UNIVERSITY OF THE WESTERN CAPE

Scalable Wireless Mesh Networks

By

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Declaration

I, Taha Abdalla, declare that this thesis "Scalable Wireless Mesh Networks" is my own work, that it has not been submitted before for any degree or assessment at any other university, and that all the sources I have used or quoted have been indicated and acknowledged by means of complete references.

Signed:

Date:

Abstract

Wireless Mesh Networks (WMNs) are wireless multi-hop networks built on wireless nodes that operate in an Independent Basic Set Identifier (IBSS) mode of the IEEE 208.11 wireless standard. IBSS is well known as an ad hoc mode which is found to build ad hoc wireless networks with the aid of routing protocols crafted to work in this mode. Ad hoc wireless mesh networks are always described as self-healing, self-configuring, easy to build, etc. However, these features do come at a cost because a WMN suffers performance degradation and scalability issues, which mainly come from the underlying IBSS mode that is used to form the physical network. Furthermore this is exacerbated by routing protocols in the upper layers which are intended to form a flat network architecture. Partitioning or clustering the flat network into smaller units has been proven to be a viable mechanism to counter the scalability problem in the communication network. The wired network for instance, presents a segmented, hierarchical architecture, where end user devices are organized in virtual local area networks (VLANs) using Ethernet switches and then Routers aggregate multiple VLANs. This thesis develops and evaluates a heterogeneous, clustering architecture to enhance WMN scalability and management. In the proposed architecture, the clustering is separated from the routing, where the clustering is done at the physical layer. At the routing level, each cluster is configured as a WMN using layer 2 routing for intra-cluster routing, and layer 3 routing for inter-domain routing between clusters. Prototypes for the proposed architecture have been built in a laboratory testbed. The proposed architecture reported better scalability and performance results compared to the traditional flat architecture.

Keywords

Wireless Mesh Networks, B.A.T.M.A.N-ADV , OLSR , BMX6 , White Space , Radio Mobile , Clustering , Scalability , Hierarchical Network.

Keywords

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Publication

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List of Abbreviations

Wi-Fi	**W**ireless **Fi**delity
AP	**A**ccess **P**oient
LAN	**L**ocal **A**rea **N**etwork
IETF	**I**nternet **E**ngineering **T**ask **F**orce
IEEE	**I**nstitute of **E**lectrical and **E**lectronic **E**ngineering
AODV	**A**d hoc **O**n-**D**emand **D**istance **V**ictor
OLSR	**O**ptimized **L**ink **S**tate **R**outing
B.A.T.M.A.N	**B**etter **A**pproach **T**o **M**obile **A**d hoc **N**etwork
MANET	**M**obile **A**d hoc **NE**twork
WMN	**W**ireless **M**esh **N**etwork
WSN	**W**ireless **S**ensor **N**etwork
HSR	**H**ierarchical **S**tate **R**outing
CBRP	**C**lustered **B**ased **R**outing **P**rotocol
OSPF	**O**pen **S**hortest **P**ath **F**irst
MPR	**M**ultiPoint **R**elay
OSPF	**O**pen **S**hortest **P**ath **F**irst
UWC	**U**niversity of the **W**estern **C**ape
CSMA/CA	**C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **A**voidance
OSI	**O**pen o **S**ystems **I**nterconnection
MAC	**M**edium **A**ccess **C**ontrol
HWMP	**H**ybrid **W**ireless **M**esh **P**rotocol
IP	**I**nternet **P**rotocol
TTL	**T**ime **T**o **L**ive
OGM	**O**ri**G**inator **M**essage
HNA	**H**ost **N**etwork **A**nnouncement
ARP	**A**ddress **R**esolusion **P**rotocol
BMX6	**B**at**M**an **e**Xperimental 6
MP	**M**esh **P**otato
FXS	**F**oreign **e**Xchange **S**tation
VOIP	**V**oice **O**ver **I**nternet **P**rotocol
SoC	**S**ystem **on** **C**hip
PBX	**P**rivate **B**ranch **eX**change
ISP	**I**nternet **S**ervices **P**rovider
ICASA	**I**ndependent **C**ommunications **A**uthority **S**outh **A**frica
BGP	**B**order **G**ateway **P**rotocol
ITU	**I**nternational **T**elecommunications **U**nion
TCP/IP	**T**ransmission **C**ontrol **P**rotocol **I**nternet **P**rotocol
QoS	**Q**uality **of** **S**ervice
ISM	**I**ndustrial **S**cientific **M**edical
Wireless	**R**egional **A**rea **N**etwork

WS	**W**hite **S**pace
RF	**R**adio **F**requency

1 Introduction

The number of wireless devices is rapidly increasing. Since 2013 there have been more mobile devices than people on the earth, 90% of the mobile devices are equipped with Wi-Fi. In addition it is been projected that by the year 2017 70% of carrier network traffic will be offloaded to Wi-Fi [1]. Wi-Fi speeds have been increasing also, from 54Mbps in 1999 , to 450Mbps in 2009 and to 1.3Gbps in 2012. This significant improvement in Wi-Fi based Wireless networks requires a revision to the way this massive number of devices are connected without compromising the network performance. Despite the advancement in Wi-Fi access in term of speed and supporting devices, the Wi-Fi based wireless deployment architecture remains the same. Wi-Fi based wireless networks can be deployed in four network setups or modes [2]:

A Infrastructure Basic Service Set: It relies on central station know as Access Point (AP) which acts as intermediate to connect two or more client stations. This is built as a single hop network that is ideal for a small scale network, such as an extension or access to a wired LAN Figure 1.1.

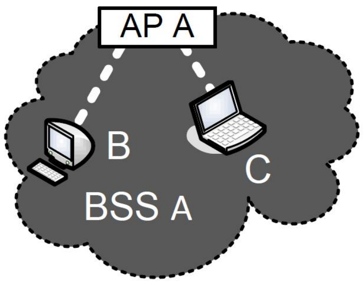

FIGURE 1.1: Infrastructure Basic Service Set Mode

B Extended Basic Service Set: In the extended mode, the APs are bridged together to form a distributed wireless system Figure 1.2. This mode allows multiple APs to be connected wirelessly; however the network throughput is badly affected.

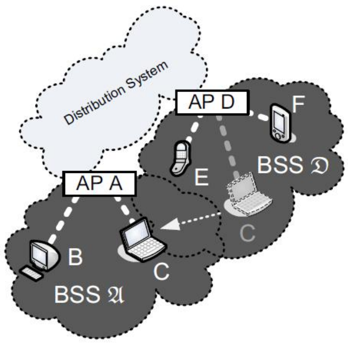

FIGURE 1.2: Wi-Fi Extended Service Set Mode

C Independent Basic Service Set (AD Hoc) mode: The Independent Basic Set mode provides peer-to-peer connection between two wireless devices without relying on an intermediate station. It provides MAC and physical feature to build a multihop wireless network, which leads to organising wireless device in MANETs and WMNs 1.3.

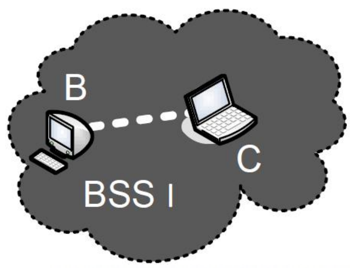

FIGURE 1.3: Independent Basic Service Set (AD Hoc) mode

D Mesh Basic Service Set(IEEE 802.11s): Recently, IEEE introduced 802.11s standard to build a native multihop wireless network using mesh basic service set (MBSS). The standard defines a mechanism to build Wireless Mesh Network [3].

1.1 Wireless Mesh Networks

IEEE Independent Mode (Ad Hoc) can provide a platform to connect multiple wireless devices without a central or base station, however this mode still needs a routing protocol to relay network traffic between wireless devices. This has encouraged the Internet Engineering Task Force (IETF) to persuade building routing protocols in order to form a multihop wireless network.

Many routing protocols such an Ad hoc On-Demand Distance Victor (AODV) [4] , Optimized Link State Routing protocol (OLSR) [5] , B.A.T.M.A.N [6] etc., have been crafted for this purpose with consideration to wireless link limitation and wireless mobility. The network has been termed a Mobile Ad Hoc Network (MANET).

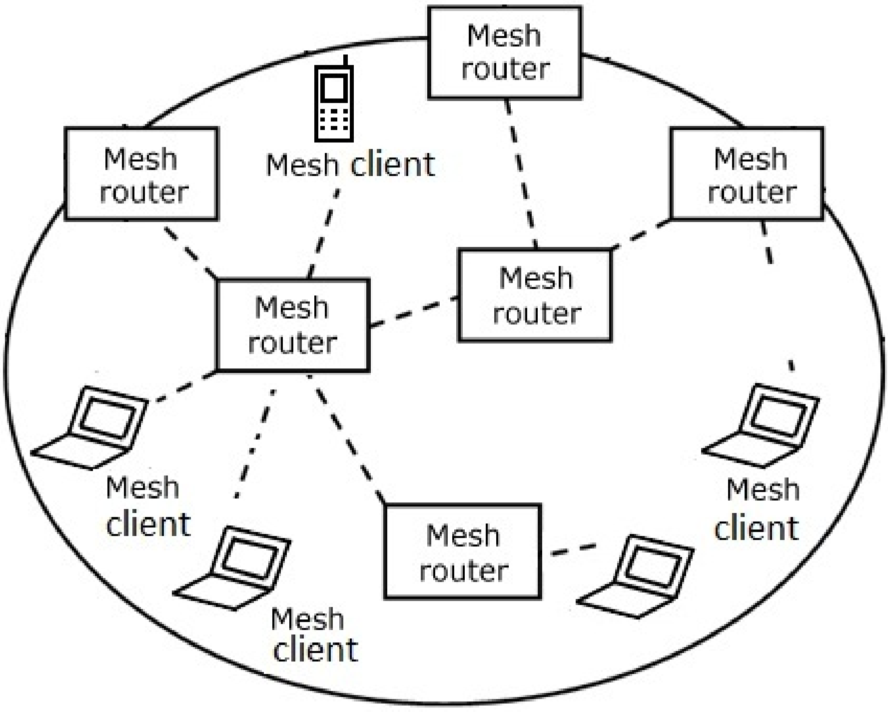

FIGURE 1.4: Wirels Mesh Network

The Wireless Mesh Network (WMN) is a type of MANET, it is built from the same Ad hoc mode using the same routing protocols, however, WMN refers to a stationary network with little or no mobility at the mesh routers level. Also wireless nodes in WMN can be categorised into two types: A) the mesh routers and B) the mesh clients. The mesh routers form the network backbone where a routing protocol is implemented to relay traffic. The mesh clients are the end-user devices attached to the backbone routers e.g. laptops, mobile phones, etc as shown in Figure 1.4. WMN is a promising network, it can provide an affordable network service when compared to a wired network. Without extending network cables can be used effectively to provide video surveillance, Internet broadband, rural community networks, etc. The 802.11s also defines protocols to build WMN, but ad hoc based WMN has existed for long time and gained more deployment. The focus in the thesis will be on Ad hoc based WMNs.

1.2 Scalability in WMNs

The network scalability is defined as the ability of the network to perform as the network grows. A network with poor scalability has a poor performance. Hence, a scalable network is a network that perform well even when it is loaded with more devices. There are multiple factors that affect the WMNs scalability. Srivathsan et al. [7] state that poor WMNs scalability is attributed to 1) the routing protocol overhead and 2) the deployment architecture.

1.2.1 Routing protocol overheads

Routing protocol overheads can be expressed as the amount of data generated by the control messages that are used by the routing protocol to maintain the routing table [8]. This is where each node in the network sends specific messages in a certain time interval to announce itself. Each routing protocol has its own mechanism for implementing these control messages. Link state routing protocols produce fewer control messages, in that, the node tends to send control messages to selected nodes. But, they require additional computation capacity in order to calculate the all possible paths. On the other hand, with distance vector routing protocols, the node has to send messages to all of its neighbouring nodes, therefore a massive number of control messages are generated. WMNs use routing protocols such as AODV , OLSR , B.A.T.M.A.N which are built to work in MANETs. Routing protocols in MANETs are built with consideration to the nodes mobility , network inconsistency and links instability , which are mostly broadcast based routing protocols exposed to more routing overheads.

1.2.2 The deployment architecture

The way in which WMNs are being deployed can also affect the WMN scalability. Wireless Mesh Networks can be deployed in either A) Flat or B) Hierarchical architecture. The flat network architecture is a network that has all its nodes at the same level. In such an architecture, the nodes share the same communication medium, where the same radio channel is used. At the network level the network router has to form a neighbour relationship with all other routers in the range, and the router maintains an individual route for each router in the network which adds more processing and routing overheads, even though it is very easy to build. In a hierarchical network architecture, the nodes are grouped (logically, geographically, etc.), and classified in multiple tiers. Each tier has different functions; the lowest tier (edges) may contain nodes to service the associated clients. The upper tier (backbone) consists of nodes that neither terminate nor originate data traffic, but route the traffic between the groups or the clusters instead.

1.3 Clustering Wireless Mesh Network

To enhance the scalability, many cluster based routing protocols have been introduced to reduce routing protocol overheads. Clustering routing protocols adapt algorithms that are intended to partition the MANET into clusters so that routing protocol overhead belonging to certain cluster will not pass to other clusters, but the cluster select cluster-head instead. Example of clustering based routing protocols for MANET such as Hierarchical State Routing (HSR) [7], Cluster Based Routing Protocol(CBRP) [9], etc for Ad hoc mesh network. However, clustered based routing protocols lack implementation capability. They are mostly only implemented in research simulation.

Optimized Link State Routing (OlSR) [5] is a routing protocol for wireless Ad hoc mesh networks. It is a link state protocol very similar to Open Shortest Path First (OSPF) [10] for a classical wired network. OSPF is a hierarchical routing protocol where the network can be divided into multiple areas, each area has predefined boundaries and is manually configured. OSPF also elects a designated router (DR) to coordinate disseminating the routing information in broadcast multi access networks. The other routers send the routing update to the DR which is the router with the highest ID. The algorithm that is used to elect the DR is very simple, after exchanging a few messages, the router determines which router should be the DR since every router is reconfigured with an ID which is the router's IP address. OLSR uses the same principle to minimize routing control massages in ad hoc and wireless mesh network. OLSR assumes that the network is unstructured and the network topology is changing frequently, so that OLSR has to introduce a very complicated algorithm to elect Multipoint Rely router MPR, see Chapter 2. The same applies to clustering based routing protocols, where such protocols adapt algorithms to organise the clustering and the path calculations as well.

1.4 Problem Statement

The presentation above highlights two different routings, one for classical wired network and another for MANET. However, WMN is neither a wired network nor a MANET, but it has characteristics of both network types. Its nodes are relatively fixed and used to deliver services traditionally provided by wired network while using routing protocols crafted for MANETs. Wired network is considered to be a stable network built from a combination of Ethernet and IP networks. Building a wired network requires well design and planning processes. On other hand, MANET is always described as self configured and self healing, where the routing protocols have to perform more functions than they would have to in wired networks, such as clustering, this situation leads to routing protocol in MANET and WMN to produce more routing protocol overheads. WMN emerged as a form of MANET two decades ago, when wireless communications was in an incubation stage, and restricted by speed limits in constrained devices. However, network equipment has evolved in terms of link speed and computational capacity. Todays' WMNs still use architecture and routing protocols designed for MANETs which makes WMNs vulnerable to scalability and usability problems.

1.5 Research aim

This thesis describes an attempt to build a modern, robust and scalable WMN to counter the scalability and usability challenges that WMN faces. We believe that the key to success for the WMN will be found by eliminating the ad hoc techniques found with in MANET and WMN. To achieve this purpose, the thesis proposes a WMN design built around the following principles:

1. Firstly, partition the network to form a clustered network to reduce the number of routes hence reducing the routing protocol overheads. We seek to separate the clustering from the routing, the clustering should be processed by routing. Instead of implementing the clustering by the routing protocols, we seek a solution to implement clustering at physical layer, by good planning and understanding the physical connectivity that builds up the network, rather than allowing the network to be self-configured and self-healing.

2. Secondly, a heterogeneous WMN: In an effort to eliminate issues associated WMN flat architecture, we look for a heterogeneous WMN network that considers multiple routing protocols in different layers.

1.6 Research question

The thesis aims to answer the following main research question: " How can a wireless mesh network be built in order to address its scalability?"

The main question can be braked down into three sub-questions:

- How should clustered, hierarchical WMNs be built in a way that can reduce routing protocol overheads and guarantee quality performance?
- Which wireless nodes would be the backbone nodes, and which ones be at the edge of in the physical layer of the clustered setup ?
- What routing protocols need to be used to build the network in the logical level?

1.7 Methodology

In order to answer the research questions, Zenzelini network which is a flat WMN built by University of the Western Cape (UWC) computer science department, is used as a case study. We seek to integrate the simulation tool and the experiments to answer the research question, the simulation to plan the network deployment and the experiments to validate the new design.

1.8 Thesis Outline

The rest of the thesis is organized as follows:

Chapter 2: Gives a background on the routing protocols that have been used to in the proposed architecture, and highlights related works.

Chapter 3: Provides an overview of the proposed design, it gives details on the design phases.

Chapter 4: Includes the experiments and performance evaluations of the proposed architectures.

Chapter 5: Reports on the results obtained from the experiment in Chapter 5

Chapter 6: Conclusion.

2 Background

2.1 Routing in WMNs

WMN is consisted from multiple wireless nodes that share the same wireless medium and utilise Carrier Sense Multiple Access with Collision Avoidance CSMA/CA in their operation. The routing operations such as path calculation and forwarding are extremely challenging and the traditional routing protocols are not feasible. Routing protocols in WMNs have to be designed with consideration of the point-to-multi-point nature of the WMNs. As a consequence, routing protocols have to be designed as broadcasting based routing protocols.

Routing protocols in WMNs can be classified as:

A Layer 3 routing protocols: Similar to the traditional routing protocols, layer 3 routing protocols work in layer 3 of the Open Systems Interconnection (OSI) model to build IP networks. To do this, WMNs routing protocols such as OLSR, Babel, advertise the IP network addresses of both the mesh routers and the mesh clients. Routing in layer 3 treats wireless clients associated with wireless routers as single networks; therefore it is not easy to track the status of individual nodes. As a consequence, mobility in WMNs routing in Layer 3 is not an easy task.

