Impact of Node Location on Quality of Service in Infrastructure Wireless Mesh Networks

by

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DECLARATION

I declare that this dissertation is my own particular unique work, done under the supervision of Prof. M.O. Adigun. It is submitted in fulfilment of the degree of Master of Science in Computer Science in the Faculty of Science and Agriculture at the University of Zululand. The dissertation has not been submitted in the past to another University for degree purposes. All sources used in the dissertation have been acknowledged accordingly. Part of this work was published and presented at IEEE N&N Global Technology for Computer and Information Services 2015 in Hammamet, Tunisia, another at SATNAC 2016 in George, Western Cape, and another in SATNAC 2017 in Barcelona, Spain.

Signature

C.N. Sibeko

LIST OF PUBLICATIONS

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DEDICATION

This work is dedicated to my family and friends

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LIST OF ABBREVIATIONS

WMN	**W**ireless **M**esh **N**etworks
IWMN	**I**nfrastructure **W**ireless **M**esh **N**etworks
MPP	**M**esh **P**ortal **P**oint
MAP	**M**esh **A**ccess **P**oint
QoS	**Q**uality **o**f **S**ervice
MPRs	**M**ulti-**P**oint **R**elays
AODV	**A**dhoc **O**n-Demand **D**istance **V**ector
RREQ	**R**oute **Req**uest
HWMP	**H**ybrid **W**irelss **M**esh **P**rotocol
NPART	**N**ode **P**lacement **A**lgorithm for **R**ealistic **T**opologies
MTF	**M**ulti-Hop **T**raffic **F**lows
MNs	**M**esh **N**odes
GARM	**G**ateway-**a**ware **R**outing **M**etric
VANETs	**V**ehicular **A**dhoc **Net**works
OLSR	**O**ptimised **L**ink **S**tate **R**outing
WLAN	**W**ireless **L**ocal **A**rea **N**etwork
DHWMP	**D**ecentralised **H**ybrid **W**ireless **M**esh **P**rotocol
MHRP	**M**esh **H**ybrid **R**outing **P**rotocol
GAs	**G**eneric **A**lgorithms
CNN	**C**ritical **N**umber of **N**eighbours
NS	**N**etwork **S**imulator
TCL	**T**ool **C**ommand **L**anguage
PDR	**P**acket **D**elivery **R**atio

ABSTRACT

Infrastructure Wireless Mesh Networks are designed as a possible solution to provide Internet connectivity to the rural community. This is because of its architecture which possesses capabilities such as dynamic self-forming, self-healing, and self-configuration. Infrastructure Wireless Mesh networks also have added benefits such as low up-front costs, reliability, robustness, as well as being easy to maintain. The infrastructure consists of static nodes which could be the routers or Portals. These nodes form and maintain the network automatically. Studies have indicated that the location of a node in the network can impact the network performance. Even though others have looked at the impact of node location their focus was limited to the number of nodes and traffic load distribution.

In general, Infrastructure Wireless Mesh networks traffic flow is either node to node or node to Portal. Even then, the impact of node location on these traffic flows has not received adequate research attention. The focus of previous studies has been limited to the effect of node location relative to the network centre, with node-to-node traffic flow being the primary consideration. As Infrastructure/Backbone Wireless Mesh networks provide a means for Internet connectivity, it is also important to investigate the impact of node location relative to the Portal, where most traffic is flowing to or from the Portal. Hence, this study extends the previous studies by exploring the effect of individual node location relative to the Portal.

The results of this study in regards to individual node location relative to the network centre, revealed that the nodes achieved low packet delivery ratio, low throughput and high delays. This concurs with the previous studies. Furthermore, the impact of node location relative to the Portal, revealed that the packet delivery ratio of the individual nodes is higher than those of the edge

nodes. The conclusion drawn from the foregoing outcome is that there is a negative impact on individual nodes closer to the network centre and a positive impact on the nodes closer to the Portal.

1. CHAPTER 1

1.1 Introduction

Wireless Mesh Networks (WMNs) are networks that aim to create wireless communication in places where there is little or no existing telecommunication infrastructure. The motivation behind these networks is to provide Internet access in places with no commercial framework and where the telecommunications operators have no economic interest because of low demand (Peixoto *et al.*, 2012). WMNs can be used in many different applications, such as broadband home networking, transport systems, health and medical systems, and community and neighborhood networks. Infrastructure Wireless Mesh networks (IWMNs) can be built using different kinds of radio technology, such as IEEE 802.11 (Akyildiz, 2009).

WMN architecture can be classified into three main categories, namely, Client, Hybrid, and Infrastructure/Backbone Wireless Mesh networks. The Client comprises client devices such as laptops, PDAs, cellphones, and printers, which participate in the mesh routing. The Hybrid mesh network consists of both backbone devices and the client mesh network. The IWMN, also known as the Backbone, is shown in Figure 1.1 It consists of a Mesh Portal Point (MPP), Mesh Access Point (MAP) and Mesh Points (MPs). MPs are wireless stations responsible for routing. MAPs are MPs with additional access point capabilities. The MPs create a mesh of links that are self-configuring and self-healing amongst themselves. These features allow the network to be quick and easy to deploy and maintain, with inexpensive set-up costs.

Moreover, MPPs are MPs that serve as gateways to other non-mesh networks like the Internet or other wired networks (Abid *et al.*, 2010). MPPs and MPs will be referred to as the backbone nodes in this dissertation.

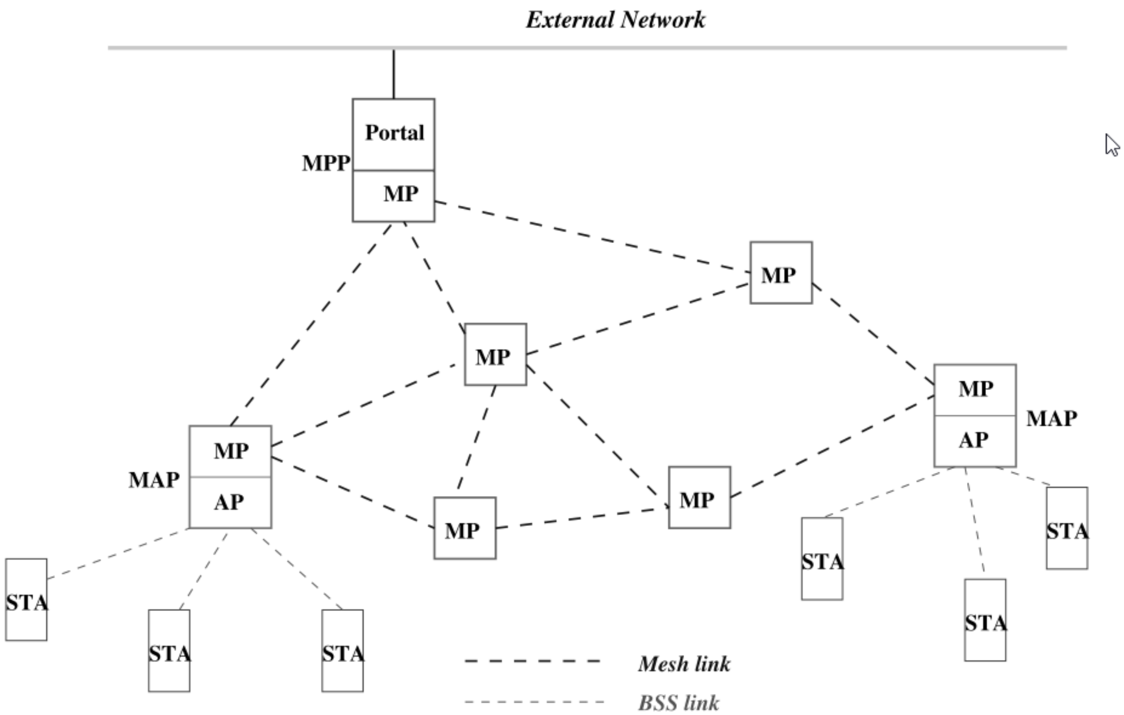


Figure 1.1: IEEE 802.11s IWMN architecture (Akyildiz, 2009)

The backbone nodes must liaise with each other and forward data packets on behalf of the backbone nodes that may not be within the transmission range of their destination (Zhang *et al.*, 2007). While the transmission of data packets is going on the network must ensure that packet loss due to unnecessary delays, are avoided. Hence it is imperative for the network to guarantee the Quality of Service (QoS) in order to achieve the best network performance. In order to ensure QoS, requirements such as throughput and delay, effective routing protocols and transport layer protocols should exist (Wu & Tseng, 2007). The ultimate goal of a routing protocol is to discover the routing path for any source-destination pair, while achieving the best network performance

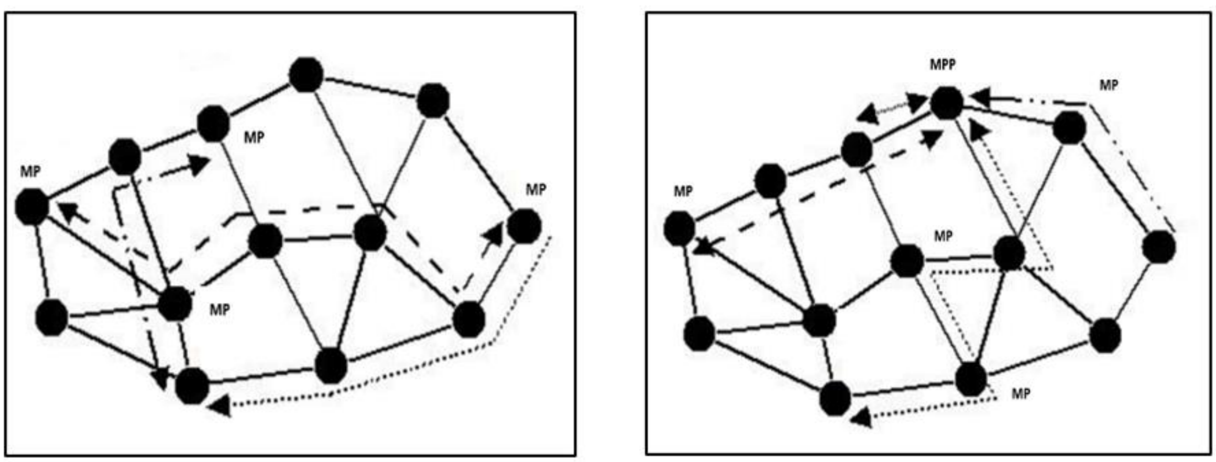
(Zhang, Luo, & Honglin, 2007). The routing protocol must possess reliable forwarding capabilities (Busson *et al.*, 2009), since it is responsible for ensuring that the routes for sending and receiving data packets are well established.

The routing protocols are classified into three categories, namely, proactive, reactive and hybrid. Proactive routing protocol is a table-driven routing protocol, exchanging topology information with other network nodes regularly. Each node selects a set of its nearby nodes called Multi-Point Relays (MPRs). MPRs are nodes chosen to forward broadcast messages during the flooding process. This flooding technique is done in order to minimise the message overhead, as compared to the classical flooding mechanism. Only MPRs generate link state information, and use hop-by-hop routing. (Clausen & Jacquet, 2003).

Reactive routing protocol starts to set up a routing path for two nodes only after traffic is generated between these two nodes (Akyildiz, 2009) (Deepak *et al.*, 2013). Ad hoc On-Demand Distance Vector (AODV) algorithm allows dynamic, self-starting and multihop routing between the network nodes. AODV enables routes to new destinations to be established quickly. The nodes need not maintain routing for inactive routes. AODV allows the nodes to respond to link breakage and changes in the network topology in a timely manner (Perkins *et al.*, 2003). When the routes are not in use they expire and are discarded, thus reducing the need to maintain routing tables. To discover routes, the source node broadcasts Route Request (RREQ) packets. When the RREQ is received by the destination node, it checks for the sequence number. Each node maintains an increasing sequence number. The sequence numbers help to avoid the possibility of forwarding the same packet more than once (Awerbuch & Mishra, 2001).

Hybrid Wireless Mesh Protocol (HWMP), specified in IEEE 802.11s, is a combination of both the proactive and the reactive routing mode, to increase scalability (Bari *et al.*, 2012). In HWMP the reactive mode is adopted for node in a dynamic environment, while the proactive mode is an effective choice for nodes in a static network topology (Akyildiz, 2009)

Since IWMNs comprise stationary backbone nodes they support both Intra-mesh and Portal-based traffic. In the Intra-mesh traffic scenario, the communication is amongst the MPs, as shown in Figure 1.2 (a), whereas in the portal-based traffic, the traffic is coming to and from the MPP as shown in Figure 1.2(b). In both scenarios all the stations in the network depend on each other to forward data packets on behalf of the other stations (Zhang *et al.*, 2007).



(a)Intra-mesh traffic (b) Portal-based traffic

Figure 1.2 : IWMN Traffic Scenario, adapted from (Mudali *et al.*, 2012)

The network design will depend on the distances between the points to be connected. Hence the traffic type can be further classified into different settlements patterns, namely, the nucleated and the dispersed settlement pattern. The nucleated settlement pattern shown in Figure 1. 3(a) is commonly associated with the normal node distribution where the nodes are located close together,

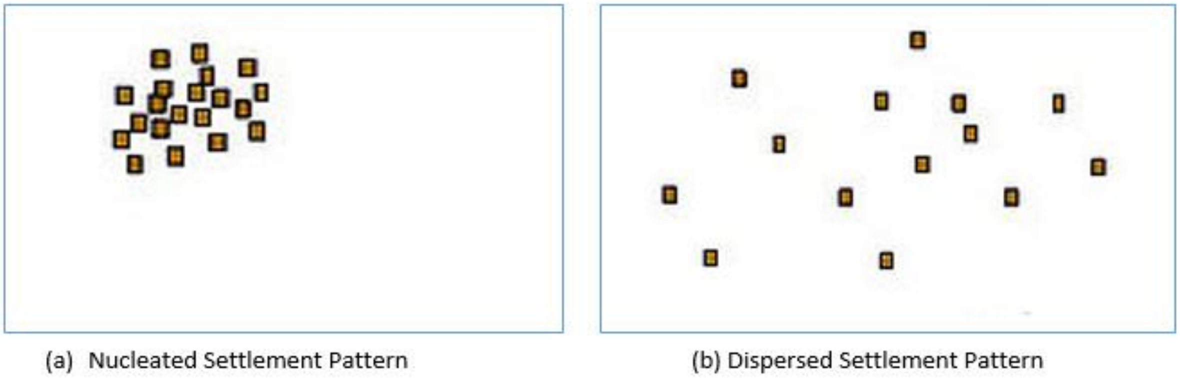


Figure 1.3 : Rural Settlement Patterns (Http://www.3dgeography.co.uk/settlement-diagrams, 2016)

as shown in Figure 1. 4(a). The dispersed settlement pattern shown in Figure 1. 3(b) is normally associated with the uniform node distribution, where the backbone nodes are spread over a wide area, as shown in Figure 1. 4(b). The uniform and normal node distributions are generated using random node placement, and form random topologies. In the random placement model, a topology area (usually rectangular) of size |A| is chosen and n nodes are placed inside it with the random probability $P_{random} = \frac{n}{|A|}$. Random topologies use a predefined topology area, and do not necessarily conform to the real network structure.

