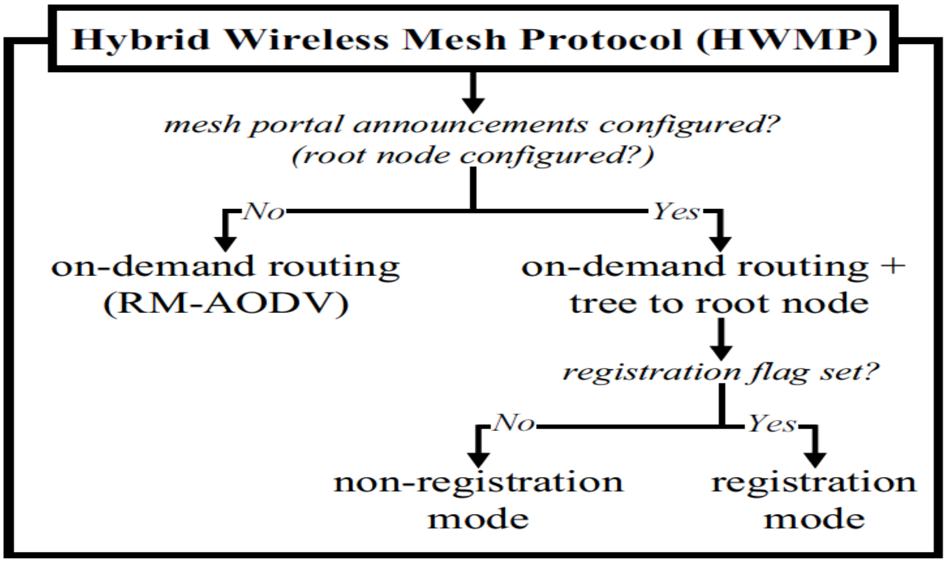

Figure 2. 3 Configurability of Hybrid Wireless Mesh Protocol (Bahr, 2006)

2.2.3.1 Radio Metric AODV (RM-AODV) (11-05/0563, 2005)

As an on-demand routing protocol RM-AODV is responsible for enabling the discovery and maintenance of optimal routes (11-05/0563, 2005). RM-AODV uses the most important mandatory features of AODV protocol as the baseline and specifies extensions to make possible the identification and maintenance of the best-metric route in a mesh network by incorporating the mechanisms in (11-05/0563, 2005).

To establish routes between two nodes Radio-Metric AODV uses a Route Request (RREQ) and Route Reply (RREP) mechanism. Each node is designed such that the node's intelligence is able to determine every link's metric cost to each of the node's neighbours. Using a metric field in the RREQ and RREP messages guarantees a broadcast in the metric information between nodes. A RREQ that is broadcast during a route discovery process contains a destination list and a metric field initialised to zero that specifies the destination node. There is a possibility of each node receiving duplicates of the same RREQ with each RREQ being transmitted in a unique path to reach the intended destination node. The RREQ is forwarded or re-broadcast only if a route is created or modified. A metric field in a RREQ that is forwarded by a node is updated to reveal that the metric of the route is increasing from the forwarding node to the RREQ's source. A unicast RREP is sent back to the source node by the destination node after the route has been created or updated.

Unlike in AODV, even if intermediate nodes in Radio Metric AODV have a route to the destination they are not allowed to generate a RREP even if they have a route to the destination. A RREP can only be generated by the destination node. A new route is updated back to the source with a fresh RREP by the destination node only if the destination node does not stop receiving RREQs messages with a better metric. As a result, an establishment of a best end-to-end metric route between the source node and the intended destination node is formed. To properly maintain a best metric path between the source and destination and enabling the nodes to adapt to the network changes a RREQ message (maintenance RREQ) is sent by each active source node to destination(s). The time taken between consecutive maintenance RREQ is called a refresh-round. However, maintaining the metric route is an optional feature. The source node drives the process of route-maintenance. The process of generating a RREQ during the discovery phase is the same as the maintenance RREQs process. To improve route stability, a form of hysteresis is used instead of switching from the best known route to a worse metric route.

2.2.3.2 Radio Aware OLSR Path Selection Protocol (Optional)

Radio Aware Optimized Link State Routing (RA-OLSR) is an integrated and extensible proactive, link-state routing framework for wireless mesh networks. RA-OLSR is an adoption of the original OLSR protocol and uses the important mandatory features of OLSR with the company of extensions from Source-Tree Adaptive Routing, presented by Garcia et al, (1999) and Fishey State Routing (Pei et al, 2000). Nevertheless, there are some differences between the above mentioned protocols including OLSR in comparison with RA-OLSR. Instead of IP addresses the RA-OLSR uses MAC addresses and instead of using hop count metric which is used in layer-3, RA-OLSR uses a radio-aware metric which is good for layer-2. For that reason, a metric field is added to all topology information messages.

Due to the fact that the discovery and maintenance of optimal routes is enabled by RA-OLSR which is based on a predefined metric, given that for each node there is s a system to find out the metric cost of a link to each of its neighbours. A metric field is used in the RREQ and RREP messages to guarantee that the metric information between nodes is propagated. To be able to decrease the related control overhead when broadcasting topology information over the network, RA-OLSR adopts three-prong approaches.

i. Multipoint relays (MPRs) are used as subset of nodes in the network, in flooding process.
ii. Based on the fisheye scopes it can control and in that way reduce the message exchange

frequencies.

iii. The message exchange process can be optionally controlled flexibly and dynamically by sustaining network topology and routing information using source trees at each node and through various routing approaches based on them.

The association discovery protocol to support legacy 802.11 stations is included in the existing RA-OLSR protocol specifications. RA-OLSR protocol is run by MAPs to select paths among MAPs and MPs and by balancing routing information among the MAPs and MPs with the information of legacy 802.11 stations associated with them.

2.2.3.3 Airtime Routing Metric for HWMP

The airtime link metric works as a mechanism to calculate the amount of channel resources consumed when sending a frame over a particular wireless link (11-05/0563, 2005).

The airtime cost for each link is calculated as:

$$c_a = \left[O_{ca} + O_p + \frac{B_t}{r} \right] \frac{1}{1 - e_{pt}} \qquad (2.1)$$

Where, O_{ca} represents the channel access overhead, O_p represents the MAC protocol overhead, B_t representing the number of bits in a test frame, and r represents the transmission bit rate in Mbit/s with e_{pt} is the frame error rate,

Table 2. 1: Airtime Cost Constant

Parameter	Value (802.11a)	Value (802.11b)	Description
O_{ca}	75μs	335μs	Channel access overhead
O_p	110μs	364μs	Protocol overhead
B_t	8224	8224	Number of bits in test frame

The airtime link metric's most significant benefit is that of considering the quality of different links. As a result the path that has the best quality is chosen by the routing. On top of that, the overhead of the test frame will be reduced to a large extent, and that is based on a condition that instead of unicasting each node broadcasts the test frames. The 802.11s standard does not clearly indicate whether the test frames will be broadcasted or unicasted. An analysis for the airtime link metric was performed by Shen and Fan, (2006) and then a new metric called Multi-metric (MM) was proposed because the airtime link metric contains quite a lot of disadvantages in some situations.

Considering proposed Multi-metric in wireless environment, it consists of interference and mesh point's transmitting capability. All these considerations are based on Frame Delivery Ratio (FDR), residual bandwidth, and mesh point's load. In unicast test frame situation the newly proposed Multi-metric has a huge overhead of the frame delivery ratio measurement. Even though the overhead is reduced by broadcast by using small test frames (44 bytes) when it is used for the first time, a big overhead still exists. If the test frames are sent at the least possible data rate (1 Mbps in case of 802.11b) that can be an issue and if the data packet is sent at higher rate the loss rate might not be less as compared to the least possible data rate.

By using larger test frames the impact of the data rate for the link may be taken into account and that is if unicast is used. On the other hand, if larger test frames were to be used, greater measurement overhead would be required. This also provides the need to have every pair of neighbouring nodes probing each other. As a consequence, the method may not be appropriate for dense networks (Draves et al, 2004). As this research considers only the IEEE 802.11s proposed routing and the problem of routing in IEEE 802.11s was conducted in (Bahr, 2006).

These studies propose the HWMP as a default routing protocol with the airtime link metric presented in this chapter. In section 2.3, we introduce the loopholes regarding the routing metric used for HWMP.

2.3 Energy Considerations for the IEEE 802.11s routing

Most of the research work presented in this chapter focuses on the HWMP design and the performance assessment. The main focus on the performance assessment is on the metrics performance such as interference, frame delivery ratio, the bandwidth, delay and routing overhead etc. However, as presented in Mhlanga et al, (2009, 2011) that there is no much work that has been done to make sure the routing protocol is energy aware. Therefore, as stated in the first chapter that energy should be taken into consideration when routing protocols for WMNs are designed. The reason is because the amount of energy the network conserves determines how long the network can survive. It is therefore, an important factor to minimise the rate at which energy is currently consumed in HWMP.

In rural areas such as Africa, where WMNs will be typically used, conserving is the most imperative thing to do in order to help conserve energy and as a result prolonging the network operational. In this research we encourage deployment of a community based network philosophy and therefore, envisage the practical deployment of a WMNs in energy constraint rural areas. If the network is deployed in rural areas, the nodes will therefore be required to be energy-efficient. This makes the study of energy conserving routing protocols for WMNs to be very critical. Energy awareness is an important issue for battery-powered devices in wireless networks and routing based on energy related parameters is used to extend the network lifetime. Assuming the wireless mesh nodes are deployed in rural areas like Africa, the nodes will have to use their energy efficiently to avoid frequent battery replacement. Many researchers specialising in wireless ad hoc networks have faced so many challenges when trying to network such nodes. The problems of routing, addressing and support for diverse classes of service are primarily tackled at layer-3, the network layer. However, this research tackles the problem of routing in layer-2 with an assumption that the network will be deployed in rural areas. This research therefore, recommends that for such a network, a more useful metric for its routing protocol performance is network survivability. This is because it is the protocol that ensures that the entire network is of the same order and the network connectivity is maintained for as long as possible.

This approach is different from the other energy optimising protocols which after discovering an optimal path they use that path for every communication, as a result, burning the energy of the nodes along that path. Using the energy of the nodes like that will leave the network with a very wide disparity in the energy levels of the nodes leading to disconnected subnets. The nodes in the centre of the network can provide connectivity for a longer duration if nodes in the whole network burn energy more equitably and that would result in the time to network partition being increased. If this is properly implemented, the network can therefore degrade gracefully as whole. The energy-aware path selection metric (EAPM) that this research proposes in Mhlanga et al, (2009, 2011), tries to guarantee that the low-energy networks lifetime is prolonged and that is the idea of survivability of the networks.

CHAPTER THREE

Literature Review

3.1 Introduction

Considering the fact that wireless terminals are operated by batteries, the use of energy is therefore imperative during the design of a wireless ad hoc network (Zhang and Mouftah, 2006). A lot of work has been done in designing energy-aware routing protocols and the designs are in two folds:

i. Choosing routes that are energy-efficient.

ii. Minimising the routing overhead.

Designing energy efficient routing protocols has been the centre of attention in recent years for researchers and as a result a lot of energy-efficient and energy-aware routing protocols have been proposed (Chang and Tassiulas, 2004).

3.2 Energy Awareness Routing

A probability function in energy-aware routing is used as a means of choosing sub-optimal paths and it is also dependent on the amount of energy consumed in each path (Akkaya and Younis, 2005). Chang and Tassiulas, (2004) state that choosing the shortest (minimum) path might not be the best option as it may cause an energy depletion of nodes along that path. An alternative to the use of a minimum path, multiple paths are available to route from the source node to the intended destination node. For the network lifetime to be prolonged, one among the many available paths is used with a certain probability.

To advance the energy efficiency of an energy-unaware path localised rerouting techniques were proposed and presented in Akkaya and Younis, (2005). Class-based addressing is used to address every node. Class-based addressing includes the location and types of the nodes. Localised rerouting techniques were proposed and presented in Liu et al, (2008). To improve the energy efficiency of an energy-unaware path, the techniques for a per-link localised optimisation were proposed. This can be achieved by rerouting in each of the high-energy links iteratively through an alternate local low-energy path. The geographical forwarding discipline was designed and presented by Zhang and Mouftah, (2006), and also presented by Xue and Li, (2001) respectively, with a purpose of performing a per-hop energy-aware forwarding for every packet to be forwarded by a node with the support of the node itself, neighbouring nodes and destination's position.

The above presented energy efficient routing protocol techniques can perform well in terms of energy conservation. To achieve that, neighbourhood knowledge at nodes is required. Zhang and Mouftah, (2006) show that substantial amount of resources can be consumed in dynamic networks to update and gather the information for the node's neighbours. To support power-aware routing Doshi et al, (2002) did a continuation on the work conducted for the DSR protocol. In the extended protocol, a power-unaware route discovery circle helps to identify a working path first. If a node would be power-efficient but not identified by the working path, the node inserts itself into the route by sending a reply message. The source node would then compute a sub lowest power route by using the information that is extracted from the route reply.

In Zhang and Mouftah, (2006) and Chang, and Tassiulas, (2000) it is stated that when using precise global state information, the energy drain rates can be balanced to maximise the network lifetime. To reduce network topology Rodoplu and Meng, (1999) introduced the distributed Bellman Ford algorithm to setup the minimum-power paths from every node to a master site. To keep the network connected for a longer period Narayanaswamy et al, (2002) introduced COMPOW which is designed to find the smallest common value of node transmission range. For this reason, the network is run by various proactive wide-area routing daemons.

COMPOW has been improved in heterogeneous networks to reduce energy consumption during packet forwarding. Packet forwarding in this regard is strongly associated to the energy aware path metric that we have designed for this research. The energy consumed for packet forwarding to be reduced, every intermediate node has to further relay a packet to other nodes in the network. As shown in its forwarding table, the power level used to transmit a packet should be adjusted such that the intended destination can still be reached.

3.3 Energy Conserving Routing Metrics

For a packet to decide on which path to choose whenever given multiple paths, Vassileva and Barcelo-Arroyo, (2007) use the following metrics.

3.3.1 Residual Energy (Vassileva and Barcelo-Arroyo, 2007)

Energy-aware routing regards the energy status of a node as the most imperative metric to be considered when selecting a route. The cost function applied for calculating the diversity of the approaches, which uses residual energy is:

$$f_i\left(c_i^t\right)=\frac{1}{c_i^t} \tag{3.1}$$

Where C_i^t is the cost of node *i* at time *t*. Toh et al, (2001) proves that the design of the cost function has similar metric even though estimated by different functions. To eliminate the energy starving nodes from route selection, a Min-Max Battery Capacity Routing (MMBC) was proposed. Singh et al, (1998) adopted the idea of using shortest path first until a certain amount of energy has been consumed before choosing an algorithm that has a power-aware. The battery capacity of the nodes determines the behaviour of a Conditional MMBCR (CMMBCR) routing algorithm.

3.3.2 Energy Drain Rate

Kim et al, (2002) presented an energy drain rate which represents the rate at which energy is being consumed, when network provisioning is increased with monitoring. In order to avoid node's failures that are caused by battery outage in a route and the lifetime of a node is known, the traffic passing through the node can be deviated. Kim et al, 2003 designed a routing metric that is meant for predicting the lifetime of a battery. An exponential weighted moving average method was used to calculate the energy drain rate and it gives the approximate energy dissipation per second. The cost function is presented as the ratio between the residual battery power (RBP) and drain rate (DR) at a node:

$$C=\frac{RBP}{DR} \tag{3.2}$$

An analogue to MMBCR is the max-min algorithm which is the Minimum Drain Rate (MDR) mechanism responsible for the implementation for the cost function presented above.

Other algorithms that share the same philosophy and objectives with CMMBR is found in the work done by (Kim et al, 2003) which provides an extension of the MDR algorithm to Conditional MDR.

3.3.3 Local Routing (Vassileva and Barcelo-Arroyo, 2007)

In the work done by Vassileva and Barcelo-Arroyo, (2007) and also complemented by Woo et al, (2001), reactive routing algorithms are denoted as global, where all nodes take part when searching for a path, at the same time the source node and the intended destination node makes the decision to conclude. For a node to take part in the route searching process (Woo et al, 2001) give authorisation and as a result the decision making process is distributed to all the nodes. There is also a criterion used by the Local Energy-Aware Routing (LEAR) algorithm designed for the energy profile of the nodes where the intermediate nodes that are willing or reluctant to reply to route or to forward data traffic are defined.

To improve the performance of a routing protocol it is, therefore, imperative to avoid exchanging control information regularly by applying the technique of shifting the accountability for reacting to changes in the energy budget of a node. This is mainly used when a routing protocol's performance has to be improved for later approaches. Even though this technique inventive it also driven by the manner in which it is implemented. The SEADSR protocol, which is presented in Domingo et al. (2003), favours routes that are highly powered. The SEADSR does not make use of a monitoring function and as a result the nodes which were extremely powered during the route selection are being used to forward a lot of traffic.

3.3.4 Expected Amount of Energy Consumption

The work done by Misra and Banerjee, (2002) is based on the idea of expected amount of energy consumption and designed from prolonging the network's operational time. The Maximum Residual Packet Capacity (MRPC) algorithm is also proposed and evaluated in Misra and Banerjee, (2002) where the residual battery energy is used as a factor when selecting routes. The addition of the expected energy spent metric is regarded as the most significant contribution in their work. As a result, the cost metric consist of a node specific parameter such as: the battery energy and link-specific parameter, packet transmission energy – for reliable communication across the link.

3.3.5 Battery-Sensitive Routing (Vassileva and Barcelo-Arroyo, 2007)

In Chiasserini and Rao, (2000) an absolutely diverse approach is presented and subsequently by (Ma and Yang, 2005). Battery-sensitive routing is used by these algorithms to apply the available battery capacity approach. These techniques are focusing on the lifetime of the battery based the two processes, which are recovery (reimbursement) and discharging loss (over-consumed power), experienced when no/new traffic is transmitted, design a cost function which value reflects the energy consumption. It is stated in the work conducted by Chiasserini and Rao, (2000) that the minimum function can also be presented as a selection function over the cost functions of all routes. In Ma and Yang, (2005) it is proven that the algorithm is a lot more sensitive with regard to battery behaviour and for battery recovery to be implemented it is therefore imperative to switch between different paths and as a result the maximum of the node's battery capacity can be attained.

3.4 Energy Efficient Routing for Wireless Networks (Yu et al, 2003)

The goal of energy efficient routing in wireless networks can be achieved by minimising the amount of energy consumed in a node during active communication and also when the communication is not active. Two approaches have been presented to minimize the energy used during active communication which is to control the power during transmission also referred to as transmission power control and the distribution of the load also referred to as the load distribution. To minimize the energy consumed during inactive communication state a sleep/power-down mode can be used. The taxonomy of energy efficient routing protocols is shown in Table 3.1. The research presented in Singh et al, (1998) discuss all the energy-related metrics that have been used instead of shortest path to determine energy efficient paths. These metrics are:

- The amount of energy consumed per packet,
- Network partitioning time,
- Node's power level variance,
- Packet cost, and
- Maximum cost of the node.

The energy that is consumed in a metric for a packet is useful in providing the path that has the minimum power to minimise the energy consumed to deliver a packet successfully. The link cost represents each wireless link with regard to the energy used for transmission in that particular link. The process of minimising the sum of the link cost is performed by the min-power path along that path. Making use of this metric may also cause an unbalanced energy spending amongst the network nodes. Nodes consume more energy when the burden given to them is unfair while trying to assist a lot packet forwarding functions. As a result, these nodes stop functioning at an early stage when comparing them to other nodes in the network which may cause network partitioning and disturbing the overall functionality of the network. For that reason, the most essential objective of energy awareness and optimisation in routing algorithms will be to maximise the network life time. When given multiple paths to choose from, it is therefore imperative to choose the one that is determined to help prolong the network operational time.

Table 3. 1 Taxonomy of the Energy Efficient Routing Protocols (Yu et al, 2003)

Approach		Protocols	Goal
Minimize Active Communication Energy	Transmission Power Control (Section 3.1)	Flow Argumentation Routing (FAR) Online Max-Min (OMM) Power aware Localized Routing (PLR) Minimum Energy Routing (MER	Minimize the total transmission energy but avoid low energy nodes.
		Retransmission-energy Aware Routing (RAR) Smallest Common Power (COMPOW)	Minimize the total transmission energy while considering retransmission overhead or bi-directionality
	Load Distribution (Section 3.5.2)	Localized Energy Aware Routing (LEAR) Conditional Max-Min Battery Capacity Routing (CMMBCR)	Distributed load to energy rich nodes.
Minimize Inactivity Energy	Sleep/Power Down Mode (Section 3.3)	SPAN Geographic Adaptive Fidelity (GAF) Prototype Embedded Network (PEN)	Minimize energy consumption during inactivity.

Three routing metrics were proposed in Yu et al, (2003) following the difficulty in estimating the lifetime for future networks to accomplish the objective of prolonging the network lifespan. A straightforward sign of energy balance is the variation of the residual energy found in a battery of nodes which can also be utilized to prolong the network operational time. The only differences that exist between cost-per-packet metric compared to metric calculating the energy consumed per packet is that the former includes the residual energy for each node to add up to the energy consumed when transmitting.