B Layer 2 routing protocols: Layer 2 routing protocols employ Medium Access Control (MAC) layer parameters of the OSI model to build the network topology. Hybrid Wireless Mesh Protocol (HWMP) [3] is protocol developed for IEEE 208.11s based WMNs, it operates entirely in layer 2. Routing in layer 2 pays attention to data link layer therefore it is capable of supporting node mobility. Firetide [11] , HWMP and B.A.T.M.N-ADV are example of layer 2 routing protocols.

2.1.1 OLSR

Optimized Link State Routing (OLSR) [5] is a proactive, link state IP routing protocol based on the Dijkstra algorithm for Mobile Ad-hoc Networks (MANETs). In proactive routing protocols, exchanging topology information and building the routing tables take place before packets have to be sent. On the other hand, reactive routing protocols build routing table upon route request. OLSR is a link state routing protocol, whereby routers maintain the whole path from source to destination, not only the exit point.

Multipoint Relays (MPRs) are the main feature in OLSR. In a WMN that is using OLSR, some routers are selected to receive and resend the routing messages. The selected routers are called Multipoint Relays (MPRs). MRPs minimize the flooding of a network by reducing redundant transmissions to the same nodes. MPRs are chosen to reach a node's two-hop neighbours via its MPRs. Therefore, this algorithm makes the broadcast flooding more efficient, as the flooding goes just through the MPRs and not through every node. The MPRs are the only nodes that rebroadcast flooding messages.

OLSR messages

OLSR [12] uses two types of messages, hello messages and topology control messages (TC). Hello messages are used for link sensing, neighbour detection and MPRs selection, while TC messages advertise the link status. Both type of message are delivered as UDP packets in port 689 in general format as illustrated in Figures 2.1 .

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Packet Length         |    Packet Sequence Number     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Message Type |     Vtime     |         Message Size          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Originator Address                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Time To Live |   Hop Count   |    Message Sequence Number    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
:                            MESSAGE                            :
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

FIGURE 2.1: OLSR General Packet Format

The general OLSR packet format Figure, 2.1 consists of:

A Packet Header: it contains,

- Packet Length field.
- Packet Sequence Number, the former is incremented by one each time the packet is generated.

B Message header: it contains

- Message Type: to indicate which type of message this packet is carrying.
- Vtime: to indicate the validity time of the message
- Message Size.
- Originator Address: the main address of the node that generated the message
- Time to Live.
- Hop count.
- Message sequence Number: the node assigns a unique identification number to each message. The number is incremented by one time each the node regenerates a message.
- Message: The general packet is extended to carry a hello message as in figure 2.2 and a TC message in figure 2.3


```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|          Reserved             |     Htime     |  Willingness  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Link Code   |   Reserved    |       Link Message Size       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Neighbor Interface Address                   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Neighbor Interface Address                   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

FIGURE 2.2: OLSR Hello Packet Format

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|              ANSN             |           Reserved            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|               Advertised Neighbor Main Address                |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|               Advertised Neighbor Main Address                |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

FIGURE 2.3: OLSR TC Packet Format

2.1.2 Better Approach To Mobile Ad-hoc network (B.A.T.M.A.N)

OLSR which was explained in the section above is still the most widely used routing protocol in WMNs. However, as a link state routing protocol, OLSR calculates a full routing path to all nodes in the network. This is a process that requires extensive computations by the processing unit.

B.A.T.M.A.N [6] is a proactive, distance vector routing protocol for wireless Ad-hoc mesh networks. As a distance vector routing protocol, B.A.T.M.A.N nodes learn only about the best next-hop for each destination. There is no need to find out or calculate the complete route, which makes a very fast and efficient implementation. Thereby wireless routers do not calculate and memorise the full path to destination. Which means the protocol is more lightweight than OLSR.

B.A.T.M.A.N also considers WMN links by adopting a statistical mechanism to evaluate WMNs link, where, the WMNs links are evaluated based on the frequency of packets arriving, the more packets received the better link quality. Therefore, B.A.T.M.A.N dynamically tracks the links status instead of relying on a provisionally learned metric that may not reflect the current link status precisely.

B.A.T.M.A.N messages

B.A.T.M.A.N nodes send IP/UDP packets that contain an Originator Message (OGM) and a Host Network Announcement (HNA). OGM is the main message used in B.A.T.M.A.N to announce the existence of the wireless node and the cost to reach it as well. HNA message is an optional message to announce the host network if it exists. These messages are delivered as UDP packets using port 4305.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    Version    |U|D|           |      TTL      |    GWFlags    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|        Sequence Number        |            GW Port            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Originator Address                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

FIGURE 2.4: B.A.T.M.A.N OGM packet format

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Network Address                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    Netmask    |
+-+-+-+-+-+-+-+-+
```

FIGURE 2.5: B.A.T.M.A.N HNA packet format

Figure 2.4 shows OGM packet fields which are:

- Version: For B.A.T.M.A.N version, nodes must be in the same B.A.T.M.A.N version.
- U : a flag to indicate whether the node is a direct neighbour or not.
- D: bidirectional or unidirectional link.
- Sequence number: The node that generates OGM incrementally numbers it.
- TTL (Time to Live): value used to define maximum number of hop OGM can transmit.
- GWflag (gateway flag): a flag can be used to announce a gateway for the internet.
- Originator Address: the IPv4 address of the interface that generated the OGM.

And Figure 2.5 HNA fields :

- Network Address: the IPv4 of the announced network.
- Network Mask: the network mask of the announced network.

Upon receiving OGMs, a B.A.T.M.A.N node maintains an originator list to function similar to the routing table in the traditional routing protocols. The originator list contents entry for each originator node that its OGM has been received. In case there are multiple OGMs originated or forwarded, the deciding factor is the sequence number.

For each originator, the following information must be maintained. Some of this this information is received through the OGMs and some is generated locally:

- Originator IPv4 Address: The IPv4 address of the originator node.
- Last Aware Time: a timestamp records the time when the OGM has been received.
- Bidirect link Sequence number: This to check whether the link is bidirectional link. The link is bidirectional when node successfully receives OGMs that it has broadcasted.
- Current Sequence Number: The latest sequence number that has been accepted from the given OGM.
- HNA list: All the announced networks of the originator with their IP-range and netmask.
- Neighbour Information List: For each direct neighbour, B.A.T.M.A.N node maintains:
  - Sliding window: For each In-Window Sequence Number it is remarked if an OGM with this Sequence Number has been received.
  - Packet Count: It is a counter to counts the number of sequence numbers recorded in the sliding window. It determines the link quality. Therefore it is used as a metric for the path to a neighbour node.
  - Last Valid Time: A timestamp records the time since the last OGM was received from a neighbour. It is declared dead if no OGM has received for during a certain interval.

- Last TTL value.

B.A.T.M.A.N was designed to be simple, it only relies on flooding OGMs. Where, a node periodically generate and broadcast OGMs within pre-configured interval time via all of its B.A.T.M.A.N interfaces. Any wireless node that is configured the same the sender node, can receive OGMs. Upon receiving such a packet, receiver nodes make a preliminary check and then decide whether to drop the packet or to rebroadcast. The packet will be dropped in following cases:

- The version number is different to the own internal version of the message.
- The sender or originator address belongs to one of the node's interfaces (generated from the same node).

Otherwise, the receiving node re-broadcasts the OGM so that nodes could not hear the OGM directly from the originator node would became aware of the existence of such node. The other will do the same until the entire the network is flooded with OGMs. While receiving OGMs, the B.A.T.M.A.N node starts ranking the originators nodes.

2.1.3 B.A.T.M.A.N-ADV

The previous section described B.A.T.M.A.N, it was developed in 2008 and an experimental RFC documenting B.A.T.M.A.N has been submitted. Another version of B.A.T.M.A.N named B.A.T.M.A.N-ADV (advanced) [13] has been introduced. It comes with major differences as the original B.A.T.M.A.N has been discontinued.

Even though, the distance vector B.A.T.M.A.N algorithm remains the same, B.A.T.M.A.N-ADV includes some differences. It operates in layer 2 of the OSI, is implemented as Linux Kernal module and has a larger numbers of messages types. The first B.A.T.M.A.N was implemented as a Linux daemon so that it is became known as B.A.T.M.A.N-D after B.A.T.M.A.N-ADV was released.

Table 2.1 shows the differences between B.A.T.M.A.N-D AND B.A.T.M.A.N-ADV.

TABLE 2.1: The difference between B.A.T.M.A.N-D and B.A.T.M.A.N-ADV

B.A.T.M.A.N-D	**B.A.T.M.A.N-ADV**
Operates in layer 3 by using UDP packets in port 4305	Encapsulating Ethernet frame using MAC addresses
Implemented in Linux user space	Implemented as Linux kernel module.
Uses only OGM message with optional HNA extension, for topology discovery and network announcement	Beside OGM B.A.T.M.A.N-ADV uses: OGMs, Internet control messages, unicast messages, fragmented unicast messages,

B.A.T.M.A.N-ADV node configuration

Traditionally, a WMN node constructed from an Ad-hoc interface to relay traffic destined to or from wireless clients. An AP interface which generates or terminates client traffic. Such a setup is well suited for IP networks where every interface is represented by a separate IP network. However, B.A.T.M.A.N-ADV operates entirely in layer 2 where every interface can only be represented by its MAC address.

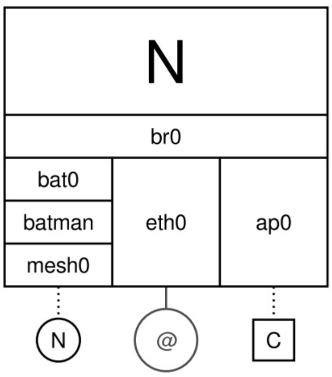

FIGURE 2.6: B.A.T.M.A.N-ADV node configuration

As a result, B.A.T.M.A.N-ADV is not only involved in forwarding the client data, it also encapsulates the data in such way it can suite this setup. For that B.A.T.M.A.N-ADV adds 32 bytes to each frame sourced from B.A.T.M.A.N-ADV. This procedure results in large frames that may exceed the MTU of the interface, therefore B.A.T.M.A.T-ADV sends fragmented frames.

B.A.T.M.A.N-ADV Challenges

B.A.T.M.A.N-ADV is a simple distance vector routing protocol that operates in Layer 2. It is best suited for small scale networks. However, it faces various challenges when used for network with large numbers of routers and clients:

- Address Resolution Protocol: A B.A.T.M.A.N-ADV network operates as a large layer 2 Ethernet network. In an Ethernet-like network, the client nodes have to broadcast ARP requests for looking up the IP address of a target node or client. ARP works effectively on a small scale network such as a wired Ethernet where the broadcasting is controlled by the Spanning Tree Protocol. However, in large broadcasting domain that is created by B.A.T.M.AN-ADV, traditional ARP is not suitable. ARP requests are flooded through the entire broadcasting domain which causes significant bandwidth consumption [14]. To perform the MAC address to IP address translation, B.A.T.M.A.N-ADV introduced Distributed ARP Table (DAT) [15]. In DAT, B.A.T.M.A.N-ADV nodes cache ARP replies locally to minimize the number of ARP packets . Since clients tend to change IP address more frequently, caching ARP reply is not always reliable and the DAT mechanism does not provide MAC to IPv6 translation.

- Security and privacy: Wireless community networks have adopted WMNs widely. It is a collaborative network where the users own and control their nodes only [16]. Using B.A.T.M.A.N-ADV as a routing protocol causes the users to disseminate the MAC addresses of their devices' across the entire network. The MAC address is a uniquely attributed to the client's device when such an address disseminated beyond the user's domain could lead to security and privacy issues, in that hackers can simply look at the B.A.T.M.A.N-ADV translation table to see the all clients connected to networks and their mobility.

- Implementation Challenges: Most of the routing protocols in WMN implementations are based on routing the users' traffic from APs interface through an Ad hoc used interface as an uplink interface. In the case of B.A.T.M.A.N-ADV, all the interfaces are in layer 2 domains. Therefore, an intermediate interface is needed to forward user traffic. Thus, a Bat0 virtual interface is brought to forward users' traffic. Additionally, B.A.T.M.A.N-ADV not only does routing of the traffic, it also inserts an additional 32 byte header for each user packet sent to the mesh. Therefore, the MTU needs to be increased. These processes could become a bottleneck that causes more delay hence limits the network performance.

- Scalability challenges: Routing protocol overheads are the main factor that determines the routing protocol scalability. They mostly depend on the routing algorithm that is used by the routing protocol. B.A.T.M.A.N-ADV uses the B.A.T.M.A.N algorithm originally designed to work with B.A.T.M.A.N-D, a layer 3 implementation of the protocol. Thereafter, the same algorithm was implemented in B.A.T.M.A.N-ADV in the layer 2 of the Internet protocol stack. In B.A.T.M.A.N-D the OGMs are sent as UDP packets on port 4305, while B.A.T.M.A.N-ADV OGMs are set as Ethernet frames. B.A.T.M.A.N-D advertises the network information as layer 3 IP network address, on the other hand, B.A.T.M.A.N-ADV announces the MAC addresses of the connected devices.

2.1.4 BatMan Xperimental version 6 BMX6

BatMan Xperimental version 6 (BMX6) [16] is a layer 3 routing protocol for WMNs. It emerged as an independent branch of BATMAN-D routing protocol, aimed at reducing the massive routing overheads generated in B.A.T.M.A.N-D. To reduce routing protocol overhead BMX6 uses different mechanisms: first, it optimises the traffic transmitted periodically through the network by means of establishing a common understanding between neighbours using compact IIDs and description hashes; secondly, it controls the flooding of messages by analysing whether a link is relevant or not, and omits non-relevant links on the flooding of OGMs.

To improve the efficiency and the scalability as well, BMX6 divides the network state throughout the time to 1) transient and 2) steady. The transient state neighbor nodes exchange information about their environment, such as node description, links etc. In the steady state, the neighbour nodes exchange small packets to monitor the status of the links and to track the variation of link metrics. Therefore, routing protocol overheads increase in the initial state of the network, and starts decreasing afterwards.

BMX6 messages

There are two type of message in BMX6: 1) periodic messages that are periodically generated by the protocol on every node; and (2) occasional messages, that are exchanged only when necessary because of a change in the network.

Periodic messages

Hello advertisement (HELLO_ADV) messages are broadcasted every HELLO_- INTERVAL, which by default is 0.5 seconds. They are used to measure the link quality (based on the number of received messages) and to know whether a link is alive or not. Similarly, report advertisement (RP_ADV) messages are periodically broadcasted as a response to the HELLO_ADV messages, and therefore at every HELLO_INTERVAL. They provide a summary of the received and lost hello messages from all neighbours and related links. OGM_ADVs or OriGinator Messages are sent every OGM_INTERVAL (which by default is 5 seconds) and propagated over the network. They are used to let nodes become aware of other nodes further than just one hop away and inform them about the path metric to the originating node. However OGM_ADVs are not flooded indiscriminately through the network, but just through so-called relevant links. A link is relevant whenever it is necessary to reach one of the nodes in the network, i.e. it is the next hop of at least one entry in the routing table.

Occasional messages

Link advertisement (LINK_ADV) and optional device advertisement (DEV_ADV) messages are broadcasted on demand (triggered by the reception of LINK_REQ or DEV_REQ messages) to describe the existence and further attributes of network devices and links from the perspective of an individual node. Each LINK_ADV message represents a link as perceived (due to previous received HELLO_ADVs) by the transmitting node to one of each of its neighbours. The order in which LINK_ADV messages are aggregated is further used as an implicit reference to a specific link of the node when creating or processing RP_ADVs messages. Description advertisement (DESC_ADV) messages are exchanged between nodes, providing a full description of a specific node, containing details such as their IP addresses, hostnames, and protocol parameters. Description messages are requested via DESC_REQs messages due to the receipt of an unknown description hash. A hash advertisement (HASH_ADV) message provides the relation of a node specific ID value to the hash of a specific node description that is used for globally non-ambiguous node identification. By means of description's hashes BMX6refers to already known nodes without having to send the full description of thenode. HASH_ADV messages are requested whenever an unknown IID referenceor a message from an unknown node is received.

2.2 Village Telco Network

The Village Telco project is an initiative to build Wireless Mesh Networks with facilities to provide cheap Telephone Communication. In order to provide cheap telephone communication open source free-of-charge toolkits have been incorporated.

2.2.1 Village Telco network infrastructure

The Mesh Potato (MP) device [17, 18] is the main component of the Village Telco network. It is a wireless router with a FXS (Foreign eXchange Station). The Wireless routers service as Wireless mesh node to relay the network packet. The FXS is used to connect an Analogue Telephone Adapter. Therefore, it is possible to make VOIP calls between Telephones connected to a network of MPs. To make a cheap VOIP calls, Mesh Potato router has to be affordable. Thus, a device with low specifications has been designed to reduce its price, it comes with these specifications:

- Atheros AR2317 system on a Chip (SoC)
- Silicon labs FXS port chipset
- MIPS 4k processor 180 MHz

- One 10/100Mbit LAN port
- 8 MByte Serial Flash EEPROM
- 16 MByte RAM

To make the MP function, an operating system is needed. OpenWRT operating system [19] is chosen. It is an open source operating system for embedded devices based on Linux kernel.

OpenWRT's main feature is its customizability; it is a generic operating system, but has the ability to be customized to suit certain needs. The Village Telco objective is to provide Telephone Telecommunications. Therefore, OpenWRT OS has been customized for this goal. As a result, Small Enterprise Campus Network (SECN) was built.

SECN is an operating system for MPs. It is has been re-factored with the necessary features and tools to build a network that can provide VOIP services, the main tools are:

- Better Approach to Mobile Ad hoc Networks Advanced (B.A.T.M.A.N-ADV). It is used to build the logical part of the network so that the VOIP and data can be exchanged.
- Asterisk: This is a software private branch exchange (PBX). It allows the telephone attached to the MPs to make calls to one another, and to have the capability to connect to PSTN and VOIP service providers.

FIGURE 2.7: Mesh Potato Router

2.2.2 Zenzelini Network

Zezeleni Network [20] is a licensed community based Internet Service Provider (ISP). It is located in Monkosi village in the Eastern Cape Province in South Africa. The network adopts Village network approach to provide affordable communication services. For these services, a WMN was built using MPs to provide affordable communication services to the local community.