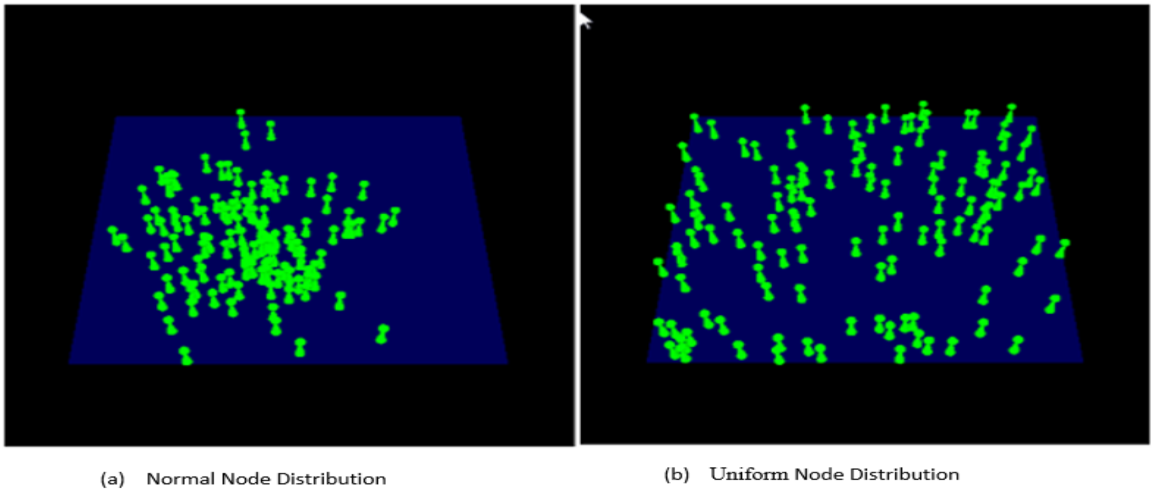
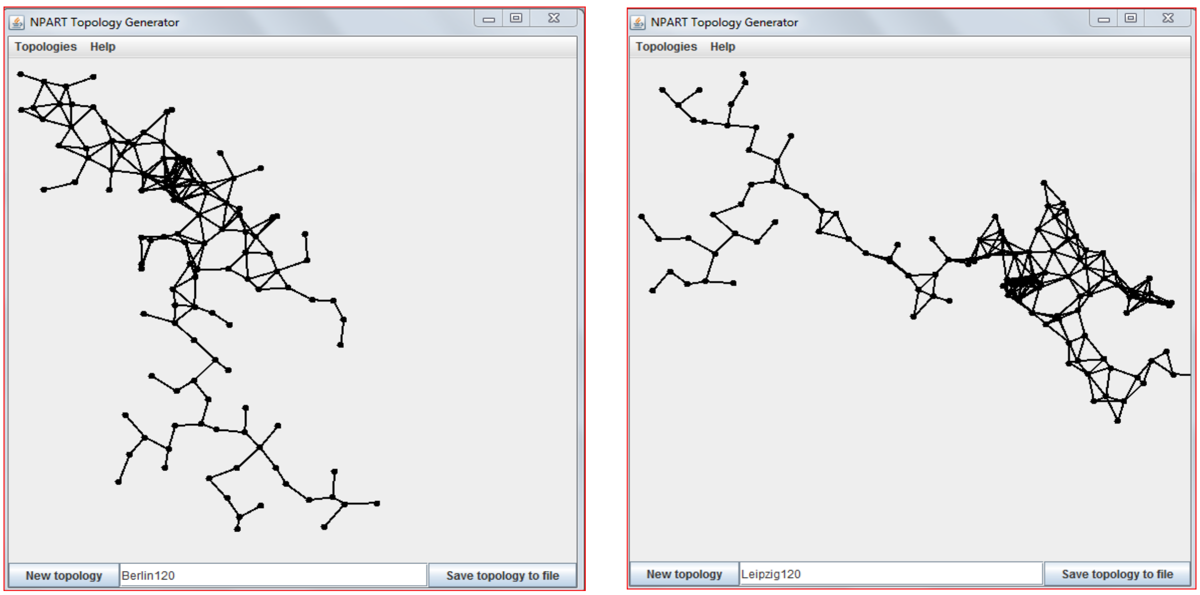


Figure 1.4: Node Distribution

Furthermore, backbone nodes can also be placed using realistic node placements. These realistic topologies have characteristics of a real network, which consider the physical constraints that nodes, in real implementation, can be subjected to. In many mesh network deployments, such as in rural environments, the mesh operator does not have complete control over the placement of the backbone nodes. For example, physical constraints such as trees, buildings, and hills, usually prevent backbone nodes from being placed on exact grid coordinates. The realistic topology considers real- life constraints such as transmission range, limited radio per node, and limited bandwidth. The node placement that involves the creation of realistic topologies can be anticipated in real-world implementation.

Realistic topologies originate from real networks, consequently, in order to generate a realistic topology, the input data should be sampled from a real network. Several assumptions regarding node placement must be made. The properties observed in reality are different than in random placement models. The network is connected but with low average node density, and the traffic distribution over nodes is highly asymmetrical. The work by Milic & Malek (2014) compared topological and link reliability properties in an open multihop wireless network in Berlin and Leipzig. After this comparison, they developed a Node Placement Algorithm for Realistic Topologies (NPART), which is a realistic topology generator for wireless network simulations. This study also adopted the NPART tool to generate Berlin and Leipzig node distribution to be evaluated using NS2, as shown in Figure 1.5.



(a) Berlin (b) Leipzig

Figure 1.5: NPART Topologies

According to Franklin & Murthy (2007) and Zhang *et al.* (2007), network topology, node distribution, and location can impact the performance of the network. Hence studies that investigate the impact of node location have been conducted. It has been further confirmed by others, Souihli *et al.* (2009), Mudali *et al.* (2009), Mudali *et al.* (2011), Ali *et al.* (2012), and Bai *et al.* (2015), that the nodes located at the centre of the network do affect the performance of the network. Souihli *et al.* (2009), showed that the nodes closer to the network centre forward more traffic compared to the nodes closer to the edge of the network when the shortest path routing protocols were employed, hence there was increase in congestion, big delays and higher routing overhead.

The outcome from another study by Mudali *et al.* (2009) reported that the nodes closer to the network centre utilised smaller transceiver powers than their edge-node counterparts. This also signified an impact on network connectivity and interference. Moreover, the nodes at the centre of the network were seen to produce greater transceiver powers savings, as detailed in a follow-up study (Mudali *et al.*, 2011).

The centre nodes are much more involved in routing process than outer nodes. This leads to congestion and high delays since few nodes will have to carry excessive loads, as was shown in a by study Ali *et al.* (2012). It was also realised by the research conducted by Bai *et al.* (2015) that when nodes want to find the shortest distance between any two nodes to transmit data fast, the centre nodes become a popular choice. This caused bottlenecks for connectivity, resulting in delays.

In addition to that, Milic & Malek (2009) compared random node placement models with realistic node placements models, using NPART. The work did an analysis in the Berlin and Leipzig networks, considering topological link quality, and traffic properties, in a Portal-based traffic scenario. The finding reveals a difference discovered in the node degree distribution and the average node degree. Unfortunately, the impact of node location was not considered.

The effects of node location relative to the network centre have been dealt with, as evidenced in the above-mentioned studies. However, not much has been done with regards to the effect of individual node location relative to the Portal. Therefore further investigation is required.

1.2 Statement of the Problem

The results from previous studies have proven that the central nodes affect network performance. Both Intra-mesh and Portal-based traffic are supported by IWMNs. The majority of the results were obtained using random node placement, mainly the Uniform node distribution. Although some studies considered Portal-based traffic, the present investigation focused on the transceiver power savings, in the belief that further investigations are needed to ascertain the effect of individual node location relative to the network centre and relative to the Portal on random node placements, mainly the Uniform and the Normal node distributions. In addition to that, the study evaluated the performance of all routing protocol types, and also explored realistic node placement in Intra-mesh and Portal-based traffic scenarios, using topologies from the Berlin and Leipzig networks.

1.3 Rationale of the Study

Previous research studies revealed that the node location does have an influence on network performance. The focus of previous studies was mostly on node location relative to the network centre. This research study is inspired by the results obtained on the node's position relative to the network centre. It intended to expand and explore node location relative to the Portal, since IWMNs support both Intramesh traffic and Portal-based traffic scenarios. The investigation also considered Random (Uniform and Normal) and Realistic (Berlin and Leipzig) topologies.

The outcome of this research will help in determining the topology to use and what QoS mechanisms to consider when deploying an IWMN in a rural community. It will also help understand the individual node's performance in terms of the routing protocols, different performance metrics, and different traffic scenarios in terms of node location.

1.4 Research Question

1.4.1 What is the effect of node location on the Quality of Service of Realistic networks and Random networks?

1.5 Research Goal and Objectives

1.5.1 Goal

The goal of this study was to determine the effect of node location on QoS mechanisms in Infrastructure Wireless Mesh Networks.

1.5.2 The Objectives

a) To conduct a literature survey on Quality of Service, realistic and randm topologies, transport layer protocols (TCP), routing protocols (hybrid, proactive, reactive), node distributions, and traffic scenarios (intra-mesh and portal-based).

b) To evaluate the effect of node distance from the network centre using Random node distribution on Intra-mesh and Portal-based traffic scenarios.

c) To evaluate the effect of node distance from the Portal using Random node distribution on Intra-mesh and Portal-based traffic scenarios.

d) To evaluate the effect of node distance from the network centre using Realistic node distribution on Intra-mesh and Portal-based traffic scenarios.

e) To evaluate the effect of node distance from the Portal using Realistic node distribution on Intra-mesh and Portal-based traffic scenarios.

1.6 Methodology

1.6.1 Primary Research Method

Simulation

This method involved simulating in NS2 and evaluating the performance of the node in QoS experienced relative to the network centre and Portal using routing protocols. Routing protocols are categorised into three classes. A protocol was selected from each category for simulation. The protocols were evaluated using three performance metrics: throughput, end-to-end delay, and the packet delivery ratio. Random and Realistic topologies were generated for the simulations. This helped to determine the impact of the nodes relative to the network centre and the Portal.

NS-2 was chosen as the simulation tool among the others simulation tools because NS-2 supports networking research and education. It is also suitable for designing new protocols, comparing different protocols and traffic evaluations. NS-2 was developed as a collaborative environment. It is distributed freely and is open source. A large number of institutes and people in development and research use, maintain and develop NS-2.

This research method helped to achieve the second, third, fourth, and the fifth research objectives.

1.6.2 Secondary Research Method

Literature Survey

This method helped to fulfil the first and second research objectives. An intensive review of related work by other scholars was conducted which helped us to understand how other researchers have tried to solve the problem we are investigating. A framework for analysing related work was formulated. The Literature survey focused on investigating different types of QoS mechanisms and investigated various ways of expressing the location and distribution of the node in the network. The study also looked at the performance metrics that were used in the evaluation.

1.7 Organisation of the Dissertation

The remainder of this dissertation is organised as follows:

Chapter 2 deals with related Literature, addressing the following key concepts: Quality of Service, metrics, topologies (realistic and random), routing protocols, and traffic scenarios(intra-mesh and portal-based).

The Primary Method (Simulation) together with the description of the measurement process used to carry out simulations is given in Chapter 3. This forms the foundation for the next two results chapters, in which the analysis are presented.

The results of each method is given in Chapter 4 and Chapter 5, respectively. A thorough analysis of Realistic and Random topologies, given different traffic scenarios is carried out. The effect of Distance from the Network Center, and the effect of distance from the Portal are evaluated using packet delivery ratio, end-to-end delay and throughput as the metrics.

Finally, the implications of the results, study limitations and future work are discussed in the Chapter 6.

2. CHAPTER 2

2.1 Overview

This section presents a detailed review of related studies in Wireless Mesh Networks conducted by other researchers. This will help in understanding how other researchers have attempted to solve the same or related problem. Section 2.1.1 presented the literature review that focuses on investigating QoS mechanisms, on different realistic and random topologies. Furthermore, Section 2.1.2 presents the evaluation of the routing protocols using intra-mesh and portal-based traffic scenarios through simulations, in WMNs. Subsequently, Section 2.2 presented common deficits to help in identifying the gaps and the opportunities in the literature.

2.1.1 Relevant WMN Topology Studies

WMN-SA System for Node Placement in WMNs : Evaluation for Different Realistic Distributions of Mesh Clients (Sakamoto *et al.*, 2014)

The study aimed at providing a solution to the node placement problem. The study revealed that there are issues in achieving maximum connectivity and coverage in WMNs. The problem with node placement has been shown to be hard to solve. Different approaches have been used in trying to find a solution to the problem. Hence the study proposed to provide a solution that would find optimal distribution using realistic distribution of Mesh Clients. This study considered realistic distribution (Subway, Boulevard and Stadium) to try to find a solution to the node placement problem. The study performed a simulation evaluation of the three realistic distributions. From the simulation results the conclusion was that the distribution of the Mesh Client reached the maximum connectivity in the Subway distribution. For Boulevard and Stadium, the Mesh Clients did not reach the maximum connectivity.

The study considered realistic distribution, which has properties of the real network. However, the study considered only the Mesh Clients. In as much as the study considered realistic distributions the focus was based on the overall performance of the Mesh Clients. This leaves an open issue to investigate the performance of individual Mesh Clients. And to investigate the location of the Mesh Client that did not achieve maximum connectivity, so determine their location on the network area, since it has been proven in other studies that nodes located near the network centre perform differently compared to nodes located far from the network centre.

Evaluation of Effects of Grid Shape in WMN-SA System for Solution of Node Placement Problem in WMNs (Sakamoto *et al.*, 2014)

The study highlighted some of the challenges that might prevent WMNs from achieving best network connectivity, stability and QoS in terms of user coverage. These challenges relate closely with node placement problems in WMNs. Node placement has been investigated in different applications of WMNs since WMNs have been attracting a lot of attention because of their capability of providing cheap broadband wireless connectivity. WMNs do not need a central node, hence the network is self-healing. The performance and operability of the network largely depends on the node placement.

The main aim of this study was to find an optimal topology to support connectivity services. The study carried out experiments on a WMN-SA system to investigate the node placement problem. The experiments were done through simulation, using Normal distribution and Grid patterns, with different network sizes. The conclusion drawn from the results was that using the proposed WMN-

SA system the nodes were able to achieve best network performance because of maximum connectivity and coverage.

The study considered the Normal distribution in order to evaluate the performance of node locations in different network sizes. However, it is not shown that the performance was gathered from individual nodes. This requires further investigation based on individual node location relative to the Portal and network centre. Furthermore, it also left a concern as to how the same nodes would perform when subjected to other distribution types, especially when using realistic topologies.

On Optimising Gateway Placement for Throughput in Wireless Mesh Networks (Zhou *et al.*, 2010)

This study is based on a proposed gateway placement scheme called Multi-Hop Traffic-flow Weight (MTW) in WMNs. The MTW algorithm is able to determine the location of the gateway by considering many different factors that impact on throughput, such as number of mesh routers, number of mesh clients, number of mesh gateways, location of gateways, traffic demand from mesh clients, and possible interference among gateways. The MTW provides a framework for how throughput can be improved. Since throughput is the most critical parameter for ensuring that the WMN meets QoS requirements. The study used pre-fixed gateways and each mesh router was associated with the nearest gateway. Hence the traffic load was evenly distributed across the network. The performance of the proposed gateway placement scheme was evaluated against other schemes. The results confirmed that the MTW performs better compared to other schemes.

The study did an evaluation using all node types in the WMN architecture. The mesh routers were associated with the nearest gateway, which meant that the performance of node location relative to the gateway was also evaluated. However, it is not clear which node distribution type was used. The assumption is that they used random distributions, hence the need to explore other node distributions such as realistic distributions.

Gateways Placement in Backbone Wireless Mesh Networks (Tang, 2009)

The authors in this study present a novel algorithm as a solution for gateway placement in IWMNs. Gateway placement has been identified as a challenge in IWMNs. The gateways are network points through which the backbone network communicates with other networks. The aim is to provide QoS while keeping the total number of gateways to a minimum. When placing the gateways it is important to guarantee maximum throughput for individual traffic flows. The authors present a novel algorithm which has several advantages, such as guaranteeing to find a gateway placement that satisfies all constraints. It also has a competitive performance and is easy to implement.

To measure the performance of the newly proposed algorithm, the authors had to compare it with three other algorithms for gateway placement through simulations. The performance of the four algorithms was evaluated and compared in terms of delay constraints, gateway capacity constraints and relay load constraints. The experimental results showed that the overall performance of the new algorithm was good compared to the other three algorithms.

When reviewing this study, it is apparent that the authors agreed with other previous studies that mentioned that the placement of the nodes has an impact on the performance of the network. However, the focus was more on placing the gateways and examining the algorithms used for the gateway placement. From the results section it is clear that the study did not consider other node types such as mesh routers or mesh clients, which also form part of the WMN, hence the need to include other node types, and additionally measure the performance of these nodes relative to the gateway.

Ad Hoc and Neighborhood Search Methods for Placement of Mesh Routers in Wireless Mesh Networks (Xhafa *et al.*, 2009)

Different topologies were used in this study in order to evaluate ad hoc and neighbourhood search methods for mesh router placement in WMNs. The main issue when deploying a WMN is to achieve maximum throughput while maintaining connectivity and stability of the network. Given that the nodes can have different distributions this study explored Normal, Uniform, Exponential and Weibull distribution of mesh clients. Furthermore, the study utilised the neighbourhood search method to optimally place the mesh routers.