The subsequent routing algorithm favours a wireless link that requires less energy when transmitting while avoiding nodes with small residual energy, because of their high node costs. Each candidate path among the intermediate nodes is annotated with maximum node cost. That is equivalent to residual energy that is minimal, and the minimal path cost, min-max path, is chosen. The lifetime of a node which is determined by the residual energy of a battery is used by some protocols instead of being used by their node cost.

3.5 Transmission Power Control Approach (Aron et al, 2008)

Given a network graph, a routing algorithm basically entails searching for the best possible route such that the transmission range for a node and its wireless link is within each (Yu et al, 2003). If the transmission power of a radio in a node is adjustable, the direct transmission range is adjustable together with the intermediate nodes. An increase in the transmission range occurs when the transmission power is stronger while the number of hops are being reduced (hop count) to the destination.

Sparse topology is caused by weak transmission power resulting to the network being partitioned and if the hop count is large, a high end-to-end is also caused. Figure 3.1, shows the benefit of the transmission power when it is controlled or when it adjusted. A presentation of two transmission power models follows, namely: a constant and a variable power models (Yu et al, 2003). If it is impossible to adjust the transmission power and consequently (Pc) is a constant like the manner in which it is presented in Figure 3.1(a), the routing path $S \rightarrow D$ optimises more energy as well as the shortest.

Transmitting packets by means of intermediate nodes may be more energy efficient, if and only if the transmission power is adjustable. This is because there is an upper-linear dependence on distance, d, i.e., $p(d) \propto d^2$ for the required transmission power, p (Stojmenovic and Lin, 2001). For instance, in Figure 3.1(b), $S \rightarrow A \rightarrow D$ route, it optimises more energy as compared to the route $S \rightarrow D$ since $p(|SD|) > p(|SA|) + p(|AD|)$. To conserve energy nose S lowers its radio power to be sufficient enough to arrive at node A, but the energy is not sufficient enough to arrive at node D.

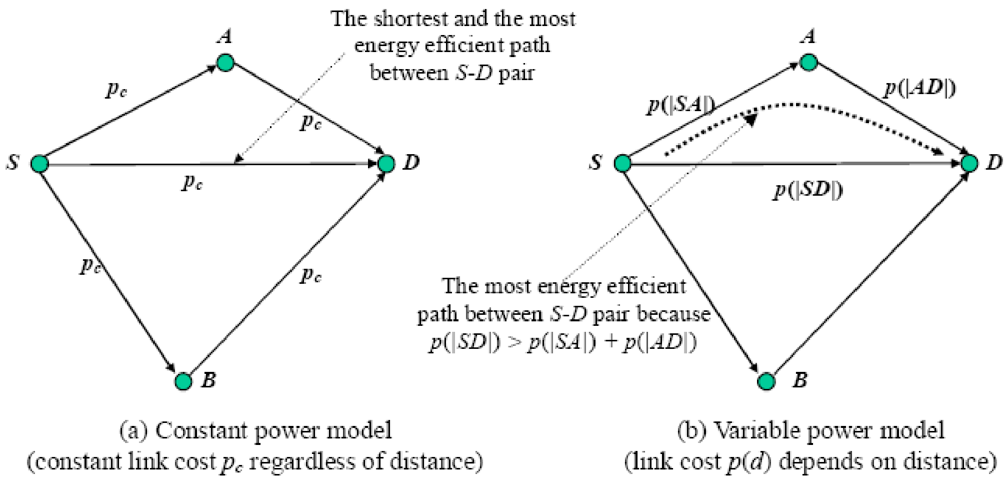

Figure 3.1 Constant and variable transmission power model (Yu et al, 2003).

A significant contribution has been done in the field of transmission power adjustment in topology control for WMNs (Mudali et al, 2009) and (Aron et al, 2008). The main objective for this approach is to keep the topology connected for as long as possible by means of minimum power. Best routes capable of minimising the power used for transmission are provided by routing protocols that are energy efficient which are also based on transmission power control. This is equivalent to a graph optimisation problem, where every link and the link cost are weighed and it is equivalent to the transmission power *(e.g.,* $p(|SA|)$ that is required for the link $S \rightarrow A$).

Discovering the most energy efficient $(\min - power)$ route from the source node S to the destination node D is equivalent to discovering the smallest amount of path cost in the weighted graph. To find the most optimal energy $(\min - power)$ route from S to D is the same as discovering the smallest amount of path cost in the weighted graph. Four of such routing protocols are introduced in section 3.5.1 and in Section 3.5.3 two link layer issues are discussed, such as retransmissions overhead and bi-directionality requirement, for implementing the transmission power control approach.

3.5.1 Optimisation of Transmission Power (Erkip et al, 2007)

Chang and Tassiulas, (2000) presented a Flow Augmentation Routing (FAR), Li et al, (2001) presented the Online Max-Min Routing (OMM) and Stojmenovic and Lin, (2001) presented the Power-aware Localized Routing (PLR) and all these protocols fall into the optimisation of transmission power category. In view of the fact that the routing algorithm is run by each node in the network, the graph optimisation algorithm is also applicable equally in a distributed approach, information such as the link cost which is the amount of energy used for transmission over a link and the node cost also referred to as the node's remaining energy. The node cost uses the technique of avoiding low energy nodes during route selection to put into equilibrium the energy consumption rate. Doshi and Brown, (2002) presented some work about Minimum Energy Routing (MER) protocol and its most important objective of makes the available path to be energy efficient than to offer energy efficient paths. This is all achieved by controlling the amount of power used for transmission to be sufficient enough to transmit to the next hop node.

Table 3. 2 Transmission power control based routing protocols (Yu et al, 2003)

Routing Protocol	Information required for every node coupled with obtained during operation	Energy efficient optimization approach and to avoid low energy nodes
FAR	Link costs of all links Node costs of all nodes Data generation rate at all nodes	- Use graph optimization algorithm - Include node cost in the link cost
OMM	Link costs of all links Node costs of all nodes	-Use graph optimization algorithm - Select the max-min path among a number of best min-power paths
PLR	Link costs of some links (from itself to its neighbors and to the destination) Node costs of some nodes (all its neighbors)	- Use graph optimization algorithm - Include node cost in the link cost
MER	None (Each source node will obtain the link costs through the routing algorithm employed).	- Adjust the transmission power just enough to reach the next hop node in the given routing path

3.5.1.1 OMM (Online Max-Min Routing) Protocol (Li et al, 2001)

OMM protocol maximises the network lifetime without knowing the information generation rate prior unlike FAR which can only optimise the network lifespan when the rate at which the data is generated is well-known. Two different metrics of the nodes are optimised by OMM in the network:

i. To minimise the rate at which power is consumed (min-power).

ii. To maximise the minimal residual power (max-min).

To prevent nodes from being overloaded the second metric is useful is used. OMM always uses Dijkstra's algorithm to find the best possible available path for a given source node and the intended destination when all link costs are given. $(P_{\min})$ is the smallest power consumed by the min-power path, however, it does not necessarily mean that it is the max-min path. The OMM protocol optimises the second metric by acquiring several paths that are regarded as near-optimal min-power paths (i.e., less than $zP_{\min}$, where $z \geq 1$). In OMM any route that proves to be optimising the min-max is chosen as the best path.

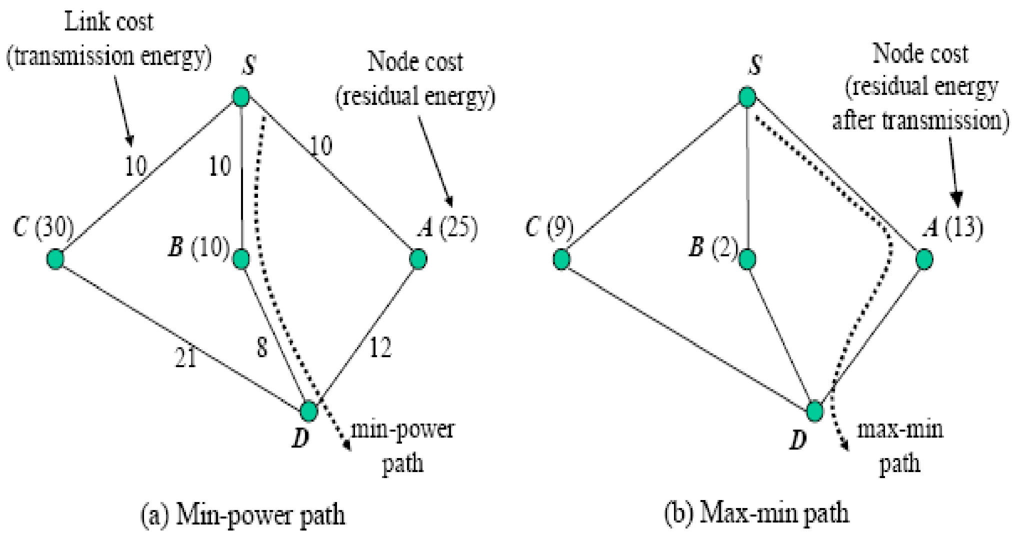

Figure 3.2 Min -power path and max-min path in the OMM protocol (Yu et al, 2003).

Figure 3.2 shows a diagram that represents the min-power path and the max-min path algorithms where the source (S) is known and the intended destination (D) pair. In Figure 3.2(a) a min-power path $S \to B \to D$ is shown and the minimal energy is ($P_{\min} = 18$) because it consumes very little energy. Whenever a path cost is in a tolerance range like ($zP_{\min} = 36$) where $z = 2$, and where the path for the optional path $S \to A \to D$ cost = 22 and $S \to C \to D$ where the path cost = 31, it can be considered.

Given three candidate paths in a network, in order to find the max-min route amongst these paths it is good to compare the amount of energy in a node with the smallest energy residing in a node for each path. The illustration given above, shows that there is only one intermediate node available and for every path there is only one intermediate node and as a result a comparison for the residual energy for the nodes (nodes A, B, and C) is conducted. In power-path the residual energy of node C is 30 but when transmitting packets from S to D using that path, the residual energy goes down to 9. Node A and B had a residual energy of 25 and 10 respectively before transmission in figure 3.2(a) and after their paths were used as shown in Figure 3.2(b), the residual energy depreciated to 13 and 2 for each node, respectively.

$S \to A \to D$ is for that reason, proving to be the max-min path when compared to the three min-power paths presented in the figure above. The trade-off between the min-power path and the max-min path is measured by the parameter z. When $z = 1$, then there is no candidate optional path to choose from except for the optimal min-power path. In this figure optimisation is done on the total energy that is consumed while the energy balance has not been considered. All feasible paths are considered when $z = \infty$ while ignoring the min-power metric. In order to determine the performance of the overall energy it is, therefore, important to select the appropriate parameter z . Yu et al, 2003, and Li et al, (2001) use a perturbation method to compute z adaptively. z is arbitrarily selected as an initial value, while the most overloaded node's residual energy is approximated because of the measurement conducted while the MANET operation was at the stage called the fixed time period. z is subsequently amplified with a tiny constant, additionally the lifespan can still be approximated after a certain period. The z parameter is amplified if the lifetime that has been recently estimated is longer than older lifetime and if the condition is the opposite then z is decreased. With regard to the fact that the two estimations for the measurements are conducted at two diverse time intervals, therefore, the entire study is grounded on the hypothesis that the distributions of the network traffic are the same as time elapses.

3.5.1.2 Power-aware Localized Routing Protocol (Stojmenovic and Lin, 2001)

While Power-aware Localised Routing (PLR) protocol is known to be an energy-aware, localised and fully distributed routing algorithm, then the information about the destination is assumed by the source through the information obtained from its neighbours to the destination. This is similar to being aware of the link costs connecting the source node and the intermediate nodes until it reaching the destination node. Therefore, when given multiple intermediate nodes from the source to the destination node, finding the best possible path to the destination without the use of the intermediate nodes is impossible. For the reason that a direct transmission may consume more energy, intermediate nodes can, therefore, be utilised to help minimise the amount of energy consumed during transmission.

As shown in figure 3.3, node A intends to transmit packets to node D. A straight packet transmission directed to D can be performed and the transmission can also be made through one of the optimal intermediate nodes ($N_1, N_{2,} or N_3$). It should be noted that node A to an intermediate node N_i is a direct transmission, while indirect transmission is from the intermediate node N_i to the destination node D with a number of intermediate nodes between N_i and D. For an optimal route to be selected, node A evaluates and does a comparison of the rate at which power is consumed for each candidate path. If a distance is known for the power consumption of the straight transmission it is, therefore, possible to compute $p(d)$:

$$p(d) = ad^{\alpha} + c \qquad (3.3)$$

whereby a and c are denoted as constants, and d denotes the distance found from one node to the other node and $\alpha \geq 2$. If indirect communication power that has been consumed can be minimised provided the transmission is transmitted by ($n-1$) for intermediary nodes that are spaced, it implies that the resultant minimum power consumption is $q(d)^2$ presented by Yu et al, (2003) with Stojmenovic and Lin, (2001). A lot of indirect communication power that has been consumed as stated by the research conducted in the literature shows that the minimisation of indirect communication power consumption is achieved when transmission is relayed by ($n-1$). Therefore, whether node (A) is denoted as a source node or whether denoted as an intermediary node, it always chooses one of the neighbours to be the next hop node ($N_1, N_{2,} or N_3$) which is best for minimising $p(|AN_i|) + q(|N_i D|)$.

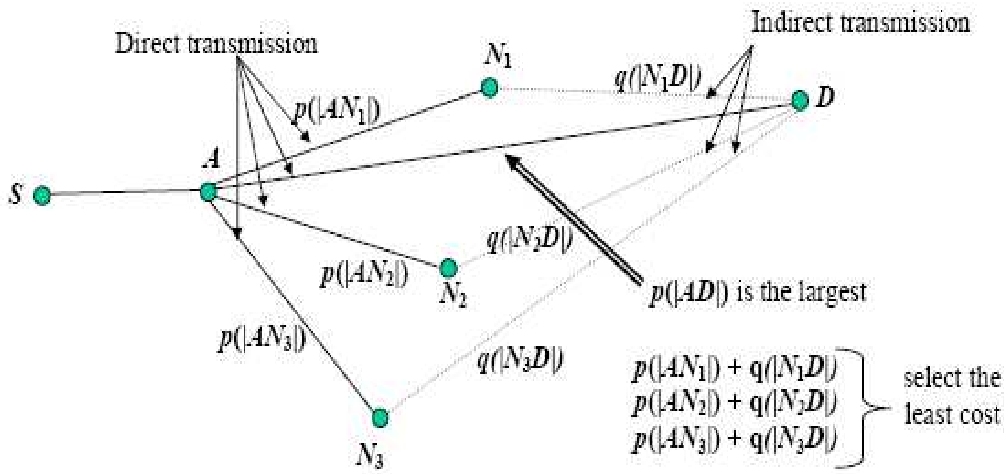

Figure 3.3 The next hop node selection process in the PLR protocol.

3.5.1.3 Minimum Energy Routing Protocol (Zhang and Mouftah, 2006)

The node costs jointly with the link costs are the power control information that is required by the transmission power control approach. To achieve minimum energy routing the subsequent issues must be addressed:

i. The preciseness of the power information gained,

ii. Energy aware routing takes into consideration the issues of routing overhead ratio,

iii. During mobility, how is maintenance done for the routes with minimum energy?

These issues are addressed by the Minimum Energy Routing (MER) protocol in Zhang and Mouftah, (2006), and (Doshi et al, 2002). The implementation of the transmission power control is the responsibility of (Johnson and Maltz, 1996). In Woesner et al, (1998) the IEEE 802.11 MAC protocol with eight best possible options is presented as shown in Table 3.3. In Option A, a route-request packet header is modified in order to take into consideration the amount of power consumed by a node to relay a packet. The receiver makes use of this kind of information and in order to receive the packet for computing the least amount of power that is needed for the transmission to be successful from a relaying node to itself it also uses the radio power level used. We refer to this as a per hop power information and it is added to every intermediary node towards the destination and a RREP packet will be sent back to the source node. The per hop power information is, therefore, inserted in the data packet header, due to the fact that the data packet is sent by the source and the intermediate node at a power level that is controlled. Option F shows how the MAC layer's ACK power control packets mechanism is applied.

Table 3. 3: Eight options in MER protocol

Options	Implementation level
A: Routing packet-based power control	Routing software / 802.11 firmware
B: Minimum energy routing	Routing software
C: Cache replies off	Routing software
D: Internal cache timeouts	Routing software
E: Multi-hop route discovery	Routing software
F: MAC layer ACK power control	802.11 firmware
G: Route maintenance using power sensing of data packets	Routing software
H: MAC level DATA/ACK snooping/ gratuitous replies	802.11 firmware

There are a lot of commonalities in options B, C and D for example is the route-cache which DSR routing algorithm maintains. For example, as shown in option B when given multiple paths from the source to the intended destination, the calculation of the total transmission energy for every candidate path is based on the power level information that is acquired when option A is applied and a route with minimum energy is chosen. Dynamic adjustment for low energy routes is applied in option G, when node mobility causes change for a required transmission. Nodes that not active in the network as demonstrated in options E and H are authorised for packet exchange sneaking and to recommend a route that is more energy efficient for the sender at layer-3 (routing layer) and the layer-2 medium access control, in a corresponding order.

3.5.1.4 The Optimisation of Power Coupled with a number of Practical Requirements

In the literature it is stated that an energy efficient technique called transmission power control can be applied for the reduction of the energy that is consumed in a MANET. On the other hand, for routing protocols to apply this kind of an approach, the link layer needs to consider some issues. These issues are addressed in the following subsections.

3.5.1.4.1 Retransmission Overhead and Link Error Rate

Intermediate nodes are used by transmission power control allows to help conserve energy when transmitting to reach the intended destination. Then again, a path with links that its long range is fewer could perform better than links with short-range in terms of energy consumption and latency. Paths with many short-range links causes link errors links and as a result of the many short-range links, more retransmissions may be caused (Barnerjee and Misra, 2002). Assume a path is established from a source S that consist of intermediate nodes to a destination node D, $N-1$ indexed as $2,3,\ldots,N$. The source and destination node index is 1 and $N+1$ respectively. The energy for transmission over a link is represented as:

$$p_{i,i+1} = ad_{i,i+1}{}^{\alpha} \tag{3.4}$$

where $d_{i,i+1}$ represents the distance from node i to $i+1$, where a is the constant and it is concluded with regard to the physical environment, and $\alpha \geq 2$. Every link of the N links ($L_{1,2}, L_{2,3}, \ldots, L_{ND}$) is assumed to be having a link error rate of $e_{i,i+1}$ that is independent, the transmissions involved from node i to node $i+1$ is a random and geometrically distributed variable X , such that

$$\Pr ob\{X = x\} = e_{i,i+1}{}^{x-1} \times (1 - e_{i,i+1}), \forall x \tag{3.5}$$

The mean number of transmissions of a single packet that is successfully transferred is thus $1/(1 - e_{i,i+1})$. The research work done by Barnerjee and Misra, (2002) show the efficient energy used when transmitting between nodes i and $i+1$, which includes the consequence of the transmission link error,

$$P_{i,i+1} = p_{i,i+1} \times \frac{1}{1 - e_{i,i+1}} = \frac{ad^{\alpha}_{i,i+1}}{1 - e_{i,i+1}} \tag{3.6}$$

Transmitting using intermediate nodes which was regarded as a benefit can be overshadowed by the inflation factor. The inflation factor denoted as $1/(1 - e_{i,i+1})$ can overshadow the benefit of using intermediate nodes to achieve the benefit of indirect transmission. Provided there is no negligibility of the packet error rate ($e_{i,i+1}$). The newly defined link error with the Retransmission-Energy Aware Routing (RAR) protocol modifies the optimisation problem (Barnerjee and Misra, 2002).

3.5.1.4.2 Bidirectionality Requirement (Yu et al, 2003)

For packets to be delivered with minimal energy, each nodes radio power is adjusted using the transmission power control approach and transmission power that differs with its transmission rates may be used at different (Zhao et al, 2007). A bidirectional link has to be shared by any pair of communicating nodes which is intended for MANET link-level connectivity to work correctly (Narayanaswamy et al, 2002). In addition to that, for a link-level reliability to be improved at the link level, it is imperative to apply control packet handshaking in error-prone wireless. A RREP packet is sent back to the sender as an ACK to the sender and another ACK is automatically retransmitted if it was not received by the sender. To help solve the hidden terminal problem an exchange of Request To Send (RTS) and Clear To Send (CTS) packets is implemented (Schiller et al, 2000). As a result, when given two nodes with different power levels, transmission will always be provided by the node that has stronger transmission power heading towards the direction of the node with weaker transmission power. Smallest Common Power (COMPOW) protocol that is presented by Narayanaswamy et al, (2002) show a much simpler solution that can be used for the maintenance of bi-directionality among two communicating nodes in a MANET.

For bi-directionality to be achieved, all nodes in a MANET should maintain a universal transmission power level (P_i). This is designed such that when P_i very low, communication is supposed to continue taking place with a few numbers of nodes in the MANET as shown in Figure 3.4(a). As shown in figure 3.4(b), it must also be possible for a node to connect with other nodes when the value of P_i is very high and this results in high energy consumption. Figure 3.4(c) also shows that a smaller P_i can still be used to directly or indirectly connect the whole network. For that reason, the optimal power level (P_i) is the power that is too low but that can still connect the entire network.