The network delivers:

- Break out calls from the 12 public phones at half of the current price.
- Internal calls among public phones (free of charge).

2.3 Radio Mobile Software Simulation

Radio Mobile [21, 22] is a software used to simulate wireless networks. It can predict the feasibility of a radio link between two points if it is provided with information about the radio equipment and a digital map of the area because it uses the terrain of the area. Therefore it is very helpful in designing and planning the wireless networks. It indicates the signal strength throughout the link between two points. It also checks the line of sight. It can simulate most of the frequency bands used for the wireless network.

2.4 Related Work

A Wireless community network is a promising network for providing low cost, participatory communications services. In recent years many community networks have been built, such as FunkFeuer [23] in Germany, Athens Wireless Metropolitan Network [24] and Guifi.net[25] in Spain. This last network, accommodates around 17,000 nodes deployed in the Catalonia region of Spain. To successfully deploy such a massive number of nodes, the network is deployed in two tiers with heterogeneous protocols. It is built from a back-haul network, using point-to-point links with BGP and OSPF routing protocols, and shorter ranges which are mesh networks using OLSR and BMX6. In [26] the Guifi.net topology pattern. The study raised the consequence of the decentralizing and self-configuring which resulted in large routing.

In [22] the authors deployed a Wireless Sensor Network (WSN) guided by simulation results obtained by Radio Mobile simulation. The study showcases the viability of the integration between the simulation and the experiments in planning and deploying wireless network, specialty in the insincerity situation.

3 Wireless Mesh Network Design

3.1 Introduction

A wireless mesh design is a network engineering process which involves the movement of the network resources to where the traffic is expected to be offered to the network during its operation [27]. Such a network engineering process can be aimed at designing 1) a flat mesh network architecture configured for example as a tree or general graph topology or 2) a hierarchical mesh network architecture configured as a backbone or a cluster-based topology.

As a wireless mesh network (WMN), the current Zenzelini network is constrained by scalability issues which were mentioned in chapter 2. These challenges partially come from the limitations of the B.A.T.M.A.N-ADV routing protocol used for traffic-engineering the network and partially from the hardware limitations of the mesh potato devices that are used as mesh nodes in the network. In Flat networks topology, a single node has many neighboring relationships, which lead to excessive routing overheads, which are not necessarily beneficial. In the modern use of networks, the vast majority of the users' traffic is destined to the Internet and the servers are located at the edge to host application. There for it is not necessary for the mesh router to maintain routes to each and every other routers in the network. Topology control can restrict neighbouring relationships between WMNs routers. WMNs routers are considered neighbors if they are found in the radio transmission range of each other, and also form other neighbor relationships in the routing level. Any effective topology control technique should consider both topologies, in order to select the most efficient for the application carried by the mesh network. To this end, this chapter examines current Zenzelini network topology and proposes a new hierarchical design using a backbone-based topology to mitigate the scalability issues in the current network.

3.2 Link Budget Simulation

A network engineering process can be guided by different processes. These involve a link budget calculation to assess the feasibility of setting wireless links in different locations in the region of interest where the mesh network is to be deployed. Such feasibility assessment process can be guided by a simulation tool such as Radio Mobile [22] which can be used to advise on the feasibility of a wireless network topology.

Radio Mobile [21] simulation is based on the characteristics of the equipment to be used as network nodes and their geo-locations exploits the elevation maps of the terrain to explore any obstruction in the light-of-sight or Fresnel zone of any link between two nodes. It derives a mesh network for a given terrain where the network is implemented according to the radio propagation model (the Longley-rice) and the regulation applied by the country in terms of wireless communication.

3.3 Zenzeleni Flat Mesh Network Design

Table 3.1 and figure 3.1 reveal respectively the GPS coordinates and a visual localization of the nodes that form the current Zenzeleni network. Its current nodes are based on the mesh potato devices which specifications are detailed below

- Atheros AR2317 system on a Chip (SoC)
- Silicon labs FXS port chipset
- MIPS 4k processor 180 MHz
- One 10/100Mbit LAN port
- 8 MByte Serial Flash EEPROM
- 16 MByte RAM

Node number	Latitude	Longitude
1	31°55'35.16"S	29°10'48.40"E
2	31°55'8.26"S	29°10'44.06"E
3	31°54'36.84"S	29°10'14.09"E
4	31°53'54.62"S	29°10'48.26"E
5	31°53'59.22"S	29°11'19.00"E
6	31°54'24.74"S	29°11'30.36"E
7	31°56'19.32"S	29°11'51.05"E
8	31°56'24.19"S	29°12'48.07"E
9	31°56'24.96"S	29°12'50.46"E
10	31°56'18.62"S	29°12'25.52"E
11	31°55'54.02"S	29°12'19.01"E
12	31°55'43.19"S	29°12'10.69"E
13	31°92'93" S	29°18'31" E

TABLE 3.1: Zenzelini Network:The GPS coordinates

FIGURE 3.1: Zenzelini Network: A visual localization of the nodes

Building upon the GPS coordinates provided above and the mesh potato device specifications, Radio Mobile was used to simulate Radio Frequency (RF) propagation in the Zenzeleni area in order to assess the feasibility of three mesh networks in three different frequency bands: 1) Wi-Fi 5 GHz, 2) Wi-Fi 2.4

GHz and 3) the white space band. The following radio parameters have been used as input to the simulation software for the different networks.

- 5 GHz:
  - Minimum frequency = 5490 MHz
  - Central frequency = 5510 MHz
  - Maximum frequency = 5530 MHz
- 2.4 GHz:
  - Minimum frequency = 2401 MHz
  - Centeral frequency = 2412 MHz
  - Maximum frequency = 2423 MHz
- White Space:
  - Minimum frequency = 670 MHz
  - Central frequency = 682 MHz
  - Maximum frequency = 694 MHz
- Antenna
  - Antenna height = 6 metres (for all the nodes)
  - Antenna gain = 8 dBi
  - Antenna direction = Omnidirectional
- Other parameters
  - Transmit power (Tx power) = 20 dBm
  - Receiver threshold = -91 dBm
  - Line loss = 0
  - Polarization = Vertical
  - Mode of viability = broadcast

The derived network topology are depicted by Figures 3.2, 3.3 and 3.4.

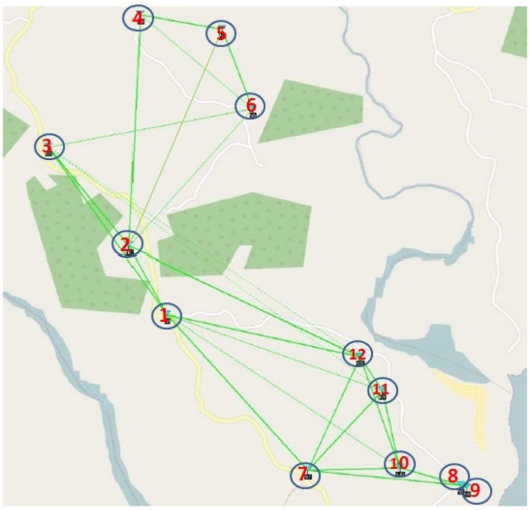

FIGURE 3.2: Zenzelini network: Connection between nodes in the 2.4GHZ frequency band

FIGURE 3.3: Zenzelini network: Connection between nodes in the 5GHZ frequency band

FIGURE 3.4: Zenzelini network: Connection between nodes in the White space frequency band

The network topology shown in figure 3.3 represents the current implementation of the Zenzeleni network. It can be noticed that while Radio Mobile revealed the non-feasibility of a connected mesh topology in the 5GHz band, a mesh network was feasible in the 2.4GHz band and the white space topology revealed a much more connected mesh network with higher node density. It also revealed that the 2.4GHZ and White space comprise 25 and 29 links receptively.

Note that at the moment of the writing of this thesis, the Independent Communications Authority of South Africa (ICASA), has started procedures to regulate the use of TV white space in broadband. Similar to processes conducted by the United States Federal Communications Commission (FCC), ICASA initiated a discussion on dynamic and opportunistic spectrum management [28]. In term of Wi-Fi 2.4GHz and 5GHz, South Africa follows the International Telecommunication Union (ITU) regulations, where 2.4GHz and 5Ghz are license-exempt with some exceptions [29].

3.4 Zenzeleni Hierarchical Network Design

The clustering is a technique to restructure the nodes into subset called clusters, where some nodes are structured to become cluster-heads with superior roles and the others are normal nodes. Hierarchical or clustered-based topology has been widely adopted in networks that comprise a large number of nodes, such as in Wireless Sensor Networks (WSNs) [30]. In

WSNs, the nodes are tiny devices which suffer from energy and transmission shortages and are unable to perform complex networking tasks. In the hierarchical or clustering topology, the network functions can be simplified by distributing the networks tasks and services through the hierarchy, for example some nodes only sense and collect data, while others route and forward the traffic, since the nodes are grouped in clusters. For this purpose, many clustering algorithms have been proposed, mainly to optimally choose which nodes could be cluster-heads and which ones will be normal nodes. Clustering is also applicable to WMNs, where the wireless nodes with relatively high capacity and general purpose operating systems act as routers. In this research, we apply a clustering solution borrowed from [31] to design the Zenzelni hierarchical network from both the 2.4GHZ and white space Frequency bands. The clustering algorithm applied for our design uses a naive approach based on building a connected graph to select a dominating set (cluster heads) of nodes which can be considered as a backbone for WMNs. It is a simple algorithm, using nodes colors, where black nodes belong to the dominating set (the backbone), grey nodes are the dominated nodes (the edge) and nodes that have not yet been processed are white as depicted listing 3.1. The algorithm takes a graph G = (V , E) of vertices V and edges E and produces a set of edges (T) that belong to the dominating set and the coloring of the nodes into black and grey colors.

LISTING 3.1: A Naive Clustering Algorithm [31]

```
initialize all nodes' color to white
pick an arbitrary node and color it grey
while ( there are white nodes ) {
    pick a grey node  v that has white neighbours
    color the grey node v  black
                foreach white neighbour u of v {
                    color u grey
                    add ( v , u ) to tree T
         }
 }
```

However, selecting node arbitrary may result in choosing a cluster head node which is not suitable as backbone node. Therefore, the connectivity of the nodes (node density) is considered as a criteria to choose nodes to be a part of the backbone. The amended algorithm is listed in 3.2.

LISTING 3.2: The Clustering Algorithm

```
initialize all nodes' color to white
pick node with highest connectivity  and color it grey
while  ( there are white nodes ) {
     pick a grey node  v that has most white neighbours
     colour the grey node v  black
     foreach white neighbour u of v {
             colour u grey
             add ( v , u ) to tree T
     }
}
```

3.4.1 The Backbone Selection

In this section, we apply the modified clustering algorithm on the network graphs which were rendered by radio mobile simulation for 2.4GHZ and white space Frequency bands. The clustering algorithm objective is to optimally map a flat network graph into a clustered network, by effectively selecting cluster heads (dominating nodes) and normal nodes (dominated nodes).

Wireless Mesh Network backbone design in 2.4 GHZ

Zenzelini network uses Mesh Potato devices which are equipped with IEEE 802.11b/g in the 2.4 GHz frequency band. Figure 3.2 shows the wireless links in 2.4 GHz frequency. The following processes were taken to select a reliable backbone.

FIGURE 3.5: Clustering 2.4GHZ: Round 1

Round 1

In the first round, Figure 3.5 , node 1 is selected, it is the node with the most number of neighbors (6 neighbors) and then highlighted with black color. Neighbor nodes (nodes 2,3,7,10,11 and 12) are assigned grey color as dominated nodes. The rest of the nodes are to be processed in the next round.

FIGURE 3.6: Clustering 2.4GHZ: Round 2

Round 2

Node 2 is added to the backbone set, because it has a direct link with the previously selected backbone node (node 1) and it has highest number of unprocessed neighbors (nodes 4, 5 and 6). The connected nodes are assigned grey color to become nodes dominated by node 2. Again, there are two unprocessed nodes left, another round is needed.

FIGURE 3.7: Clustering 2.4GHZ:Round 3

Round 3

Node 7 is selected and added to the backbone nodes set to service node, 8 and 9 as in Figure 3.7.

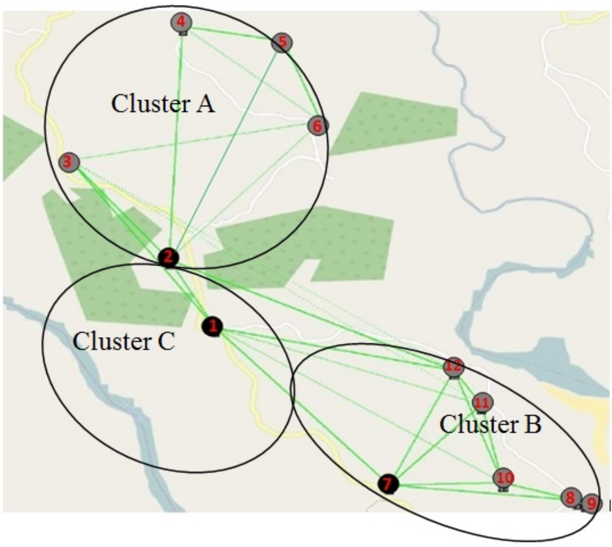

FIGURE 3.8: Zenzelini network in clustered design based on 2.4GHZ frequency band

Applying the clustering algorithm on the 12 nodes of Zenzelini network graph using 2.4HGZ frequency band produced 3 dominating nodes and 9 dominated nodes. In order to form a clustered based WMN, the dominating sets were grouped with their dominated nodes Figure 3.8 which shows the 3 possible clusters which can be generated for the flat Zezelini network.

3.4.2 Wireless Mesh Network backbone design in White space

Similar to steps taken in section above, for the 2.4GHZ bands, the amended naive algorithm has been applied to the network graph with TV white space band. After two iterations, nodes 1 and 2 were chosen to be the backbone nodes for the network in two clusters. Cluster A with node 1 as a backbone node and nodes (7 , 8, 9, 10 ,11 and 12) as edges nodes. Clusters B with node 2 as a backbone node and nodes (3 , 4 ,5 and 6) as edges nodes as in Figure 3.9.

It can be shown that clustering scheme proposed in this section can guide the topology control to restrict physical neighbouring relationship between nodes, where neighboring relationships take place between cluster heads to form the backbone of the WMN and between the cluster heads and the cluster slave to form the edge of the network. The clustering procedure reduces the wireless vertices to 18 links in 2.4GHz Wi-Fi and vertices 23 links in white space.

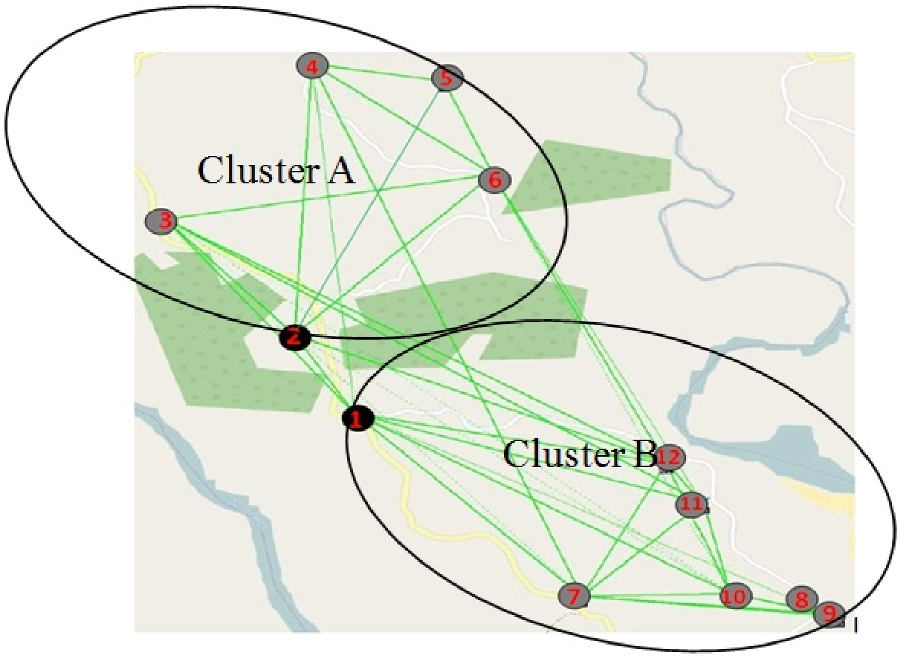

FIGURE 3.9: Zenzelini network in clustered design based on White Space frequency band

3.5 A Novel Network Architecture

Transmission Control Protocol/Internet Protocol (TCP/IP) is the main protocol behind the Internet success. It is a protocol suite built from multiple layers. Each layer established to achieve a specific purpose and the networks devices are designed with consideration to the layers. For instance in the wired network,the network routers are used to perform layer 3 functions and the switches to perform layer 2 switching. Each group of these devices work independently from another, to enable a scalable and stable network architecture which has resulted into successful data centers, campus networks, and other form of network in traditional Ethernet network, the routers are mainly used to implement routing functions and switches facilitate layer 2 Ethernet for the end devices which are attached. Therefore, the wired network a clustered heterogeneous network made of multiple types of devices in different TCP/IP layers.