The WMN is characterised by properties such as robustness, self-configuring and reliability, and the node placement plays a crucial role in achieving these properties. The authors also concur with other studies which stated that node location affects the performance of the network. Hence node placement has been regarded as a critical design issue in WMNs. In some cases the node placement is not pre-defined. Any available position in the deployment area can be used for placing the nodes.

This study focused on an approach in which the nodes are distributed arbitrarily in a fixed position that will maximise the network connectivity and coverage of the mesh routers. The nodes were placed using different topologies. Both mesh router and mesh client placement were evaluated. The study considered node placement, using different node distributions, but the focus was only on mesh routers and mesh clients and their performance. In as much as node placement has been considered in this work, and the nodes were placed on fixed positions, the effect of distance has not been considered.

Single Gateway Placement in Wireless Mesh Networks (Muthaiah & Rosenberg, 2008)

The need for proper gateway placement is increasing as WMNs are becoming popular for providing broadband access. Hence this study investigated the importance of gateway placement on network throughput for realistic configurations of WMNs. The focus of this study is based on a single gateway multi-hop WMN, where the traffic flows from the gateway to node or node to gateway. The study showed that gateway placement has an important impact in achieving maximum throughput. To determine the exact gateway placement the study employed a "brute force" approach which does not take into consideration the placement of gateways and computed throughput for all potential gateway positions. Different network types were involved, including Compact Grid, Irregular Grid, and Uniform distributions. The conclusion drawn from the results is that it is important to place the gateway optimally so that the network throughput can be maximised.

A typical WMN architecture is formed by various node types, including gateways, mesh routes. In this study the focus was on the placement and the performance of the gateway, to investigate if the gateways leave a gap in other nodes that forms part of the architecture. In as much as it is important to evaluate the performance of the gateway it is equally important to investigate other nodes within the network, since the traffic flows through all these network nodes. Investigations can be based on the effect of distance on QoS in the gateway-based traffic, using Random or Realistic topologies.

Deploying Rural Community Wireless Mesh Networks (Ishmael *et al.*, 2008)

In this study the authors present in detail different technical challenges when deploying a rural community WMN and its positive impact on the users. As technology is advancing daily rural areas are often left behind, hence the motivation to investigate alternatives for rural communities that still suffer from a lack of suitable broadband services. The investigation included a range of deployment challenges and operational issues. This study used a realistic network of Wray village, which covers approximately two square kilometers. The nodes were places strategically throughout the village. These nodes were equipped with IEEE 802.11 technology. The AODV provided the routing to the network backhaul of the Portal-based traffic.

The investigation was monitored over a period of time, observing unexpected behaviours. There was low connectivity and high latency, which was caused by the positioning of the node's aerial. To improve connectivity, they installed additional nodes and extended the aerial height. After careful observation of the network's behaviour, the authors developed a network topology called Wray network topology. This topology supported peer-to-peer file sharing services. They also developed a monitoring system which was able to capture information such as details of the individual flows on each node, delays at Gateways, and path selection through the mesh network. This data was used to analyse overall usage patterns and to indicate heavy users.

Even though the study considered the performance of individual nodes, it only focused on the aspect of transmission. The study revealed that two nodes cannot transmit at the same time. This resulted in negative impact of individual node throughput, and the network had poor QoS. To provide good QoS the study had to employ restrictions which used a leaky-bucket traffic-shaping algorithm. This algorithm was able to shape traffic into a steady stream on the network.

The study looked at realistic topology, and considered the performance of individual nodes in both Intra-mesh and Portal-based traffic scenarios. The study has the potential to explore other realistic topologies and other routing protocol types. It could also have explored the effect of distance on node location relative to the Portal.

Node Placement Algorithm for Deployment of Two-Tier Wireless Mesh Networks (Franklin & Murthy, 2007)

Placement of Mesh Nodes (MNs) is one of the important issues to consider when deploying WMNs, since the performance of a WMN is greatly affected by the location of these MNs. In the real network deployment, it may be somewhat difficult to place the MNs in a regular pattern. It is important to find the optimal location in the deployment environment. This study aimed to find locations of MNs that will maximise seamless coverage and connectivity of the network. The MNs should be placed such that there is better coverage and connectivity. The deployment process of a WMN must satisfy the traffic demand. The study then proposed an efficient local searching algorithm. An algorithm finds the best placement. The MNs are added one by one to the network and this iteration is repeated until all MNs are placed. This local search algorithm gives optimal performance compared to exhaustive searching.

The study mentioned that the location of nodes greatly affects the performance of the network. For the experiments the study used Grid node distribution, with a Portal-based traffic scenario. The results were obtained from the performance of the overall network. Even though the distribution of nodes in the Grid pattern may have fixed density distribution and transmission range, some MNs may not be within the same transmission range of the Portal. Hence it cannot be assumed that the performance of these nodes will be constant. Therefore, it is important to evaluate the performance of individual node location relative to the Portal.

Gateway-aware Routing for Wireless Mesh Networks (Acharya *et al.*, 2010)

WMN has been regarded as an attractive method for providing Internet connectivity in developing countries. Traditional mesh routing protocols are usually designed to achieve high throughput multihop paths in the network. However, these solutions did not consider constraints such as bottlenecks that may be imposed due to the capacity at the Portals. This study emphasised the importance of intelligent choice of Portals in WMNs. The study presented the design of a new portal-aware routing metric that identifies high throughput routes in the presence of heterogeneous Portals.

In developing countries, especially in the rural areas, the WMN architecture is used for Internet access provisioning in Home neighbourhood application scenarios, where the routers are placed in homes to provide in-residence wireless access. Few dedicated routers have gateway functionality and they are connected to the Internet. These Gateway nodes use different technologies such as WIFI, WIMAX, and DSL.

Traditional mesh routing solutions have focused on finding the best routes to the Gateway. This is done with two assumptions. The first assumption is that all gateway nodes have equal capabilities in terms of resources. The second assumption is that the capacity bottleneck is in the wireless multihop portion of the WMN. This study then did an examination of these assumptions in the context of rural community WMNs. A new routing metric Gateway-aware Routing Metric (GARM) was developed and implemented in IEEE 802.11s using simulation and testbed. The

GARM metric showed improved network performance by increasing the overall network throughput using existing resources.

This evaluation considered Grid node distribution for both Portals and backbone nodes. In a Grid distribution, some backbone nodes can be located near the Portal and some further from the Portal. The study only looked at the overall network performance and did not consider the performance of individual nodes, since the nodes are located in different positions within the network. The study could have used other types of node distributions.

Generating realistic node mobility and placement for wireless multi-hop network simulation (Milic & Malek, 2012)

There are quite a number of node placement models and algorithms designed for WMNs. Most of these topologies created using existing models do not resemble a real network. As a solution to this fundamental issue, Node Placement Algorithm for Realistic Topologies (NPART) was developed. NPART creates topologies that have properties of a real network, and also consider node degree distribution, number of cut-edges and vertices. The topologies were created using the open wireless multihop network in Berlin. NPART was used to evaluate the effect of integration between existing open community wireless multihop networks and Vehicular Ad hoc Networks (VANETs). The goal of this study was to compare the QoS metrics in WMNs and VANETs through simulations. Numerous parameters were considered in terms of varying the number of nodes, routing protocols. The results show that open networks offer higher levels of performance and network availability to the mobile end users, despite limited coverage and unusual topological properties.

This study did a comparison of node degree distribution and considered one type of node distribution within NPART. It could also have been an opportunity to investigate the performance of node location relative to the Portal in other distribution types.

2.1.2 Relevant Routing Protocol Studies

Evaluating Routing Protocols for the Wireless Mesh Backbone (Ashraf *et al.*, 2007)

WMN offers a promising solution for extending wireless coverage and increased communication reliability. For Internet connectivity, the wireless mesh backbone serves as an access network for a large number of different networks. These wireless mesh network backbones comprise dedicated routers which are immobile and suffer energy constraints. Ad hoc routing protocols are mostly developed for ad hoc networks, and concentrate mostly on mobility and how to save energy. This study did an analysis of the performance of four popular ad hoc routing protocols, of which two are reactive (AODV and DSR) and two are proactive (OLSR and DSDV) for the mesh backbone, through simulation. The authors considered static backbone nodes and mesh clients. These two types of nodes were treated as different entities since their performance is different in terms of characteristics and routing requirements. The mesh architecture used consists of Gateway Nodes and Mesh routers. The Mesh Router forms an infrastructure of wirelessly connected nodes, providing wireless access to other nodes and the Gateway node provides connection to the Internet.

The mesh backbones were being randomly distributed but the location of Gateways followed a Grid pattern. The Gateway-based traffic was considered. The experiments were conducted through simulation by considering the packet delivery fraction, end-to-end delay, and routing overhead metrics. The results showed that, in general, reactive routing protocols perform better than proactive routing protocols, due to low routing overhead. In as much as the study considered the Gateway-based traffic scenario, and used routing protocols to evaluate the performance of a IWMN, the hybrid routing protocols were not considered. It should also be noted that the study did the evaluation based on the entire network. The study did not consider the hybrid routing protocol. Hence, a gap still remains in terms of evaluating the performance based on individual node location, using all categories of the routing protocols.

Performance Study of Hybrid Wireless Mesh Protocol (HWMP) for IEEE 802.11s WLAN Mesh Networks (Bari, Anwar, & Masud, 2012)

WMNs have been seen as the solution to the next generation wireless networking, which can be helpful in many applications. Many applications have been proposed and developed. The current 802.11 based wireless networks depend on wired infrastructure to carry the user's traffic. However, this reliance can be expensive and not as flexible as Wireless Local Area Network (WLAN). The network performance depends on the design of the routing protocol and the routing metrics associated with them. This study investigated the performance of HWMP when subjected to different traffic conditions.

Simulations were done on Qualnet 5.1. The throughput, end-to-end delay, and jitter were used as the performance metrics to measure and compare the HWMP in both proactive and the reactive modes. The simulation was tested in voice, video, email FTP, and http applications. The evaluation results show that the throughput for the proactive mode is higher than that of the reactive mode, and that this was experienced in all applications except for voice. The results for the average end-to-end delay also show that proactive mode performs better than the reactive mode. This trend is also observed in the results for the jitter.

The study evaluated the performance of HWMP in random distributions, specifically the uniform node distribution. The study did not evaluate the normal node distribution, in which the nodes are located closely together.

Performance evaluation of reactive and proactive routing schemes for Infrastructure Wireless Mesh Networks.(Carrillo & Ramos, 2011)

In the times that we live in, the use of wireless devices is growing fast. In the same manner, connecting to the Internet is becoming a need for societies. These factors demand total connectivity, enabling users to access the information wherever they are. WMNs have been seen to be addressing this issue. The researchers studied the performance of the reactive and the proactive routing schemes in depth. The study focused on the evaluation of the performance of AODV and DSDV routing protocols in IWMNs. To evaluate the performance of these protocols six different performance metrics were used, namely, throughput, end-to-end delay, delivery ratio, routing overhead, traffic distribution, and loss pattern. The comparison was done through simulations in NS2.34. The aim was to test how the routing protocol performs in different conditions. Forty-nine static nodes, one which was a Portal, were placed in a 1600mx1600m area inter-cropping forming a 7x7 grid. The number of static nodes varied from [10, 30, 50, 100, 150], while transmission rate varied from [10, 20, 50, 100, 150, 200, 250, 300] kbps. For every simulation a UDP transport layer protocol was used with 512 Bytes as the packet size. Simulation was run for 1000 seconds. The results indicate that the use of the AODV protocol shows a better performance in IWMNs.

The focus of the study was to evaluate the performance of reactive and proactive routing schemes. AODV and DSDV routing protocols were considered. The study used Portal- based traffic, but the study did not reveal how individual nodes perform when subjected to different distances from the Portal.

MRP : Wireless mesh networks routing protocol (Jun & Sichitiu, 2008)

In this study the researchers showed that most traffic is to and from the gateway, and that the nodes have to be differentiated as stationary or mobile nodes. They then proposed a MRP routing protocol and evaluated the performance using simulation. Generally, MANETs routing protocols can be used in WMNs. The expectation is that the protocol that has the particularities of WMNs will perform better than the general routing protocol. This study evaluated the performance of the proposed MRP routing protocol via simulation. The evaluation was measured in terms of the network throughput, packets delivery ratio, routing overhead, average hop count, and the end-to-end delay.

The simulation results show that the proposed MRP routing protocol performs better than the existing MANETs routing protocols. The MRP will perform better for Portal-based traffic. However, for the intra-mesh traditional traffic, MRP may not ideal. Further investigations of MRP should be done in realistic topologies.

Performance Evaluation of Scalable Routing Protocols using Routing Metrics for Wireless Mesh Networks under different Network Scenarios (Nagegowda *et al.*, 2014)

WMNs has been considered as the solution to the wireless networks, that provides rural communities with broadband connectivity. More research must be conducted in terms of the performance degradation usually caused by unexpected behaviour of the routing protocols, given various network scenarios. In this study the authors perform a thorough investigation and recommend an appropriate routing protocol and suitable measurement using routing metrics. The IEEE task team adopted the IEEE 802.11s standard and proposed the default routing protocol. However, it is also important to examine the performance of different classification of routing protocols under different network scenarios.

The performance of reactive, proactive and hybrid routing protocol categories are considered as common protocols to be used in various network setups. The routing protocol must take advantage of the available multiple interfaces efficiently. The current wireless 802.11 based networks rely on wired infrastructure to transmit traffic. This results in an expensive wired infrastructure. The extension of WLANs' capability of coverage can be achieved through the help of the mesh concept. The way in which the WMNs will perform depends on the design of the routing protocol. The routing protocol selects the best path from source to destination.

The existing routing protocols in WMNs rely on the network layer and use hop count to enable multi-hop communication, but do not provide a suitable solution for choosing the best path from the sender to the receiver. Hence, the IEEE task team, which is called IEEE 802.11s, had to design and develop an integrated mesh networking solution. The task team classified HWMP as the default routing protocol and airtime as the default routing metrics for WMNs. This cannot be the same in different network scenarios and application traffic. In this study, a different classification of routing protocols is considered, i.e. proactive (OLSR), reactive (AODV), and hybrid (HWMP).

The performance of these routing protocols is evaluated under different network scenarios using different routing metrics.

The evaluation of the routing protocols in WMNs settings is simulated using Qualnet 5.2. 250 static nodes are created and located randomly in a 1500m x 1500m area. The simulation time is set to 800 seconds, and the average data collected was analysed. Performance metrics are ETX, ETT, WCETT and airtime. The simulation results show that HWMP performs better than AODV and OLSR. HWMP has a clear advantage over the other routing protocols.

All three categories of the routing protocols were evaluated, using different random topologies, and nodes were located randomly in a rectangular area. Within the distributions some nodes will be located near the network centre and some on the edge of the network. The study could furthermore have evaluated the impact of node location relative to the network centre.

Non-root-based Hybrid Wireless Mesh Protocol for Wireless Mesh Networks (Singh *et al.*, 2013)

WMNs are wireless networks comprising mesh clients and mesh routers. The mobility of mesh routers is minimal and forms the infrastructure of WMNs. The challenge with the use of WMNs is the wired connection between mesh routers. Therefore, it is required to connect mesh routers via wireless links. In WMNs, routing protocols can be categorised as reactive, proactive or hybrid. The hybrid routing protocol (HWMP) has been classified as the default routing protocol for IEEE 802.11s based WMNs. For the proactive mode, HWMP is centralised and controlled by the root node, resulting in a bottleneck at the root node, whilst in the reactive mode HWMP starts broadcasting path discovery messages and this consumes power resources. HWMP still cannot support route optimization. This study proposes a new routing protocol for WMNs based on HWMP, referred to as the Decentralised HWMP (DHWMP). It provides different routes for different transmissions. In the proactive mode of the proposed routing protocol source, Mesh Points (MPs) create PREQ for the destination MP and transmit it to MPP. When a source MP needs to transmit data packets to a destination MP, the source MP checks its routing table for the path to the destination. It will only create a new route if there is none.

In reactive mode, when a source MP requires a path to a destination MP, the source MP will check the routing table and find a path. The source node sends a hello message to the next MP, if a node is in a sleep mode, then after receiving the hello message that node becomes activated and ready for action. If a node is busy in any other transmission, then the node gets information that one more action is waiting to be processed.