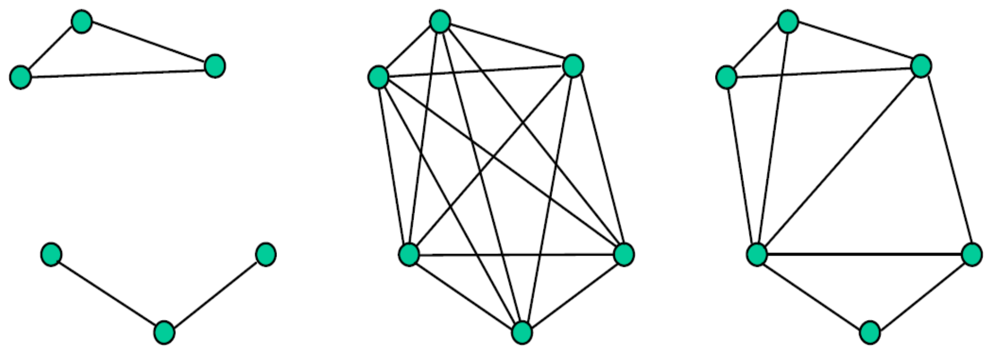

Figure 3. 4 Proper selection of the common transmission power level in COMPOW (Yu et al, 2003)

The work presented by Yu et al, (2003) in COMPOW, assumes that a small number of discrete power levels ($P_1, P_2, ..., P_{max}$) should determine the transmission power levels as a replacement for the transmission power levels that is arbitrarily adjusted (Narayanaswamy et al, 2002). Because of the fact that the ranges for radio transmission are different, the different power levels cause different node connectivity.

This kind of techniques allow the nodes to maintain a routing table with each routing table having its power level ($RT_{P1}, RT_{P2}, ..., RT_{P\max}$) as in proactive routing method. The number of nodes that are reachable at P_i is represented by the number of entries in RT_{Pi} denoted as $|RT_{Pi}|$. This consists of intermediate nodes which are indirectly connected nodes and directly connected nodes. The minimal P_i can be found by nodes when routing tables are exchanged which satisfy $|RT_{Pi}| = n$ for all nodes, where n represents the total number of nodes in the network. The research presented by Narayanaswamy et al, (2002) discusses extended solutions for problems such as when there is too high discrete power level and when neglecting the latency is not possible which is involved when switching the power levels.

3.5.2 Load Distribution Approach (Challen et al, 2009)

Routes with underutilized nodes are chosen to help balance the amount of energy used, which is a main goal for the load distribution approach rather than the shortest route. Instead of providing the lowest energy route, overloading is prevented by protocols whose base is on this approach which then helps prolong the network lifetime. The research conducted by Xie et al, (2007), Woo et al, (2001) and Toh, (2001) respectively on Localized Energy-Aware Routing and Conditional Max-Min Battery Capacity Routing protocols is conducted below.

3.5.2.1 Localized Energy Aware Routing (LEAR) Protocol (Xie et al, 2007)

The foundation of the LEAR routing protocol is an adaptation of the original DSR protocol, however, for energy consumption to be balanced in the network the LEAR modifies the route discovery procedure. In DSR the corresponding route is selected due to the fact that when a RREQ message is received by a node, the node adds its distinctiveness in the RREQ header and it is therefore forwarded to the intended destination. If messages are always relayed by the intermediate node to other nodes then the corresponding route will be selected. However, even if the RREQ message should be forwarded or not, the residual battery power of the node (E_r), can only be forwarded provided E_r is higher than the threshold value (Th_r) and if not the case, it refuses to forward packets and drop them.

The intended destination node can only receive a RREQ message from the source provided the battery levels of the intermediate nodes are good; as a result the battery power for nodes with limited battery levels can be conserved. Distributed algorithm such as LEAR uses local information for each node to choose which route to take such as E_r and Th_r. To be able to identify energy-rich and energy-hungry nodes, the value of Th_r must decrease when E_r decreases. If there is no RREP message back to the source node from the destination node, while the source had sent a RREQ message earlier, the same RREQ message will be re-sent for a route to be established. If a duplicate RREQ message is received by the intermediate node, the intermediate node will adjust it's Th_r for transmission to continue.

To distinguish between the original RREQ message and the one that is being re-sent, a sequence number is used. It is imperative to avoid complications that may arise if the evaluation of the entire intermediate node's residual battery levels that follows when the route-cache replies are sent to the source node directly. Route-cache which is a control message is used to prevent this complication from happening, figure 3.5 shows a new control message, route-cache that has been utilised. In DSR, the intermediate node stops sending broadcast messages to other nodes in the network only if its route cache has discovered a route. Even though the intermediate nodes in LEAR also stop broadcasting the RREQ message, the difference between these protocols is that LEAR continues to send the route-cache message in a unicast mode, for example ($B \rightarrow C_1 \rightarrow C_2 \rightarrow D$). There is no significant traffic that is added to the network because of the unicast delivery of the route-cache message.

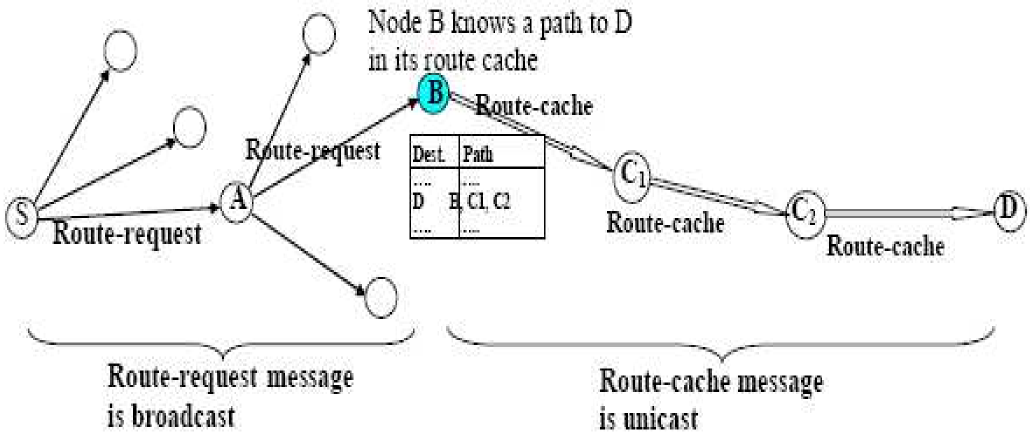

Figure 3.5 Route-cache message in the LEAR algorithm (Xie et al, 2007).

3.5.2.2 Conditional Max-Min Battery Capacity Routing (CMMBCR) Protocol (Zhang and Mouftah, 2006)

For each node's lifetime to be maximised and to fairly use the battery, the CMMBCR protocol makes use of the theory of a threshold. If there is a larger remaining energy for transmission from the source node and an intended destination node than the given threshold value, the route with min-power between those nodes is selected. A max-min route is selected if and only if there are nodes with lower capacity compared to the given threshold. Since the threshold value is fixed for CMMBCR unlike LEAR, this is because in CMMBCR the design is simpler compared to LEAR.

A performance metric to measure the energy balance was proposed by the authors of CMMBCR protocol and an expiration sequence is presented which is a sequence of times taken by the nodes to exhaust their energy capacities (Toh, 2001). The variation of residual battery capacity are the metrics designed for energy balance, residual battery energy, the ratio of minimum energy to average energy and the network lifespan. To measure the network lifespan, Toh, (2001) calculates the time taken by a node to run out of energy for the first time. Limited information is offered by these metrics on energy balance. The fairly expansion of energy is given by the sequence of times that the node battery capacity has been exhausted as stated in the literature that limited information is offered by these metrics about energy balance in the nodes.

3.5.3 Sleep/Power-Down Mode Approach (Yu et al, 2003)

This approach pays concentration on the communication time that is not active. Owing to the fact that most radio hardware supports a number of low power states, therefore, it is imperative to put the radio subsystem into the sleep state. Table 3.4 gives a brief summary of hardware states with low power and the Bluetooth wireless LAN protocols, the IEEE 802.11. 250 mA and 300 mA is consumed by the *Lucent's WaveLAN-II* when receiving and during transmission respectively and this approach is adopted from the *IEEE 802.11 wireless LAN standard.* 9 mA is consumed in sleep mode (Kamerman and Monteban, 1997).

Table 3. 4: Power down modes and states

<table>
<tr><td colspan="3">IEEE 802.11
(Lucent's WaveLAN-II supporting 2 Mbps
with radio range up to 250 meters)</td><td colspan="2">Bluetooth
(Nokia's Bluetooth supporting 768 Kbps
with radio range up to 10~100 meters)</td></tr>
<tr><td>Hardware State</td><td colspan="3">Mode of Operation (MAC-level)</td><td>Hardware State</td></tr>
<tr><td rowspan="3">Awake</td><td rowspan="2">Active</td><td>Transmit (300mA)
Receive (250mA)</td><td rowspan="2">Active (40-60mA)</td><td rowspan="4">Connection</td></tr>
<tr><td>Idle or Listen (230mA)</td></tr>
<tr><td colspan="2">Power Save</td><td>Sniff</td></tr>
<tr><td rowspan="2">Doze</td><td colspan="2" rowspan="2">Sleep (9mA)</td><td>Hold
Park</td></tr>
<tr><td>Standby (0.55mA)</td><td>Standby</td></tr>
</table>

In a MANET packets cannot reach the destination if the nodes in the network are sleeping and not listening to any call. To solve this problem there has to be a master node chosen which will help with the communication coordination on behalf of its slave nodes. For energy conservation purposes the slave nodes can always be put to sleep. The slave nodes periodically wake up to check if there is some information to receive or not. If there is no information to send the slave nodes sleeps again to conserve energy. In MANET the entire network cannot be covered by a single master node, therefore, there it is imperative to have more than one master node.

A master-slave network architecture is represented by mobile nodes as shown in figure 3.6 where energy is conserved with the exclusion of master nodes by putting their radio hardware into low power state. Figure 3.6(a) uses a symmetric power model to present the master-slave architecture. The radio power of a master node in a symmetric power model is equivalent to that of a slave node and the transmission range is the same. In figure 3.6(b) an asymmetric power model is shown where longer transmission ranges are contained by the master nodes. This kind of hierarchical network architecture is good for the following reasons: to reduce interference in the network and the ease of location management (Perkins, 2001). To decide which master nodes to be selected is still a problem let alone sustaining the master-slave structural design using the dynamic node configurations is still a tough issue.

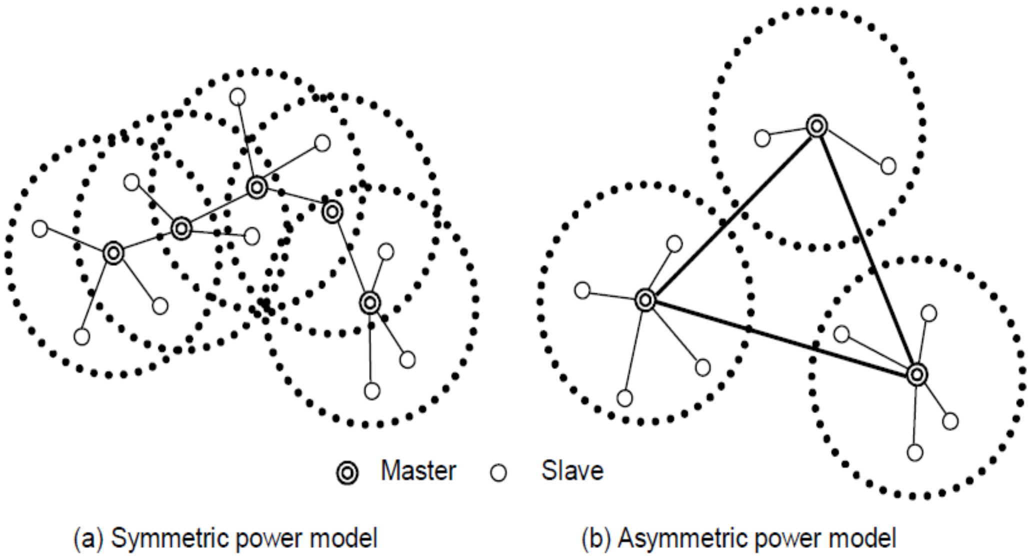

Figure 3.6 Master-slave MANET architecture (Yu et al, 2003)

Three routing algorithms are introduced in this section and they are responsible for exploiting the low power states of the radio hardware. The *Geographic Adaptive Fidelity* (GAF) protocol presented by Xu, et al, (2001) and The *SPAN* protocol presented by Chen et al, (2001) utilize the master-slave architecture and to save energy the slave nodes are put in low power states. Girling et al, (2000) presented the third protocol called the *Prototype Embedded Network* (PEN) protocol which uses the sleep mode function in an asynchronous approach and still not including the master nodes.

3.5.4 SPAN Protocol (Khanna et al, 2008 and Chen et al, 2001)

A distributed master eligibility rule is utilised by the SPAN protocol in order to select master nodes in a dynamic configuration. If this technique is implemented properly each node in the network can therefore consider the odds of becoming a master node or not. If there is no direct communication between two neighbours, even by means of one or two master nodes then the node has to become a master itself. In figure 3.7 the method used for selecting a master node shown as not deterministic. An example is that of node B and D electing themselves as masters but if either of the nodes does not elect itself as a master then an eligible node H elects itself as a master node. Even though a robust connectivity with significant energy conserved during transmission, this rule does not yield the minimum number of master nodes. Every master node in the network checks at regular intervals whether it should pull out from being a master to prevent overload and to also give a chance to other nodes to be converted into master nodes and to guarantee equality. Owing to the master eligibility rule it is, therefore, possible non-master nodes to determine whether they can convert to a master node or not. Figure 3.6(a) shows that the master-slave architecture provides a routing backbone which is an added advantage in routing. The routing backbone is responsible for assisting in avoiding the flooding of a RREQ broadcast in the channel contention and as a result control traffic will be reduced.

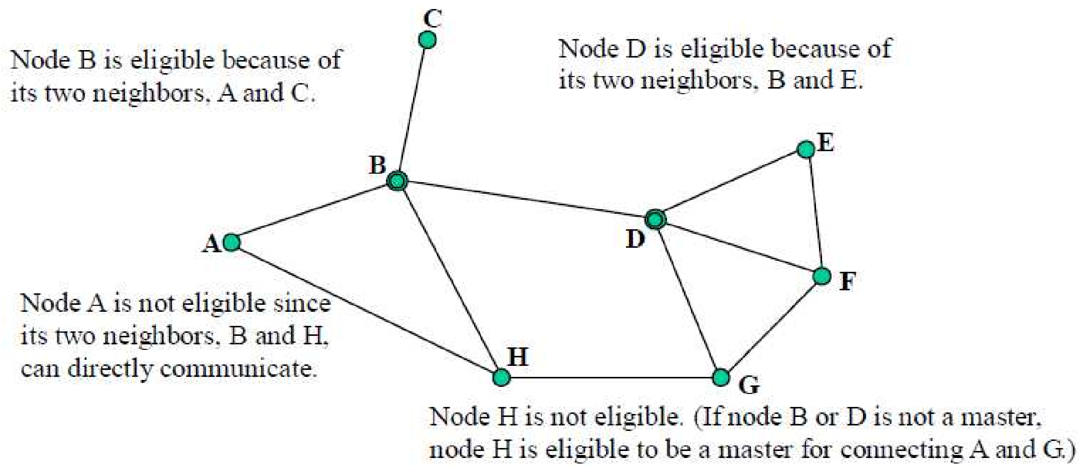

Figure 3.7 Master eligibility rule in the SPAN protocol (Yu et al, 2003).

3.5.5 Geographic Adaptive Fidelity (GAF) Protocol (Li and Zuo, 2009 and Xu, et al, 2001)

In order for every node that is based on a GPS to associate itself with a virtual grid in GAF protocol, it uses location information. The node that becomes the master grid is the one that has more residual energy within each grid due to the fact that the whole area is separated into a number of square grids. Some nodes can be regarded as redundant when the focus is on packets forwarding in the same grid and without sacrificing the routing the nodes can be safely put to sleep. Due to the assurance that in every grid one master node will stay awake for packets to be routed, slave nodes can therefore switch between off and listening.

A virtual grid structure is shown in figure 3.8 under the GAF protocol where one of the nodes among nodes 2, 3 and 4 in the virtual grid B can relay packets between nodes 1 and 5 despite the fact that the other two nodes can go to a sleep mode to save energy. The grid size r shown in figure 3.8 can be deducted from the bond between the radio range which is represented by R and r as $r^2 + (2r)^2 \leq R^2$ or $r \leq R/\sqrt{5}$.

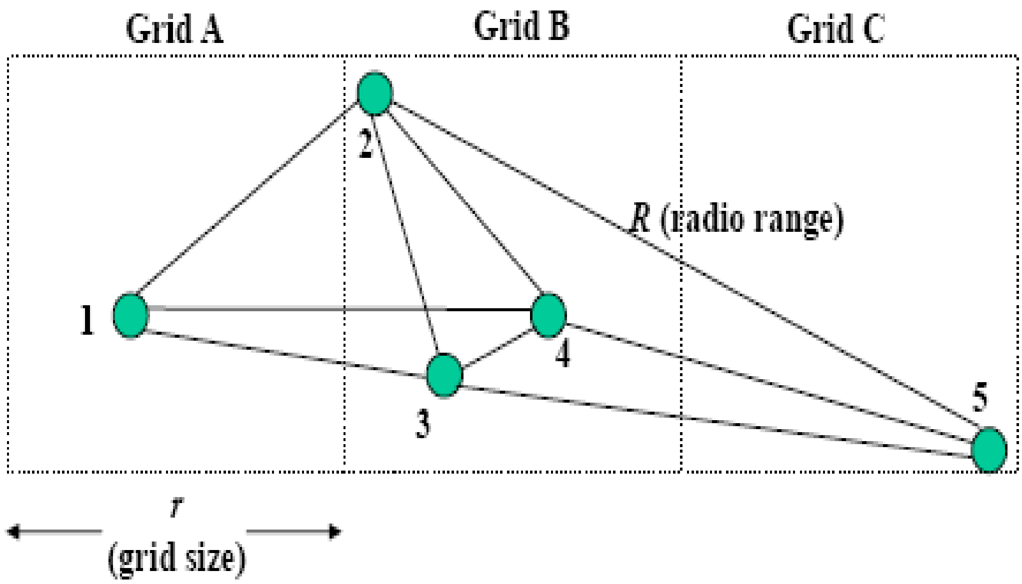

Figure 3.8 Virtual grid structure in the GAF protocol.

Figure 3.9 below shows that the design of a master election rule in GAF has three state designs for the nodes which are: *sleeping, discovering* and *active state*. Other nodes that are within the same grid are found by using node's exchange discovery messages in the discovery state including the grid IDs. A node becomes a master node provided it does not hear any discovery messages for a predefined duration T_d. The node that becomes a master if multiple nodes are in the discovery state is the node with the longest expected duration. To take over the role played by a master node, sleeping nodes are required to wake up earlier in scenarios with high mobility, where the estimated time the node stays in the grid determines the sleeping time T_s.

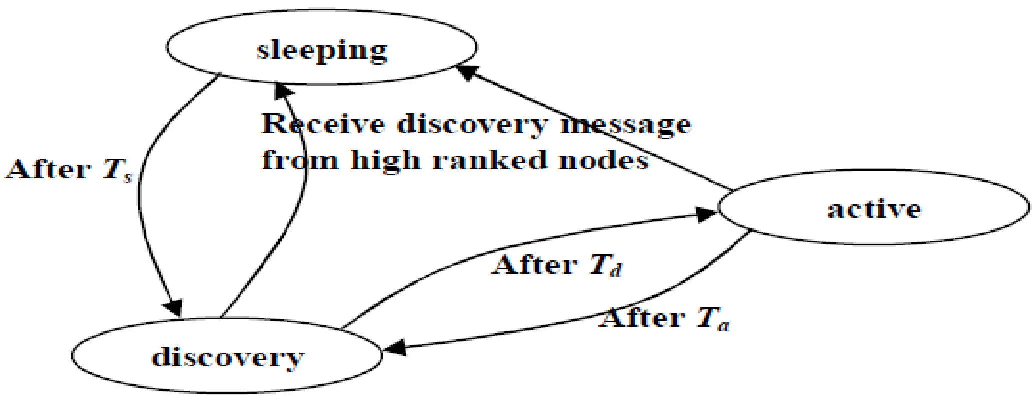

Figure 3.9 GAF protocol state transitional (Yu et al, 2003).

3.5.6 Prototype Embedded Network (PEN) Protocol (Garling, et al. 2000)

This section presents the low duty cycle of communication activities which provides mechanisms that avoid spending much time in the idle state by powering down during idle times. However, the difference between SPAN and GAF, in PEN the nodes perform an asynchronous communicate exclusive of master nodes and, therefore, expensive master selection method with the master overloading setback can be avoided. If nodes have to communicate without a central coordinating node, therefore nodes will have to wake up periodically and advertise that it is presence by broadcasting beacons. The nodes will also have to listen for a short time for any transmission request prior to powering down again. During the listening period the transmitting source node has to hear a beacon signal from the intended destination. The intentions of communication are made aware during the listening and let the communication process begin. Figure 3.10, shows the source and server node along a time chart.