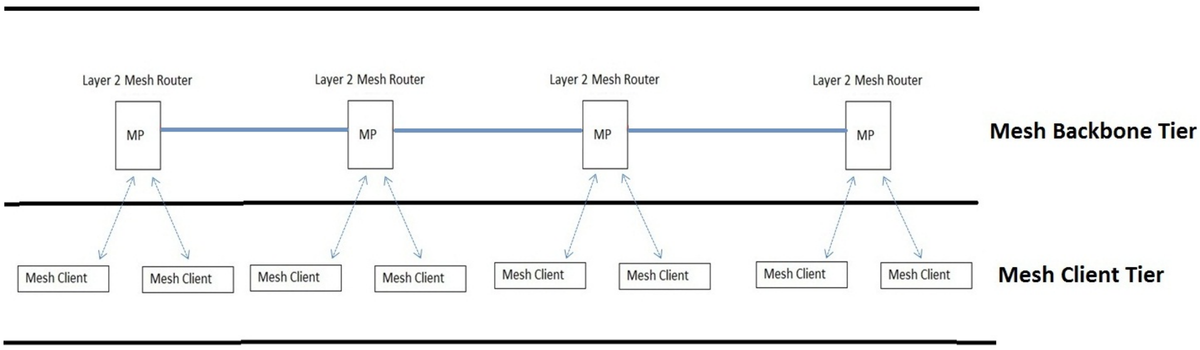

FIGURE 3.10: Zenzeleni WMN Architecture

WMNs are proposed as an alternative to the traditional wired networks, especially in areas where deploying the wired network is not feasible. Architecturally, WMNs are slightly different from the wired network as depicted by Figure 3.10, WMNs consist of at two tier: 1) mesh backbone and 2) mesh client. The mesh backbone is built from the wireless routers which perform the functions of mesh forming and connecting clients as well. These two functions are performed into a single wireless router device, where the radio interface in the wireless router is divided into two sub-interfaces: (A): Ad hoc sub-interface to work as an uplink to connect to other wireless routers in the range, (B): AP sub-interface to connect end-user devices. Inherited from the Ad Hoc networks, WMNs maintain routes to the mesh interface connected to other nodes and also each client device attached to the wireless node. Note that the client devices are mostly mobile. Such operation could lead to a crowded routing table that requires massive exchanging of control messages. Furthermore, most of the current Wireless Mesh Network deployments use single routing protocol with single type of wireless router. Village Telco networks for instance, is a flat network which uses B.A.T.M.A.N-ADV routing protocol for Mesh Potato wireless routers which they face various challenges explained in Chapter 2.

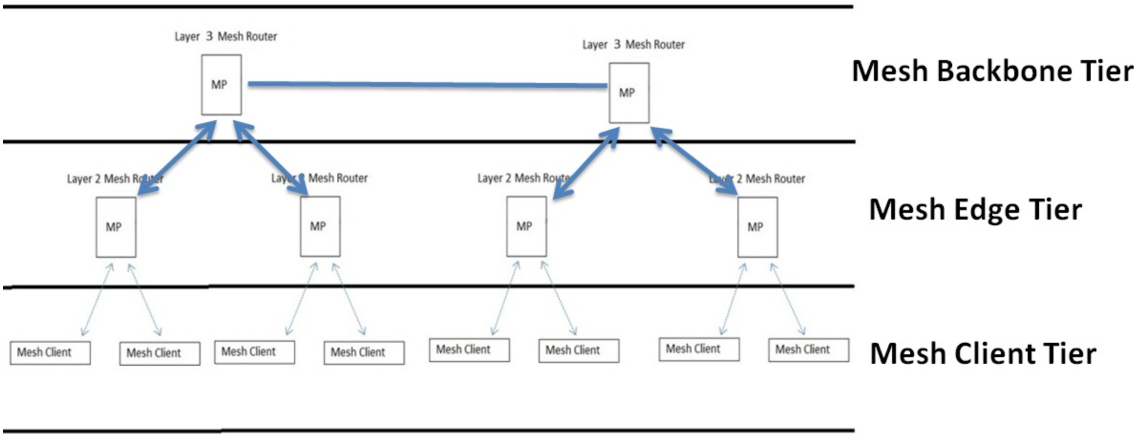

FIGURE 3.11: The Clustered , Heterogeneous network architecture

Borrowing from the wired Ethernet network architecture, this research introduces a novel WMN architecture to tackle the scalability and usability issues found in the traditional flat WMN architecture. In the new architecture, depicted by Figure 3.11, a new tier (the edge) is added to the traditional two tiers WMN to separate the client devices from the backbone. Separating the clients from the backbone, could open a way to build an intelligent backbone that is dedicated to provide enhanced network functions and services such as security and Quality of Service (QoS). The edge tier deals with end-user devices. WMNs normally service large number of end-user devices such as the wireless community networks , Wireless Internet Service providers and Internet of things (IoT) service providers, the edge tier can provide a resilient platform to connect and manage such large number of devices by subdividing the end-user devices to multiple edges, facilitated by the clustering algorithm and multiple edge routers can be used to connect clients devices within the same geographical or functional entities as clusters aggregated into the backbone.

Figure 3.11 shows the new architecture,it consists of:

- Wireless Ethernet Switch (WES), the edge tier: B.A.T.M.A.N-ADV as a layer 2 routing protocol works entirely on MAC layer. It utilises Ethernet frames to disseminate routing information and also builds the routing table from the MAC address of nodes and clients that participate in the network. As a result, Routers using such routing protocol form a WMN similar to layer 2 Ethernet network, with a single subnet. The Ethernet switches build MAC table in a reactive manner while B.A.T.M.A.N-ADV build originators tables in a proactive way. The Ethernet Switches in wired network work mainly as access to devices is used to connect the end users PC. This research proposes the use of wireless nodes with B.A.T.M.A.N-ADV as access nodes to connect wireless clients which can be mobile devices and even sensor networks. In such an architecture, B.A.T.M.A.N-ADV is the edge protocol of the network where the local traffic between the local clients is switched around the local nodes in layer 2 basis. Traffic destined outside the local segment is routed out through a node that is dedicated as a gateway or last resort node. Moreover, roaming between nodes in layer 2 is deemed to be very fast and efficient since there is no need for mobile client to change IP address. One of B.A.T.M.A.N-ADV's feature is layer 2 roaming [32].

- The Backbone tier: It consists of a wireless nodes, that link up the edge or cluster of network with other clusters. The Wireless routers are located between the edge and the backbone. Therefore equipped with two radios wireless interfaces, one for the edge and the other to backbone. The first interface is configured with B.A.T.M.A.N-ADV as other node in the cluster B.A.T.M.A.N-ADV gateway option is enabled. The second interface, is configured with layer 3 routing e.g. BMX6 , OLSR. It can be used to route traffic between clusters since each cluster is defined as a subnet.
- The Client tier is the same as in the traditional WMNs, where the end-user devices such as laptops and mobile phones are attached.

3.6 The Trade off between Wi-Fi and White Space

3.6.1 Comparison between 2.4Ghz and WS links

In section 3.4, the optimised clustering from the flat WMN was designed. More specifically, we looked at the best way to convert the flat network where all the nodes perform the same functions into a clustered network with multiple levels of function and roles. In order to gain conclusive results, we have considered the 2.4GHZ, 5Ghz and White space networks to identify their quality through compression. Using Radio mobile software simulation modeled the feasibility of building a clustered mesh network based on 2.4GHz and white space.

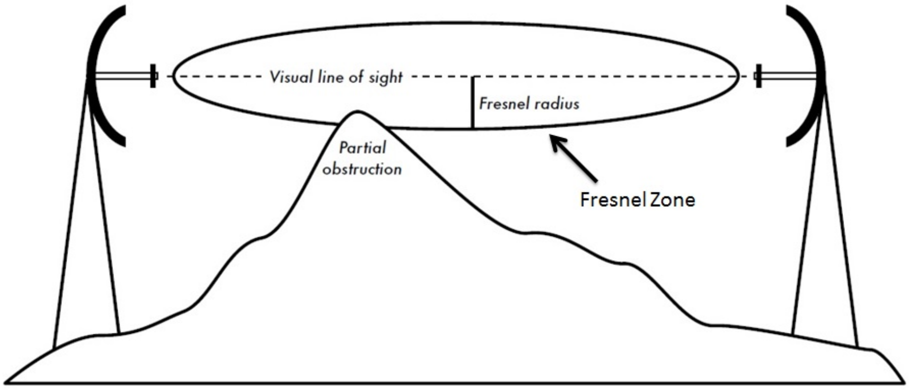

FIGURE 3.12: The Fresnel zone [33]

This section investigates the links characteristics in both candidates radio bands, 2.4GHz and white space of the Zenzelini network area. The investigation is drawn from the wireless links comprising the clustered network as in Figures 3.8 and 3.9. Since there are two clustered networks, one in the 2.4GHz Wi-Fi and another in White space, we have considered links that appeared in both topologies. Using Radio Mobile, we have measured link margin and the Fresnel zone between each link. The link margin identifies how the wireless links perform under certain conditions. It can be calculated from the devices' transmission power, transmit Antenna gain, receive Antenna gain, cable loss and received signal strength. The link margin comes from the addition of gains and deduction of losses measured in Decibel (dB) interpreted as the amount of the attenuation that a link can tolerate [22]. All the mentioned parameters are provided from the Mesh Potato data sheet. A Fresnel zone is a cylindrical ellipse space around the radio link connecting two points. The size and the shape of the ellipse depends on the frequency of operation and the distance between the two points. Its importance lays on the fact that some radio waves travel directly from sender to the receiver, while others widen around the direct link [33]. In this section we measure the Fresnel zone and link margin to see how 2.4Ghz and White space networks would behave in the Zenzelini network.

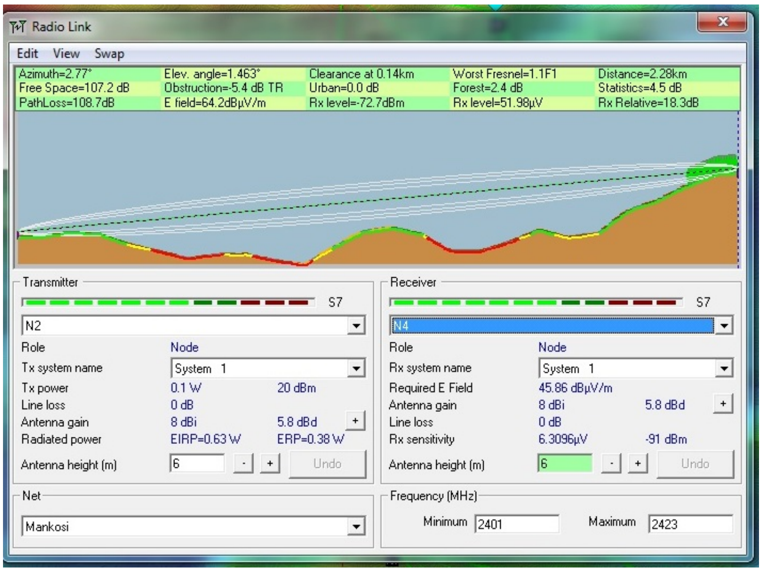

FIGURE 3.13: The radio characteristics in 2.4Ghz as presented by Radio Mobile

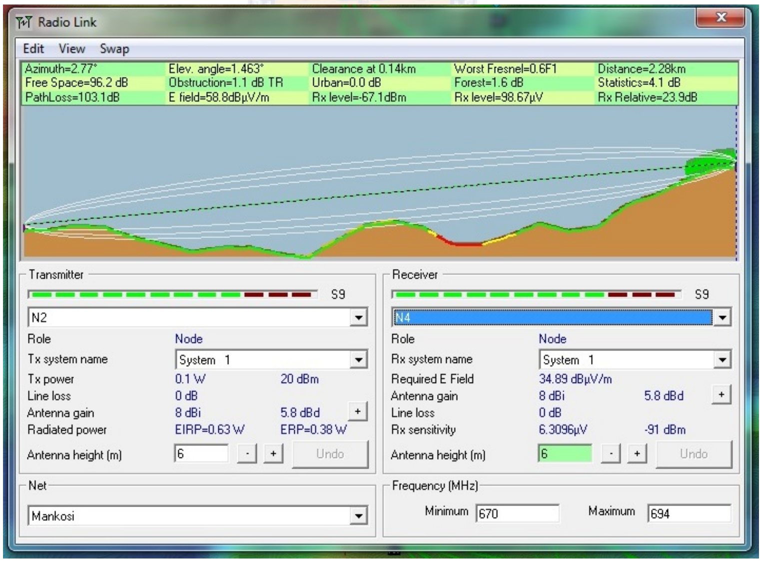

FIGURE 3.14: The radio characteristics in White Space as presented by Radio Mobile

TABLE 3.2: The Fresnel zone and link margin in 2.4GHz and white space

Backbone Links	2.4 GHZ		White Space	
	Link Margin	Fresnel Zone	Link Margin	Fresnel Zone
Link 1 (Nodes 1 & 2)	13.5dB	0.1F1	26.5dB	0.0F1
Link 2 (Nodes 1 & 7)	18.7dB	3.7F1	Edge Link	
Edge Links				
Link 2(Nodes 1 & 7)	Backbone Link		21.8dB	2.0F1
Link 3 (Nodes 2 & 3)	24.0db	1.2F1	32.0dB	0.6F1
Link 4 (Nodes 8 & 9)	47.0dB	3.0F1	57.3dB	1.6F1
Link 5(Nodes 8 & 10)	23.9dB	0.5F1	30.3dB	0.3F1
Link 6 (Nodes 2 & 4)	18.3dB	1.1F1	23.9dB	0.6F1
Link 7 (Nodes 10 & 11)	25.7dB	1.1F1	34.4dB	0.6F1
Link 8(Nodes 7& 10)	17.2dB	1.9F1	31.4dB	0.1F1
Link 9 (Nodes 10 & 12)	23.4dB	0.9F1	29.7dB	0.5F1
Link 10(Nodes 11 & 12)	29.9db	2.4F1	40.8dB	1.3F1
Link 11(Nodes 7 & 12)	17.4dB	2.5F1	28.0dB	1.3F1
Link 12(Nodes 3 & 6)	11.3dB	0.3F1	12.2dB	0.2F1
Link 13(Nodes 4 & 6)	14.4dB	2.9F1	26.2dB	1.5F1
Link 14(Nodes 4 & 5)	21.9dB	1.3F1	36.8dB	0.7F1
Link 15(Nodes 5 & 6)	20.8dB	1.8F1	33.2dB	1.0F1
Link 16(Nodes 7 & 11)	17.9dB	3.5F1	30.6dB	1.9F1
Link 17 (Nodes 2 & 6)	15.5dB	1.2F1	26.1dB	0.6F1
Link 18(Nodes 7 & 8)	18.7dB	1.2F1	28.3dB	0.6F1

Figures 3.13 and 3.14 show the link characteristics between two nodes as rendered by Radio Mobile and table 3.2 show the radio link margin and Fresnel zone of 18 radio links from Zenzeleni network. The results revealed that in all of the 18 radio links, the White space network performs better than the 2.4GHz Wi-Fi network in term of link margin and Fresnel Zone. For instance the link between node 8 and node 9 has a 0.1 Meter First Fresnel zone where the radio signal would be negatively affected by obstruction in this area. On the other hand 2.4GHz radio signal would be affected with obstacles within 3 meter of the light of sight. The table also show that white space has a greater link margin, which makes the white space radio link more tolerable to the signal attenuation. From the compression depicted by Table 3.2 it can be seen that white space networks provide better link margin and less obstructed Fresnel zone on the link of the Zenzeleni network.

3.6.2 Comparison Summary

Wi-Fi based wireless networks play a very important role in the wireless communication as they provide high throughput in unlicensed frequency. However, Wi-Fi uses the Industrial , Medical and Scientific(IMS) frequency bands such as 2.4GHz and 5 GHz which are limited in terms of coverage and are vulnerable to the interference from other devices operating in the same ISM bands [34]. TV White space consists of the unused portions of the radio spectrum that licensees do not use all of the time or in all geographical location, where such frequencies bands are available but not used. TV white space usees Ultra high frequency (UHF) and Very High frequency (VHF) band which can be used to send signals further than Wi-Fi. Furthermore, TV white space is good for non-light-of-sight radio propagation, which makes it ideal for the mountainous rural areas such as the Makosi villages where the Zenzelini network is located. TV white space is a technology enabler for Wireless Regional Area Network (WRAN), for which the IEEE 802.22 standard has been drafted [27]. It is also considered suitable for short range transmission as in IEEE 802.19af [35]. From the compression depicted by Table 3.2, it can be seen that that white space networks provides better link margin and less obstructed Fresnal zone on the links of the Zenzelini network.

3.7 Conclusion

This chapter presents a new heterogeneous WMN along with the processes taken to desing the new model. The new design aimed to build a modern, robust, scalable WMN out of the current flat WMN in Zenzelini network. Since the network consists of physical and logical components, in this chapter both aspects have been considered in designing the new model. In the physical layer, a clustering algorithm has been developed to convert the current flat network which has many undesirable wireless links into a hierarchical. Applying a clustering algorithm has shown the possibility of eliminating unnecessary links. It has been shown that a flat network with 25 links could be converted into a clustered network with 18 links clustered into 3 clusters, in case 2.4GHZ band is used to build the network. On the other hand, a white space flat network could be reduced from 29 to 23 links shared by 2 clusters in case of white space. The chapter also reveals that using while space bands in Mankosi area is feasible and of more interest it could outperform Wi-Fi bands.

In the logical routing layer, we have introduced a novel multilayer WMN architecture using multiple routing protocols in different network layers. The next chapter describes prototypes from the proposed design.

4 Experiments

4.1 Introduction

The previous chapter presented the new WMN design proposed by this thesis. This chapter, describes WMN prototypes built from the new design. The chapter also describes experiments conducted to evaluate the new design. The experiments were set to benchmark the clustered, heterogeneous architecture against the current flat wireless mesh network in terms of scalability and network performance. Measuring the network scalability is not straight forward process, but the attribute that determines the network scalability can be measured. As a factor that affects the routing protocol scalability, we considered a passive approach to measure the routing protocols overheads as a metric for the network scalability and an active approach to measured the network performance, we measured the network latency, network jitter and throughput. Since the backbone of the clustered architecture is an IP network that is open to layer 3 routing protocols, the experiments considered two layer 3 routing protocol:(BMX6 and OLSR). The objective was to test which routing protocol perform better when placed in the backbone. Network simulations tools such as NS3 are widely used to test network protocols. However, B.A.T.M.A.N-ADV and BMX6 are yet to be integrated into the available simulation tools. Therefore a physical laboratory testbed was used as the most appropriate choice for these experiments.

4.2 The experimental setup

The laboratory testbed consisted of :

- ALIX6 PC engine [19]: The wireless router device used to build the networks. It is small and affordable embedded device but capable to run generic operating systems like Linux based on its x86 processor. It can be customized to perform various task such as network routing, firewall , a network attached storage. It is based on AMD LX800 CPU @ 500Mhz, 256MB DDR SDRAM, One CF card slot typically used for the system software. Additionlly, two PCI slots can be used to accommodate up to two PCI wireless radio cards. 12 wireless routers have been used, equaling to the number of nodes of the Zenzeleni Network.