For the simulation, they use NS2 to analyse the performance of these routing protocols. A total number of 100 nodes are placed in a 1000 x 1000m area. Four performance metrics are used in this simulation comparison, namely, channel capacity, packet delivery ratio, end to end delay, and routing overhead. After the simulations the results show that the proposed protocol DHWMP outperforms the existing routing protocols.

The Decentralised HWMP (DHWMP) was evaluated against the traditional HWMP, using uniform node distribution. However, it is not clear how these protocols will perform in other types of node distribution such as normal node distribution or realistic distribution.

M-HRP for Wireless Mesh Networks and its Performance Evaluation (Paul *et al.*, 2014)

WMNs are a subset of MANETs, where stationery routers form an infrastructure backbone. WMN provides coverage and connectivity to the mobile clients for data communication. Routing protocols for MANETs may not be directly applied to WMN scenarios. In this study the scholars propose a Mesh Hybrid Routing Protocol (MHRP) which exploits the advantages of E-AODV and M-OLSR. The performance and suitability of MHRP in WMNs was assessed by comparing the proactive routing protocol, i.e. M-OLSR, and the reactive routing protocol, i.e. E-AODV. For the proactive routing protocolthe node maintains a routing table, which describes the address of the destination node, next hop address, and hop required to reach the destination. The hop allows the router to send data to the destination node in the network. For the reactive routing protocol the node will only establish the path if there is a request.

The simulation was conducted on a Qualnet simulator, with the performance metrics being throughput, packet delivery ratio, network routing overhead, and end to end delay. A Random waypoint movements mode was adopted. They varied the number of nodes, mobility, and traffic load in different scenarios. For the first scenario, the performance of M-HRP was evaluated in a sparse network. Traffic load conditions which has varying number of data packets sent per second, and the number of flows remained constant throughout the simulation. The results observed in this type of scenario which is the performance of the routing protocol, shows that M-HRP performs better than M-OLSR and E-AODV. The throughput increased as the traffic load increased. For the PDR, as the traffic load increases the PDR also decreases for all three protocols, because of the increased interference and contention.

In M-HRP and M-OLSR the average end-to-end delay increases in a linear fashion. For the second scenario the scalability of the routing protocol was analysed with the network dynamic in a sparse network. Simulation evaluation was performed by changing the speed of mobile devices in different load conditions. It was observed that as the speed increased, throughput and packet delivery ratio dropped. This applied to all protocols. For the third scenario the average node density was also varied. This helps to determine how protocols scale with the node density. The observation was that the throughput increased for all protocols when the node density increases. This was because the nodes had a close association and they were available in the network, which minimised the chances of link breakages. Packet delivery ratio decreases for all protocols as the node density increases, because of the increase in number of hops. Overall, for the packet delivery ratio the newly proposed protocol M-HRP performs better compared to E-AODV and M-OLSR.

The study proposed MHRP for WMNs which was evaluated in different scenarios in the uniform node distribution. Performance measurements were varied, including the network size, mobility and traffic load. However, it is not clear how the node location relative to the network center and relative to the Portal impact on the performance of individual nodes.

Performance Comparison of AODV and HWMP Routing Protocols in Wireless Mesh Networks (Ibrahim *et al.*, 2013)

WMN is drawing attention from researchers in the telecommunications industry, due to its ability to provide Internet broadband access at low cost, coverage in wireless local area networks, and network connectivity to mobile and static nodes. WMNs has wireless routers that are used to transmit each other's data packets in a multi-hop manner. In this type of network all nodes must cooperate in order to transmit data from one node to another. Mesh routers usually have gateway functionality, which allows the network to be connected to the Portal. Sending nodes and the receiving node can be several hops away from each other; the data packets must be routed and sent in the network itself.

Thus a routing protocol plays a vital role in maintaining the connectivity of WMNs. The success or failure of the network depends on the routing protocol. This study aimed to investigate the performance of the reactive routing protocol (the AODV) and the hybrid routing protocol, the HWMP, which is specifically designed to be compatible with WMNs in 802.11s. To ensure fair comparison both routing protocols were simulated using NS3. The simulations were done in two random network technologies, varying the network size. UDP connections was the type of connection used. Node location, the pair of sending and receiving nodes, number of connections, and the period of each connection during the simulation were considered in order to perform a fair comparison. Simulation ran for 300 seconds. Number of nodes and simulation area were also varied. Three performance metrics are used for the performance evaluation, namely, packet delivery fraction, time delay, and throughput.

The results confirmed that HWMP performs better than AODV in terms of delay, throughput and packet delivery fraction in both smaller and larger network sizes.

WMN is gaining popularity with researchers in the field of telecommunication engineering. This popularity is because of its potential to provide Internet broadband access, coverage for wireless local area networks, and network connectivity for static and mobile nodes. Nodes rely on each other to transmit packets in a multi-hop pattern, therefore the routing protocol plays an efficient role in maintaining the connectivity of WMNs. In the network the source and destination nodes may not be close to each other, and it may require several wireless hops to send the packets from source to destination. Routing protocol plays a vital role in ensuring that the packets are transmitted.

This study compared the performance of two types of routing protocol, i.e. the reactive routing protocol (AODV) and the hybrid routing protocol (HWMP). Both of these protocols are compatible with WMNs 802.11s. An NS3 simulator was used to measure the performance of these protocols. In order for a comparison to be fair the all categories of routing protocols, position of the node relative to the Portal had to be considered.

Performance Evaluation of Routing Protocols in Wireless Mesh Network (Zakaria *et al.*, 2013)

WMNs are being considered as a promising solution to offer broadband connectivity in rural communities. The reality is that Internet availabilty is still low in rural areas. WMNs deployment are scalable, cheap, easy to maintain, and has the ability to provide extended coverage. However, throughput degradation, latency and interference are the weaknesses, due to multi-hop transmission and nodes that might potentially be isolated during WMNs deployment. This study investigates a proper routing protocol in the context of offering rural broadband communication. In the investigation they evaluated three classifications of routing protocols, namely reactive (AODV), proactive (OLSR) and hybrid (HWMP).

The impact of the evaluation is conducted through simulation. The simulation helps in analysing the performance of different routing protocol in the WMNs environment. Qualnet 5.2 is the simulator used . 100 static nodes are randomly positioned within an 800m x 800m area. Each scenario is simulated for 500 seconds. The result is obtained by taking the average of the simulation runs. The perfomance of the routing protocols in WMNs is evaluated by using various rouitng metrics, namely, throughput, end to end delay, traffic load, network size and the number of sources. From the results it is clear that HWMP outperforms AODV and OLSR. HWMP is able to keep up with the increased number of nodes in the network.

The study can also perform the same evaluation in realistic topologies, whereby the network topology consider real life constraints.

Performance Analysis of Unicast Routing Protocol In IEEE 802 .11s Wireless Mesh Network (Fumtiwala *et al.*, 2015)

WMNs are growing technology in the world of wireless networks. WMNs aim to deliver braodband access to applications like community networks. A major feature of WMNs is inexpensive deployment costs. Additionally, the network is easy to maintain, robust, self-healing, self-organising, and self-configuring. This inpires a number of applications. WMNs can be considered as part of MANETs. WMNs are a type of networks comprising mobile nodes and routers. The nodes can form a dynamic or static topology. All these nodes communicate with one another in a mesh topology. The routers have the capability to provide Internet to the other mobile nodes. In most cases, the network usually has few routers because of its high cost. The main aim behind developing wireless mesh networks is to eliminate the restrictions of single hop communications.

The IEEE 802.11 continued to develop functionalities intended to assist in the incorporation of WMNs with other networks. One of the fundamental attributes of WMNs is the rouitng. In order to take advantage of WMNs features, WMNs must have new and improved routing protocols. The routing protocols' strength and weakeness can affect the perfomance of WMNs. Since WMNs are part of MANET, routing protocols used in MANETs can also be used in WMNs.

The scholars in this study performed the analyisis of unicast rouitng protocols, i.e. AODV, OLSR, and HWMP, using PDR, end to end delay and bit rate as the performance metrics in an NS3 simulator. The performance analysis was done between the protocols and packet delivery ratio, end to end delay and bit rate. NS3 version 3.20 was the simulator used to conduct experiments. They obtained their results by varying the number of nodes against the performance metrics. The results show that OLSR performs better compared to AODV and HWMP. As the number of nodes increase, AODV performance decreases. Extreme delay is experienced in AODV compared to OLSR and HWMP. According to the overall results OLSR outperforms HWMP and AODV in delay and PDR. For the data transfer speed the option should be HWMP.

The study evaluated the performance of all categories of the routing protocols in WMN. However, the study only considered the performance of the entire network, and did not look at the performance of individual nodes, especially when these nodes are located relative to the Portal.

Performance Analysis of WMNs-GA Simulation System for different WMNs Architecture considering OLSR (Barolli *et al.*, 2015b)

WMNs can be visualised as a special kind of wirelss ad hoc nrework. All the nodes are connected to each other based on the mesh topology. This connection allows information to be transmitted amongst the network nodes, in more than one path. There is no need for a central node. This allows flexibility amongst the nodes to recover if there is any node failure. In WMNs the task for the mesh router is to provide ntework connectivity services to the mesh clients. the performance of the

WMNs will depend on how these mesh routers are placed within the deployemnt area, in order to achieve network connectivity and mesh client coverage.

There is a lot of attention from the wireless network researchers on WMNs. Problems regarding node placement have been investigated for quite some time. Work has been done to evaluate WMNs-GA system which is based on Generic Algorithms (GAs). This helps to get the best location assignment for mesh routers. Furthermore, in this study, the authors did the perfomance evaluation of normal and uniform node distribution for two WMNs architectures, namely, hybrid WMNs and Infrastructure/Backbone WMNs.

The work that has been done in previous studies considered the placement of mesh routers and mesh clients in a fixed position using arbitrary distribution in a grid area. For this work the scholars focus on using topology generated by a WMNs-GA system. The performance evaluation is conducted through simulations, using NS3 and OLSR as the proactive routing protocol. Performcance metrics considered are delay, throughput and energy level. The simulation results show that for both node distributions the throughput obtained by the hybrid WMNs is higher than the throughput obtained in I/B WMNs architecture. In terms of delay the Hybrid WMN has low delay compared to the I/B WMN. The delay for Hybridd WMNs in both distributions is almost the same. However, for I/B WMNs delay is lower in uniform distribution. In terms of energy, in normal distribution the energy decreases sharply, because of the high node density. For uniform the energy that remains is higher compared with normal distributions.

The study considred both uniform and normal node distributions, using only the proactive routing protocols. The study did not show how the reactive or the hybrid routing protocol performs. Furthermore, the study could further consider using realistic topologies.

Evaluating Transceiver Power Savings Produced by Connectivity Strategies for Infrastructure Wireless Mesh Networks (Mudali, Mutanga, & Adigun, 2011)

IWMNs seem to be bridging the digital gap in the rural community. Most of the African countries need energy efficient IWMNs. In the rural African context electrical power is often unreliable or does not exist. The backbone nodes may need to be battery-powered, due to the absence of reliable energy supplies. IWMNs must maintain connectivity and function properly. However, the devices use maximum transceiver powers, which is a disadvantage. Using maximum transceiver power is seen as a shortcoming which results in a high level of interference and increased contention for the shared transmission medium, reducing network capacity and transceiver power consumption. According to this study, the authors stated that there exist two main types of connectivity strategies in the literature. These connectivity strategies have shown that they have the ability to create the interference-efficient network topologies. The focus was mainly on the Critical Number of Neighbours (CNN) method.

To evaluate the strategy, simulations were done through an NS2 simulator, using an OLSR proactive routing protocol. The performance metrics used were network connectivity, transceiver power savings, transceiver power assignment, and the network lifetime. The network size varied from 20 to 120 nodes simulated with uniform node distribution. The evaluation results show that cumulative transceiver power savings of an additional 10% can be achieved. The ability of the node to produce these transceiver power savings depends on the node location relative to the network centre.

The study considered the performance of uniform node location relative to the network centre, in terms of energy consumption. The study could further investigate the performance of individual nodes in realistic topologies.

Evaluating the Effect of a Topology Control Scheme on Application Layer Traffic Scenarios in Infrastructure Wireless Mesh Networks (Mudali, Mutanga, Adigun, & Ntlatlapa, 2012)

IWMNs have been seen as a promising solution for providing connectivity in rural areas. The hindrance is the lack of energy efficient nodes. In the absence of reliable power supplies in rural areas, battery-powered nodes become a feasible solution. This study investigates the effect of the Plain TC Topology Control scheme on the Portal-based and Intra-mesh traffic flows via simulations. With the existence of the different traffic flows, the QoS must also be ensured on the network. The deployment of IWMN nodes mostly depends on the use of maximum transceiver powers. This results in ineffectiveness of the network, such as high levels of interference, network capacity being reduced, and excessive transceiver power consumption.

A Topology Control scheme was developed as a result of these lacks linked with maximum power consumption. The purpose of Topology Control is to improve QoS guarantees of the WMN by enhancing transceiver powers whilst maintaining the network connectivity. This study evaluates the effect of TC scheme on the Intra-mesh and Portal-based traffic flows through simulation. The simulation was done using a NS2.34, with the number of nodes ranging from 20 to 120. OLSR was the routing protocol used, with the network connectivity, transceiver power savings, packets delivery ratio and throughput as the performance metrics. The results revealed that the TC scheme employed is more suitable for smaller network sizes.

The study considered Intra-mesh and Portal-based traffic scenarios supported by IWMN. The study looked at the performance of Intra-mesh and Portal-based traffic using different performance parameters. Since the study considered both traffic scenarios, the study had an opportunity to investigate the effect of node location relative to the network centre, and effect of node location relative to the Portal. Furthermore, evaluate the same scenarios in Realistic topologies.

Ad Hoc Networks Load-balancing in MANET shortest-path routing protocols (Souihli, Frikha, & Hamouda, 2009)

MANETs are types of wireless network with no infrastructure. The nodes are mobile, connected via wireless links. The communication can be through bandwidth- limited, variable capacity, error-prone and wireless channels that are insecure. Also, congestion can be a challenge, since wireless links have low capacity compared to wired links. Other constraints could be limited battery power which can limit services and applications in each node. The traffic is supposed to be evenly distributed among the mobile nodes to prevent nodes from being heavily loaded which might cause congestion delays or even drain energy quickly.

A survey on load balancing in MANET was conducted because most MANET routing protocols lack load-balancing. Shortest-path MANET routing usually utilises nodes at the centre participate in a large number of routes. This causes a few nodes to be carrying unnecessary load, resulting in high congestion, high delays, low packet delivery and high routing overhead.

This study presents a new load-balancing mechanism that is able to push traffic away from the centre of the network in order to lessen load at central nodes.

The proposed mechanism should balance the network load and directs traffic away from the network centre. Using the shortest path plays a role in load unbalance, it is therefore important to provide a metric that takes into account the degree of node centrality when deciding a path.

Instead of using a shortest path, the nodes should consider using relatively short paths that are formed by nodes far away from the centre of the network. The assumption is that nodes at the centre should have the highest number of routing tables.

In this study the focus is on two types of routing protocols, namely the proactive (OLSR) and the reactive (AODV). The performance metrics used are load distribution, end-to-end delay, packet delivery fraction, and routing overhead. NS2.29 is used for the simulation, with ten different scenarios defined. The nodes are distributed in a uniform fashion. Fifty nodes are placed in a rectangular area of 670m x 670m, with a simulation time of 900 seconds.

In the case of the reactive routing protocol, the results show that the nodes that are closer to the centre of the network participate in more routes than the nodes far from the network centre. In the case of proactive routing protocol, it was also proven that the nodes at the network centre forward more traffic.

In terms of the performance metrics, before they employed the load-balancing mechanism the traffic was uneven throughout the network. However, after using the load-balancing mechanism the load of the nodes in the centre of the network was greatly reduced.

The study mentioned that the node location relative to the network centre has an impact on the network performance. The study considered the Intra-mesh traffic scenario, and did not measure the performance of node location in a Portal-based traffic, and consider different types of node distributions.