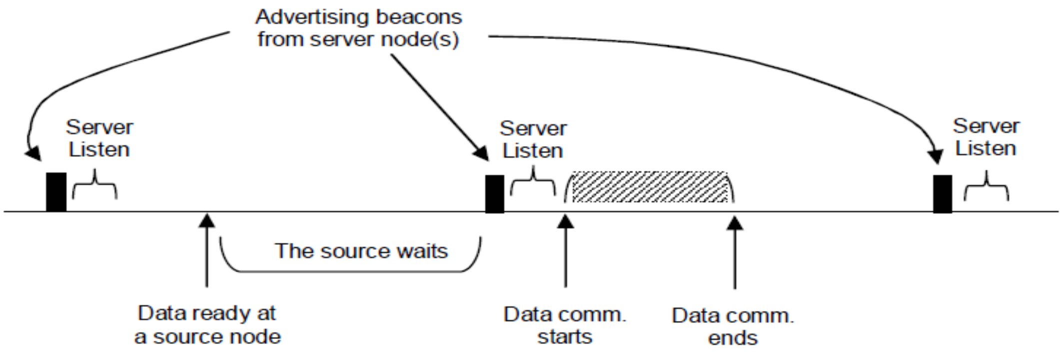

Figure 3.10 Source and server node activities

The procedures for discovering and maintaining routes are the same as those presented in AODV (Perkins and Royer, 1999). One good example would be the route table exchange and the on-demand route searchon-demand route table exchange between neighbour nodes. A considerable amount of energy is saved by the PEN protocol by reducing the amount of active time which is due to its asynchronous operation. The only time the PEN protocol is efficiently useful is when the rate of communication is quite low. The PEN protocol is not good for large data traffic but good for applications that involves simple command traffic. For routing that is based on a metric, to maximise the networks lifetime different kinds of metrics are used. The energy consumption in PEN is evenly distributed among all the nodes as presented in Perkins and Royer, (1999) and Rudolph and Meng, (1999).

In MBCR (Minimum Battery Cost) algorithm Toh, (2001) the metric incorporates the battery capacity. Yet again is the energy expected to reliable send a packet using a dedicated link is also considerable (Sanchez et al, 1999). In Perkins and Bhagwat, (1994), a cost function was defined to help maximise the network lifetime. The cost function considers the residual battery capacity and the energy consumed for one packet transmission. In addition the energy estimated to be spent to transmit all packets in the queue in (Ramanathan and Rosales-Hain, 2000) and the queue load condition are considered. Wattenhofer et al, (2001) present a study of diverse battery discharging property and also possible applications are presented in the same study. The battery activity introduces idle time, which can facilitate the charge recovery. However, due to critical nodes with very little battery capacity but not guaranteed to be protected is a problem of routing. And the majority energy efficient algorithms are analysed mathematically; therefore it has grown to be easier said than done to assess the performance with genuine routing protocols.

3.6 Common Deficiencies

In all the previously cited studies a common characteristic has been observed, which is the application of a minimisation of the maximum cost function (min-max). If the cost amount of energy used in routes is used as a criterion when selecting routes, then a problem arose and this resulted in the min-max algorithms to be implemented to overcome the problem. During the process nodes that have very little energy reserves are, therefore, excluded. The problem of network lifetime extension for a longer duration persists because protocols analyses are based on how long the networks operate. The simulation results presented by Cao et al, (2007) show how the energy of the nodes diverges along the path which is another common characteristic.

The above study presented in Cao et al, (2007) proves to be recent and most comprehensive; it shows the evaluation and the performance of several routing protocols that are energy-aware. Its demonstration proves that all the routing protocols take into consideration the distribution of the energy in the network. The majority of the energy-aware routing protocols consider the metrics that are energy-wise and no other parameters are considered. The inclusion of the speed is an improvement which determines how long the battery will last (battery lifetime). Traffic is deviated to save the node from powering down and that is when a certain threshold is reached. On the other hand, all the energy-aware routing protocols stated in the literature are designed for layer 3. The consequent retransmissions involved in layer-2 consume a lot of energy and the residual energy metric cannot present them.

Not much work has been done in making sure that layer-2 routing also called path selection has energy-aware protocols. Even though this research is design for layer-2 path selection and forwarding, some of the techniques that are used in layer-3 have also been adopted to be used in this research. The chapter that follows discusses the energy-metric that we have adapted from the sensor networks for this research. The metric looks at the initial energy, the residual energy and the transmission energy.

CHAPTER FOUR

Algorithm Design and Metric Development

4.1 Introduction

To have an energy efficient wireless network is everybody's dream which, therefore, triggers the need to address the problem that was raised in chapter one. Therefore, this chapter presents an energy-aware and optimising wireless mesh routing algorithm with a metric that guarantees connectivity is maintained in the network for as long as possible. Energy optimisation is regarded as the key factor to guarantee that the network does not get partitioned due to paths that have run out of energy. This method discovers the best possible path and then uses the energy of the nodes along the path efficiently. Some of the work reported in Mhlanga et al, (2009, 2011) show that a network that uses this kind of a technique, with unbiased energy spending in the nodes along the chosen path may help decrease the time to network partition. However, if the nodes along the discovered path are used more frequently as a result providing connectivity for longer durations, again that may lead to a more graceful degradation of the network resulting in network partitioning.

To help solve the problem of network partitioning, we, therefore, proposed an energy-aware path cost metric (EAPM) for path selection in hybrid wireless mesh protocol HWMP. The energy aware path cost metric will result in an unbiased energy spending among the nodes. The energy aware path cost metric is adopted from the research done by Chang and Tassiulas, (1999, 2009). More battery is consumed when some nodes are unfairly burdened in a wireless mesh network to support many functions that relay packets. The overall network functionality is disturbed when this happens and as a consequence it causes some nodes to stop transmitting earlier than other nodes. For that reason, the most essential goal for the energy-aware path cost metric is to maximise the network lifespan. When given multiple paths to choose from when routing, choose the path that won't consume much energy as compared to the others which therefore helps increase the network's operational time. This idea of choosing paths that will result in their network operational time being prolonged is used for the survivability of wireless networks. The proposed EAPM for the HWMP protocol ensures that networks with low-energy nodes are kept alive. The HWMP protocol does not use the one good path it has discovered for every transmission; instead a set of good paths are kept in its routing table and one good path is chosen among the many available paths based on a probabilistic fashion. Therefore, different paths are utilised varying times instead of using the single path for every transmission in the network and in return energy depletion in certain nodes is avoided to avoid network portioning.

The use of sub-optimal paths occasionally may be essential for the increase of network lifetime because it ensures that optimal paths don't get energy depleted and network partitioning does not occur as the network degrades elegantly as a whole. It is therefore achievable when considering that there are multiple routing paths found between the source node and the destination node. The possibility of each path being chosen is dependent on the energy metric that we have adopted. A single path is randomly selected each time there is data to be routed from the source to the intended destination node. This helps to ensures that there is no frequent use of any route, thereby preventing network partitioning which is caused by the energy depletion on nodes when used more frequently than other nodes. Therefore, different paths have to be tried continuously to improve tolerance to nodes in the network. The proposed and adopted energy aware path selection metric only uses a single path at all times. However, when considering the probabilities when routes are selected, an evaluation of different routes can be continuously conducted and the probabilities will be chosen accordingly. In this research three phases have been used for the implementation of the algorithm (Mhlanga et al, 2009, 2011):

A. The Setup Phase

i. The connection is initiated by the source node and before the request could be sent, the cost field is set to zero.

$$Cost(N_S) = 0 \tag{4.1}$$

ii. The intermediate node forwards the request to its immediate neighbours. As a result at a node N_i, the request message is forwarded only to a neighbour N_j which satisfies:

$$d(N_i, N_S) \geq d(N_j, N_S) \tag{4.2}$$

$$d(N_i, N_D) \leq d(N_j, N_D) \tag{4.3}$$

where $d(N_i, N_j)$ represents the distance calculated connecting N_i and N_j.

iii. As soon as the request has been received, the energy metric is then calculated by the neighbour responsible for sending the request and it is then added to the path's total cost. This means that if node N_i sent the request to node N_j, N_j does the calculation of the path cost as:

$$C_{N_j, N_i} = Cost(N_i) + Metric(N_j, N_i) \tag{4.4}$$

iv. Paths with extremely elevated costs are discarded and not added to the forwarding table. Paths that are added to the forwarding table FT_j of N_j are paths of low cost like the neighbours N_i.

$$FT_j = \{i \mid C_{N_j,N_i} \leq \alpha.(\min C_{N_j,N_K})\} \tag{4.5}$$

v. Each of the neighbours N_i has been assigned the probability of node N_j in the forwarding table FT_j. Where α is the weighting factor with the probability and the cost inversely proportional to each other:

$$P_{N_j,N_i} = \frac{1C_{N_j,N_i}}{\sum_{k \in FT_j} 1C_{N_j,N_k}} \tag{4.6}$$

vi. As a result, in order for packets to be routed to their intended destination every node N_j can use a number of its neighbours. To reach the intended destination the standard cost is computed by N_j with the use of neighbours in the forwarding table:

$$Cost(N_j) = \sum_{i \in FT_j} P_{N_j,N_i} C_{N_j,N_i} \tag{4.7}$$

vii. As an average cost $Cost(N_j)$ is sent in the "Cost" field of the request packet and the intermediate nodes forward it in the direction of the source node as in equation (4.2) and (4.3).

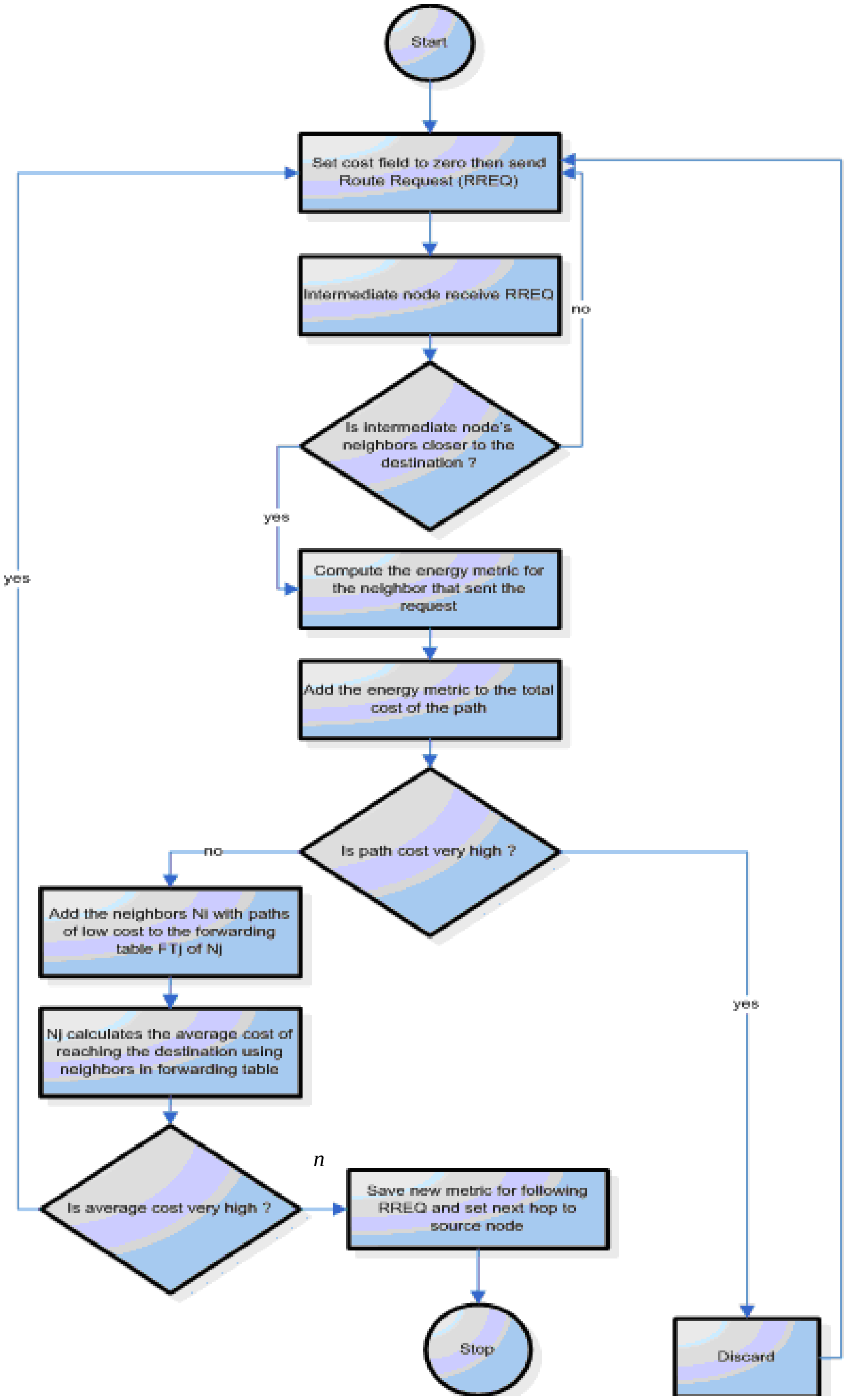

Figure 4. 1 Flow Chart for Energy-Aware Path Selection

4.2 Energy Conserving Path Selection Algorithm for IEEE 802.11s WMNs

Consider wireless mesh static nodes in a WMN that are randomly distributed in an area where there is limited battery supply for each node which is mainly used for transmission of data (for instance, a battery). This research assumes that each node is generating information that is intended for delivery to nodes designated as gateway nodes. The approach in this research, an assumption is made about the wireless mesh nodes having the ability to forward packets, i.e.,

- Relaying packets to one of its neighbour's nodes.
- To receive data correctly, the energy used for transmission can be adjusted to be in a level that is good enough to transmit and receive.
- The recipient should be within the transmission range for this to be achievable.

Before the arrival of the new information that is generated at the node or information relayed from other nodes, the first thing is to know the neighbouring nodes where data has to be sent. Instead of minimising the energy consumed in a wireless mesh network this research considers the performance goal which is maximising the network's operational time. The network lifetime maximisation approach is the same as maximizing the time to network partition. The problem of maximising the network partitioning time is regarded as an NP-complete problem whiles the maximum lifetime problem is identified as a linear programming problem. These kinds of problems are solvable in polynomial time so is the linear programming problem.

This research does not consider the single destination version of the problem but the multi-commodity case as an extension, where there is an intended destination for each commodity. This research assumes that the network is a static WMN topology furthermore; the path selection is responsible for discovering the traffic splits that optimise the energy that is consumed. The results for this research should be applicable to wireless mesh networks and static networks generally.

4.3 Path Selection to Maximise the System Lifetime.

When considering a WMN graph that is modelled as $G(N,A)$ a directed graph, where N represents all the set of nodes in the network and all set of directed links (i,j) are represented by A, where $i,j \in N$. All the set of nodes that can be reached by node i are represented by S_i and its dynamic range has a power level. We assume that if $j \in S_i$ therefore link (i,j) exists. Let an initial battery energy E_i be assigned to each node i, and let the rate at which information is generated at node i be represented as $Q_i^{(c)}$ and it all belongs to $c \in C$ commodity, where all the set of commodities are represented by C. Assuming that the required transmission energy from node i to its neighbouring node j is e_{ij}, and the information transmission rate of commodity c from node i to node j is called the flow $q_{ij}^{(c)}$. Let the aggregate flows be Q_i and q_{ij} for all commodities, i.e.,

$$Q_i = \sum_{c \in C} Q_i^{(c)}, \tag{4.8}$$

and

$$q_{ij} = \sum_{c \in C} q_{ij}^{(c)}. \tag{4.9}$$

For every c commodity, information is generated at the set of origin nodes $O^{(c)}$,

i.e., $O^c = \{i \mid Q_i^{(c)} > 0, i \in N\}$, (4.9.1)

and a set of destination nodes D^c that is responsible in making sure that any node is reached for a successful transfer of commodity c. For a given flow $q=\{q_{ij}\}$, the lifetime of node i is given by

$$T_i(q)=\frac{E_i}{\sum_{j\in S_i} e_{ij}\sum_{c\in C} q_{ij}^{(c)}}. \tag{4.9.2}$$

Under flow q the system lifetime can therefore be defined as the time it takes for the first battery to run out of energy among all nodes in N. Because of its equivalence, the system lifetime can also be presented as the minimum lifetime over all nodes, i.e.,

$$T_{sys}(q)=\min_{i\in N} T_i(q) \tag{4.9.3}$$

$$\min_{i\in N}\frac{E_i}{\sum_{j\in S_i} e_{ij}\sum_{c\in C} q_{ij}^{(c)}}. \tag{4.9.4}$$

Our aim is to find the flow that can help in maximising the network lifespan under the conditions of flow conservation. The difficulty to maximise the network lifespan is also presented in Chang and Tassiulas, (1999) and it can be presented as follows:

$$\text{Maximize } T_{sys}(q)=\min_{i\in N}\frac{E_i}{\sum_{j\in S_i} e_{ij}\sum_{c\in C} q_{ij}^{(c)}} \tag{4.9.5}$$

$$\text{s.t.} \qquad q_{ij}^{(c)}\geq 0, \qquad \forall i\in N, \forall j\in S_i, \forall c\in C, \tag{4.9.6}$$

$$\sum_{j:i\in S_j} q_{ji}^{(c)}+Q_i^{(c)}=\sum_{k\in S_i} q_{ik}^{(c)}, \forall i\in N-D^{(c)}, \forall c\in C \tag{4.9.7}$$

Commodity c's flow conservation condition at node i applies to each commodity separately which falls under the category of linear programming problem. What follows is the problem of linear programming which is equivalent to the problem of maximising the network lifetime, on condition the generation rate of information $Q_i^{(c)}$ is given at the set of origin nodes $O^{(c)}$ and the set of destination nodes $D^{(c)}$ for each commodity c.

Maximize $\quad T$ (4.9.8)

$$\text{s.t.} \qquad \hat{q}_{ij}^{(c)} \geq 0, \qquad \forall i \in N, \forall j \in S_i, \forall c \in C, \tag{4.9.9}$$

$$\sum_{j \in S_i} e_{ij} \sum_{c \in C} \hat{q}_{ij}^{(c)} \leq E_i, \qquad \forall i \in N, \tag{4.10}$$

$$\sum_{j:i \in S_j} \hat{q}_{ji}^{(c)} + TQ_i^{(c)} = \sum_{k \in S_i} \hat{q}_{ik}^{(c)}, \forall i \in N - D^{(C)}, \forall c \in C, \tag{4.10.1}$$

where $\hat{q}_{ij}^{(c)} = Tq_{ij}^{(c)}$ represents the quantity of data of commodity c transmitted from node i to node j until time T. The above presented linear programming can be observed as a difference between the conventional maximum flow problems with node capacity. For each node, if the transmission energy is rigid and without any considerations of the transmitted energy level at each node, it is rigid regardless of its next hop node, i.e., if energy control is not there,

$$e_{ij} = e_i, \quad \forall j \in S_i, \tag{4.10.2}$$

and solving this problem is the same as solving the maximum flow problem where the capacity of a node is given by

$$\sum_{j \in S_i} \sum_{c \in C} \hat{q}_{ij}^{(c)} \leq E_i / e_i, \quad \forall i \in N. \tag{4.10.3}$$

$$\cancel{\frac{e_i}{1}} \sum_{j \in S_i} \sum_{c \in C} \hat{q}_{ij}^{(c)} \leq \cancel{\frac{E_i}{e_i}} \times \cancel{\frac{e_i}{1}} \tag{4.10.4}$$

$$e_i \sum_{j \in S_i} \sum_{c \in C} \hat{q}_{ij}^{(c)} \leq E_i \tag{4.10.5}$$

Equation (4.10.3) shows the node capacity as a quantity that is fixed, therefore a node can be replaced by two nodes and a link having the same capacity in (4.9.2), which makes the problem to be changed to a link capacity version and enabling the use of max-flow-min-cut theorem in (4.9.3). Nevertheless, the research problem that we are solving is not similar to the above stated problem. The amount of energy resource that is consumed by a unit flow is dependent on the transmission energy consumed to the next relaying node. Therefore, finding the min-cut nodes is not trivial, and it should again be possible to identify the traffic split if it is assumed that they were found.

4.4 Flow Augmentation Routing in HWMP

To maximize the sum of link costs in a path, flow augmentation routing (FAR) first presume a network that is static and then identifies the best possible routing path for a particular source and a destination nodes. In this research we apply the concept of flow augmentation (FA) algorithm which uses the shortest cost path first. The algorithm design is described in the following: the shortest cost path from a source node to its intended destination nodes in $D^{(c)}$ is calculated in every iteration and in every origin node $o \in O^{(c)}$ of commodity c. Therefore, the amount of $\lambda Q_i^{(c)}$ augments the flow for the shortest path cost, where λ represents the augmentation step size. After the flow augmentation, the shortest cost paths are recalculated, and, therefore, repeat the procedures until any node $i \in N$ exhaust its initial total energy E_i. The flow to split the incoming traffic properly and to be used in every node is, therefore, obtained as a result of the algorithm.