- OpenWRT: Attitude Adjustment 12.02.
- B.A.T.M.A.N-ADV 2013.2.0 release
- , BMX6: 0.1-alpha.
- OLSR2
- TCPdump: To capture the network work traffic.
- Wireshark : For analysing the network traffic.
- IPerf: To generate the network traffic to measure the network performance.

In order to obtain accurate results, three prototypes were designed and tested; A) clustered network with OLSR in backbone and B.A.T.M.A.N-ADV in the edge, B) clustered network with BMX6 in backbone and B.A.T.M.A.N-ADV in the edge and C) flat network prototype with B.A.T.M.A.N-ADV.

4.2.1 Prototype 1

It is an instantiation of the clustered, heterogeneous WMN architecture was described in Chapter 3, which is built of a combination of layer 2 and layer 3 routing protocols. BMX6 was used as the layer 3 routing protocol in the backbone, while B.A.T.M.A.N-ADV is a layer 2 protocol used at edges, Figures 4.1 and 4.2 depict the prototype configuration and the layout respectively

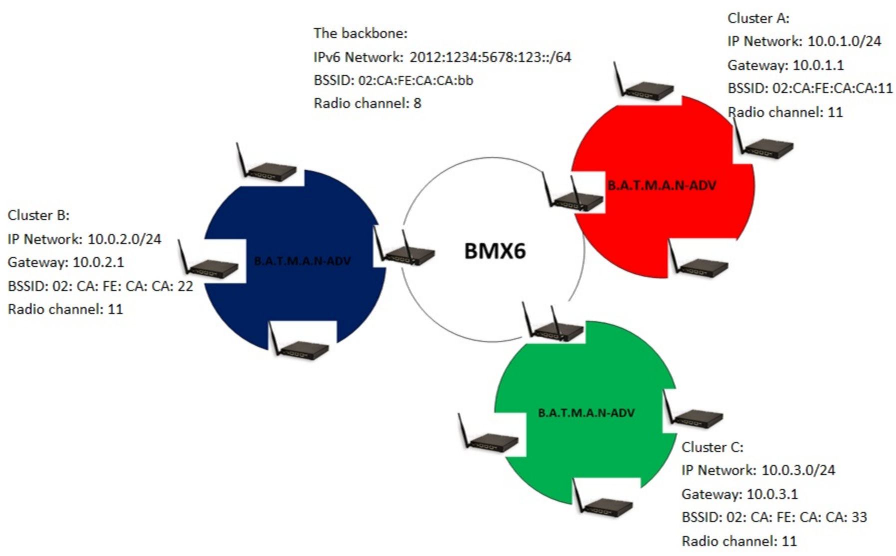

FIGURE 4.1: Clustered, Heterogeneous WMN configuration: BMX6 at backbone with B.A.T.M.A.N-ADV at the edges

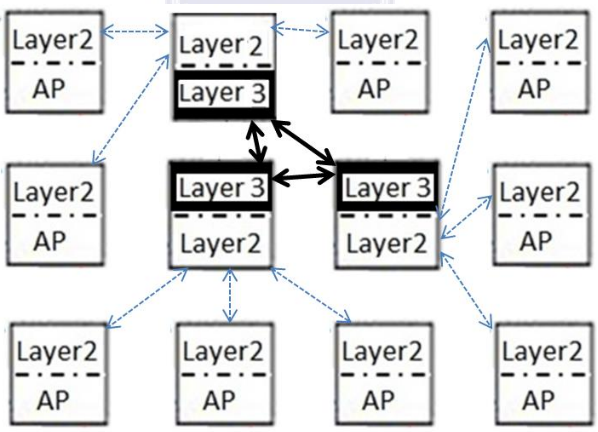

FIGURE 4.2: Clustered, Heterogeneous WMN layout: BMX6 at backbone with B.A.T.M.A.N-ADV at the edges

The network edge

The network edge is composed of clusters of B.A.T.M.A.N-ADV nodes. Where each cluster is configured with same IP network, Wi-Fi channel and gateway as well. In this prototype the network 10.0.0.0/8 is divided into three clusters/subnets; 10.0.1.0/24 for cluster A , 10.0.2.0/24 for cluster B and 10.0.3.0/24 for cluster C. The nodes IP addresses are assigned manually, while the clients get network IP configuration from a DHCP server. One node in the cluster is dedicated to be a gateway node. It is a dual radio node, the first radio card configured as the rest of nodes in the cluster with only difference that the B.A.T.M.A.N-ADV gateway option is enabled.

The network backbone

It is made from the gateway nodes of each clusters and specifically, use the second radio card in the gateway nodes. It is built using BMX6 as routing protocol to route traffic between clusters, with the cluster network IP. For instance, the gateway node advertises 10.0.1.0/24 network to the other nodes, which represents the entire clusters nodes and clients. BMX6 operation is slightly different from other routing protocols,since it builds an overlay IPv4 network on top of IPv6 network, by creating an IPv6 tunnel to carry IPv4 user data traffic while the routing control messages are exchanged using IPv6. No IP address needs to be manually configured as BMX6 uses the Unique Local Address (ULA) IPv6 address which is converted from the interface MAC address. The commands listed below are used to configure BMX6 in the gateway nodes to obtain the configuration in Table 4.1 :

```
Cluster A gateway node:
bmx6 -c tunDev=Default /tun4Address=10.0.1.1/24
 /tun6Address=2012:1234:5678:123::1/64


Cluster B gateway node:
bmx6 -c tunDev=Default /tun4Address=10.0.2.1/24
/tun6Address=2012:1234:5678:123::2/64

Cluster C gateway node:
bmx6 -c tunDev=Default /tun4Address=10.0.3.1/24
 /tun6Address=2012:1234:5678:123::3/64
```

Cluster A Gateway node	ULA IPv6 address FE80::92A4:DEFF:FEF7:3CD0 IPv6 Tunnel Address 2012:1234:5678:123::1 IPv4 Tunnel Address: 10.0.1.1
Cluster B Gateway node	ULA IPv6 address:FE80::21B:B1FF:FE07:D2CF IPv6 Tunnel Address: 2012:1234:5678:123::2 IPv4 Tunnel Address: 10.0.2.1
Cluster C Gateway node	ULA IPv6 address:FE80::92A4:DEFF:FEF7:3CD0 IPv6 Tunnel Address: 2012:1234:5678:123::3 IPv4 Tunnel Address: 10.0.3.1

TABLE 4.1: BMX6 Configuration

In this situation three steps will be followed if a client in cluster A with IP address 10.0.1.30 for example, wants to connect to a client in cluster C assigned with IP address 10.0.3.11. Firstly, the traffic will be forwarded to cluster gateway node with the IP address 10.0.1.1. secondly, the gateway looks up in its routing table and finds that network 10.0.3.0 is reachable through its second interface. However, as no IPv4 is assigned to this interface, it encapsulates the IPv4 packets into IPv6 packets and forward them through its ULA IPv6 to cluster C gateway. Lastly, Cluster C gateway will do the revise by extracting the IPv4 header for the IPv6 packet and forward the packet to the final destination.

4.2.2 Prototype 2

Prototype 2 is much similar to the previous one, with the exception that the OLSR routing protocol is used in the backbone. The edge network is the same as prototype 1, this section describes only the backbone of the network. As opposed to BMX6, OLSR requires IP addressing to be configured in the interfaces participating in the mesh network. Consequently, network 11.0.0.0/24 was configured as backbone 11.0.0.1/24 , 11.0.0.2/24 and 11.0.0.3/24 configured as the gateway nodes for cluster A,B and C respectively as descried in Table 4.2

Cluster A Gateway node	Radio one interface IP address : 10.0.1.1/24, Radio Two interface IP address : 11.0.0.1/24
Cluster B Gateway node	Radio one interface IP address : 10.0.2.1/24, Radio Two interface IP address : 11.0.0.2/24
Cluster C Gateway node	Radio one interface IP address : 10.0.3.1/24, Radio Two interface IP address : 11.0.0.3/24

TABLE 4.2: OLSR Configuration

The OLSR protocol's objective is to route traffic between clusters or any other gateway node such as the Internet. To do so, the network IP network address of the cluster is inserted in the OLSR configuration file so that it can be advertised to the other nodes. For instance, network 10.0.1.0/24 is inserted in cluster A OLSR configuration. As a result the backbone is formed as a cluster itself with its own IP network that can function in the core of the network to host network services that require to be centralized.

4.2.3 Prototype 3

The flat architecture is used in traditional WMN networking with one routing protocol. In this thesis, the flat network is built using B.A.T.M.A.N-ADV routing protocol. to mimic the logical topology of Zenzelini network as depicted by Figure 4.3

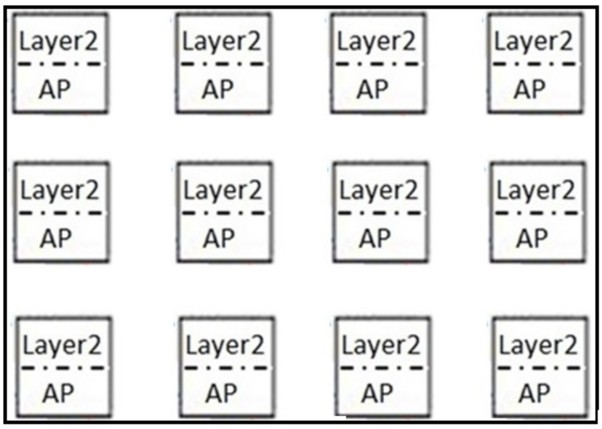

FIGURE 4.3: The layout of the Flat network

The nodes are placed in a grid topology so that each would form neighbour relationship with all other nodes. It is the worst scenario but it also allows us to track the network status as it grows. In other words, every node added to or removed from the network would have direct impact on all other nodes. The grid topology differs from selectively placing nodes, in order to form neighbour relationship only with node in their transmission range.

4.3 The routing overhead measurement

4.3.1 Flat network

For conducting the test, the testing network was set up in n:n full flat mesh topology which is the worst scenario for wireless mesh networks. To identify the pattern in which the overhead signalling increases, the test was set to measure traffic as the network grows.

Starting with two nodes, additional nodes were added in rounds, one node for each round, up to the twelfth node in a spiral way. For each round, TCPdump captured and stored inbound and outbound traffic of the Ad Hoc interface which is set to send and receive B.A.T.M.A.N-ADV traffic. The process lasted 10 minutes, which was sufficient time to monitor the network behavior. The data were stored in .pcap file format.

In the first round, only two B.A.T.M.A.N-ADV nodes were connected. Figure 4.5 displays the dump file that contains all the captured traffic. It shows the B.A.T.M.A.N-ADV OMGs. Since B.A.T.M.A.N-ADV is a layer 2 routing protocol, it floods the OMGs frame using the MAC address of the node as source address and the Ethernet broadcast (FF:FF:FF:FF:FF:FF) as a destination address. The left corner of Figure 4.5 shows the endpoints of the traffic in Wireshark traffic analyser, which reveals two B.A.T.M.A.N-ADV endpoints (excluding the IPv6 multicast and IPv4 broadcast). The two Nodes MAC's addresses are 32:14:4A:48:CD:B4 and 32:14:4A:48:CD:22 respectively. Figure 4.5 shows that 2990 Packets weighing 200146 byte were captured, with 2988 Packets destined to the broadcast address. They were equally divided between the two nodes; 1499 from node one, 1491 from node two.

Beside the packet numbers, the Wireshark also calculated the average number of packets per second and the average packets' size as well. Such parameters are useful to determine the stability and the consistency of the routing protocols.

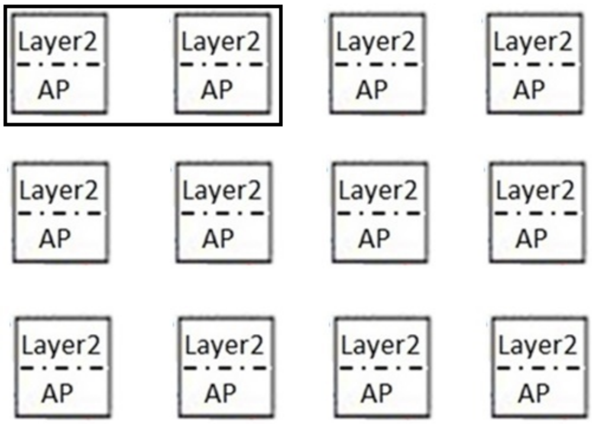

FIGURE 4.4: The layout of the Flat network with two nodes connected

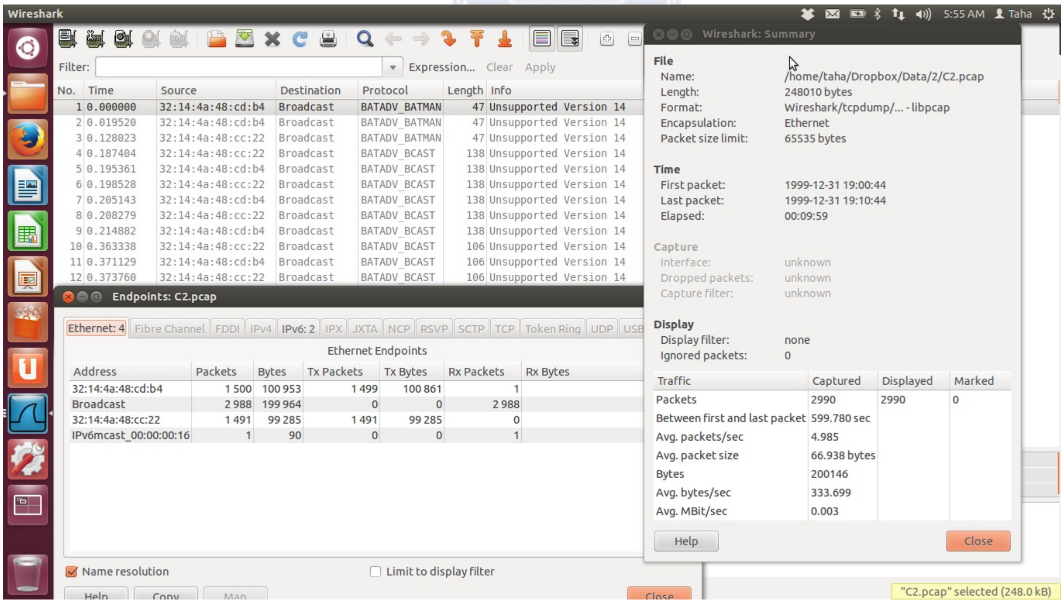

FIGURE 4.5: Log file in Wireshark when two B.A.T.M.A.N-ADV nodes connected.

In the second round a new B.A.T.M.A.N-ADV node was added. Figure 4.7 shows the collected traffic with three B.A.T.M.A.N-ADV nodes connected. With three B.A.T.M.A.N-ADV nodes, TCPdump captured 6304 B.A.T.M.A.N-ADV OMGs frames, revealing a 33% increase.

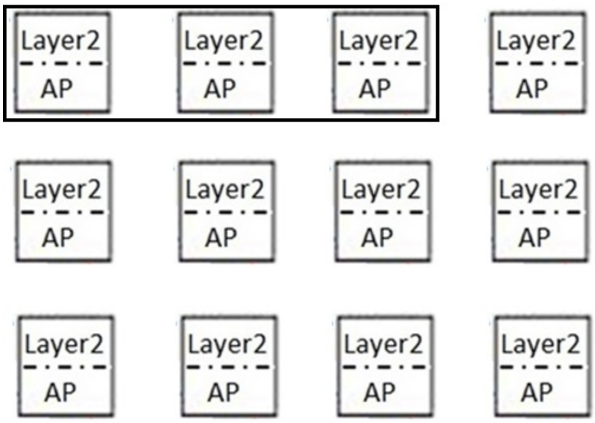

FIGURE 4.6: The layout of the Flat network with three nodes connected

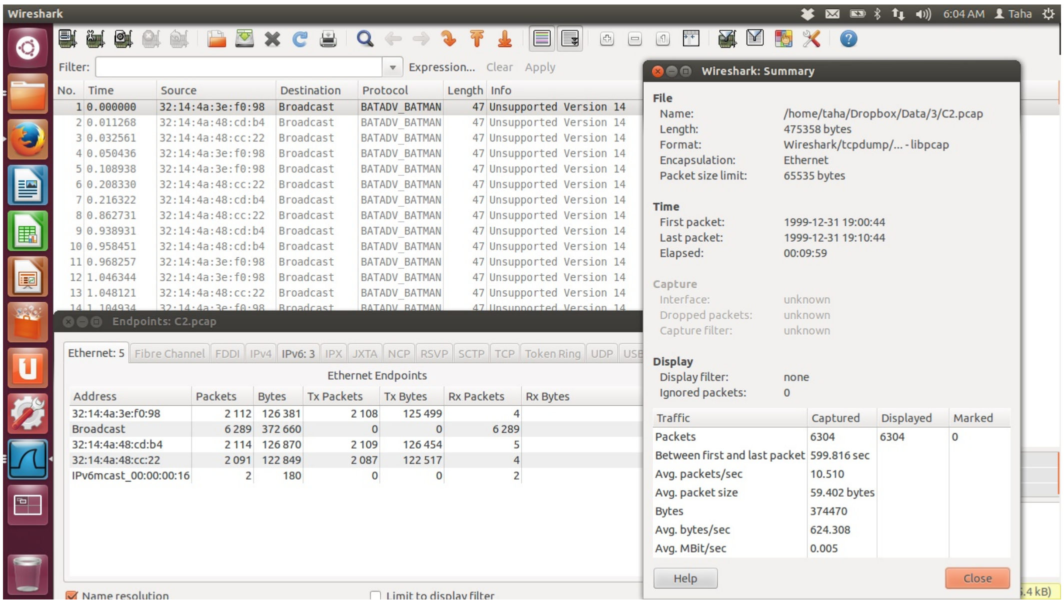

FIGURE 4.7: Log file in Wireshark when three B.A.T.M.A.N-ADV nodes connected.

Likewise, the fourth round recorded 11359 packet with a 18.932 packet per second rate as shown in Figure 4.10.