2.2 Common Deficits as Research Opportunity

The above-mentioned studies showed the result of the performance of random and realistic networks when routing protocols, transport layer protocols, node distribution and traffic types are used. The previous studies reported evaluation results based on the entire network performance and based on the node location relative to the centre of the network. It is clear that not much has been done in evaluating all the three types of routing protocols in random and realistic topologies. Furthermore, most studies overlooked the traffic types. Hence, this study aimed to investigate the impact of individual node location on QoS mechanisms in IWMNs. This will be accomplished by considering random and realistic topologies, Intramesh and Portal-based traffic, AODV, OLSR, and HWMP, using throughput, end-to-end delay and packet delivery ratio as the performance metrics. The next chapter details how the investigation was conducted.

3. CHAPTER 3

3.1 Setup of Experimental and Simulation Environment

3.1.1 Introduction

In general, there are many techniques that can be used to assess the performance of a network. This includes, but is not limited to, theoretical analysis, simulation, emulation, virtualisation and test beds. The theoretical analysis involves mathematical modelling, whereby state transition diagrams can be used to evaluate the network performance. Developing mathematical models can be difficult and consume a large amount of time. In simulating a network, simulator can be used to allow the researchers to model the real environment.

When conducting research on networks, creating a real- time scenario may be a challenge (Aseri, 2015). Sometimes, the real- world system may not be available, hence, a simulation tool can be a solution to complex and expensive systems. The use of a simulation tool is gaining popularity in wireless networks research. Simulation can determine whether the obtained solution can be deployed in real- life implementation. However, many different simulators have been developed, including NS2, OPNET, NETSIM, VISUALSIM, JSIM, OMNETT++, GLO-SIM, and QUALNET. These simulators have different uses, characteristics, advantages and drawbacks. Some advantages of using a simulator are that it is easy to increase network topologies, especially in applications that require high scalability. The simulation process is easy to maintain. New routing protocols can be developed and tested through simulations. Testing expenses are usually reduced. The simulation process can be repeated to obtain more accurate results. The researcher has full control of the simulation process, and the process of creating, modifying, preparing and data gathering is efficient and easy.

The researcher has to choose the simulator according to the needs of the research and the type of evaluation.. The next section explains the justification for the chosen simulation tool.

3.1.2 Selection of the Performance evaluation Tools

Network Simulator (NS2) is open software while the other types are proprietary software. NS2 is a discrete event-driven simulator that is used widely in network research. NS2 is used to model wired, wireless and satellite scenarios. NS2 can model large- scale network topologies which could be costly to implement in test-bed experiments. NS2 is designed to be able to work on different platforms such as Linux, Windows and Mac. NS2 has a wide range of built in C++ classes. These classes can be used to set up a simulation through a Tool Command Language (TCL) script. The NS2 package is able to simulate real network behaviour, by creating network topologies, log the events that happen in any transmission, and generate trace files which are text-based simulation result. The behaviour of the network can be analysed by extracting a subset of text-based data. Trace files contain all the information about the packet, which includes the layer, routing protocol, and the event which determines whether the packet was sent, received, dropped, or forwarded.

3.2 Simulation Setup

3.2.1 Random Topologies

The simulation process for Random topologies involves creating a node placement file and the traffic patterns using setdest and cbrgen, which are built-in functions within NS2. The two files are then used in the TCL script. Other parameters such as the simulation time and the routing protocols are set on the TCL script. The simulation begins and executes events chronologically until the clock reaches the threshold value, and generates the trace file. Figure 3.1 shows the simulation process for Random topologies.

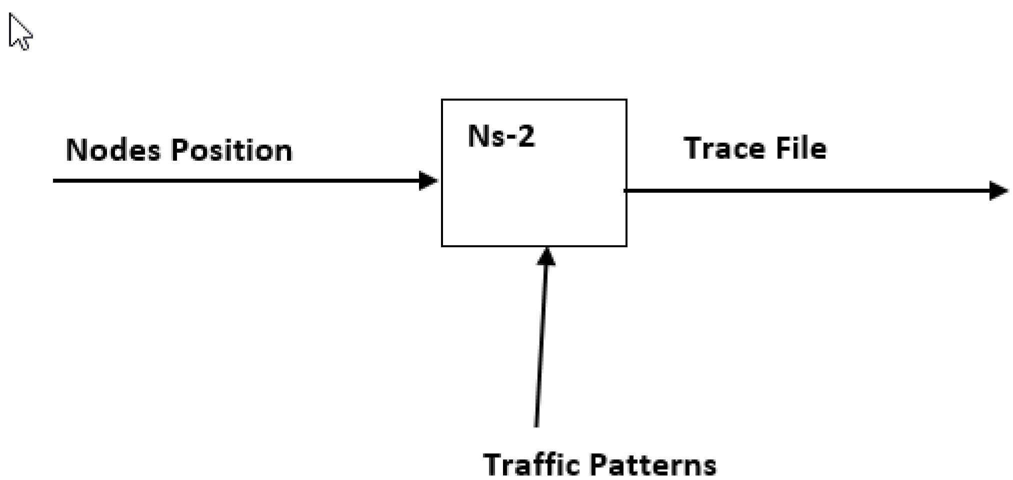


Figure 3.1: Random Topology Simulation Process (Sibeko *et al.*, 2017)

The simulation process derives from NS2.34 using a fixed 512 bytes as the packet size. The network nodes are fixed and equipped with a sending rate of 4 packets per second. The network area is a flat grid of 600m by 600m used for all nodes ranging from network sizes of 20, 40, 60, 80, 100 and 120 nodes. The nodes are placed randomly in a uniform or normal node distribution. The simulation time is set to 1000 seconds. TCP traffic sources are used to generate data traffic.

There are two traffic types considered, i.e. node to node (Intramesh traffic) and node to Portal (Portal-based traffic). The detailed simulation setup is shown in Table 3.1.

Table 3.1: Simulation Parameters for Random Topologies

Parameter	**Value**
Number of Nodes	20-120
Network Area	600m x 600m
Distance from the Portal and network centre	Metres
Routing Protocols	AODV, OLSR, HWMP
Performance metrics	Throughput, End-to-end delay and Packet Delivery Ratio
Transport Protocol	TCP
Node distribution	Uniform, Normal
Simulation Time	1000 seconds
Packet Size	512 Bytes
Traffic type	CBR
Traffic rate	4 packets per second

3.2.2 Realistic Topologies

There are many different topology generation algorithms which can be used in simulations, but the difficulty is finding the algorithm that will produce output similar to the real network. This work also explored the use of the Node Placement Algorithm for Realistic Topologies (NPART) which can create realistic topologies. The NPART algorithm is adaptive, flexible and can take different data input to produce different realistic topologies. When NPART was created, sociological and technological factors that shape the topology of a real network were considered. These factors need to consider that a new backbone node may join the network, and a backbone node anticipate to have at least one communication link, which connect to the remainder of the network. Subnets can be created.

The NPART algorithm was designed such that the topology area is determined based on the input parameters. It is not defined by the user. The development of the NPART algorithm includes parameters such as the number of backbone nodes to be positioned, communication radius of backbone nodes R, and node degree. The node degree is used in order to provide a compromise between input detail level and the feasibility of sampling in real networks. The backbone nodes are added one by one. The topology area, usually a rectangle, contains the backbone nodes that have been placed. To demonstrate the adaptivity and quality of NPART, samples from WMN in Berlin and Leipzig were used.

The simulation process caters for the strengths of both the NS2 simulation tool and NPART which is a tool to create realistic topologies as shown in Figure 3.2. The first phase uses the NPART tool to generate realistic topologies using parameters such as specifying the number of nodes, communication radius, Berlin or Leipzig node distribution type, and the output format. It is of importance to specify the output format for NS2, since NPART can output to various formats. When using NPART to create a network topology, the created network is fully connected because of the high node degree. NPART creates a fully connected network topology based on the WMNs for Berlin and Leipzig node placements.

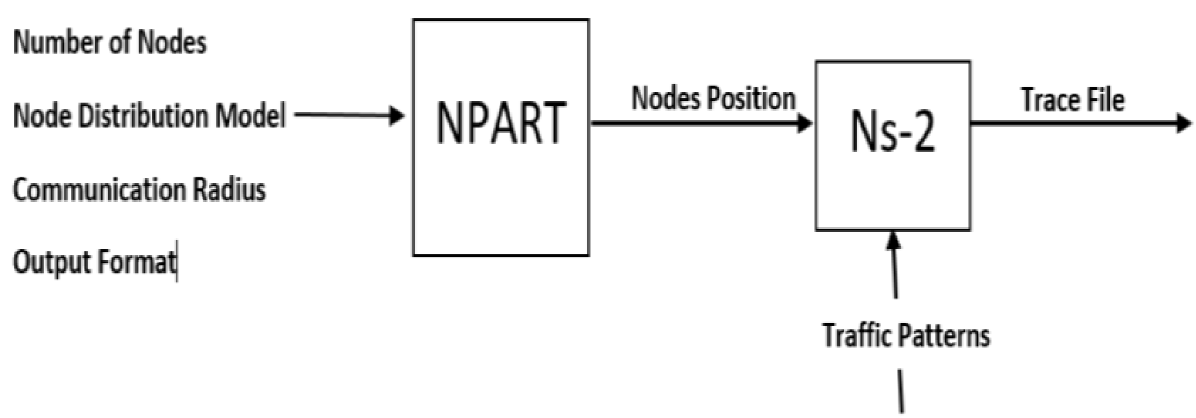


Figure 3.2: Two-phase Simulation Setup (Sibeko, Mudali, & Adigun, 2017)

It has been mentioned that the type of topology used has an impact on the simulation results obtained. This work had to consider the parameters involved in designing a realistic topology. These parameters are presented in Table 3.2 and Table 3.3 below:

Table 3.2: Parameters of the Berlin Node Distribution

	120 Nodes	100 Nodes	80 Nodes	60 Nodes	40 Nodes
Communication Radius	90	90	90	90	90
Average Node Degree	4.03	4	3.85	3.7	3.35
Links	242	200	154	111	67
Bridges	53	44	32	20	14

Table 3.3: Parameters of the Leipzig Node Distribution

	120 Nodes	100 Nodes	80 Nodes	60 Nodes	40 Nodes
Communication Radius	90	90	90	90	90
Average Node Degree	4.78	4.72	4.57	4.46	4.15
Links	287	236	183	183	83
Bridges	25	23	14	9	8

The second phase is to use the NS2 simulation tool. NS2 offers broad support for traffic models and node placement models. However, NS2 does not support the creation of realistic topologies. Thus this work use NPART to create realistic topologies, and integrate the node placement file into NS2 Intramesh and Portal-based traffic patterns, which were created using NS2 cbrgen tool. NS2 TCL script will run to generate trace files. These trace files will then be analysed using the NSTraceAnalyser to extract the desired information based on the performance of individual backbone nodes.

The impact of backbone node location relative to the network centre and relative to the Portal was measured. The backbone nodes were subjected to different distances from the network centre, and distance from the Portal. Perl script was used to calculate the distance of each backbone, and measured in metres. The detailed simulation parameters are shown in Table 3.4

Table 3.4: Simulation Parameters for Realistic Topologies

Parameter	**Value**
Number of Nodes	40-120
Network Area	Defined by NPART tool
Distance from the Portal and Network Centre	Metres
Routing Protocols	AODV, OLSR, HWMP
Performance Metrics	Throughput, end-to-end delay and Packet Delivery Ratio
Transport Protocol	TCP
Node Distribution	Berlin, Leipzig
Simulation Time	1000 seconds
Packet Size	512 Bytes
Traffic Type	CBR
Traffic Rate	4 packets per second

The next step is to perform the post simulation phase or the analysis phase, whereby the performance of the simulated network is being analysed. While the simulation is running, all the details of packet flow are recorded on the trace file. The performance is measured by extracting information such as throughput, packet delivery ratio and the delay achieved by the individual node at the Application layer (AGT). The information extracted from the trace file is analysed with the NS2 Trace Analyser and the graphs plotted using GNUPLOT 5.0

In both realistic and random topologies, the nodes were subjected into two different scenarios, namely, the effect of distance from the network centre and the effect of distance from the portal.

3.3 Performance Metrics

The performance metrics used in this research are presented in this sub-section. Each experiment was repeated 5 times. The average per node was obtained and used for the analysis. The behaviour and performance of individual nodes relative to the Portal and the network centre were considered. Perl script was used to calculate the distance from the network centre or the Portal. The Packet Delivery Ratio (PDR), End-to-End Delay and Throughput are generally used as the standard performance measurement. These measurements are used for each of the routing protocols being evaluated. The performance metrics were measured against the distance from the network centre and the distance from the Portal. Three experiments were performed under each performance metric. The TCP is kept constant for all experiments. TCP is the predominant transport layer protocol in the Internet today (Manoj & Murthy, 2005). TCP is capable of transporting a larger percentage of Internet traffic. The three routing protocols used are AODV, OLSR and HWMP. The protocols were tested with the same loads and under the same environment conditions, to guarantee fair comparison. Different scenarios with different traffic loads were generated for the actual simulation. Two types of topologies were considered: random and realistic. For the random topologies, the uniform and normal node distribution were considered. Berlin and Leipzig node distribution we considered for the realistic topologies.

3.3.1 Packet Delivery Ratio (PDR)

Packet delivery ratio (PDR) is the percentage of data packets sent that successfully reached the intended destination node. The PDR is measured from when the simulation starts until the simulation ends. The PDR is calculated per individual node. The node can be a sending or receiving node. The process was done for different network sizes. A PDR of 0% represents the total failure of the network to deliver its data packets whilst a PDR of 100% shows that all the data packets in the network were successfully delivered. The mathematical formula used to calculate the PDR is presented below:

$$packet\ delivery\ ratio = \frac{total\ packets\ received}{total\ packets\ sent} \times 100$$

3.3.2 End to End Delay

The aim of the experiments is to determine the time taken by data packets when travelling from source to the intended destination at the Application Layer (AGT). Only data packets that are successfully delivered to the destination are counted. The end-to-end delay was measured from the node to Portal, and from the Portal to the node. The results are measured in milliseconds (ms). The end-to-end delay is measured against the distance from the network centre and the Portal, in Normal, Uniform, Berlin and Leipzig node distributions. Three routing protocols, i.e. AODV, OLSR and HWMP, were selected for measuring the QoS of the individual node performance. A network with good performance will ensure as little end-to-end delay as possible. The lower value of end-to-end delay indicates the better performance of the protocol. The mathematical formula for the end-to-end delay is shown below:

$$\text{end to end delay} = \frac{\sum(arrive\ time - send\ time)}{\sum number\ of\ connections}$$

3.3.3 Throughput

Throughput indicates the number of bits received at the node. Throughput is the rate of successfully delivered packets in a particular period. Throughput should be maximised while ensuring that QoS requirements are met. The throughput is calculated per individual node. This is done to enhance the performance of individual nodes and eliminate the negative effect on the throughput of the entire network. The experiments were performed for different network sizes ranging from 20 to 120 nodes, and throughput results extracted separately for each node. The tracefile produced by NS2 records each traffic flow. The values for each node were extracted using NS2 Visual Analyser. The simulation process was planned to span different network sizes. The mathematical throughput formula is presented below.

$$throughput = \frac{total\ packets\ received}{simulation\ time}$$

The simulation results are categorised into two scenarios: the effect of the distance from the network centre, and the effect of the distance from the Portal. In the effect of distance from the Portal, only the Portal-based traffic scenarios were investigated. The scenarios are further sub-divided according to the node distribution, that is the Normal, Uniform, Berlin and Leipzig node distributions. The findings of the experiments performed are presented in the next Chapters.

4. CHAPTER 4

4.1 Results Analysis of the Random Topologies

The previous chapter presented the measurement methodology and experimental setup, which explain the simulation process for random topologies. The x-axis represents the effect of distance from the network centre, and the effect of distance from the portal, respectively. The y-axis represent the different matrics used. In the Portal-based traffic scenarios both the effect of distance from the network centre and the effect of distance from the portal were measured. In the Intra-mesh traffic scenario, only the effect of distance from the network centre was measured. The results are presented in terms of the performance metrics, namely, packet delivery ratio, end to end delay, and the throughput achieved by individual nodes.

4.2 Experiment 1: Packet Delivery Ratio

4.2.1 Scenario 1: The Effect of Distance from the Network Centre

This section presents the PDR results for individual nodes' communication with each other in a normal and uniform node distribution. Two traffic types were considered, that is the Intramesh and the Portal-based node distributions. With both traffic types only the distance from the network centre was considered. Figure 4.1 is an attempt to characterise the packets transmission over the network in a uniform node distribution. Figure 4.2 shows the packets transmission over the network in a normal node distribution. It is clearly shown that the nodes located at the centre of the network have more traffic compared to the nodes at the network edge, as more data packets are sent or received in the centrally located nodes. A study by Souihli *et al.* (2009) stated that the nodes closer to the network centre are more heavily loaded than the nodes located far from the network centre. The same trend is also observed in Figure 4.3 and 4.6 since a high number of routes occurs around the network centre.