4.5 Energy Aware Path Selection Metric for HWMP

The main research objective of energy-aware path selection metric (EAPM) is to find a cost function that will make available an optimal path that will help maximise the network lifetime. The EAPM metric is an extremely significant module of the HWMP because the most efficient routes are evaluated and selected using this metric. The information that can be incorporated in the metric is the costs of the energy that is used for the nodes along the chosen energy efficient path and the network topology etc. The link cost has to be calculated first in order to achieve the path cost. However, to calculate the path cost metric, a link cost metric has to be calculated first (Mhlanga et al, 2009, 2011). The metric is represented as:

$$C_{ij} = \frac{e_{ij}^{x_1} E_i^{x_3}}{R_i^{x_2}}. \tag{4.10.6}$$

When the energy-aware link cost metric C_{ij} is calculated three parameters should be considered for link (i, j). Where,

a) e_{ij} represents the amount of energy consumed during transmission over the link,

b) E_i represents the original energy which is also referred to as the initial energy of a node i,

c) R_i represents the residual energy at the transmitting node i.

d) x_1, x_2 and x_3 represents weighting factors that are negative for each item.

Since the objective is to help all the nodes to maximise their minimum lifetime therefore a good candidate path should be able to avoid nodes with little residual energy and be able to augment the path that consumes less energy. Optimisation cannot be done for both techniques at the same time, which reflects that a trade off exist between the two. Before any transmission begins whereby every node has plenty of energy, it is better to choose the path that has a minimum total consumed energy, whereas it is significant to avoid the small residual energy node towards the end. Because of that rationale, the metric cost has to be designed in such a way that there is emphasis on the energy expenditure term when there is still plenty of energy in the nodes and as the residual energy becomes smaller there should even be more emphasis. Therefore, we substitute equation (4.10.5) in equation (4.10.6):

$$C_{ij} = \frac{e_{ij}^{x_1}\left(e_i \sum_{j \in S_i} \sum_{c \in C} \hat{q}_{ij}^{(c)}\right)}{R_i^{x_2}} \qquad (4.10.7)$$

In this algorithm development a link consuming little energy during transmission compared to the other links is preferred, which is ($e_{ij}^{x_1}$). A node that would leads to a better energy balance by transmitting with a node that uses high residual energy ($R_i^{-x_2}$) selected. This is again dependent on the parameters x_1, x_2 and x_3, in which an equivalent routing algorithm would accomplish a goal that is different. Note that if $\{x_1, x_2, x_3\} = \{0,0,0\}$ the cost of the link is at all times 1. With this in mind the minimum hop path is therefore regarded as the best possible path.

The minimum transmitted energy path uses $\{1,0,0\}$ as its parameters and as a result regarded as the shortest path. The use of normalized residual energy implies that $x_2 = x_3$, while $x_3 = 0$ symbolize that the absolute residual energy is used. The algorithm is referred to as $FA(x_1, x_2, x_3)$ in the rest of the work which indicates the parameters, and for reference what the parameters mean is summarised in Table 4.1. By summing the link costs along a particular path produces a path cost. All active shortest path algorithms can be used to implement this algorithm.

Table 4. 1: The meaning of parameters in flow argument algorithm

$FA(x_1, x_2, x_3)$	Meaning
$FA(0,0,0)$	Minimum hop path
$FA(1,0,0)$	Minimum transmitted energy path
$FA(\cdot, x, x)$	Normalized residual energy s used
$FA(\cdot,\cdot,0)$	Absolute residual energy is used

Even though a wireless link (i, j) uses e_{ij} and $e_i \sum_{j \in S_i} \sum_{c \in C} \hat{q}_{ij}^{(c)}$ as constants and while the communication traffic moves on, R_i continues to drop. Solutions that are most favourable keeps changing now and again, meaning that at one moment it can be regarded as it can be as the best possible solution and it can again not be the most favourable at a later time for the reason that R_i's and the link costs that are corresponding have changed. Based on this explanation, the overall optimal solution is solved by flow argument routing FAR in an iterative fashion (Mhlanga et al, 2009):

a) For the first time step the optimal route can be solved,

b) Another optimal route can be solved after updating the energy that is remaining in the nodes and link costs for the next time step, etc.

Each and every single node is assumed to be having the data generation rate beforehand during each time step. The calculation of the path cost which is represented as C_{pi} is done by summing the link costs on the path that is chosen as the most optimal path as shown in (Mhlanga et al, (2009, 2011)). The path cost is presented as follows:

$$C_{pi} = \sum_{\substack{i=m \\ j=i+1}}^{n} C_{ij} = C_{m,m+1} + C_{m+1,m+2} + C_{m+2,m+3} + \ldots + C_{n-1,n} + C_{n,n+1} \quad (4.10.5)$$

$$= \sum_{\substack{i=1 \\ j=i+1}}^{n=10} C_{ij} = C_{1,2} + C_{2,3} + C_{3,4} + \ldots + C_{10-1,10} + C_{10,11} \tag{4.10.6}$$

In the process of discovering the most optimal route between the source node to an intended destination node, there is a possibility of having multiple possible paths available for use to route to the destination. However, only one optimal path can be chosen by making sure that along the chosen path nodes have sufficient energy for transmission and the most favourable when it comes to selectivity. All paths that have little energy can never be chosen by the source nodes, which mean that even if the transmission energy that is consumed is minimal. Choosing paths with little energy in their nodes would result in the network getting partitioned more quickly and that will definitely affect the network lifetime.

CHAPTER FIVE

Simulation for Algorithm Validation and Performance Evaluation

5.1 Introduction

In the previous chapter, we presented the Energy-Aware Path Selection Metric (EAPM) for HWMP. In this chapter we start by outlining the techniques that are used to evaluate the network performance for EAPM. Traditionally, there are three techniques that are used for the network performance assessment, namely: analytical modelling, simulation and measurement. Simulation was, therefore, chosen as a technique to be used for this research. In section 5.2 we explain the motivation for evaluating our metric performance using simulation as chosen technique.

5.2 Selection criterion for Network Performance Evaluation

The most important criterion in this design is criterion, procurement, and use of computer systems. To get the utmost performance for a given cost, computer systems professionals such as engineers (computer, electronics, electrical etc), scientists, analysts and users must have a thoughtful knowhow about the techniques used for performance evaluation as their main goal. The reason behind choosing simulation as a technique used for this research is because not much hypothesis is considered necessary compared to analytical modelling. Simulation is also the most appropriate method to get more details as compared to the other techniques. Another factor that makes simulation to be the most favourable technique and chosen is because of the considered reasons: accuracy, the time on hand for evaluation and the cost allocated for this research. Given the opportunity to use simulation as a technique, researchers should be given the platform to read and understand a system in well-known conditions, repeatedly if required in order to comprehend events. There is also a drawback for using simulation which is the inherent risk of over simplification. Replicating the whole world inside a computer model is not possible; as a result some of the things have to be approximated statistically or otherwise. If the behaviour of first-order factors is not being captured properly, it can lead to drastically incorrect results.

5.3 Computer Network Simulator Tools

A number of simulator tools are available for use, such as: OMNET++, Network Simulator 2 (NS-2), OPNET Modeller and GloMoSim etc. NS-2 (version 2.32) is therefore chosen for this research because it is an object, oriented, discrete event driven network simulator tool. NS-2.32 is written in C++ and OTcl and it was developed at UC. The usefulness of NS-2 is to simulate local and wide area networks. As soon as one gets to know NS-2 it is then fairly easy to use it for simulation. Since there are few user-friendly manuals available for use it therefore makes it a bit challenging for a novice.

Regardless of the in depth explanation of the simulator in a lot of documents written by the developers, it is written with the depth of a skilled NS-2 user. The simulation scripts written in OTcl are interpreted by NS-2. Different components like event scheduler objects, network components libraries and setup module libraries are set up by the user in the simulation environment. The user's simulation is written as an OTcl script, the network components are therefore plumbed together to the complete simulation.

5.4 Simulation Environment

The simulation environment for this research is made of a set of extensions designed for wireless static networks from the web pages of the Carnegie Mellen University Monarch Project. The physical and link layer behaviour of a wireless network's comprehensive model is made available by the wireless static extensions and it is also responsible for permitting illogical movement of nodes within the network. Other researchers have widely used these wireless extensions and the release of the standard VINT release of NS-2 was as a result of the adoption of these versions for the wireless extensions.

Free space and ground reflection propagation for practical modelling of factors are provided at the physical layer. In the previous section, it is stated that NS-2 is used to run the simulations and the files describing the exact packets from each node is accepted as input. The detailed trace file formed by every run is stored to disk, furthermore an analysis is done using a variety of scripts, for the most part the one with the extension *.tr that counts for the amount of energy consumed in a path and to be able to choose routes that are energy efficient to avoid network partitioning. It also accounts for supplementary information regarding the domestic functioning of each script executed. Additionally, an AWK file and Microsoft Excel is used to analyse the data to produce the graphs.

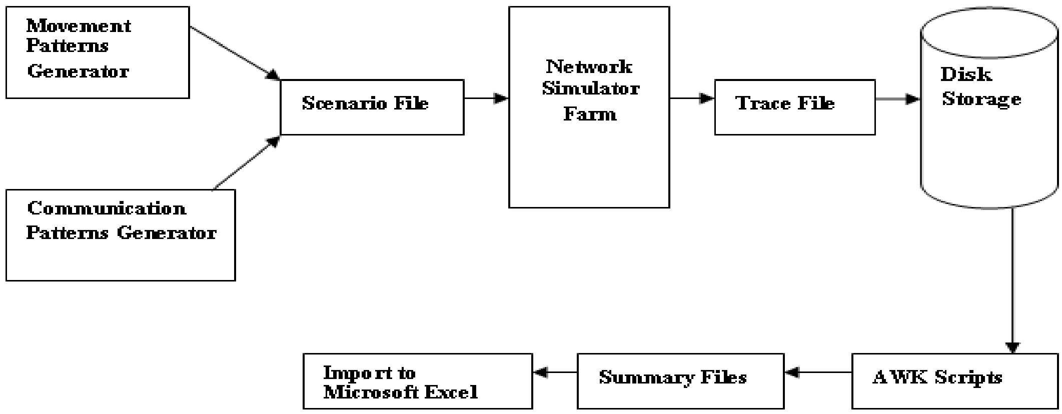

Figure 5. 1 Overview of adopted simulation model (Usop et al, 2009)

The simulation models are built by means of the (NS-2) version 2.32 and it uses a norminal bit rate of 2 Mbps to run the simulation. A fixed number of packet sizes (512-bytes) are used by the experiments with a changing of pause times. Fixed nodes and a packet rate of 4 packets per seconds are used in this simulation. The field configurations used is a flat grid of 1500m x 1500m with 81 static mesh nodes. The simulation time for all simulations was set to be 15 minutes (900 seconds). The constant bit rate (CBR) UDP traffic sources were used to generate the data traffic for this experiment.

5.5 The Simulation Assumptions

What follows are the assumptions that are taken into consideration while building the Tcl script:

1. It is assumed that the type of traffic source is the same for all the flows in the network. A constant bit rate (CBR) traffic is assigned to each sender with the data rate/number of stations packet per second;
2. From the nodes to the gateway there is only one way traffic that is used.

3. The wireless mesh network has fixed nodes.
4. The wireless mesh network is implemented in a grid environment using HWMP.

The experiments performed are presented in section 5.6 below where each experiment was performed 10 times. Results were also obtained for experiments and the average values were used for analysis. In Mhlanga et al, (2011) as part of this work, we show the performance comparison of the energy-aware path selection metric (EAPM) with ETX, Airtime link metric and Multi-metric (MM). Graphical and theoretical techniques were used for analysis.

5.6 Experimental Setup and Results

A brief description of experiments is presented in this section and the results for three experiments conducted. In section 5.6.1 we test the effect of network lifetime. Section 5.6.2 presents experiments to test the effect of energy efficiency of the entire network. Section 5.6.3 presents experiments to test the effect of network size (scalability) of our approach.

Table 5. 1 *Simulation parameters for all the experiments*

Parameters	**Environment**
Number of nodes	9, 18, 27, 36, 45, 54, 63, 72, 81
Area	1500m x 1500m
Simulation Time	900 seconds
Packet Size	512 bytes
Packet Rate	4 packets/sec
Routing Protocol	HWMP
Experimental Metrics	Network Lifetime, Packet Delivery Ratio (PDR), End-to-End Delay, Energy Efficiency, and Scalability.

5.6.1 Experiment I: Network Lifetime

In Aron et al, (2008) the network lifetime is defined as the time taken by the network during its operation before the first node runs out of energy and causing network partitioning. The number of nodes in the network should be varied to be able to run the tests for the network lifetime. It is, therefore, imperative to make sure that all the nodes that remain alive are used in order to calculate and measure the network lifetime over a period of time. However, the network is disconnected after a certain period of time. When using EAPM as a metric, nodes start to deplete their energy at a later time.

This problem is caused because the currently used protocols and metrics for wireless mesh networks which discovers the shortest path in the network and then make use of that path for every communication. As a result, using the same path for every communication leads to a quicker energy exhaustion of nodes that are transmitting messages along that path. This kind of path selection leads to fewer nodes alive as the nodes in the network continues to transmit messages compared to the lifetime of the nodes using EAPM as it's metric for path selection.

Figure 5.2 below, shows the route request process (RREQ) which is performed in order to enable the source node to have a route to a destination node when there is data to be sent. Before sending the data to the destination node the source node will first have to check if its routing table has a suitable path to the intended destination node. If a suitable path to the destination node is not discovered, a route discovery will therefore be initiated by the source node by creating a route request (RREQ). A RREQ ID then comes in, to help identify a particular RREQ that is considered with the IP address of the originating node. This allows a duplication of the RREQ message reception to be detected. The source node has a sequence number which is contained by the sequence number field of the source. If a path to the source node already exists the node will verify if it has to be updated or not.

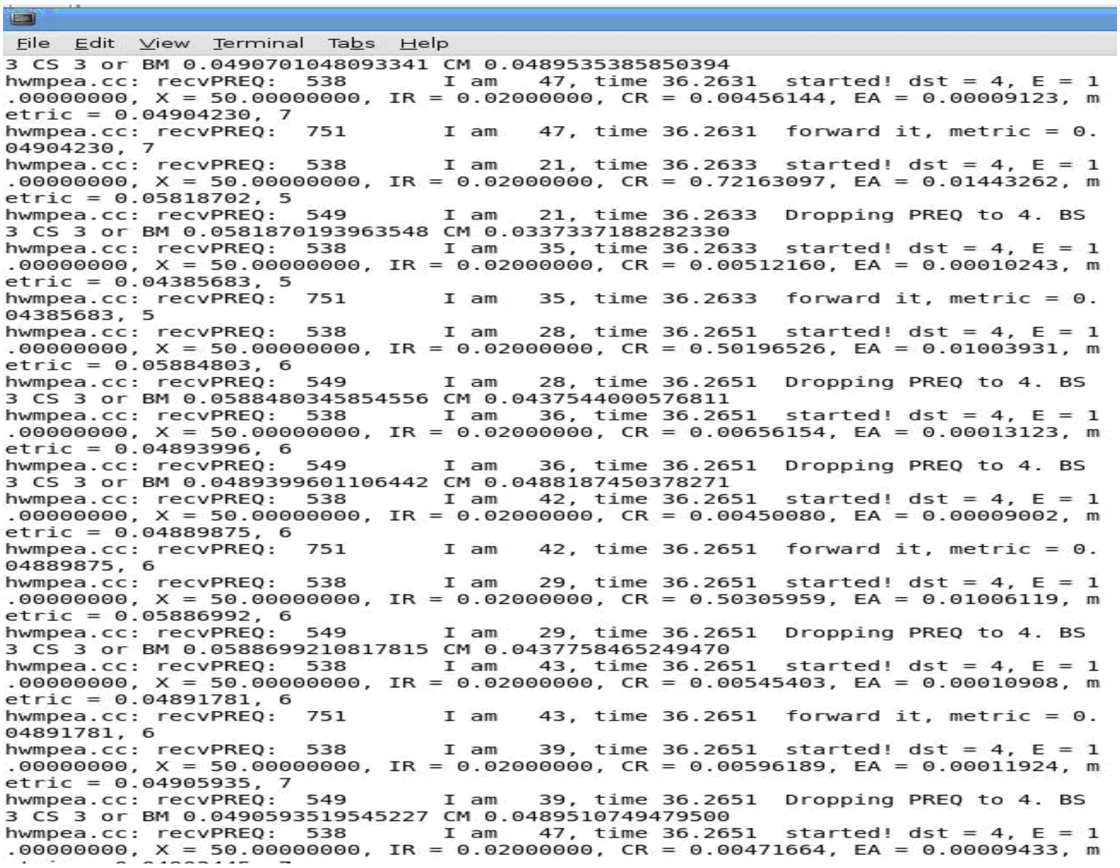

Figure 5. 2 EAPM simulation screenshot for a PREQ

If the sequence number of the source node for the existing routing table is less or equal to the sequence number of the RREQ, the existing path to the source can, therefore, be updated. This is also possible when a new metric used in the RREQ proves to be superior as compared to the metric in the entry for the routing table. If the RREQ's sequence number is bigger than that of the corresponding routing, updates will therefore be performed all the time by at least a configurable threshold value. Updates are made if and only if a new RREQ is received with a greater RREQ ID.

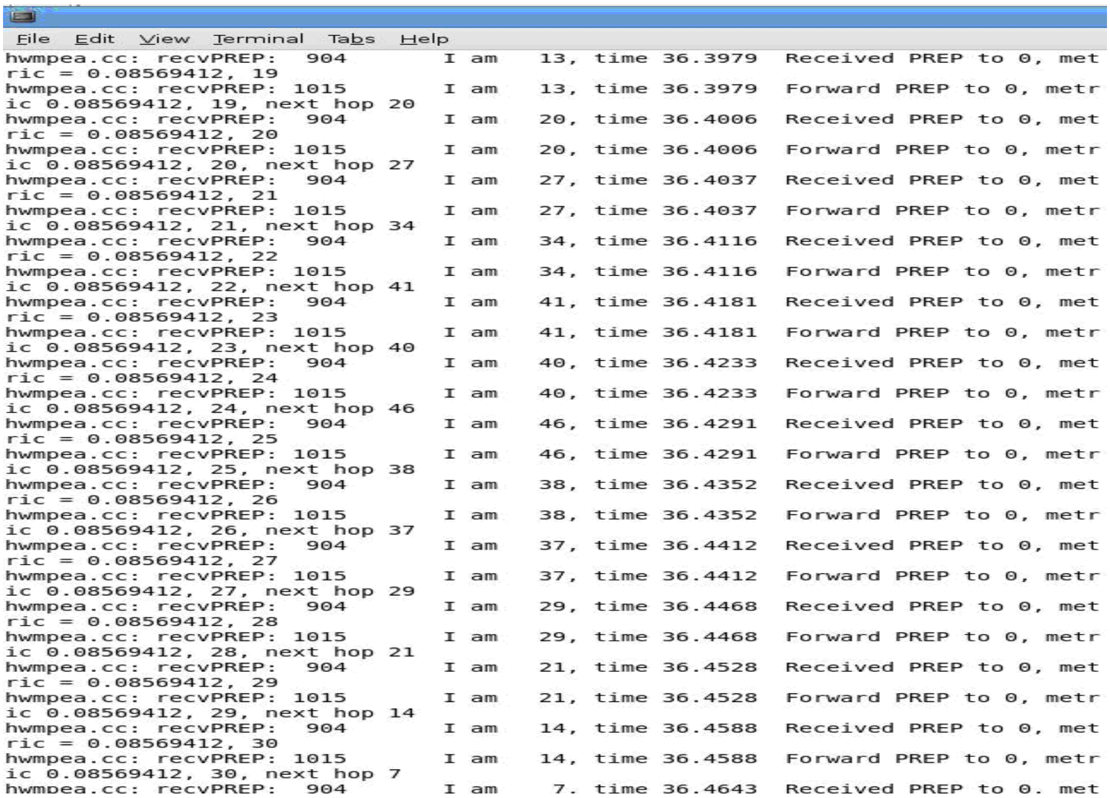

Figure 5. 3 EAPM simulation screenshot for the processing of RREP

Figure 5.3 above, shows how the route reply message (RREP) is processed which is responsible for setting up the routing path from the source node to the intended destination. The RREP is sent back in a unicast mode using the reverse path that was created during the RREQ process. The creation of the route is triggered or updated after the RREP has been received by the source node. To update the RREP the value of the hop count is incremented by one. The previous hop's link metric is added to the current metric field and therefore resulting to the creation of a route to the destination.

If the sequence number in the routing table is smaller as compared to the sequence number in the RREP, the route can, therefore, be updated or if the RREP has a better path metric and previous paths have not changed. The next hop node in the route towards the destination node is determined by the RREP transmitter. The node that is currently carrying the updated RREP will forward it to where the route discovery originated. The source address field of the RREP message can only indicate the source if the entry of the routing table has been updated or created. If the originator of the RREQ is the current node, therefore, the buffered data frames intended for the destination can now start doing the forwarding.