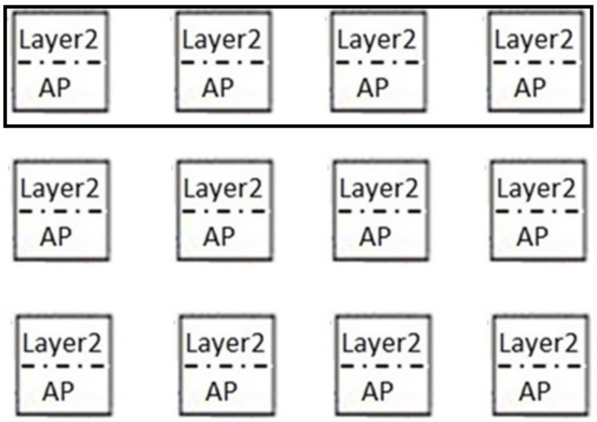

FIGURE 4.8: The layout of the Flat network with four nodes connected

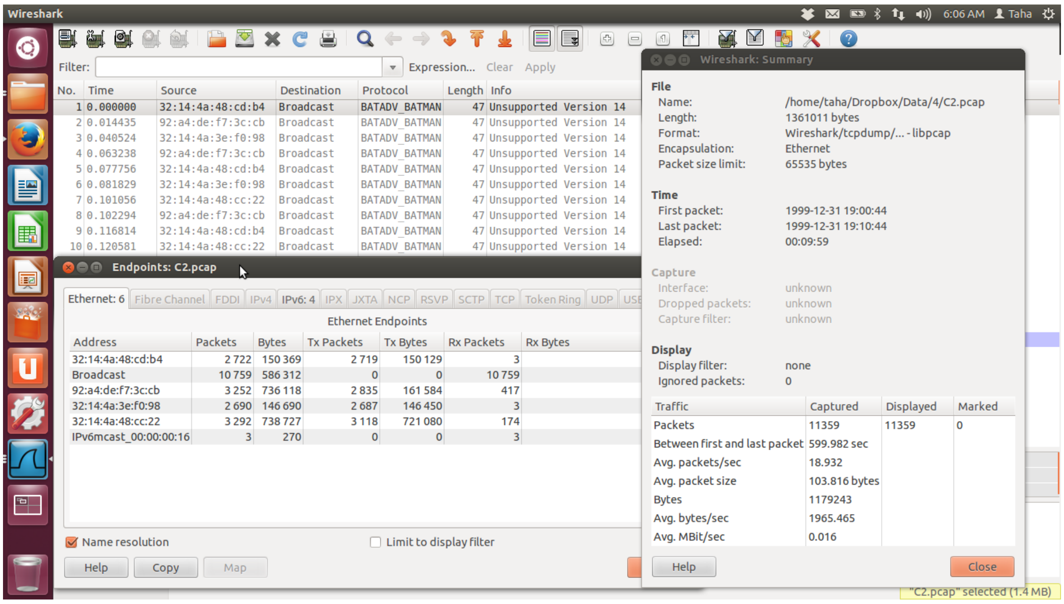

FIGURE 4.9: Log file in Wireshark when four B.A.T.M.A.N-ADV nodes connected.

The test continued with adding a node in each round until the twelfth node was reached as shown in figure 4.10. Table 4.3 displays the captured data traffic for all the rounds. It contains the number of nodes for each round along with the packet numbers, the amount of data rounded to Mbps , the average of receipt and sent packets per second and the average of the packet size as well.

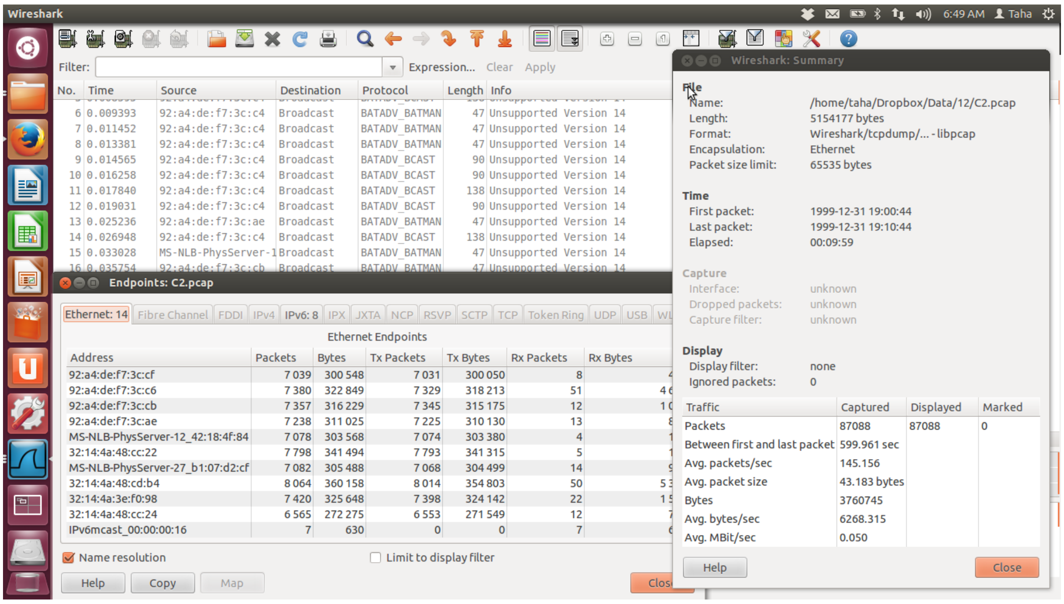

FIGURE 4.10: Log file in Wireshark when twelve B.A.T.M.A.N-ADV nodes connected.

TABLE 4.3: Overhead data

No of nodes	No of Packets	Amount of Data in MPs	Avg. Packet per sec	Avg. Packet Size in byte
2	2990	195.46	4.985	66.94
3	6304	365.69	10.51	59.40
4	10432	560.56	18.03	55.24
5	15678	709.31	26.134	46.33
6	22428	1086.49	37.384	49.61
7	30354	1248.31	50.594	42.11
8	39365	1668.52	65.617	43.40
9	49665	2205.89	82.779	45.48
10	61052	2765.41	101.767	46.38
11	69646	2856.28	116.078	42.00
12	87088	3672.62	145.183	43.12

4.3.2 Clustered, heterogeneous network

The routing overhead measurement in the clustered network comprise of accumulated measurements for both the edge and the backbone of the network. While the edge was fixed for B.A.T.M.A.N-ADV, the backbone was designed; once using BMX6 and the other operated with OLSR. To reach our goals; the first objective was to validate if the clustered architecture produces lesser accumulated routing overhead than the flat architecture. The second object was to the find out which of the routing protocols performs better: a) B.A.T.M.A.N.ADV in the edge with BMX6 at the backbone or b)B.A.T.M.A.N-ADV and OLSR.

Similar to the flat architecture measurement, the experiments was conducted in several rounds, with only difference that the clustered, heterogeneous architecture considered two routing protocols.

BMX6 in the Backbone with B.A.T.M.A.N-ADV edge

The test processes started by building the backbone of the network with the BMX6 routing protocol. BMX6 is installed and configured for each backbone node. Appendix A contains more details.

Similar to the measurements conducted for the flat architecture, the clustered architecture test starts with two backbone nodes running BMX6 routing protocol. In Figure 4.11 wireshark displays captured traffic from a backbone node running BMX6. The figure reveals how nodes running BMX6 exchange information. As shown in the figure, BMX6 is using IPv6 to build the network topology. It tunnels IPv4 traffic over the IPv6 network, which means all the routing control traffic is exchanged in IPv6, and the user traffic is routed in IPv4. That is why no IPv4 packets were sighted. All the BMX6 routing control messages were sourced from the node's IPv6 link-local address to the broadcast address ff02::2 as UPD packets port 6240. With two nodes, BMX6 generated 2384 packets to carry 213850 bytes of routing data.

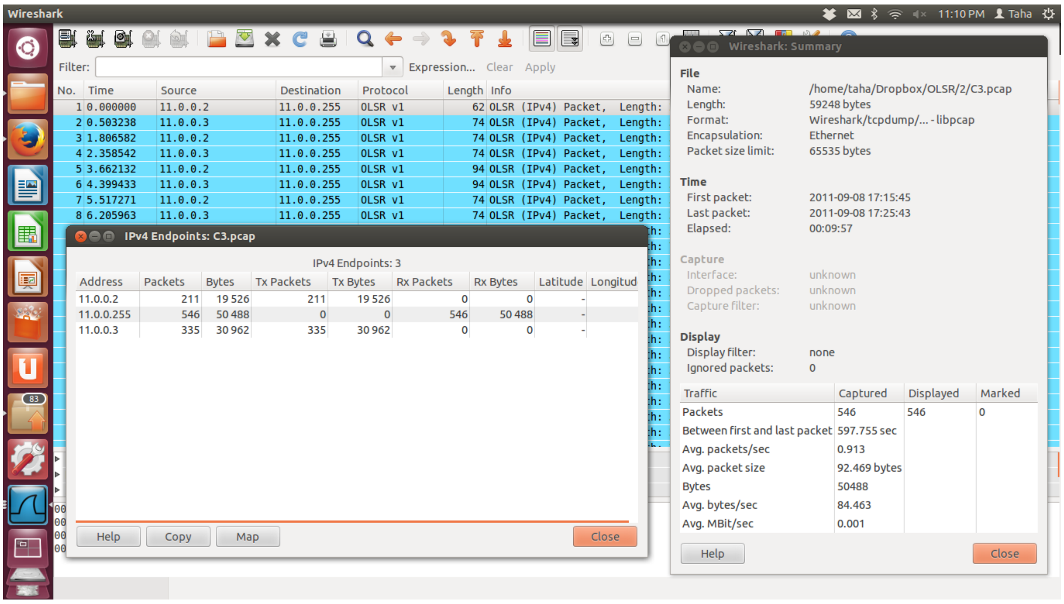

FIGURE 4.11: Log file in Wireshark when two BMX6 nodes connected

Figure 4.12 presents BMX6 routing messages from a node in network of three nodes, which are the backbone of the network. It records 3592 IPv6 packets with 93633 byte packet size.

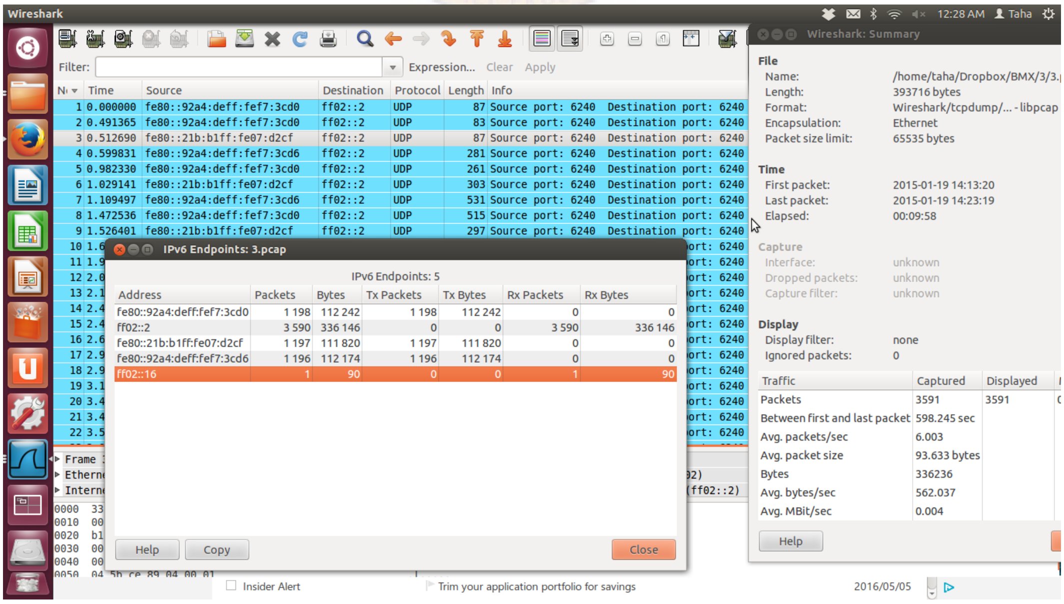

FIGURE 4.12: Log file in Wireshark when three BMX6 nodes connected.

OLSR in the Backbone with B.A.T.M.A.N-ADV edge

Secondly, OSLR was configured in place of BMX6. Figures 4.13 and 4.14 display the routing control overhead from OLSR in two and three nodes respectively.

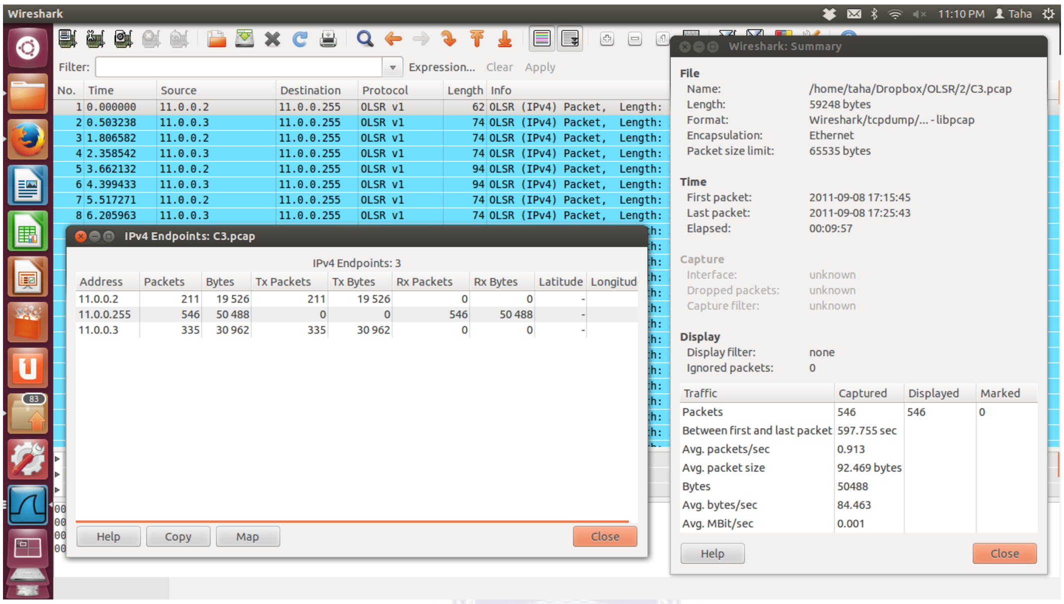

FIGURE 4.13: Log file in Wireshark when two node running OLSR connected

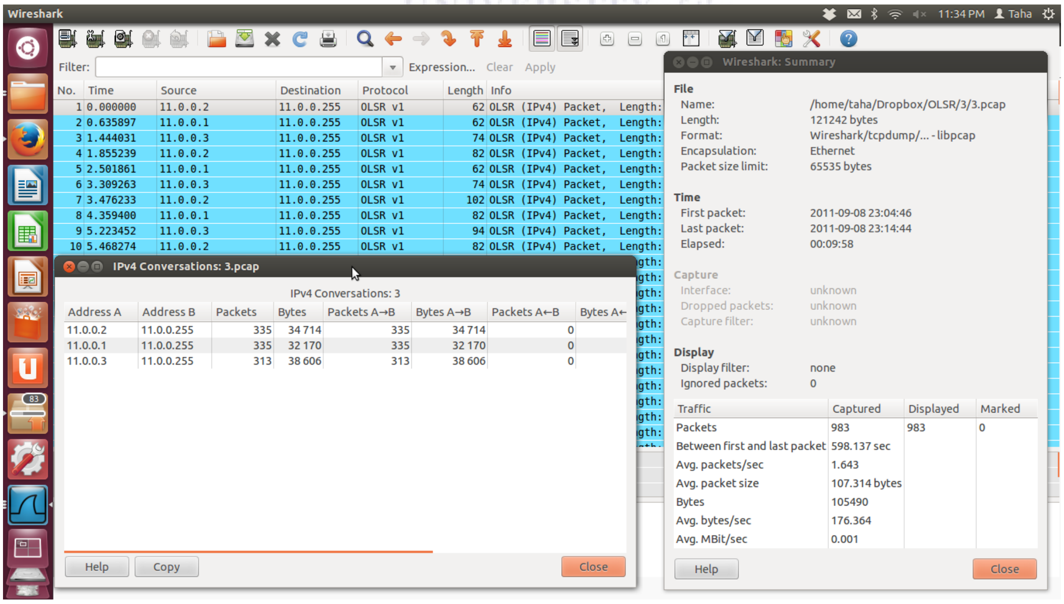

FIGURE 4.14: Log file in Wireshark when three node running OLSR connected

4.4 Conclusion

In this chapter, prototypes from the new WMN design, proposed by the this research were presented. The prototypes showed that it is possible to build a hierarchical, clustered WMN using heterogeneous routing protocols. The next chapter presents the results obtained from experiments conducted to evaluate the new design.

5 The Results

5.1 Introduction

Chapter 4 presented the experimental setups and described process used to measure the protocol overheads. This chapter reports on the tool and mechanisms used to validate our proposed design. It presents the experimental results obtained by looking at two main network parameters: 1) Routing overheads in terms of signaling traffic generated by different network configurations and 2) The routing performance in terms of throughput, jitter and delay.

5.2 Routing overheads

Firstly, results from quantifying the routing overheads for both the flat and the clustered architecture were presented in terms of the packets number and amount of the routing traffic as well.