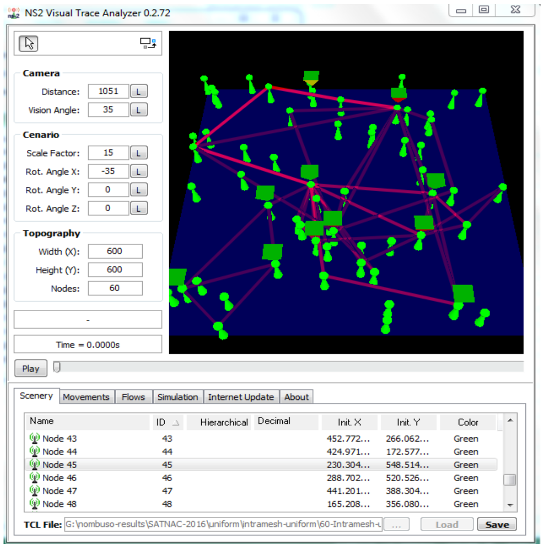


Figure 4.1 Intramesh Uniform Node Distribution: Packets transmission.

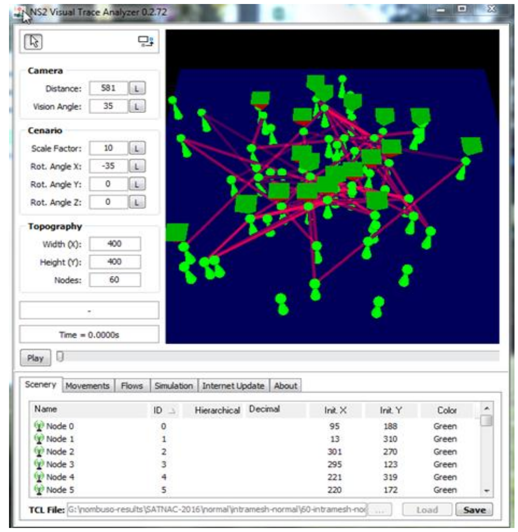


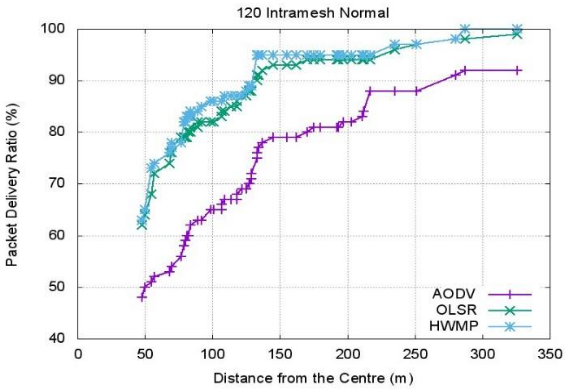
Figure 4.2: Intramesh Normal Node Distribution: Packets transmission.

Figures 4.3 – 4.6 show the results of the packet delivery ratio when the individual nodes are subjected to distance from the network centre. using AODV, OLSR and HWMP routing protocols in normal and uniform node distribution. When examining the results displayed in Figures 4.3 (a-f) – 4.6 (a-f), the results show that the backbone nodes located near the network centre achieved low packet delivery ratio compared to nodes far from the network centre. The graph starts to climb as the distance from the network centre increases.

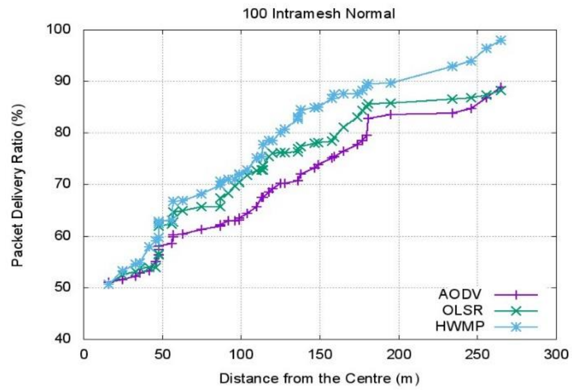
Figure 4.3(a) clearly shows that AODV is the least- performing routing protocol. AODV does not necessarily maintain fresh routes or send updated information to all backbone nodes. If the routes are not being used, they expire. Furthermore, if there is a route break, it becomes difficult to determine if the route is still available. AODV only establishes the route if there is a request. The request is broadcast via flooding. Flooding can lead to potential high overhead, whereby the data packet can be delivered to many nodes which do not necessarily need to receive them. It also lowers reliability of data delivery and makes it hard to implement reliable broadcast delivery without increasing overhead.

There is a trend observed in large-sized networks, namely that the nodes closer to the network centre obtain just above 50% in the normal node distribution.The uniform node distribution obtained the packet delivery of just above 40%. The justification for the percentage delivered is the nature of the node distribution. With the uniform node distribution, the nodes are positioned far from each other, as shown in Figure 4.1 There is a wider transmission range and the packets has to travel longer distances before reaching the intended destination. With the normal node distribution, the nodes are located closely to each other, reducing the transmission range and the distance that the packets have to travel before getting to the destination.

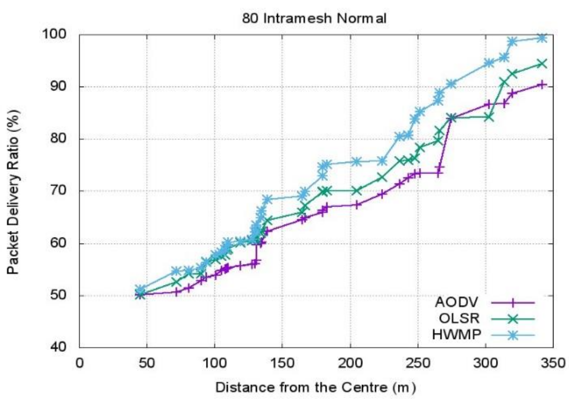
a) Intramesh traffic in Normal Node Distribution



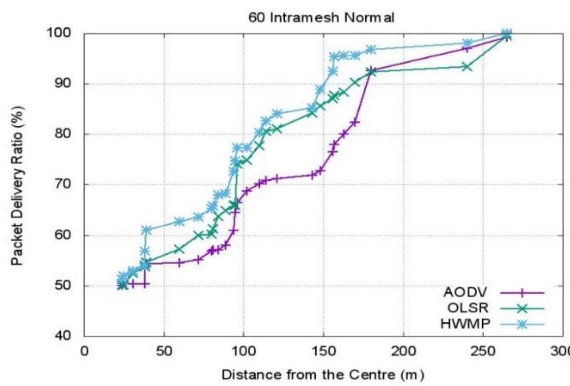
a. 120 Node Network



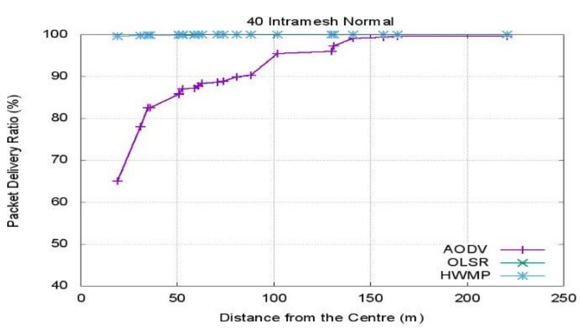
b. 100 Node Network



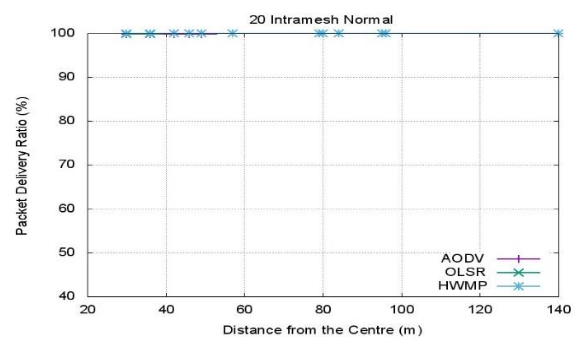
c. 80 Node Network



d. 60 Node Network



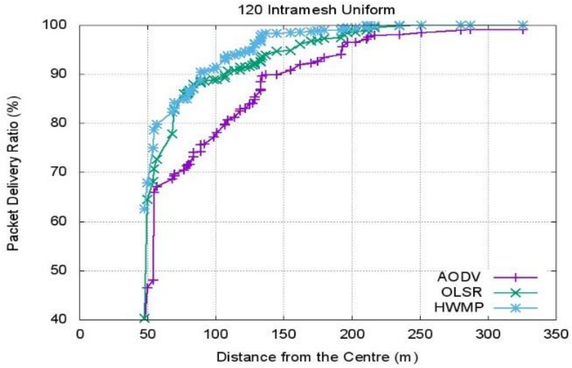
e. 40 Node Network



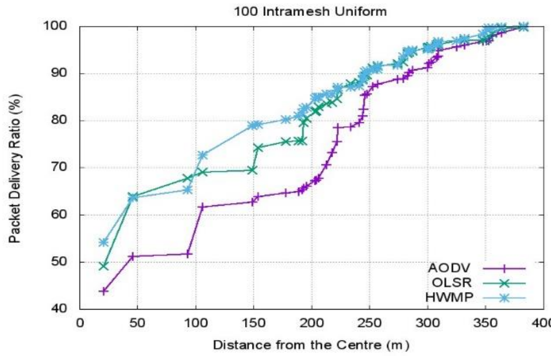
f. 20 Node Network

Figure 4.3 : Packet Delivery Ratio vs Distance from Network Centre in Intramesh Normal Node Distribution

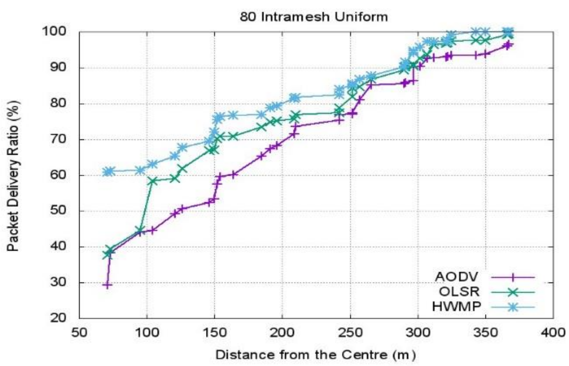
b) Intramesh traffic in Uniform Node Distribution



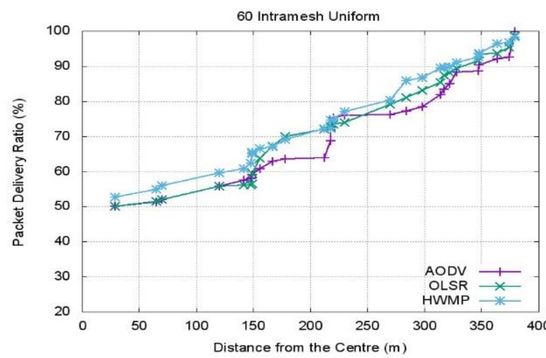
a. 120 Node Network



b. 100 Node Network

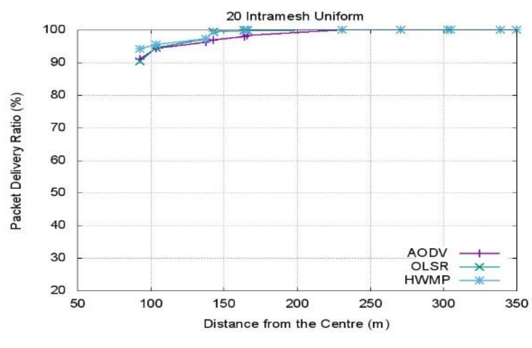


c. 80 Node Network



d. 60 Node Network

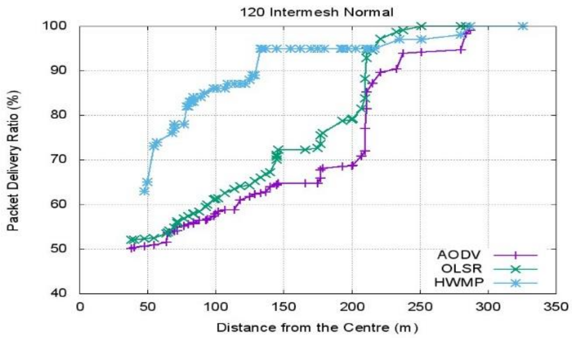
e. 40 Node Network



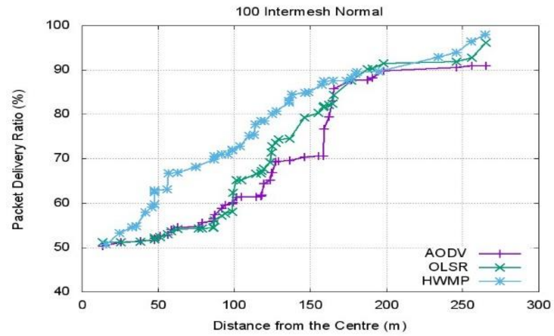
f. 20 Node Network

Figure 4.4: Packet Delivery Ratio vs Distance from Network Centre in Intramesh Uniform Node Distribution

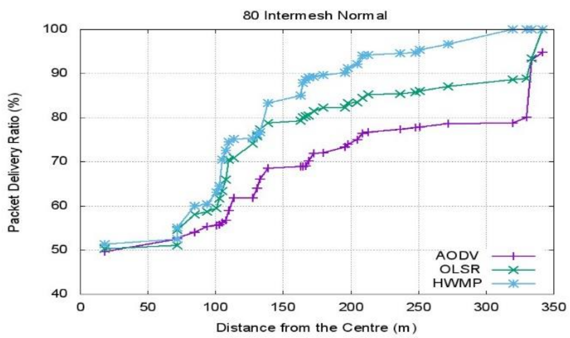
c) Portal-based traffic in Normal Node Distribution



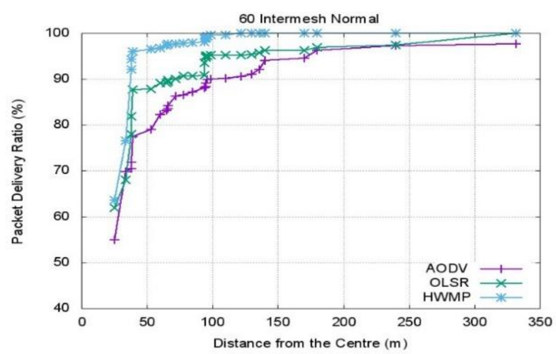
a. 120 Node Network



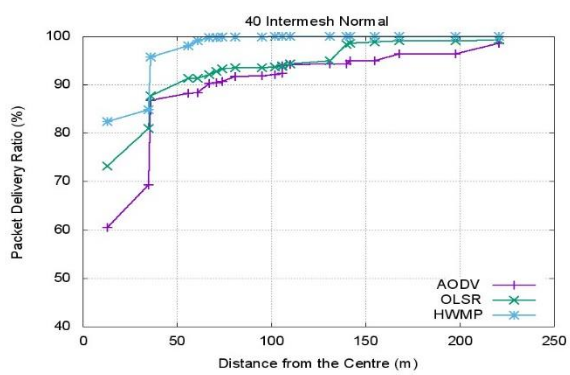
b. 100 Node Network



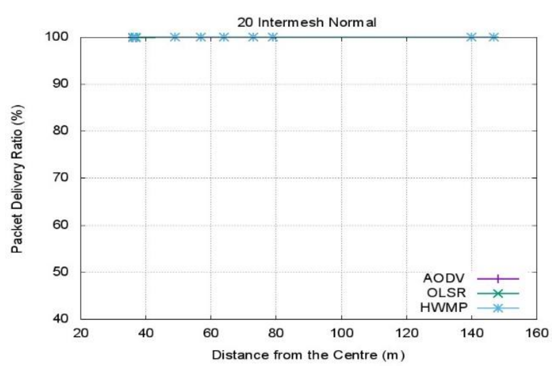
c. 80 Node Network



d. 60 Node Network



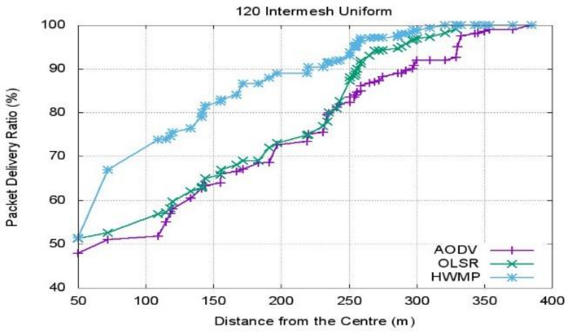
e. 40 Node Network



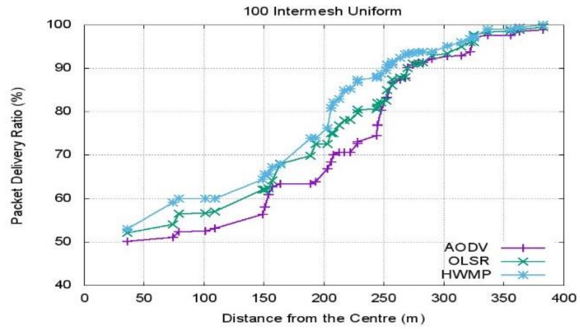
f. 20 Node Network

Figure 4.5: Packet Delivery Ratio vs Distance from Network Centre in Portal-based Normal Node Distribution