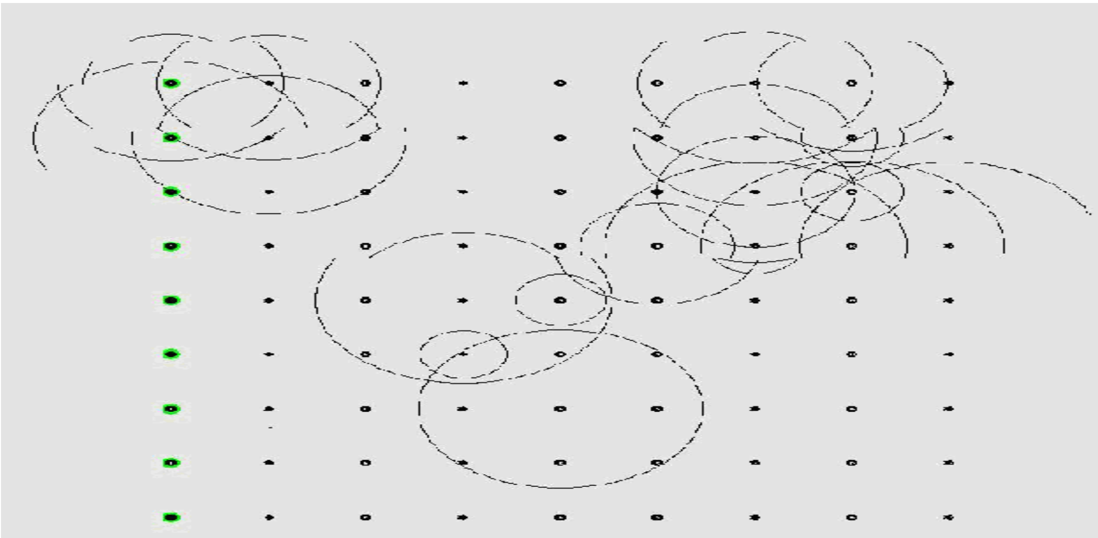

Figure 5. 4 The EAPM topology with green nodes showing the chosen route for packet forwarding.

The results presented in figure 5.4 above, the green colour indicates that there is enough energy (initial energy) in all the nodes along that path. Transmitting from the source node (bottom left) to the destination node (the top left), the link evaluation is done by the link cost stated in the previous chapter. The link cost metric was designed considering the amount of energy consumed when transmitting over a link (e_{ij}), the initial energy denoted as E_i and the remaining energy denoted as R_i at the transmitting node i. For the minimum lifetime of all nodes to be maximised, a good candidate path that consuming less amount of energy on the other hand avoiding nodes with little residual energy is chosen. A link that requires a lesser amount of transmission energy is preferred.

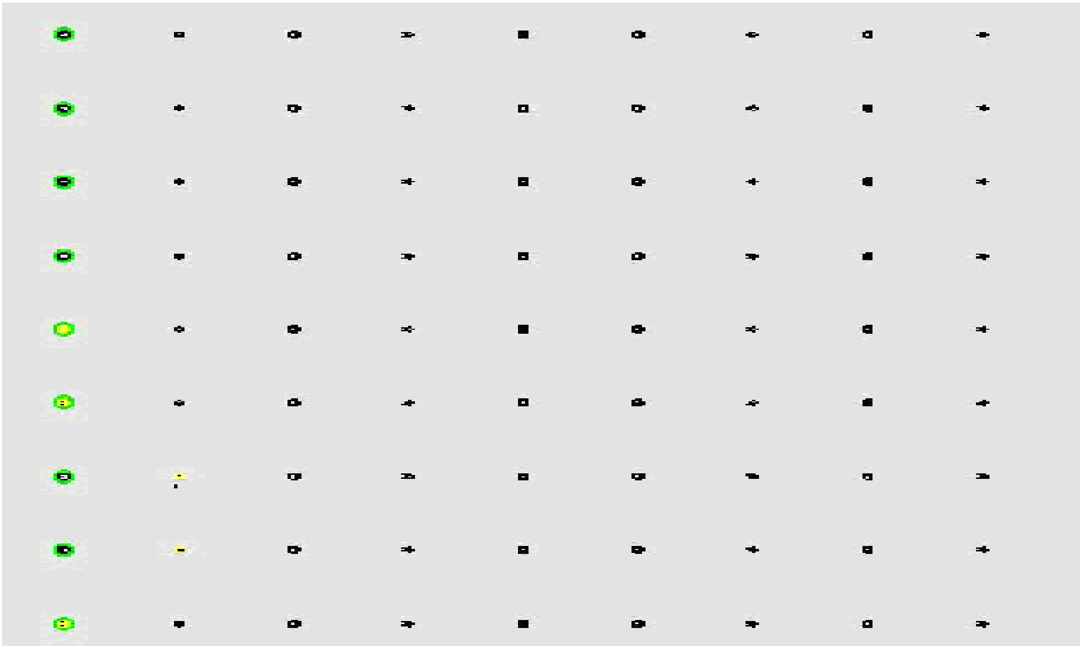

Figure 5. 5 EAPM topology with yellow nodes which shows caution of nodes to run out of energy in a chosen route for packet forwarding.

An observation can be made from the figure above that instead of using the initially chosen route with the green nodes on the straight line, the route selection changed from node 0, 1, 2, 3 to node 0, 10, 11 and then back to node 3 forming a curve route. This is for the reason that the link between node 0, 1, 2 consumes a lot of energy when transmitting using it, which may also cause network partitioning. As a result a new route is selected that is energy efficient.

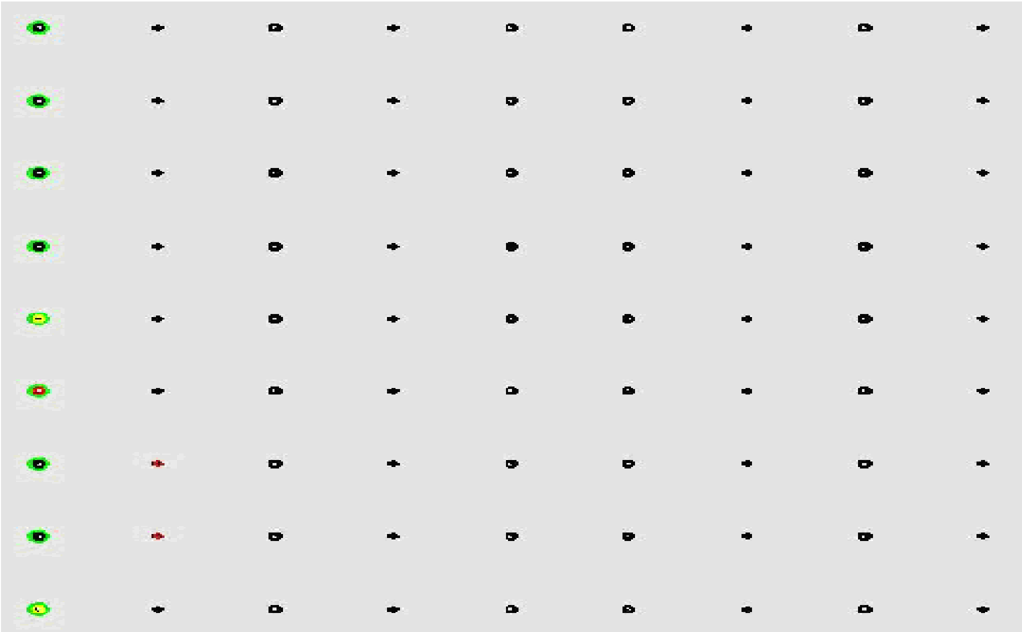

Figure 5. 6 EAPM topology with red nodes showing danger of using energy drained nodes which causes network partitioning.

In figure 5.6 above, the red colour symbolises energy drained nodes and to continue using them will definitely cause network partitioning. Therefore, once the node's colour changes from yellow to red, given alternative routing paths, the EAPM algorithm will choose a routing path with the most remaining energy in the nodes. A probability function is always considered in EAPM when selecting a path and it is dependent on the energy expenditure of each path (Akkaya and Younis, 2005). The use of shortest paths in this regard as argued by the above mentioned approach may lead to the energy of the nodes being depleted along the chosen path. The shortest path is not always the best path; instead the algorithm uses a single path with a certain probability and it is chosen from the much available energy efficient paths so that the whole life time increases.

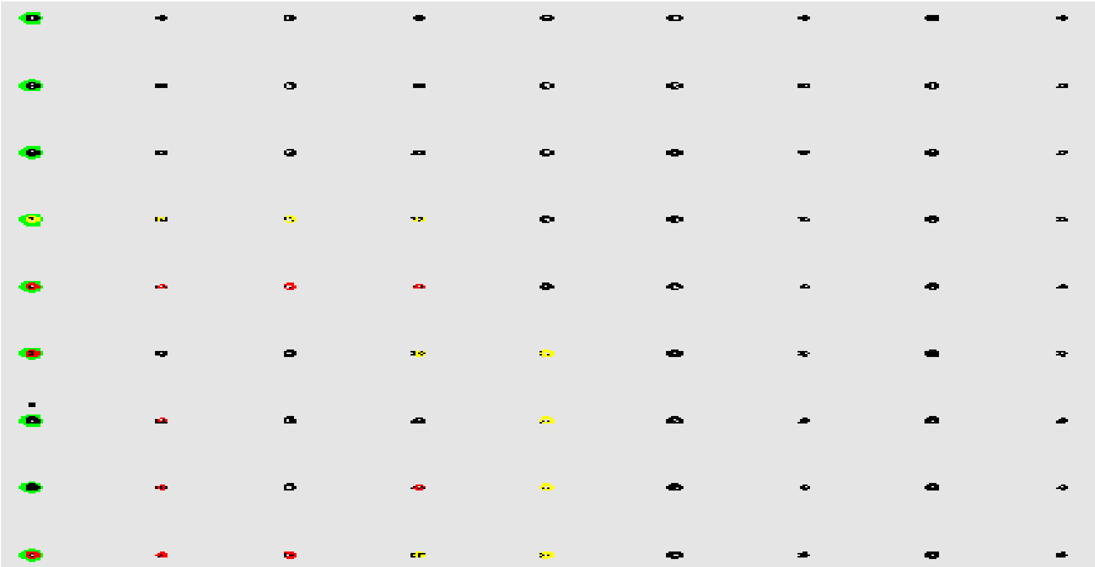

Figure 5. 7 EAPM topology with red nodes showing danger of using energy drained nodes which causes network partitioning.

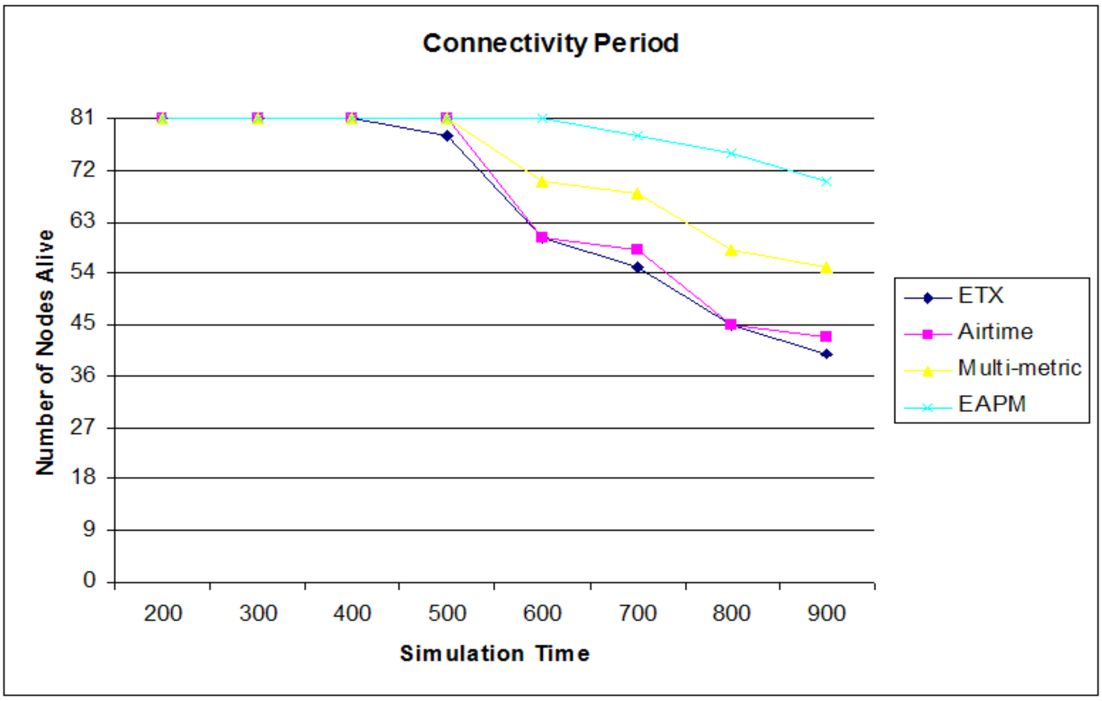

Figure 5. 8 A performance comparison of the number of nodes alive versus simulation time (sec) for a network of 81 nodes.

Figure 5.7 above, shows a performance evaluation of four metrics with regard to their network lifetime in a network of 81 nodes with 30 traffic connections used during the simulation. An overall of 1024 packets were sent with 512 bytes of data. It can be observed that ETX based network nodes starts to deplete the energy in their reserves in the area of 400 seconds of simulation time. Both the airtime and Multi-metric begin to deplete their node's energy at an area of 500 seconds of simulation time. The network using the EAPM metric as expected remains connected up to the area of 600 seconds of simulation time. This is for the reason that channel contention is reduced at reduced per node transmission energy. The total amount of energy used in a node during transmission is reduced as it is adjusted to reach few neighbour nodes and ultimately the whole energy consumed in the network is reduced.

As soon as EAPM realises that the remaining energy in a node is below the threshold that is set for every node in order for it to be able to transmit, it chooses another available path to use in the network, with regard to energy. The energy that is remaining in a node is always monitored and eventually the overall consumed energy is reduced. It is very apparent that the four metrics are consuming energy at different rates as it can be observed that at 900 seconds of simulation time, EAPM has about 86% of the number of nodes that are still active whereas Multi-metric has about 68% which makes a difference of 18%. Multi-metric has 15% more of nodes alive compared to Airtime with 53%.

The airtime link metric has 4% more of live nodes compared to ETX which has 49% of active nodes. This also proves that EAPM has more network lifetime compared to the other metrics evaluated for this experiment. The reason why this happens is because in a WMN environment, EAPM considers energy when selecting an optimal path while the other metrics considers issues like the mesh point's transmitting capabilities. For example Multi-metric considerations are based on residual bandwidth, frame delivery ratio (FDR), and mesh point's load with no energy consideration. This then results in EAPM being superior to the rest of the metrics.

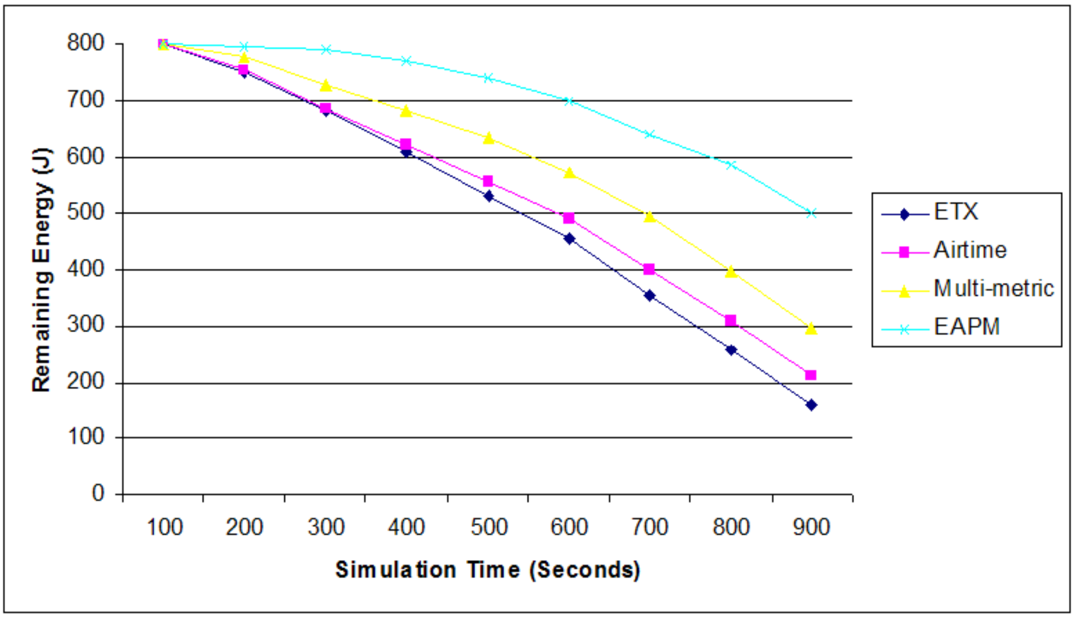

Figure 5. 9 Performance comparison of remaining energy (J) versus simulation time (sec)

Figure 5.8, presents the different changes with regard to the remaining energy in the nodes for the whole network inconsideration with the time changing in the four metrics. In a network of 81 wireless mesh nodes, each node's initial energy would be 8J. Figure 5.8, presented above shows that the network's remaining energy for EAPM is more than the rest of the other metrics. This is because every time when data is to be sent to the intended destination, the source chooses one path randomly by considering the energy that each path consumes. So the path that consumes very little energy is preferred depending on the probabilities. As stated before, no single path is used all the time but one path among the many available paths is used based on a probabilistic fashion. EAPM uses a single route at a time and it is able to switch to other routes to improve tolerance in the network due to the fact that different paths are tried continuously. The selected path must have nodes with sufficient amount of energy for transmission and the selectivity must be the highest. The source node cannot choose paths that have insufficient energy, despite the fact that those nodes might be consuming very little energy when transmitting in the network. Choosing paths that do not have enough energy would result in the network dying out more quickly which is not a good thing for the network lifetime.

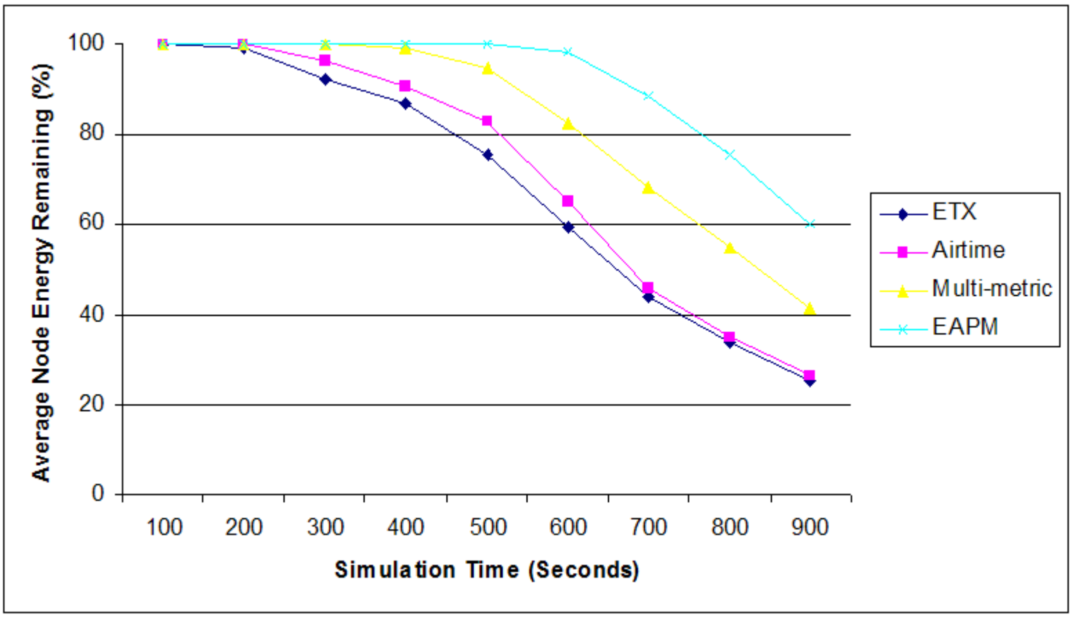

Figure 5. 10 Performance comparisons in terms of average node energy remaining versus the simulation time (sec).

Figure 5.9., shows an assessment of an average node energy remaining for four metrics evaluated in the network namely the ETX, airtime link metric, multi-metric and EAPM. In this experiment ETX and Airtime link metric starts depreciating in the area of 200 seconds. A very small difference of the average node energy remaining is seen from the area of 700 to 900

seconds between ETX and Airtime link metric where the average node energy remaining drops dramatically. The percentage of average node energy remaining starts dropping from the area of 400 seconds for Multi-metric and it starts dropping at 500 seconds in the graph presented above. In the area of 900 seconds, figure 5.9 shows that the network based on EAPM has about 60% average node energy remaining. ETX has 26% of average node energy remaining while airtime and multi-metric has 27% and 42% respectively. The amount of conserved energy leads to an extended network lifetime and EAPM will result in a balanced energy spending among the nodes because it is energy aware. Nodes consume more energy when they are unfairly burdened and such nodes are most likely to stop running earlier than the rest of the nodes are nodes that support many packet-relaying functions of the network. Thus in the above figure, EAPM has achieved successfully the fundamental goal of maximising the network.

5.6.2 Experiment II: Packet Delivery Ratio (PDR)

In this figure the PDR experiment was carried out to find out what the ability of the network is for data packets delivery being sent from the source to the intended destination node. This is achieved by measuring the generation rate of data packets by nodes and their successful delivery rate in percentage. For example, the network's total failure of delivering data packets is 0% PDR while 100% PDR shows a delivery of packets that is completely perfect. An illustration of the PDR for all the routing metrics that were evaluated in this experiment is shown in figure 5.10. It can also be observed in this experiment that an ability to deliver data packets and to also ensure that the network is redundant which is achieved by a network with higher node degrees as it tends to have multiple routes from the source to the destination node. The number of connections or edges the node has to other nodes is what determines the node degree.