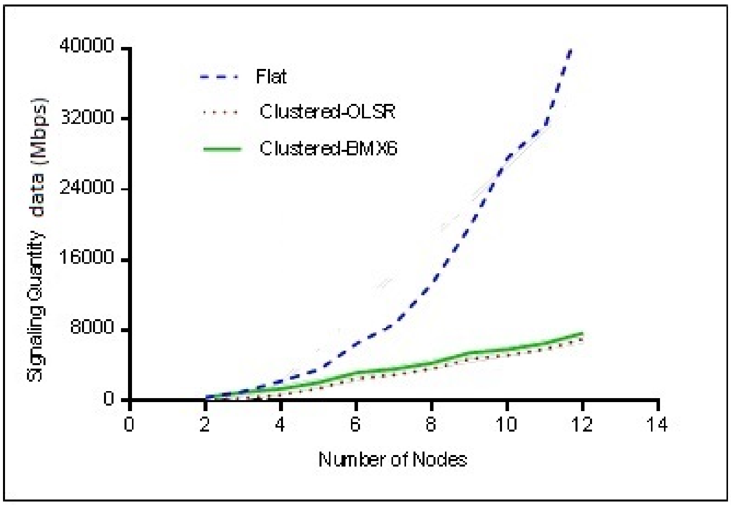

FIGURE 5.1: The quantity of signaling data generated per number of nodes

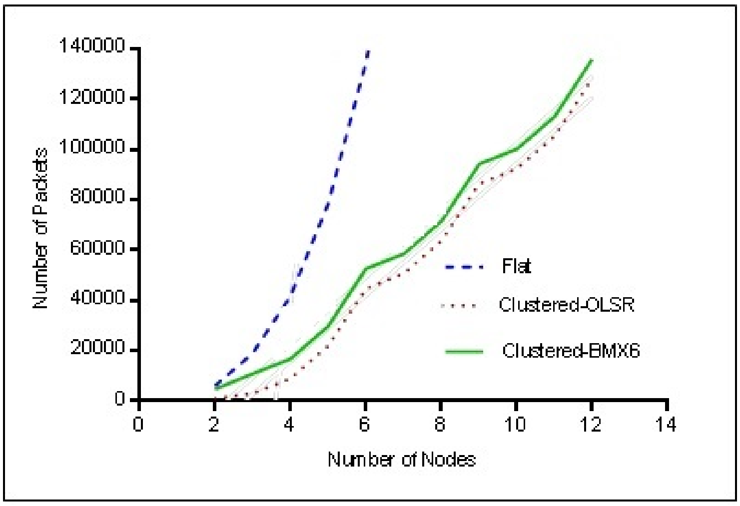

FIGURE 5.2: The number of packets generated per number of nodes

Figures 5.1 and 5.2 show the routing control overheads in packet number and amount of signaling data generated in Mbps respectively. The figures present cumulative routing control overheads from both the flat and the clustered network with BMX6 and OLSR as designed in Chapter 3.

The results confirm that the networks produce less control routing overheads when configured in clustered architecture than in flat architecture. It also revealed that OLSR based clustered network outperforms BMX6 based clustered.

When OLSR or BMX6 are used in the clustering backbone, it records less control messages than the flat network. For instance, a clustered network of eight nodes produces 63589 packets and 3648.13 Mbps, while, the same number of nodes in flat architecture produces 314920 packets and 13348.16 Mbps.

The reduction in control messages overhead is attributed to the clustering mechanism that is adopted, where the 8 nodes are divided into two clusters. This clustering mechanism aims at localizing the routing control messages, in that, the routing control traffic from a cluster does not pass to another cluster but only user traffic does. The network is divided into two clusters, the first cluster consisted of 4 nodes including the cluster head, and 3 nodes in the second cluster, along with a backbone network connecting the clusters together. Therefore, this clustered network yields control traffic from the first cluster to the second cluster and the backbone network as well. On the other hand, the same nodes when configured in flat architecture produced 314920 packets carrying 13348.16 Mbps of data.

The previous section explored results for the quantity of the routing overhead that generated by the routing protocols, with objective to benchmark the flat architecture against the clustered architecture. It gave an indication on which network can scale better as the less routing overhead the good scalability.

This section focus on further analyzing the signaling overhead throughout the time for the individual routing protocols. For that, the network running time is divided to multiple time slots to understand the routing protocol behavior as the time passes. Using the log files generated by Tcpdump the monitoring software, the data is filtered in wireshark based on time slots.

Routing protocol as soon as enabled in a wireless router starts sending control massages to declare the node existence and also forward messages received from other nodes. Each routing protocol implements certain algorithm that governs sending and resending routing control messages. The right routing protocols accompanied with right network architecture always produces scalable and stable network.

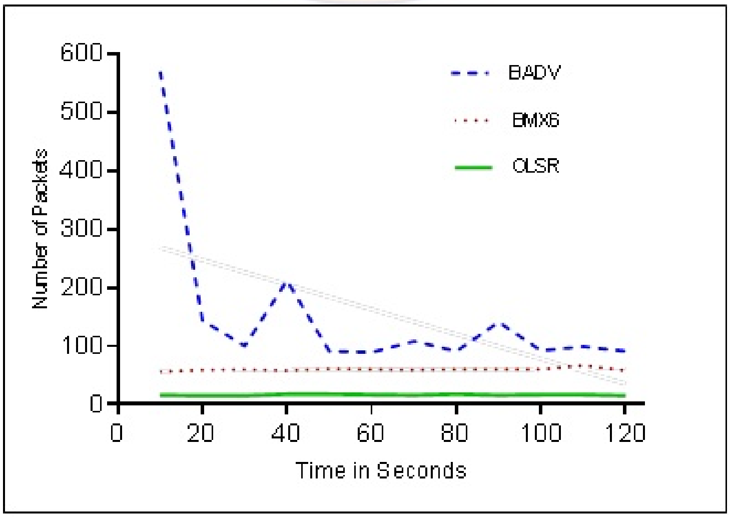

FIGURE 5.3: The number of packets processed per seconds

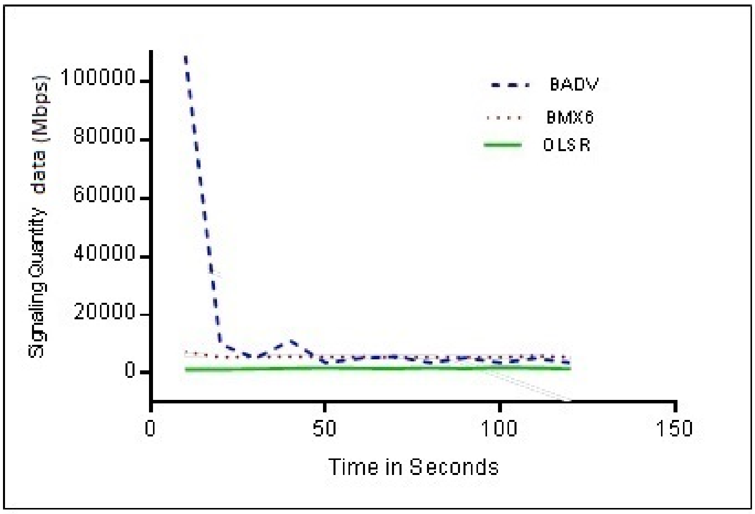

FIGURE 5.4: The quantity of signaling data Processed Per Seconds

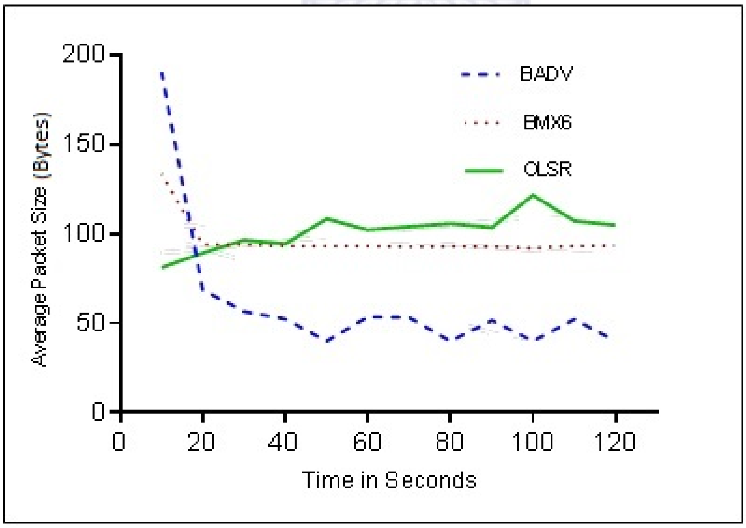

FIGURE 5.5: The average of packets size per second

Figure 5.5 shows the size of packets that carry the routing data, it shows the size of IP packets in OLSR and BMX6 along the size for B.A.T.M.A.N-ADV OMGs frames.

5.3 Routing measurement

The signalling overhead measurement in section above is an indication for the protocols behaviour in different topology. In this section, the network performance in the two network architecture is benchmarked, in terms of throughput, delay and jitter.

Iperf is used to measure the jitter and the throughput, on other hand, Ping utility is used to measure network delay. The measurement was conducted in end-to-end , where two PCs attached to two mesh nodes. The two PCs had iperf installed to generate traffic between the two points. To measure the jitter and throughput, Iperf is set in server mode in the first PC while the other PC in client mode. For the throughput TCP packets with 16 Kbyte window size sent from the client to server and UDP packets to measure the network jitter. The test is conducted for flat network architecture and two clustered architecture; one with OLSR anther with BMX6 in the backbone.

5.3.1 Throughput

The network throughput is the rate of the successful messages sent in the communication medium. It can be an indication for the network capacity.

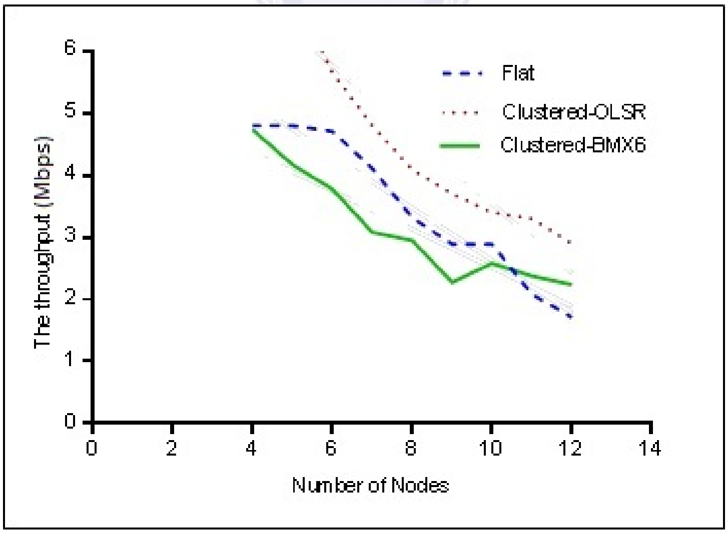

FIGURE 5.6: The throughput in Mbps per number of nodes

Graph 5.6 shows the network throughput from both the flat network and the clustered networks in MB/s. The throughput was measured as the network grows. The graph reviled that clustered network with OLSR in the backbone provides more throughput followed by the flat network, at least in networks made up from less than 10 nodes.

In network with less than 10 nodes, the throughput in the both networks is almost equal and decreases in similar pattern, even though flat network records more throughput. The reason is in the clustered network the traffic passes through the network backbone, which means more hops to pass. However, in more nodes number the flat recorders less throughput than clustered network due to fact that adding a node to one cluster has an impact only on the clustered where it is added.

5.3.2 Delay

Graph 5.7 represents the delay measurement in ms for the flat network and the clustered networks. It shows that in up to 5 nodes the delay time is equal for the both networks. Similar to results for the throughput measurement, the delay time increased rapidly in the flat network when the network grows.

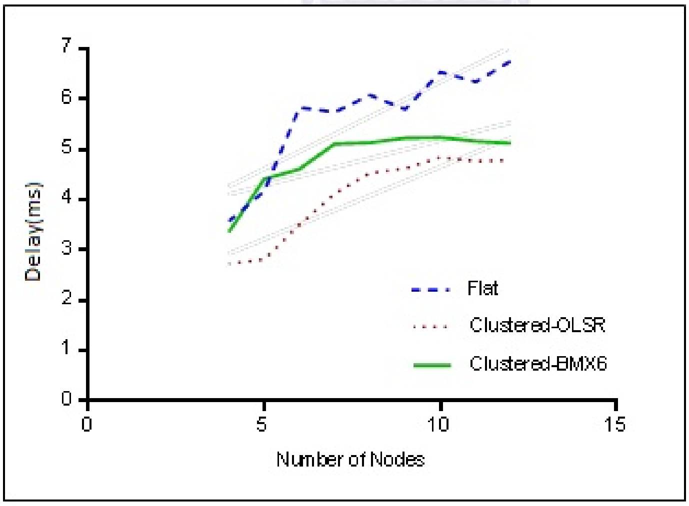

FIGURE 5.7: The network performance: The Delay in MS per number of nodes

5.3.3 Jitter

The Jitter is the difference between the forwarding delay of two consecutive received packets belonging to the same stream. It depends on the network latency and it validates the network robustness.

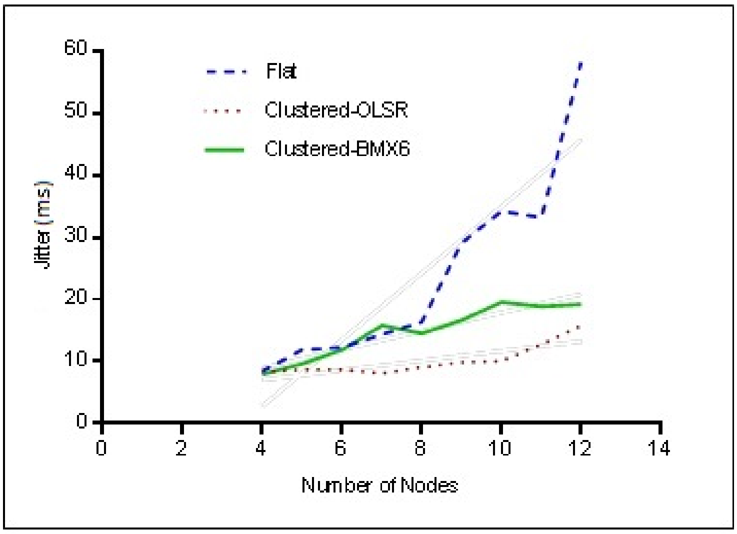

FIGURE 5.8: The network jitter in MS per number of nodes

Figure 5.8 shows the jitter measurement of the jitter for the clustered and the flat network. Similar to results from the throughput and delay, the jitter in both flat and clustered, records similar measurements until eight nodes were reached, after width, the jitter in the flat network increased rapidly as opposite to clustered network.

5.4 Summary

In this chapter, the results obtained from the experiments conducted to measure the routing overheads and the routing performance were presented. The results presented in this chapter along with prototypes described in the previous chapter, were set to answer the research question. Next chapter provides the thesis conclusion.

6 Conclusion and Discussion

6.1 Introduction

This thesis presented a clustered, hierarchical Wireless mesh network architecture constructed from a combination of two types of routing protocols, where layer 2 routing is used to build the clusters, while, layer 3 is routing used to connect the clusters. The architecture is to respond to the scalability challenges facing current WMNs generation which come from the flat architecture that inherited these issues from the broadcasting nature of wireless communication.

Building upon this architecture, a new design was proposed for Zenzeleni network and found to be more scalable than its current configuration. B.A.T.M.A.N-AVD was used at the edge of the network while two different protocols were evaluated as potential core routing protocols for such network: OLSR and BMX6. Furthermore, two types of devices were used in the heterogeneous network proposed in this thesis: Mesh Potato in the edge and Alix board in the core.

The Wireless mesh design proposed in this thesis built upon a simple graph coloring algorithm which was adapted to achieve wireless mesh clustering.

6.2 Discussion

The study found that there is possibility to physically cluster the Zenzilini network in the 2.4GHZ and white space band. The study also found that a current network could be clustered into 3 segments, and 2 segments in the 2.4GHZ and white space respectively. Furthermore, the study found that, when operating in the 5GHZ band, the design would not lead to neither a mesh nor a clustered mesh solution. Of the two prototype considered in this thesis, OLSR core was found to be the most efficient compared to BMX6 core. The main BMX6 drawback is its mechanism used to build the IP network.

BMX6 does not explicitly build an IP network but rather builds a complex IP network that uses IPv6 tunneling in a network where the end users devices are IPv4 enabled. BMX6 made it possible to route network traffic between clusters based on tunneling IPv4 traffic through an IPv6 backbone network. This could result in an IP network that is neither easy to be manage nor secure. On the other hand, OLSR built a simple and robust IP network that clearly separates the core from the edge networks. But when used in the core of the mesh network both BMX6 and OLSR revealed better scalability and better performance compared to the flat WMN. In the clustered architecture, the routing overheads are distributed among the clusters so that each cluster deals only with its own routing overhead. Therefore adding a node or end device does not affect the other clusters. As a consequence, the proposed architecture provided better performance than the flat WMNs.

A AppendixA

Appendix A, Configuration files to build the network,

Building network starts by physically prepare the equipment, where three ALIX6 pc routers dedicated to work as backbone nodes therefore additional radio interfaces PCI card installed for each router. In the second step the operating system was prepared and installed. The operating system is OpenWRT. It was downloaded from OpenWrt website https://downloads.openwrt.org/attitude_adjustment/12.09/x86/ and saved on a PC. To install openwrt , it was written to ALIX campact flash using DD tool with command :

```
$: dd if=/path/to/openwrt-x86-generic-combined-ext2.img of=/dev/sdg
```

Then the CompactFlash connected to the Alix, powered it on and connected to the PC through one of the Ethernet interfaces (the one having 192.168.1.1 as the default IP address) via:

```
 telnet 192.168.1.1
```


The second step was to install the software package. The requires packages such as BMX , OLSR , TCPDUM . etc and their decencies were download installed.