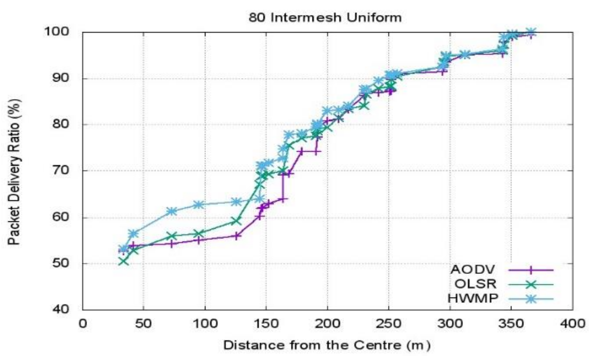
d) Portal-based traffic in Uniform Node Distribution



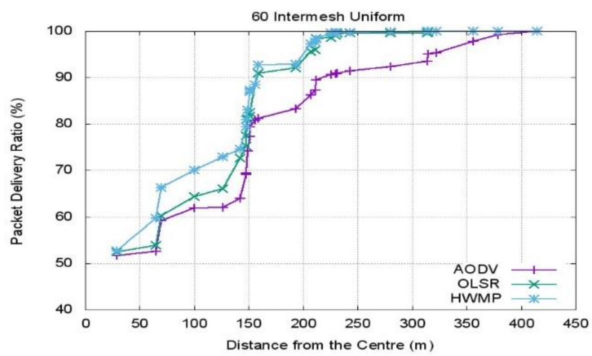
a. 120 Node Network



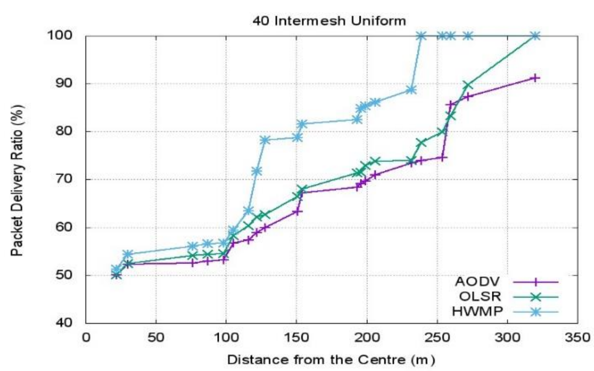
b. 100 Node Network



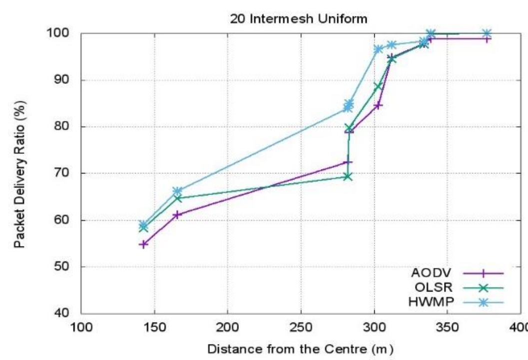
c. 80 Node Network



d. 60 Node Network



e. 40 Node Network



f. 20 Node Network

Figure 4.6: Packet Delivery Ratio vs Distance from Network Centre in Portal-based Uniform Node Distribution

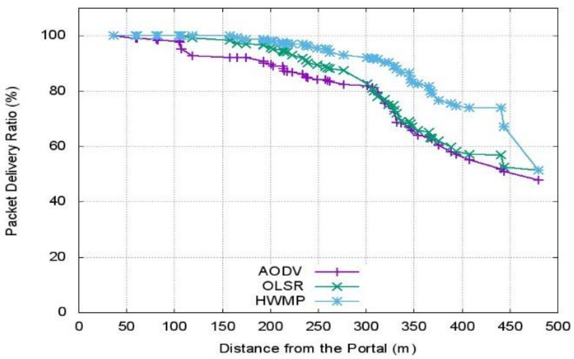
4.2.2 Scenario 2: The Effect of Distance from the Portal

This section presents the PDR results obtained from individual nodes. These nodes are located relative to the Portal, and distributed in a uniform and normal node distribution. Looking closely at the PDR produced by the three routing protocols, a declining trend can be observed in Figure 4.7 and Figure 4.8 show the relationship between the packet delivery ratio of individual nodes and the distance from the Portal.

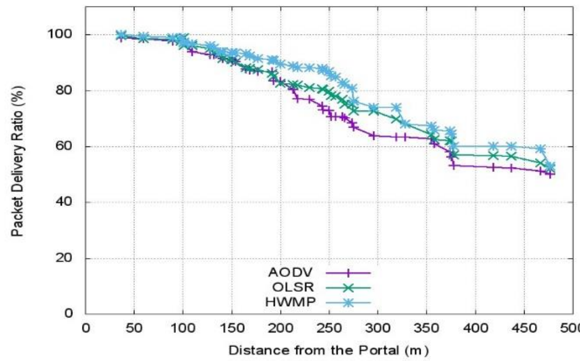
The evaluation results show that the nodes closer to the Portal experience high packet delivery ratio compared to nodes far from the Portal. This occurrence is observed for both uniform and normal node distributions and across all network sizes being evaluated. The high packet delivery ratio on the nodes closer to the Portal can be attributed to the fewer number of hops that a data packet has to travel before reaching the destination. The fewer hops travelled by the data packet minimises the packet loss ratio. Backbone nodes located far from the Portal can be prone to having packets travel many hops. When data packets travel multiple hops some packets can be dropped or even get lost. The packet loss or packet drop experienced by the nodes further from the Portal can be caused by queue overflow in the network, transmission errors, route failure or route change.

If the link is being used to100% capacity packet loss begins to occur. If a packet arrives when the queue is already fullit gets dropped.The correlation between the position of the node relative to the Portal and the PDR is not limited to the node distribution.

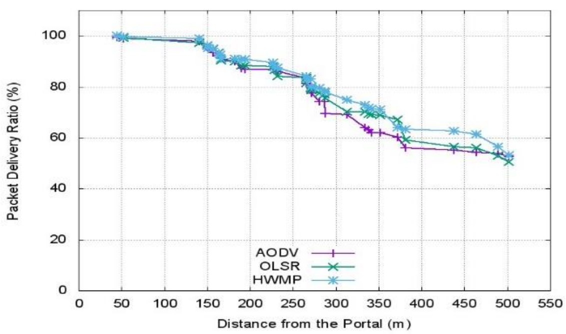
*a) **Portal-based traffic in Uniform Node Distribution***



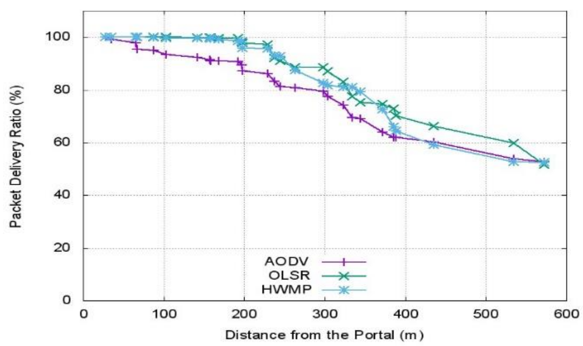
a. 120 Node Network



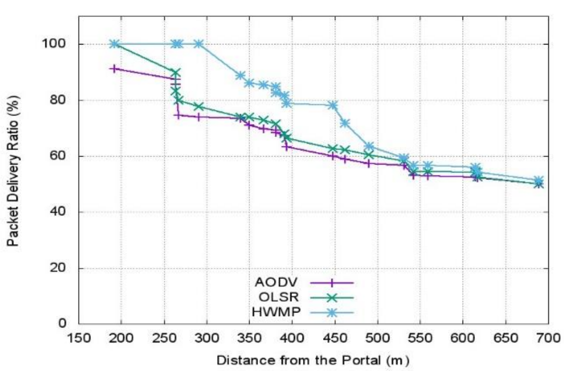
b. 100 Node Network



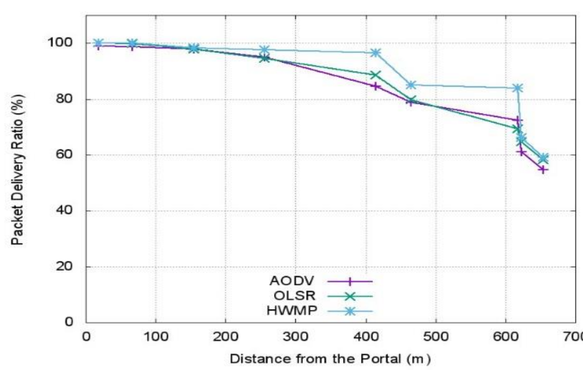
c. 80 Node Network



d. 60 Node Network



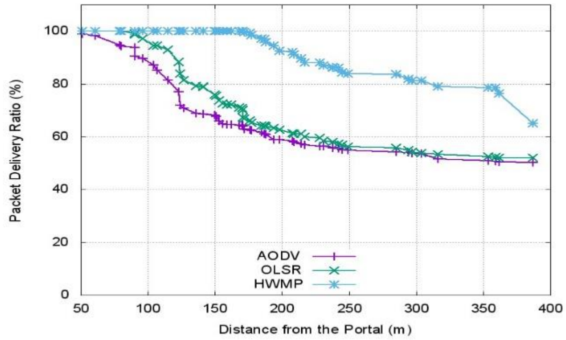
e. 40 Node Network



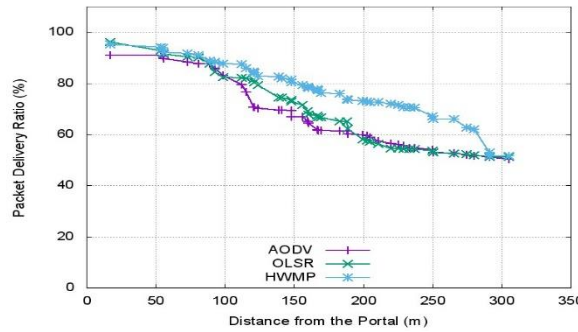
f. 20 Node Network

Figure 4.7 : Packet Delivery Ratio vs Distance from the Portal in Portal-based Uniform Node Distribution

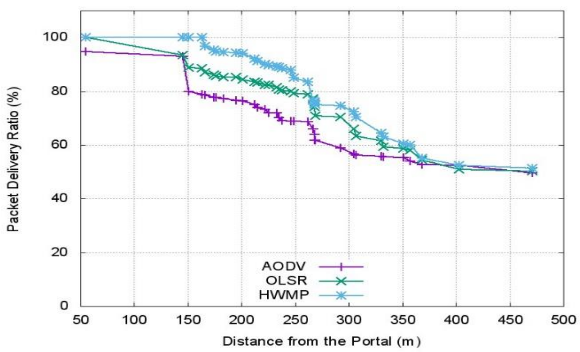
*b) **Portal-based traffic in Normal Node Distribution***



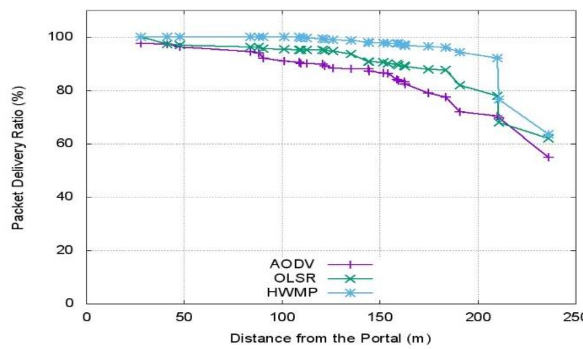
a. 120 Node Network



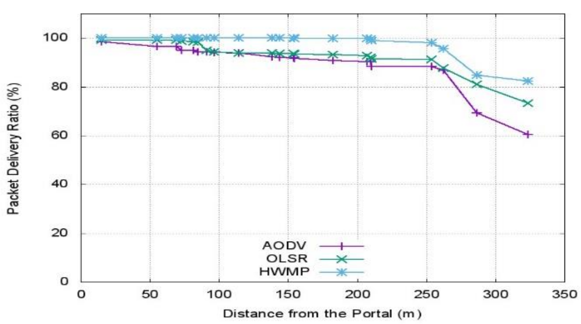
b. 100 Node Network



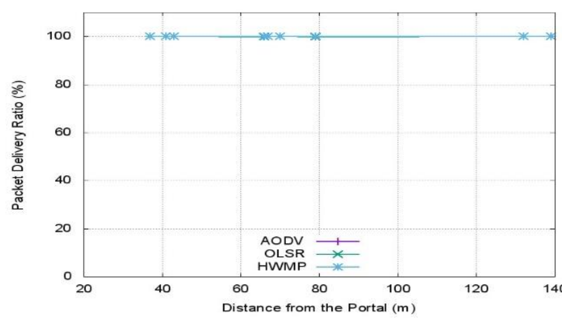
c. 80 Node Network



d. 60 Node Network



e. 40 Node Network



f. 20 Node Network

Figure 4.8 Packet Delivery Ratio vs Distance from the Portal in Portal-based Normal Node Distribution

4.3 Experiment 2: End-to-End Delay

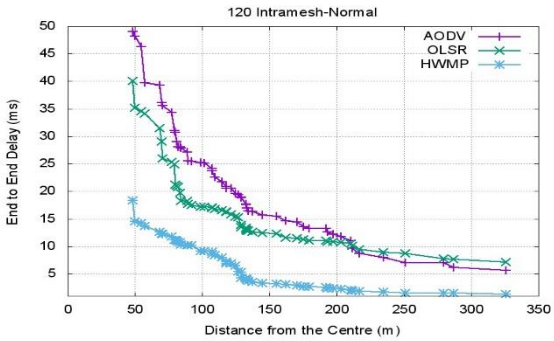
4.3.1 Scenario 1: The Effect of Distance from the Network Centre

In this section, the effect of distance from the network centre is being measured. Figures 4.9 - 4.12 present the experimental results of the performance of node location relative to the network centre when the Intramesh traffic scenarios are used in the normal and uniform node distributions. The results presented in Figures 4.9 (a-f) – 4.12 (a-f) clearly show the rapid decrease of the end-to-end delay on the nodes far away from the network centre. When the nodes transmit data packets they compete for channel access. Channel access or the link must be available for packet transmission. If the channel access is used to its maximum, packet loss starts to occur. When the channel access has reached its maximum size, and new packets arrive, those packets are dropped. The dropped packets have to be retransmitted. The retransmission process imposes delays on the network. In other routes the nodes will be saturated as the distribution of flows focus on the centre nodes.

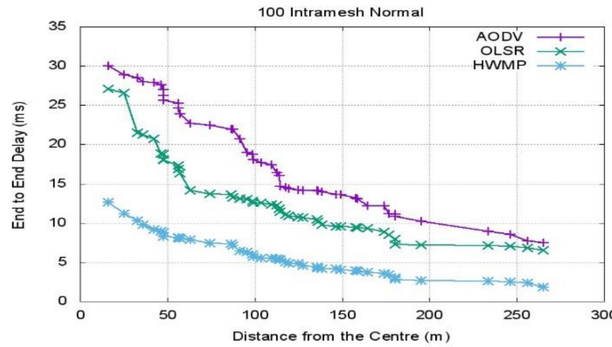
It is observed that large delays are noticed in the performance of AODV, reaching 50ms for nodes located near the network centre. Delays are usually introduced if the data packets are sent in large batches and the network performance is likely to degrade. HWMP is the best performing routing protocol, achieving a delay of just below 20ms on the nodes near the network centre. HWMP optimises the strength of the reactive and proactive modes. The proactive mode provides optimal routes in terms of the number of hops which are always available immediately when required.