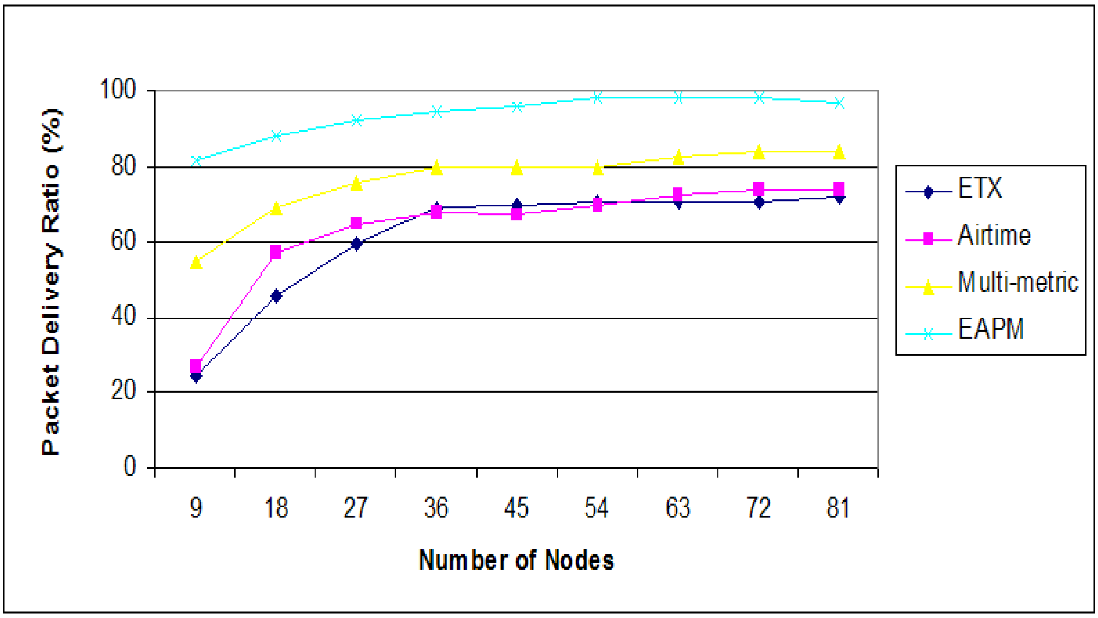

Figure 5. 11 Packet Delivery Ratio versus number of nodes

Figure 5.10 saves as evidence that the proposed EAPM metric provides better data delivery rate ratio compared to the other metrics evaluated in the experiment. The successful packet delivery ratio of EAPM achieved about 97% on average compared to 84% for Multi-metric, 74% for Airtime and 72% for ETX. The reason why EAPM outperforms the other metrics is because of the fact that EAPM considers energy when choosing an optimal path and as a result the chosen path is guaranteed to continue transmitting data packets for a longer duration guaranteeing a delivery of a data packet. However, other than EAPM all the evaluated metrics in this experiment do not consider issues of energy awareness and interference which may cause network partitioning resulting to a low packet delivery ratio. The most important focal point is on scaling the network while making sure other parameters are constant. Our main objective is to design a wireless mesh algorithm that can scale to as many nodes as possible. This research, therefore, focuses on how the algorithm scales while performing better with networks of different sizes. It has been observed that the ratio at which packets are delivered in EAPM is larger for all the network sizes as indicated by the performance of EAPM in figure 5.10 above. In this experiment it is obvious that EAPM proves to be improving much more when the source nodes are increasing.

5.6.3 Experiment III: End-to-End Delay

Figure 5.11., shows an experiment of four metrics that are evaluated based on end-to-end delay that is caused when data packets are relayed from the source node to the intended destination node under the newly proposed EAPM for HWMP.

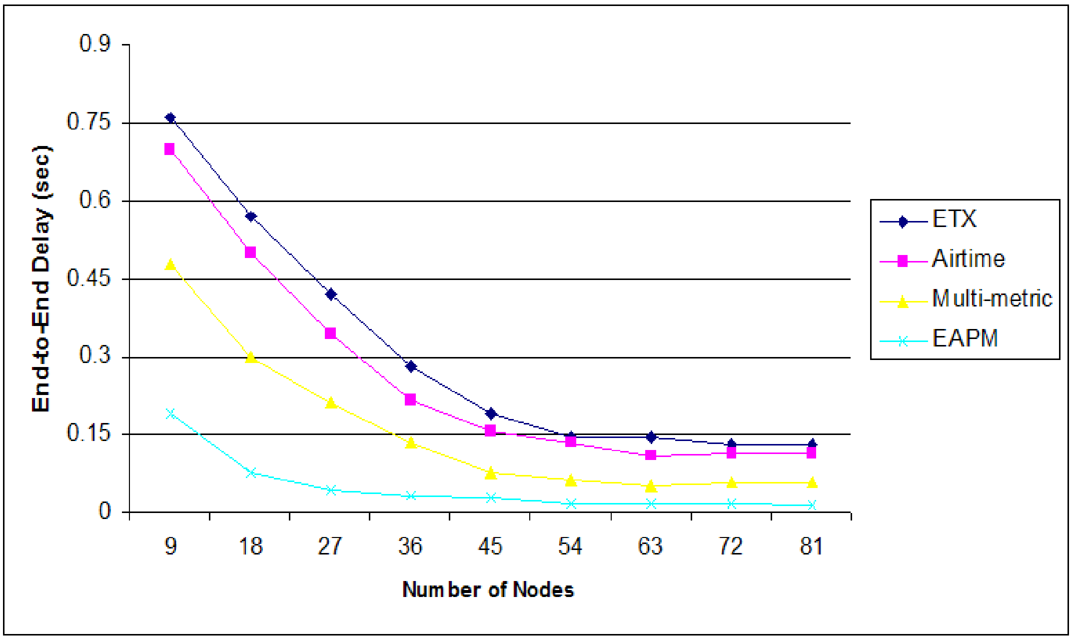

Figure 5. 12 Performance comparisons in terms of end-to-end delay based on the number of energy exhausted nodes in the network.

This experiment shows a scenario where the network that consist of a smaller number of source nodes which is also regarded as a network with lower average node degrees experienced a very high end-to-end delay when comparing to high average node degrees in a network. While EAPM attains an end-to-end delay that is very low, on the other hand a very high end-to-end is suffered by the rest of the other metrics that are also evaluated in the experiment. However, when the number of sources is increased in the network, an end-to-end delay reduction is, therefore, seen as shown in the above experiment.

A drastic increase of end-to-end delay is seen among the other three metrics (ETX, Airtime and Multi-metric) which is attributed by the more few number of source nodes, and congested routes. Having multiple simultaneous transmissions also contributed in worsening the delay experience. To buffer during route discoveries, retransmission delays and interface queues may also be the cause of other possible delays. A well designed network's end-to-end delay must be low because it produces a better application performance. The performance of the protocol is regarded as not good if end-to-end delay is high which is caused by issues such as network congestion. So EAPM has a good performance as it produces the lowest delay compared to the rest of the metrics evaluated in this experiment.

5.6.4 Experiment IV: Energy Efficiency

The main objective of this experiment is to show how efficient is the network with regard to energy when comparing the four metrics as shown in figure 5.12 below. Energy efficiency is therefore denoted as ξ (Mhlanga et al, 2011), which is the average ratio of the total transmission energy consumed to the total maximum transmission energy per node over the range of nodes in the network. It is given by:

$$\xi = \sum_{\substack{i=1 \\ j=i+1}}^{n} \left\{ \left[\frac{C_{pi}}{S_{pi} C_{ij}} \right] / n \right\}, \tag{5.1}$$

where C_{pi} is the path cost that was calculated in the previous chapter, S_{pi} is the selectivity of the path pi chosen as an optimal path. C_{ij} represents the link cost connecting two nodes i and j. n represents the sum of all the nodes in the network. Once the algorithm $\xi = 0$ has been executed or used to it exhaustion, where full energy is used for transmission by each node and that is regarded as the worst case scenario. If the energy efficiency value is higher as shown in figure 5.12 for EAPM, this means that the energy saved in the resultant network is more. It is for this reason that the energy used for transmission cannot be reduced to a zero value. In reality the value of $\xi \leq 1$ does not hold because in practice ξ can never be equal to 1, when one considers that connectivity should be maintained.

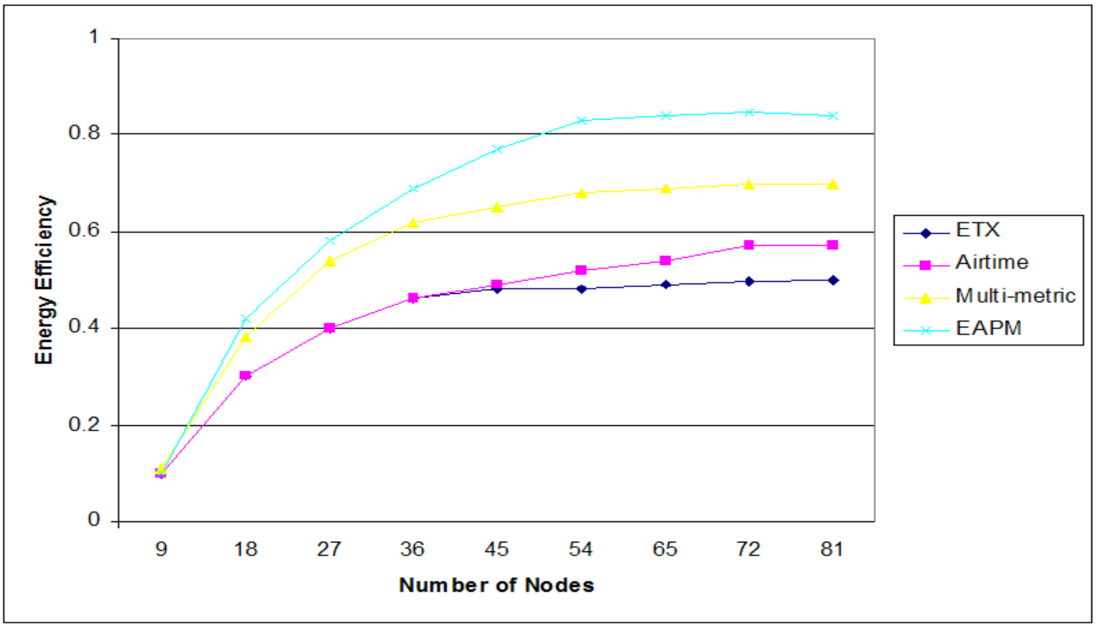

Figure 5. 13 Performance comparison in terms of energy efficiency based on the number of nodes in the network.

Figure 5.12., shows an energy efficient based comparison of the four metrics that are evaluated in this experiment for the whole network. Considering a situation when the network has fewer nodes e.g., in the area of 9 to 18 nodes for all the metrics, we observe a below 0.5 average energy efficiency which implies that the energy that is saved is less than 50%. Unlike in densely populated networks, connectivity in sparsely populated networks consumes more energy because of the distance which requires more energy in order to be able to transmit from one node to the next. However, as the nodes are increasing in the network, the energy efficiency is seen rising to 50% and above for all the metrics as shown in figure 5.12. The EAPM metric even went beyond 80% when the number of nodes was approaching 55. The reason being that nodes in a dense network are nearer to one another as a result they lessen their transmission energy. The energy will be lessened with a bigger margin to ensure connectivity and this ensures connection to the closest neighbours. The network becomes stable in the area of 36 nodes for ETX, Airtime and Multi-metric. It starts stabilising in the area of 36 nodes for Multi-metric, Airtime and ETX.

5.6.5 Experiment V: Scalability

The most important objective of this experiment is to test how scalable is the network when comparing the four metrics evaluated in this experiment. When a protocol is designed scalability should always be considered as it is an imperative feature for WMNs. A good protocol is one that scales well and adapting to the changes in the network topology with regard to sizes. Thus scalability means that as the size of the network increases or growing bigger the protocol performs well. In order for the protocol to be regarded as good, it has to perform good even whenever there is an increase in the workload.

To be able to trace how the protocol varies, it is therefore, imperative to consider the amount of nodes in the network. There are two indispensable ways of varying the number of nodes in a network. The first one is by showing a discrepancy of the field size, which can be accomplished by keeping node density constant. The second one is to increase the density and then keep the field size constant. The increase in the density of the node decreases the quadratic consumption of the energy. When nodes in the network are broadcasting the RREQ messages, the recipient of those messages would be closer allowing each node to transmit with a less amount of energy compared to when the nodes are far apart and as a result the amount of energy consumed is reduced.

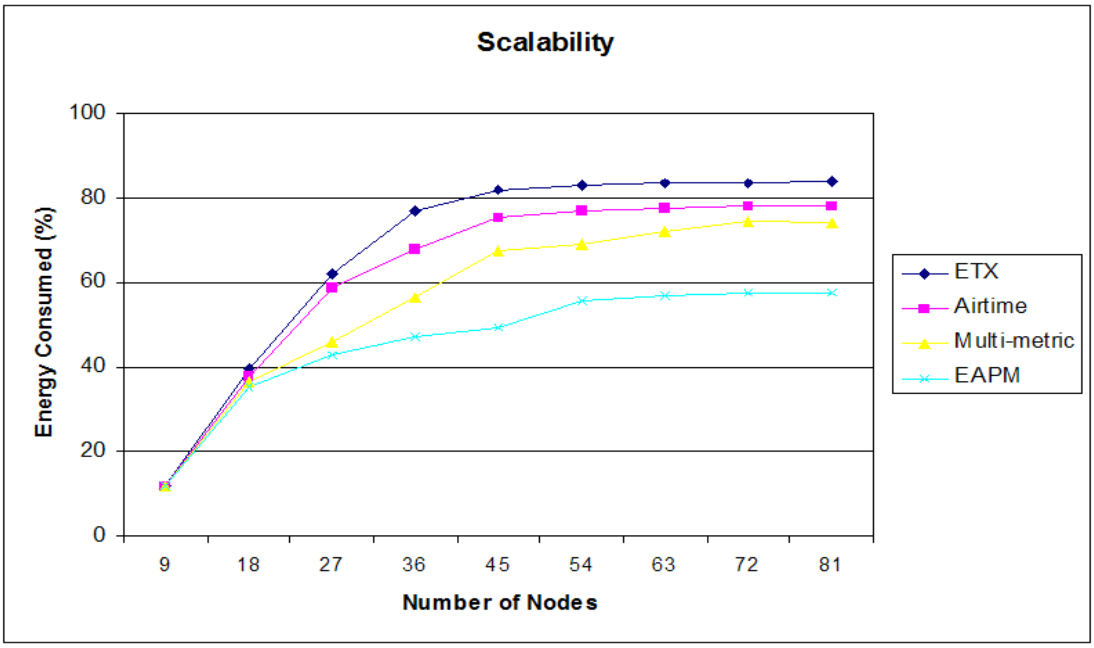

Figure 5. 14 Performance comparisons of the proposed EAPM and three metrics with regard to scalability in a network of 80 nodes.

The EAPM metric proves to be more scalable compared to the other metrics even in bigger networks, taking into account that the intermediate nodes is responsible for the message as decisions are based on the locally gathered information. In the area of 20 nodes the EAPM based network stabilises up to when the nodes are 81. The energy consumption rate for the networks based on the four metrics starts increasing exponentially from the area of 0 to 18 nodes but Airtime and ETX starts stabilizing from the area of 0 to 27 nodes and 0 to 36 nodes respectively. It can be observed that even though the network based on ETX starts stabilizing a bit earlier than the Airtime link metric, ETX still consumes more energy compared to the rest of the metrics. The basis of this is the fact that ETX does not consider issues of network interference. However, as soon as the number of nodes is increased, the energy consumed stabilises as shown by all the networks. Figure 5.13, has proven that EAPM is more scalable than the other metrics.

CHAPTER SIX

Conclusion and Future Work

6.1 Overview

This dissertation has presented an analysis of prior work on the field of energy-aware and optimising routing algorithms for wireless multi hop networks. This was motivated by the ambition to connect more or less than 450 million rural Africans that have no access to broadband ICT infrastructure and services. The research conducted by the CSIR Meraka Institute in (Ntlatlapa, 2007) reveals that energy efficiency in wireless mesh networks (WMNs) is the best possible solution to the problem of digital divide in Africa. WMN is regarded as the best possible wireless solution to the problem of digital divide especially in Africa and to the next generation wireless networking.

To optimise energy, an energy-aware and optimising path selection algorithm was adopted from sensor networks and applied in wireless mesh Network (WMNs) and a simulation was conducted to determine the optimal path. The energy optimising algorithm was designed and implemented together with the energy-aware path selection metric (EAPM). A performance evaluation of the EAPM was subsequently undertaken by comparing its lifetime against that achieved by a network not considering the EAPM. The energy optimising algorithm is comprised of the following components: 1) the three protocol phases, 2) maximising the network lifetime and 3) the flow argument routing.

A key feature of the algorithm is the use of the EAPM which helps to maximise the network lifetime. The EAPM's main responsibility is to evaluate the links in terms of energy usage from one node to the neighbour node (intermediate node). Once the cost every link is known, the path cost is, therefore, determined by summing up the link costs. Four parameters were considered when calculating the link cost metric. The parameters are: 1) transmission energy, 2) initial energy, 3) residual energy, and 4) non-negative weighting factors. The main objective was to let nodes be able to maximise their minimum lifetime, where a good candidate path is able to avoid little residual energy and thereby argument the path that consumes less energy.

Before any transmission could begin, assuming every node has more than enough energy, it is said to be better to choose the path that has a minimum total consumed energy, whereas avoiding nodes with small residual energy towards the end was also considered vital. The emphasis was, therefore, on the energy expenditure term when there is plenty of energy in the nodes and there should be more emphasis as the residual energy becomes smaller. To achieve the goal of this research work, the following objectives were set: First, to identify and investigate existing energy aware and efficient routing metrics, algorithms and protocols in wireless ad hoc networks. Secondly, to develop an energy-aware and optimising path selection algorithm that maximises the network lifetime. The third one is to evaluate the performance of the proposed algorithm through a simulation.

The successful simulation of EAPM in order to evaluate its performance culminated in the achievement of the third objective of the research. This performance was compared to the performance of a network wherein EAPM was not employed. The simulation results showed that EAPM improved in terms of the energy efficiency and the network lifetime, packet delivery ratio, end-to-end delay, the energy efficiency, scalability. To the best of our knowledge the issue of energy optimising routing algorithms for WMNs have never been investigated addressed in the past.

6.2 Limitations and Future Enhancements

In this section we outline some weaknesses of our research and indicate the future focus of this work. Some of the concerns given in this section are not directly related to our problem statement or research questions, but their importance to wireless mesh routing cannot be ignored. Although introducing energy-aware and optimising routing algorithms in WMNs will enhance the capabilities of wireless mesh networks. Problems such as quality of service (QoS) still need to be completely worked out.

The memory and processing requirements of our solution is another important issue needing further investigation. For successful application of EAPM in the pervasive environment, the metric together with the protocol must be lightweight enough to be deployed in handheld and other capacity-constrained devices. In order to come up with realistic results, real life experiments still need to be conducted. Ideally a real life test-bed should be used to experiment with the ideas reported in this research as future work. A fairly large number of participating nodes are required to obtain any meaningful results for scenarios such as network merging. Therefore, in this work we used simulations only to test the performance of our solution. A test-bed implementation using the MERAKA test-bed should be conducted. In the future, we plan to do a cross-layer routing (layer-2 and layer-3). We also plan to consider doing some experiments on routing with cognitive radio networks.

REFERENCES

Akkaya, K. and Younis, M. "A survey on routing protocols for wireless sensor networks" Ad Hoc Networks Volume 3, Issue 3, May 2005, Pages 325-349

Aoki, H. "802.11 TGs Simple Efficient Extensible Mesh (SEE-Mesh) Proposal. IEEE P802.11 Wireless LANs, Document IEEE 802.11-05/0562r0", June 2005.

Aron, F.O. Olwal, T.O. Kurien, A. and Odhiambo, M.O. "A Distributed Topology Control Algorithm to Conserve Energy in Heterogeneous Wireless Mesh Networks" PWASET VOLUME 30 JULY 2008 ISSN 1307

Bahr, M. Proposed routing for IEEE 802.11s WLAN Mesh Networks, The 2nd Annual International Wireless Internet Conference, Boston, MA, USA, August 2006.

Banerjee, S. and Misra, A. "Energy Efficient Reliable Communication for Multi-Hop Wireless Networks," ACM Baltzer Wireless Networks (WINET), 2001.

Belair Networks, http://www.belairnetworks.com.

Cao M, Ma W, Zhang Q, Wang X. "Analysis of IEEE802.16 Mesh Mode Scheduler Performance". IEEE Trans. Wireless Communication, 6(4): pp. 1455-1464, 2007.

Chang, J.-H. and Tassiulas, L. "Energy conserving routing in wireless ad-hoc networks", in Proc. IEEE INFOCOM'00, 2000, pp. 22–31.