Appendix B

Preparing the radio interface:

```
config wifi-device  radio0
        option type     mac80211
        option channel  11
        option hwmode       11g
        option path         'pci0000:00/0000:00:0c.0'
        option disabled 0

config wifi-iface
        option device   radio0
        option network  lan
```

```
     option mode      ap
     option ssid      C1BMX6
     option encryption none

config wifi-iface 'bmx6'
     option device 'radio0'
     option ifname 'adhoc0'
     option network 'bmx'
     option mode 'adhoc'
     option ssid 'bmx'
     option bssid '02:CA:FE:CA:CA:bb'

config wifi-device  radio1
      option type      mac80211
      option channel   11
      option hwmode      11g
      option path        'pci0000:00/0000:00:0e.0'
      option disabled 0

config wifi-iface
        option device   radio1
    option network   lan
    option mode      ap
    option ssid      C1BADV
    option encryption none

config wifi-iface 'BADV1'
    option device 'radio1'
    option ifname 'adhoc1'
    option network 'badv'
    option mode 'adhoc1'
    option ssid 'badv'
    option bssid '02:CA:FE:CA:CA:11'



config interface lan
```

```
        option ifname   'eth1 bat0 wlan0 wlan1'
        option type     bridge
        option proto    static
        option ipaddr   10.0.3.4
        option netmask  255.255.255.0


config interface  'bat0'
      option ifname 'bat0'
      option network lan

config interface 'mesh'
        option mtu '1532'
        option proto 'batadv'
        option mesh 'bat0'
```

BMX6

To run BMX6, the flowing commands interested in the

```
 of the ALIX PC device so that routing
protocol start as soon as the devices is initiated.
\begin{lstlisting}
```

bmx6 dev=adhoc0

```
This command starts BMX6 routing protocol in the interface Adhoc0.
bmx6 -c tunDev=Default /tun4Address=10.0.2.1/24 /tun6Address=2012:123
bmx6 -c tunOut=v4Default /network=0.0.0.0/0 tunOut=v6Default /network
```

The above commands were entered into the other nodes, so that these

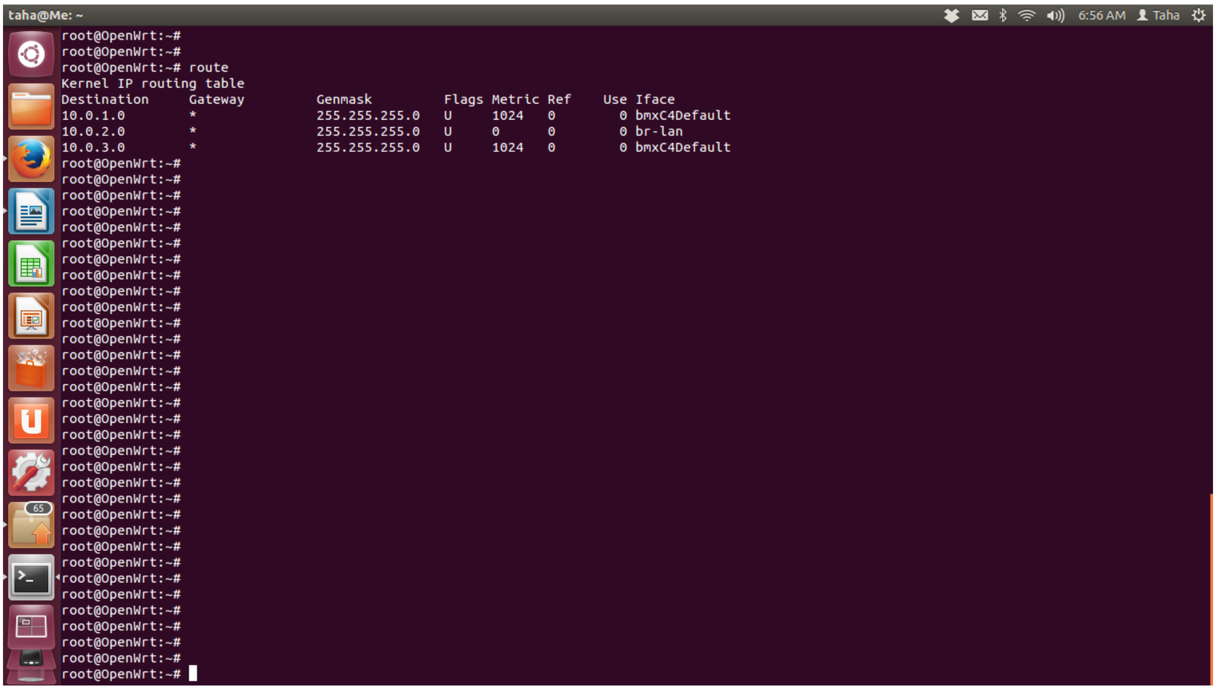

FIGURE A.1: BMX6 IP network

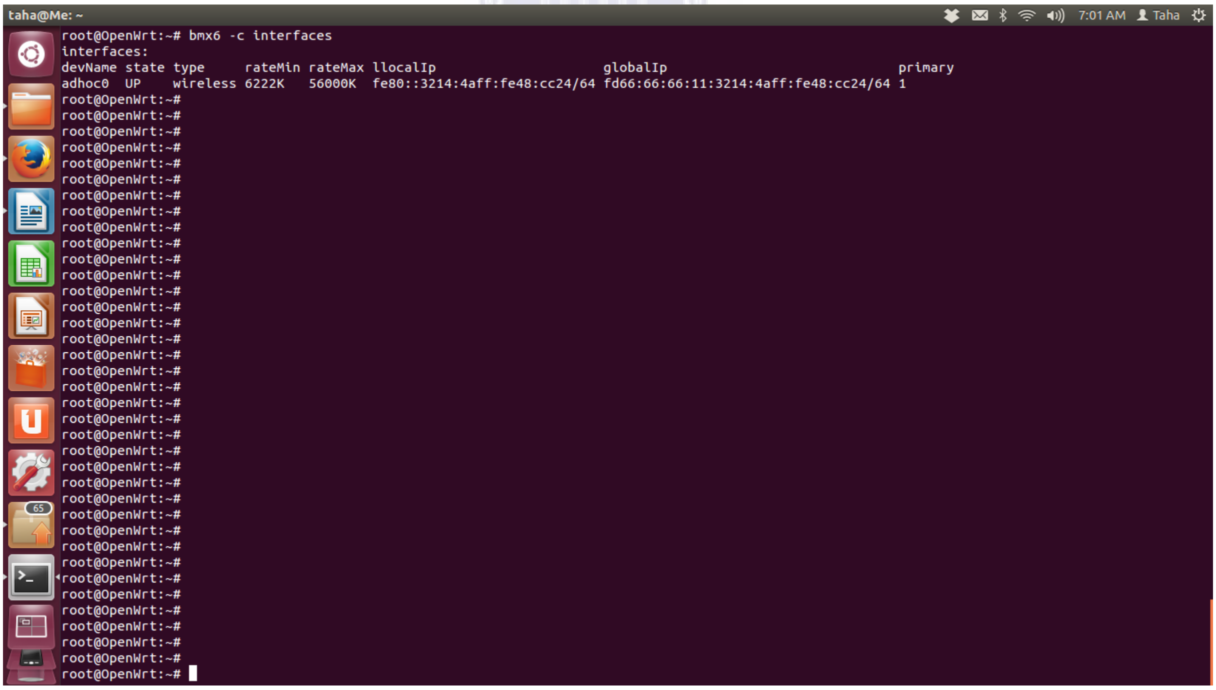

FIGURE A.2: BMX6 interfaces

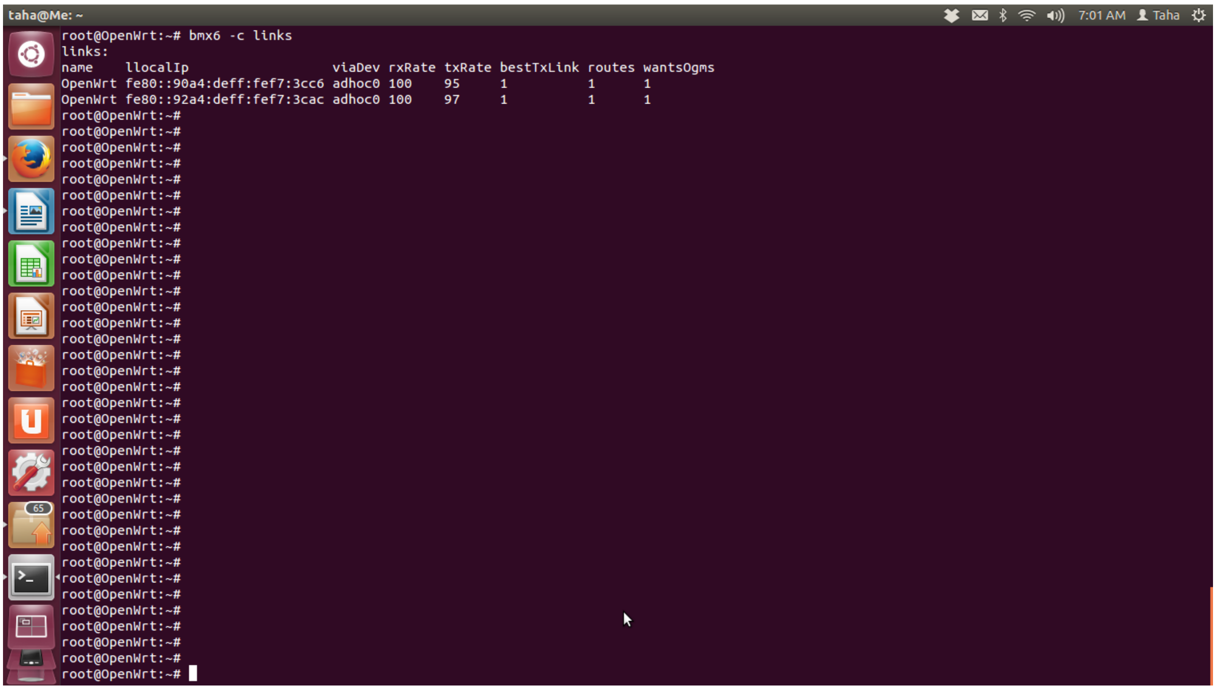

FIGURE A.3: BMX6 links

OLsr:


```
/etc/config/olsrd
config olsrd

option IpVersion '4'

config LoadPlugin
option library 'olsrd_arprefresh.so.0.1'

config LoadPlugin
option library 'olsrd_dyn_gw.so.0.5'

config LoadPlugin
option library 'olsrd_httpinfo.so.0.1'
option port '1978'
list Net '0.0.0.0 0.0.0.0'
```

```
config LoadPlugin
option library 'olsrd_nameservice.so.0.3'

config LoadPlugin
option library 'olsrd_txtinfo.so.0.1'
option accept '0.0.0.0'

config Interface
list interface 'olsr'

config 'Hna4'
option 'netaddr' '10.0.1.0'
option 'netmask' '255.255.255.0'
```

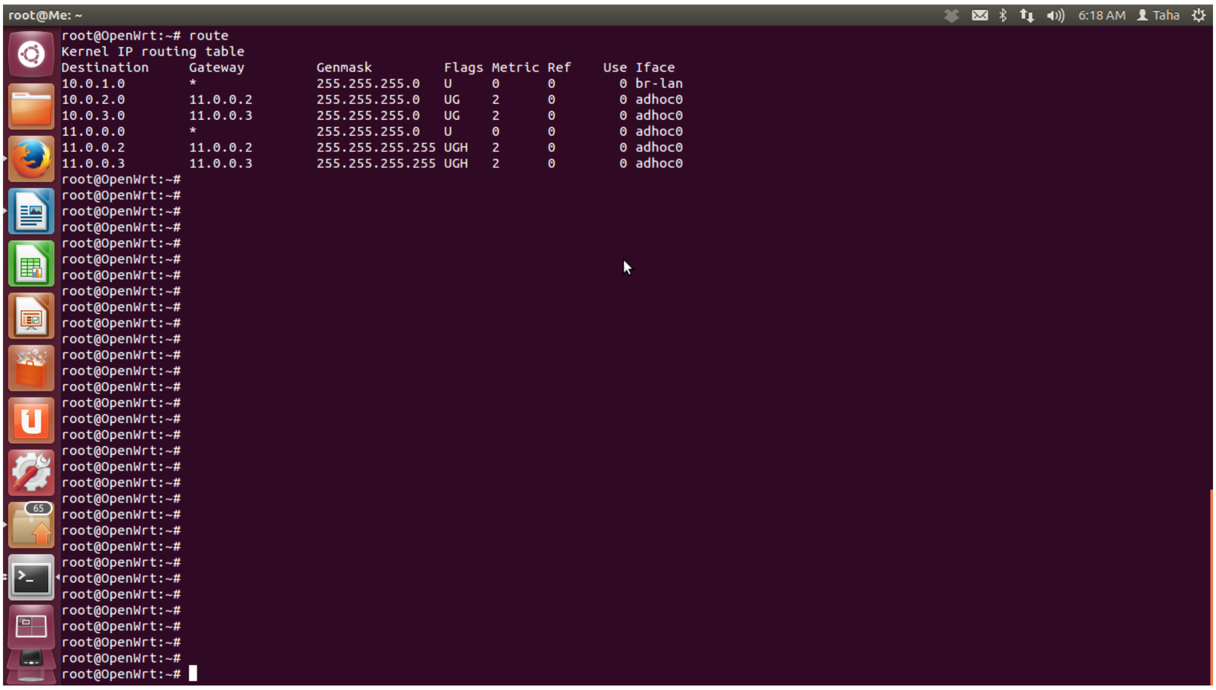

FIGURE A.4: OLSR IP network

B.A.T.M.A.N.N-ADV

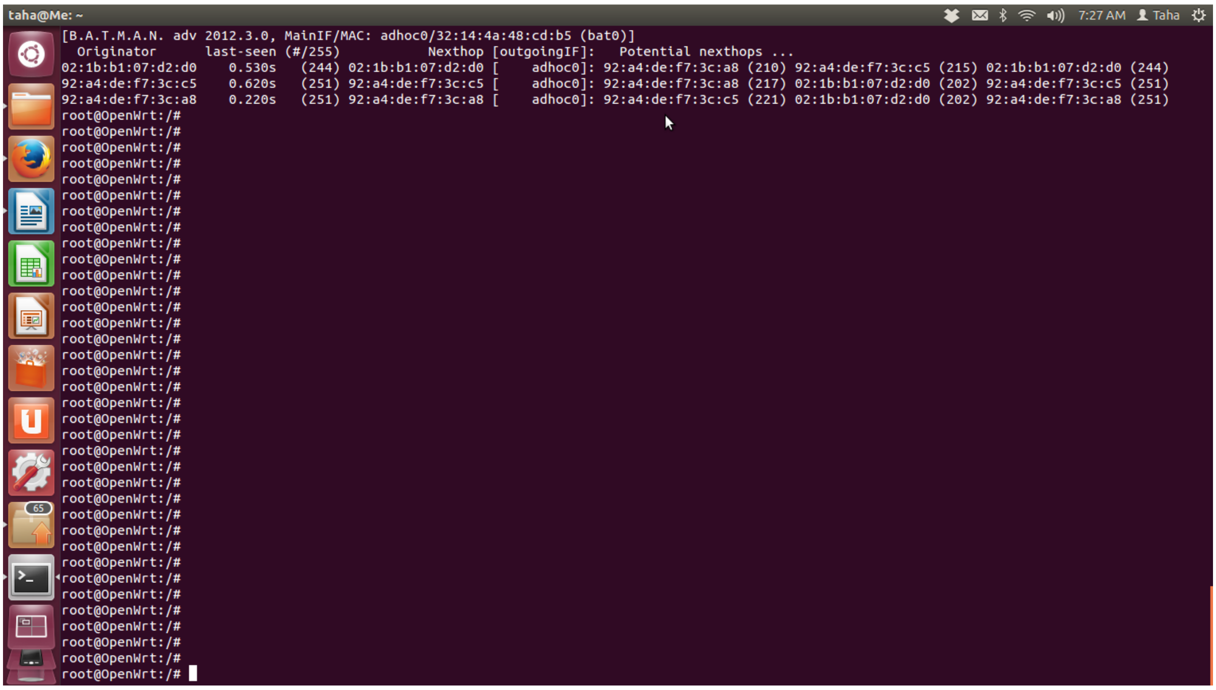

FIGURE A.5: B.A.T.M.A.N-AVD Originators

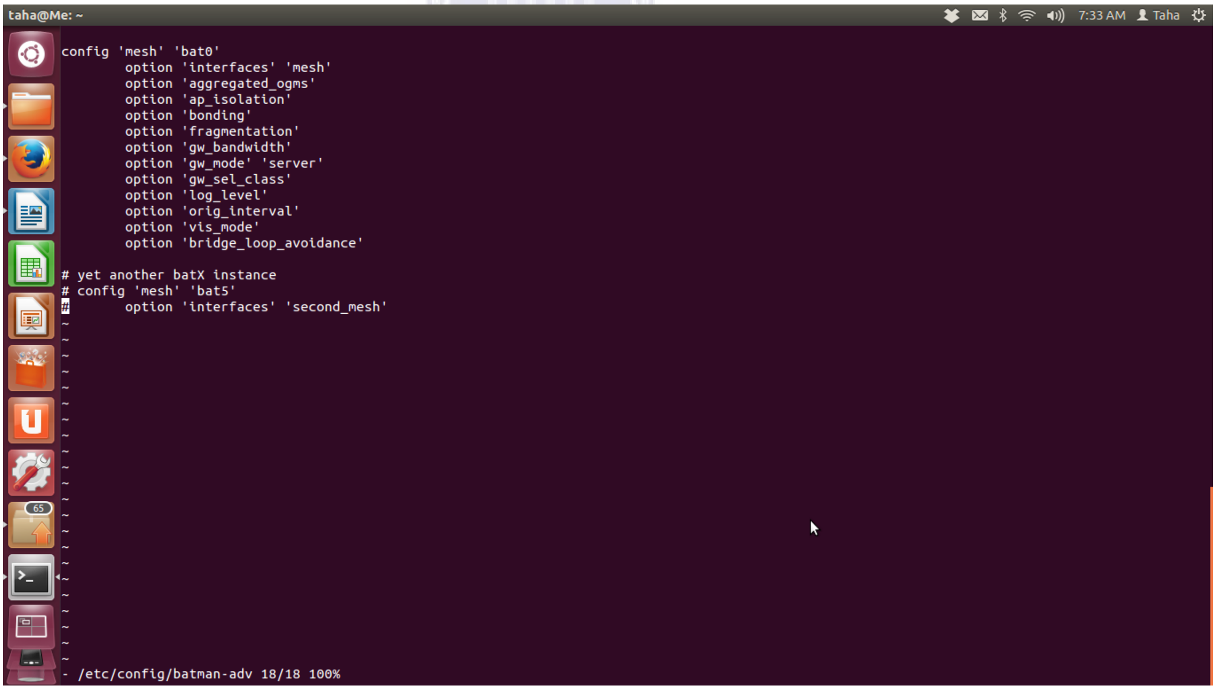

FIGURE A.6: B.A.T.M.A.N-AVD gateway

the following code to rum tcpdump

```
tcpdump -w /C3C.pcap -i adhoc0 &     # start
tcpdump to capture traffic on interface adhoc0
process=$( ps | grep tcpdump)
# retrieve the tcpdump process ID
process_id =${p:0:5}
# trim process ID to 5 digit
sleep 600
# wait for 10 minutes while tcpdump workng
kill $ process_id
# terminate tcpdump
```

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