Chang, J-H. and Tassiulas, L. "Maximum lifetime routing in wireless sensor networks", IEEE / ACM Trans. Networking 12, 2004, no. 4, 609-619.

Challen, G.W. Waterman, J. and Poster, M.W. "Abstract: Integrated Distributed Energy-Awareness for Wireless Sensor Networks" 2009.

Chakeres, I.D. and Perkins, C.E. "Dynamic MANET On-demand Routing Protocol". IETF

Internet Draft, draft-ietf-manet-dymo-12.txt, February 2008. (Work in Progress). html

Chen, B., Jameson, K., Balakrishnan, H., and Morris, R., "SPAN: An energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks", ACM Wireless Journal 8, (5), pp. 481 – 494, 2002.

Chiasserini, C.-F. and Rao, R.R. "Routing protocols to maximize battery efficiency", in Proc. IEEE MILCOM, 2000, pp. 496 – 500.

Conner, W.S. IEEE 802.11 TGS Usage Models, IEEE P802.11 Wireless LANs, Document IEEE 802.11 – 04/0054r2, Jan. 2004.

Clausen, T. Jacquet, P. Laouiti, A. Minet, P. Muhlethaler, P. Qayyum, A. and Viennot, L. "Optimized Link State Routing Protocol," Internet Engineering Task Force (IETF) draft,March, 2002. Available at http://www.ietf.org/internet-drafts/draft-ietfmanet-olsr-06.txt.

Draves, R. Padhye, J. and Zill, B. "Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks," in ACM Mobocom, 2004.

Draves, R. Padhye, J. and Zill, B. "Comparisons of routing metrics for static multi-hop wireless networks". ACM Annual Conference of the Special Interest Group on Data Communication (SIGCOMM), Portland, pp. 133-144. Aug. 2004.

Doshi, S. Bhandare, S. and Brown, T.X. "An on-demand minimum energy routing protocol for a wireless ad hoc network", ACM SIGMOBILE Mobile Computing and Communications Review, vol. 6, no. 3, 2002, pp. 50–66.

Erkip, E. Liu, X. Wang, Y. and Goodman, D. " System-Level Power Optimization for Wireless Multimedia Communication Power Aware Computing " SpringerLink, 2007.

Garroppo, R.G. Giordano, S. Lacono, D. and Tavanti, L. "On the development of a IEEE 802.11s mesh point prototype" in Proceedings of the 4th International Conference on Testbeds and research infrastructures for the development of networks & communities, Innsbruck, Austria, 2008.

Girling, G. Wa, J.L.K. Osborn, P. "The Design and Implementation of a Low Power Ad Hoc" Protocol Stack, Proceedings of IEEE Wireless Communications and Networking Conference, 2000.

Gomez, J. Campbell, A.T. Naghshineh, M. and Bisdikian, C. "PARO: Conserving transmission power in wireless ad hoc networks," in Proc. IEEE ICNP'01, 2001, pp. 24–34.

Hee, S. and Ko, Y. "An Efficient Multi-hop ARP Scheme for Wireless LAN based Mesh Networks". First Workshop on Operator-Assisted (Wireless Mesh) Community Networks (OpComm), Sep. 2006.

Johnson, D. Maltz, D.A. and Broch, J. "The dynamic source routing protocol for mobile ad hoc networks (Internet-draft)", in: Mobile Adhoc Network (MANET) Working Group, IETF, 1998.

Johnson, D.L. and Lysko, A. "Comparison of MANET Routing Protocols Using a Scaled Indoor Wireless Grid ," Mobile Networks and Applications, 2008.

Kalantari, M. Shayman, M. "Routing in multi-commodity sensor networks based on partial differential equations", in: Proceedings of the Conference on Information Sciences and Systems, Princeton University, NJ, March 2006.

Kemal Akkaya *, Mohamed Younis A survey on routing protocols for wireless sensor networks Department of Computer Science and Electrical Engineering, University of Maryland, Baltimore County, Baltimore, MD 21250, USA Received 4 February 2003.

Khanna, VK. Gupta, HM. Maheshwari, S. "A high throughput and low power ad-hoc wireless LAN protocol" Wireless Networks, 2008 – Springer

Kim, D. Aceves, G.–L. Obraczka, K. Cano, J-C. and Manzoni, P. "Power-aware routing based on the energy drain rate for mobile ad hoc networks", in Proc. 14th ICCCN, 2002, pp. 565 – 569

Kim, B.C. Lee, J.Y. Lee, H.S. and Ma, J.S. "An ad-hoc routing with minimum contention time and load balancing", in Proc. IEEE GLOBECOM, 2003, pp. 81 – 85.

Kyasanur, P. and Vaidya, N. "Multi-Channel Wireless Networks: Capacity and Protocols". Tech. Rep., University of Illinois at Urbana- Champaign, 2005.

Lee, S.-J. and Gerla, M. "Dynamic Load-Aware Routing in Ad hoc Networks", in IEEE ICC, 2001.

Lin, T. "Mobile Ad-hoc Network Routing Protocols: Methodologies and Applications," unpublished doctoral dissertation, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, March 2004.

Li, Q. Aslam, J. and Rus, D. "Online Power-aware Routing in Wireless Ad-hoc Networks". Proceedings of Int'l Conf. on Mobile Computing and Networking (MobiCom'2001) 2001.

Li, L. and Zuo, M. "A Dynamic Adaptive Routing Protocol for Heterogeneous Wireless Sensor Network", Networks Security, Wireless Communications and Trusted Computing, 2009. NSWCTC '09.

Ma, C. and Yang, Y. "Battery-aware routing in wireless ad hoc networks – part I: energy model", in Proc. 19th ITC-19, 2005, pp. 293 – 302.

Mhlanga, M.M. Nyandeni, T.C. Olwal, T. Ntlatlapa, N. and Adigun, M.O. "http://www.satnac.org.za/proceedings/2009/papers/progress-oral/Paper%20135.pdf"

Mhlanga, M.M. Olwal, T. Mutanga, M.B and Adigun, M.O. "Energy Optimization based Path Selection Algorithm for IEEE 802.11s Wireless Mesh Networks" to be presented at the IEEE AFRICON, Livingstone, Zambia, September 2011.

Misra, A. and Banerjee, S. "MRPC: Maximizing network lifetime for reliable routing in wireless environments", in Proc. IEEE WCNC, 2002, pp. 800 – 806.

Motorola Wireless Broadband Mesh Networks, available at: http://www.motorola.com/mesh.

Mudali, P. Nyandeni, T.C. Ntlatlapa, N. and Adigun, M.O. "Design and Implementation of a Topology Control Scheme for Wireless Mesh Networks" AFRICON, 2009.

Mukhija, A and Bose, R. "Reactive Routing Protocol for Mobile Ad-hoc Networks", Masters Thesis, IIT Delhi, 2001. http://www.ifi.unizh.ch/~mukhija/masters.pdf.

Narayanaswamy, S. Kawadia, V. Sreenivas, R.S. and Kumar, P.R. "Power control in ad-hoc networks: Theory, architecture, algorithm Power control in ad-hoc networks: Theory, architecture, algorithm and implementation of the COMPOW protocol", in Proc. European Wireless Conference, 2002, pp. 156–162.

Ntlatlapa, N. "Energy-Efficient Wireless Mesh Networks". Wireless World Research Forum, 2007.

Ogier, R.G. Lewis, M.G. Templin, F.L. and Bellur, B. "Topology Broadcast Based on

Reverse-Path Forwarding (TBRPF)," INTERNET-DRAFT, MANET Working Group, March. 2002.

Okada, H. Mase, K. Nozaki, M. and Zhang, B. "A Low-Overhead Handling Scheme of STA Association Information for IEEE 802.11s". IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Sept. 2007.

Pei, G. Gerla, M. and Chen, T.-W. "Fisheye State Routing: A Routing Scheme for Ad Hoc Wireless Networks". Proceedings of IEEE Int'l Conf. on Communications (ICC) 2000; 70-74.

Perkins, C. and Bhagwat, P. Highly Dynamic Destination-Sequenced Distance-Vector Routing(DSDV) for Mobile Computers. Computer Communications Review 1994; 234-244.

Perkins, C.E. Belding-Royer, E.M. Das, S.R. "Ad hoc On-Demand Vector (AODV) Routing". IETF Experimental RFC 3561, July 2003.

Ramanthan, R. and Hain, R. "Topology control of multihop wireless networks using transmit power adjustment," in: Proc. IEEE INFOCOM vol. 2 (2000) pp. 404–413.

Rudolph, V. and Meng, T.H. "Minimum energy mobile wireless networks", IEEE J. Sel. Areas Comm., vol. 17, no. 8, 1999, pp. 1333–1344.

Rudolph, V. and Meng, T. "Minimum energy mobile wireless networks", Proc. IEEE Int'l Conf. on Communications, 1998, pp. 1633-1639.

Rudolph, V. and Meng, T.H. "Minimum energy mobile wireless networks" IEEE Journal of Selected Areas in Communications 17(8), 1999, pp. 1333- 1344.

Schiller, J. "Mobile Communications", MA: Addison-Wisley, 2000.

Srinivas, A. and Modiiano, E. "Minimum energy disjoint path routing in wireless ad-hoc networks”, Proc. 9th Ann. ACM / IEEE Inter. Conf. on Mobile Computing and Networking, 2003, pp. 122-133.

Shah, R. and Rabaey, J. "Energy Aware Routing for Low Energy Ad Hoc Sensor Networks", in the Orlando, FL, March 2002.

Shen, Q. and Fan, X. “A Multi-metric AODV Routing in IEEE 802.11s”, International Conference on Communication Technology (ICCT), Nov. 2006.

Shyy, D. “Military Usage Scenario and IEEE 802.11s Mesh Networking Standard”. Military Communications Conference (MILCOM). Oct. 2006.

Singh, S. Woo, M. and Raghavendra, C.S. “Power-aware routing in mobile ad hoc networks,” in Proceedings of Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking, Dallas, TX, Oct. 1998, pp. 181–190.

Stojmenovic, I. and Lin, X. “Power-Aware Localized Routing in Wireless Networks”. IEEE Trans. Parallel and Distributed Systems 2001; 12(11):1122-1133.

Subramanian, Nalin V. “Energy-Aware Routing and Routing Protocols for Sensor”. Technical Report, Computer Science, University of North Carolina, Charlotte, 2004.

Toh, C.–K. Cobb, H. and Scott, D. A. “Performance evaluation of battery-life-aware routing schemes for wireless ad hoc networks”, in Proc. IEEE ICC 2001, pp. 2824 – 2829.

Toh, C.–K. “Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks”, IEEE Comm. Mag., June 2001, vol.39, issue6, pp. 138 – 147.

Tønnesen, A. “Implementing and extending the optimized link state routing protocol”. Master's thesis. University of Oslo, Norway, 2004.

Usop, N.S.M. Abdullah, A. and Abidin, AFA. “Performance Evaluation of AODV, DSDV &

DSR Routing Protocol in Grid Environment" IJCSNS International Journal of Computer Science and Network Security, VOL.9 No.7, July 2009.

Vassileva, N. and Barcelo-Arroyo, F. "A Survey of Routing Protocols for Energy Constrained Ad Hoc Wireless Networks", in IEEE Future Generation Communication and Networking, Dec. 2007, pp. 522-527.

Vimal K. Khanna, Hari M. Gupta, Satyavardhan Maheshwari, "A high throughput and low power ad-hoc wireless LAN protocol" Kluwer Academic Publishers Hingham, MA, USA,. 2008.

Watterhofer, R. Li, L. Bahl, P. and Wang, Y.M. "Distributed Topology Control for Power Efficient Operation in Multihop Wireless Ad Hoc Networks" Proceedings of the Conference on Computer Communications (IEEE Infocom 2001) 2001.

Woesner, H. Ebert, J.P. Schlaeger, M. Wolisz, A. "Powersaving mechanisms in emerging standards for wireless LANs": the MAC-Level perspective, IEEE Personal Communications (Special Edition on Power Saving) 5 (3), 1998, pp. 40 - 48.

Woo, K. Yu, C. Lee, D. Youn, H. and Lee, B. "Nonblocking, localized routing algorithm for balanced energy consumption in mobile ad hoc networks", in Proc. ACM/IEEE MSCOTS, 2001, pp.117 – 124.

Xie, F. Du, L. Bai, Y. and Chen, L. "Energy Aware Reliable Routing Protocol for Mobile Ad Hoc Networks" Wireless Communications and Networking Conference, 2007.WCNC 2007. IEEE

Xue, Y. and Li, B. A Location-aided power-aware routing protocol in mobile ad hoc networks, in Proc. IEEE Globecom'01, 2001, pp. 2837–2841.

Yu, C. Lee, B. and Youn, H. "Energy efficient routing protocols for mobile ad hoc networks"; Wireless pp. 959–973, 2003.

Zhang, B. and Mouftah, H.T. "Adaptive energy-aware routing protocols for wireless ad hoc networks", in Proceedings of the First International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks (QShine), 2004, pp. 252–259.

Zhang, B and Mouftah, H.T. "Energy-aware on-demand routing protocols for wireless ad hoc networks", Wireless Netw, pp. 481-494, 2006.

Zhao, Z. Zhang, X. Sun, P. Liu, P. "A Transmission Power Control MAC Protocol for Wireless Sensor Networks", Networking, 2007. ICN '07. Sixth International Conference

Zhou, A. and Hassanein, H. "Load-Balanced Wireless Ad Hoc Routing", Electrical and Computer Engineering Conference 2001, Vol.2, pp.1157-1161, May 2001.

11-05/0563, "802.11 TGs Simple Efficient Extensible Mesh (SEE-Mesh) Proposal" 2005.

APPENDIX : Energy-Aware Path Selection Metric (EAPM)

```
HWMPEA::recvPREQ (Packet *p)
{
		struct hdr_hwmpea_preq		*preq
		= HDR_HWMPEA_PREQ(p);
		struct hdr_cmn			*ch
		= HDR_CMN(p);
		hwmpea_rt_entry			*rtback,
*rtforw, *rtnext;

   double initialEnergy = energyModel_->initialenergy();
   double residualEnergy = energyModel_->energy();
   double energyRatio = initialEnergy / maxEnergy_;
   double energyChange = (initialEnergy - residualEnergy) /
initialEnergy;
   double energyaware = energyRatio;
		if (residualEnergy < initialEnergy) {
		   energyaware = energyRatio * energyChange;
		}

		if(preq->preq_src == index_)
		{
				// Needed to avoid "path to me is
throw perlink"
				Packet::free(p);
				return;
		}
		rtback = rtable.rtable_lookup(preq->preq_src);
		if(rtback == NULL)
				rtback = rtable.rtable_add(preq-
>preq_src);
		preq->preq_hop_count++;
   preq->preq_energyaware += energyaware;
// Acceptance criteria

HDPRINTF("started! dst = %d, E = %2.8f, X = %2.8f, IR =
%2.8f, CR =
%2.8f, EA = %2.8f, metric = %2.8f, %d",
						preq->preq_dst[0],
						initialEnergy,
						maxEnergy_,
						energyRatio,
						energyChange,
						energyaware,
						preq->preq_energyaware,
						preq->preq_hop_count);
   if((preq->preq_src_seqno < rtback->rt_dst_seqno) ||
((preq->preq_src_seqno == rtback->rt_dst_seqno) && (preq-
>preq_energyaware > rtback->rt_energyaware)))
		{
		   HDPRINTF("Dropping PREQ to %u. BS %u
CS %d or BM %2.16f CM %2.16f",
							preq-
>preq_dst[0],
							preq-
>preq_src_seqno,
					rtback->rt_dst_seqno,
					preq->preq_energyaware,
					rtback->rt_energyaware);
				Packet::free(p);
				return;
		}
		// Effect of receipt:
		rtnext = rtable.rtable_lookup(ch->prev_hop_);
		if(rtnext == NULL)
				rtnext = rtable.rtable_add(ch-
>prev_hop_);
```

```
		if(preq->preq_flags & PREQ_F_PROACTIVE)
		{

HDPRINTF("Received proactive PREQ; current mode is %s,
preq_src = %d, root_node = %d\n",
							(mode ==
PROACTIVE)?"PROACTIVE":"REACTIVE",
							preq-
>preq_src,
							root_node);
				if((mode == PROACTIVE) &&
(preq->preq_src != root_node))
				{
						Packet::free(p);
						return;
				}
				mode = PROACTIVE;
				root_node = preq->preq_src;
				HDPRINTF("Proactive mode started!,
metric = %2.4f, %d",
							preq-
>preq_energyaware,
							preq-
>preq_hop_count);

				// 1. update route to root
				rt_update(
							rtback,
							preq-
>preq_src_seqno,
							preq->preq_id,
							preq-
>preq_hop_count,
							preq-
>preq_energyaware,
							preq-
>preq_lifetime,
							ch-
>prev_hop_,

		MAC_BROADCAST,

		IS_TO_ROOT);
				// Update reactive route to my
neighbor
				rt_update(
		rtnext,
							preq-
>preq_src_seqno,
							preq->preq_id,
		1,
							energyaware,
							preq-
>preq_lifetime,
							ch-
>prev_hop_,

		MAC_BROADCAST,

		NOT_TO_ROOT);
				// send PREP back to root
				HDPRINTF("Proactive PREP
initiate!, metric = %2.4f, %d",
							preq-
>preq_energyaware,
							preq-
```

```
>preq_hop_count);
                                    Packet *buf_pkt;
                                    while((buf_pkt =
rqueue.deque()))
                                         forward(rtback,
buf_pkt);
#ifdef MYTRACE
                        printf("%d: %d->%d\n", preq-
>preq_id, index_, ch->prev_hop_);
#endif
                        seqno ++;
                        if(seqno < preq->preq_src_seqno)
                                    seqno = preq-
>preq_src_seqno;

                        sendPREP(
                                    preq->preq_src,
                                    preq->preq_src_seqno,
                                    index_,
                                    seqno,
                                    0,
                                    0,
                                    preq->preq_lifetime);
                        // 3. forward PREQ further
                        preq->preq_hop_count++;
                        ch->addr_type()         =
NS_AF_INET;
                        ch->ptype()             =
PT_HWMPEA;
                        ch->direction()         =
hdr_cmn::DOWN;
                        ch->prev_hop_ = index_;
                        ch->num_forwards()++;
#ifdef MYTRACE
                        printf("PREQ:index:%d\n", index_);
#endif
                        Scheduler::instance().schedule(target_,
p, 0.0);
                        return;
            }
            rtforw = rtable.rtable_lookup(preq->preq_dst[0]);
            if(rtforw != NULL)
            {
                        if(rtforw->rt_lifetime <
CURRENT_TIME)
                                    rtforw->rt_flags =
RTF_OLD;
            }
            else
            {
                        rtforw = rtable.rtable_add(preq-
>preq_dst[0]);
                        rtforw->rt_prev_hop = ch-
>prev_hop_;
                        rtforw->rt_flags = RTF_NOPREP;
            }
            rt_update(
                                    rtback,
                                    preq->preq_src_seqno,
                                    preq->preq_id,
                                    preq->preq_hop_count,
                                    preq->preq_energyaware,
                                    preq->preq_lifetime,
                                    ch->prev_hop_,
                                    rtforw->rt_next_hop,
//prev hop. If unknown - broadcast
```

```
                                    NOT_TO_ROOT);
            rt_update(
                                    rtnext,
                                    preq->preq_src_seqno,
                                    preq->preq_id,
                                    1,
        energyaware,
                                    preq->preq_lifetime,
                                    ch->prev_hop_,
                                    MAC_BROADCAST,
                                    NOT_TO_ROOT);
            Packet *buf_pkt;
            while((buf_pkt = rqueue.deque(rtback->rt_dst)))
                        forward(rtback, buf_pkt);
            if(((u_int32_t)(ch->last_hop_)) == index_) {
                        HDPRINTF("Delivered. PREP, metric
= %2.8f, %d",
                                                preq-
>preq_energyaware,
                                                preq-
>preq_hop_count);
                        seqno ++;
                        if(seqno < preq->preq_src_seqno)
                                    seqno = preq-
>preq_src_seqno;
                        sendPREP( preq->preq_src,
                                    preq->preq_src_seqno+1,
                                    index_,
                                    seqno,
                                    preq->preq_energyaware,
                                    preq->preq_hop_count,
                                    preq->preq_lifetime);
                        Packet::free(p);
                        return;
            }
if((rtforw->rt_flags == RTF_ACTUAL) && !(preq-
>preq_dst_flags[0] & PREQ_DO)) {
HDPRINTF("Delivered. Intermediate PREP to %d about %d,
metric = %2.4f, %d",
                                    preq->preq_src,
                                    preq->preq_dst[0],
                                    preq->preq_energyaware,
                                    preq->preq_hop_count);
                        seqno ++;
                        if(seqno < preq->preq_src_seqno)
                                    seqno = preq-
>preq_src_seqno;
                        sendPREP(     preq->preq_src,
                                                preq-
>preq_src_seqno,

                                                preq-
>preq_dst[0],
                                                rtforw-
>rt_dst_seqno,
                                                rtforw-
>rt_energyaware,
                                                rtforw-
>rt_hop_count,
                                                preq-
>preq_lifetime);
                        if(!(preq->preq_dst_flags[0] &
PREQ_RF)){
                                    Packet::free(p);
                                    return;
                        }
            }
```