In general, the delay drops as the network size decreases for both the Uniform and Normal node distributions. High delays occur when there is a high number of nodes competing for the transmission medium. The high delay on nodes closer to the network centre correlate with the low throughput as well as the low packet delivery achieved by the same nodes. The delay of all the routing protocols decreases gradually together with the distance from the network centre. The nodes far from the network centre achieved minimum end-to-end delay.

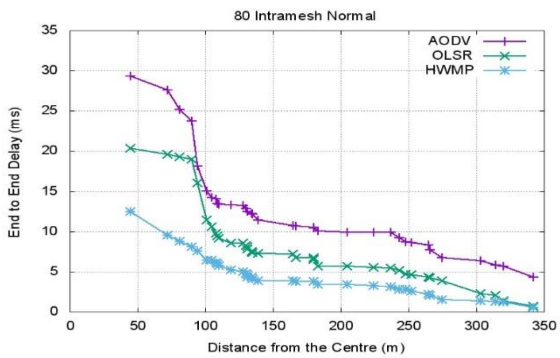
a) Intramesh traffic in Normal Node Distribution



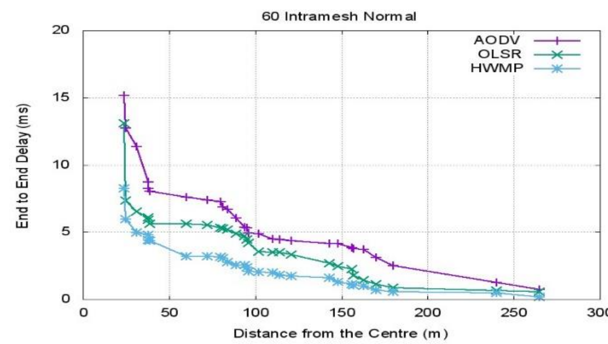
a. 120 Node Network



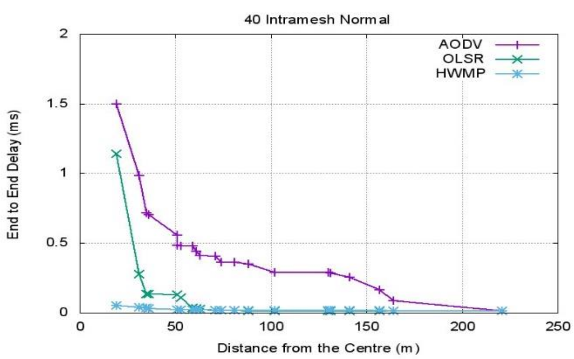
b. 100 Node Network



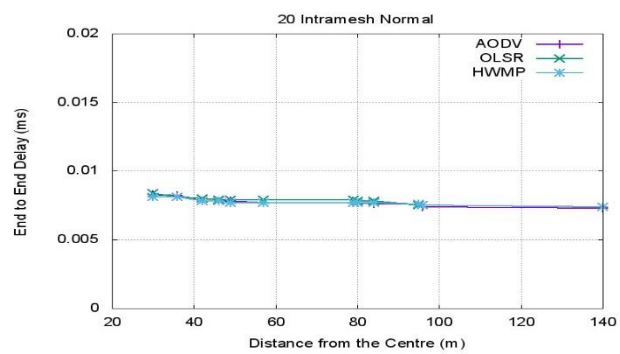
c. 80 Node Network



d. 60 Node Network



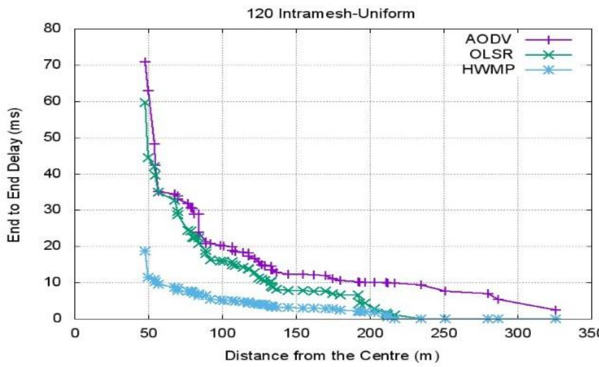
e. 40 Node Network



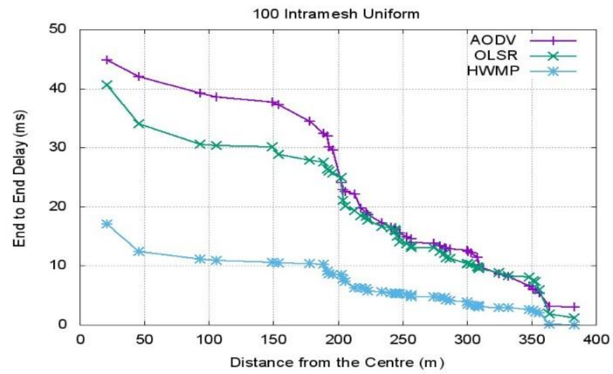
f. 20 Node Network

Figure 4.9: End to End Delay vs Distance from Network Centre in Intramesh Normal Node Distribution

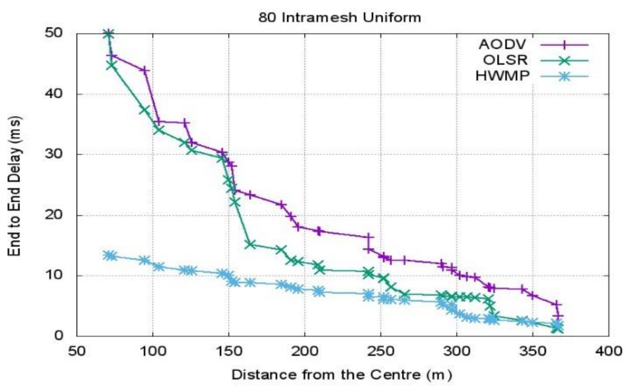
b) Intramesh traffic in Uniform Node Distribution



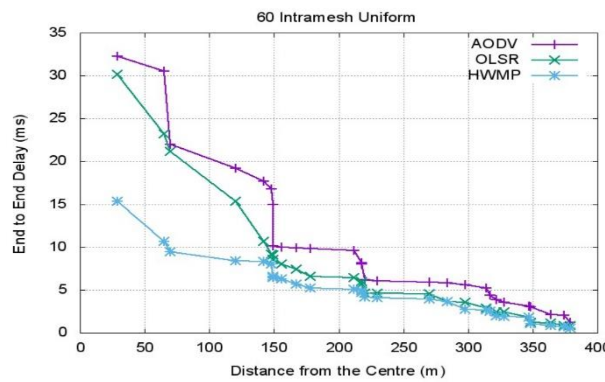
a. 120 Node Network



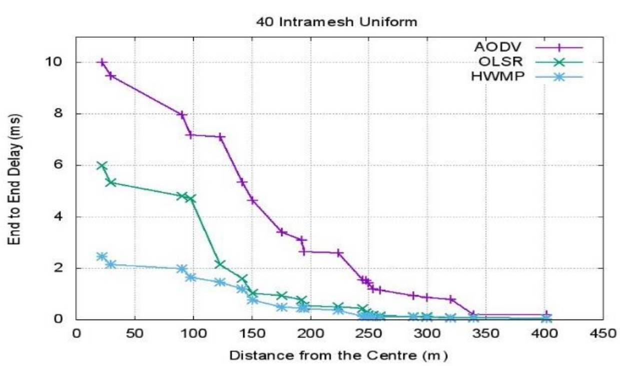
b. 100 Node Network



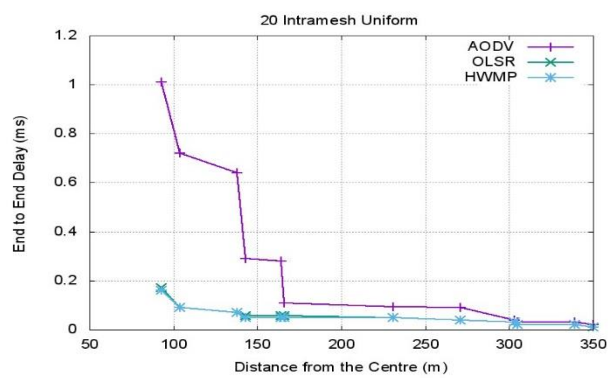
c. 80 Node Network



d. 60 Node Network



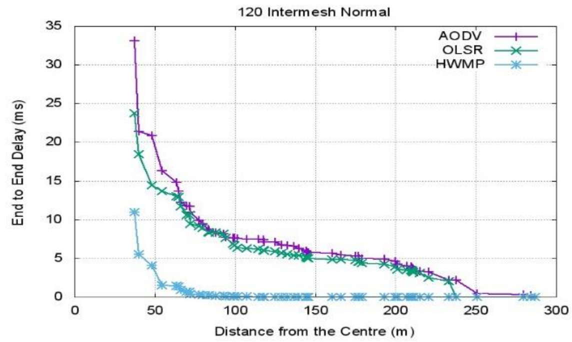
e. 40 Node Network



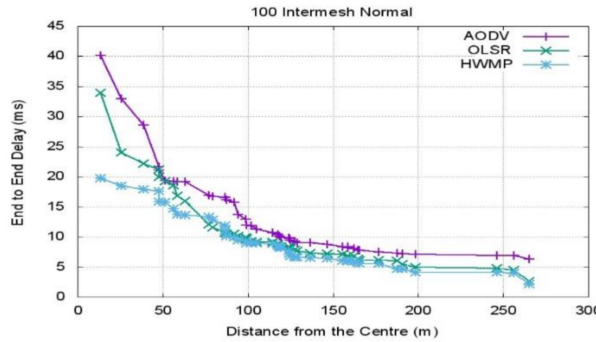
f. 20 Node Network

Figure 4.10: End to End Delay vs Distance from Network Centre in Intramesh Uniform Node Distribution

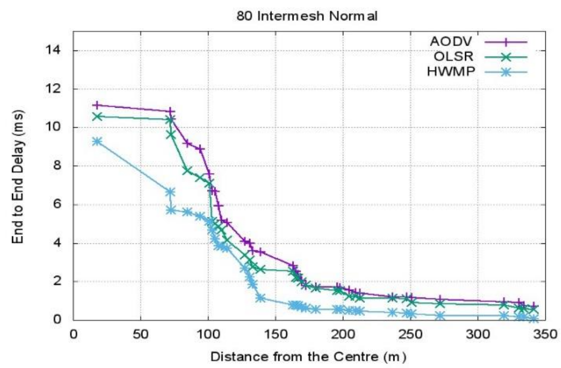
c) Portal-based traffic in Normal Node Distribution



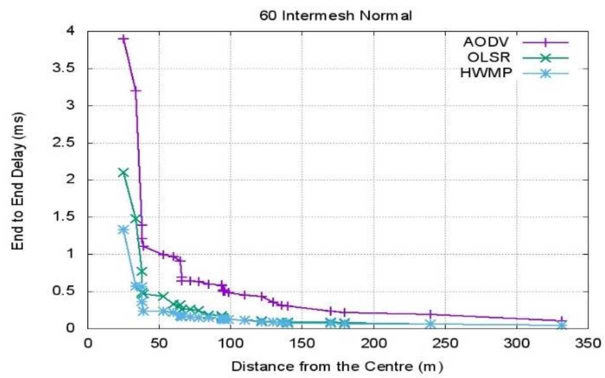
a. 120 Node Network



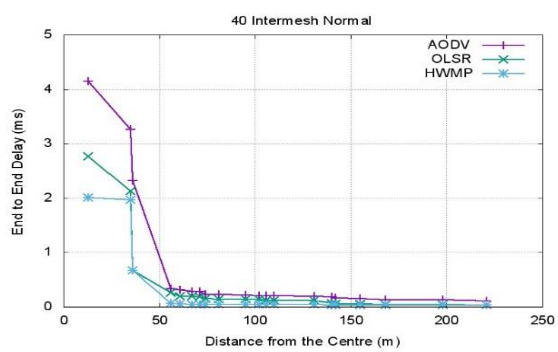
b. 100 Node Network



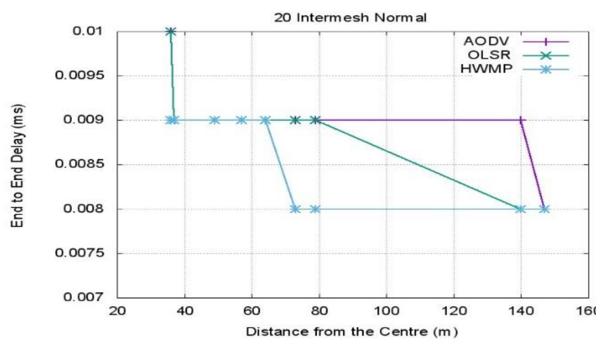
c. 80 Node Network



d. 60 Node Network



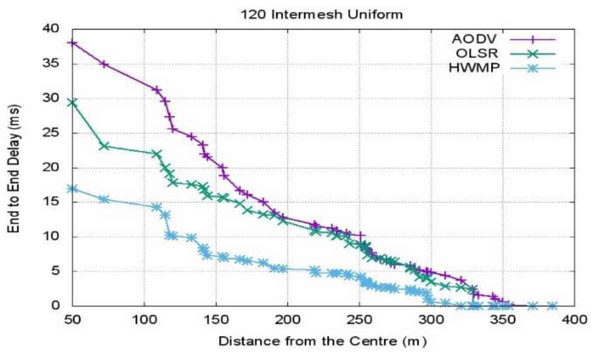
e. 40 Node Network



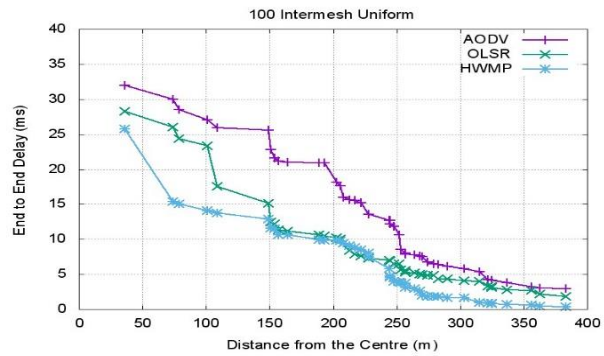
f. 20 Node Network

Figure 4.11: End to End Delay vs Distance from Network Centre in Portal-based Normal Distribution

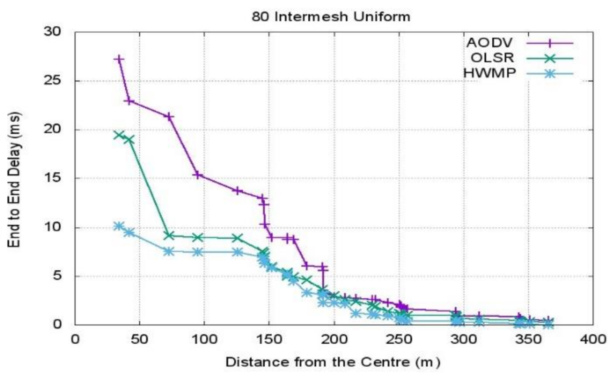
d) Portal-based traffic in Uniform Node Distribution



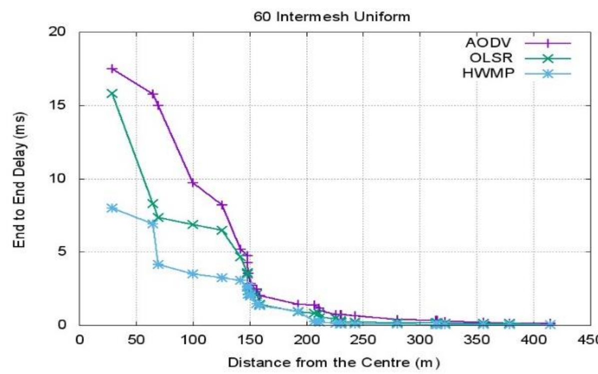
a. 120 Node Network



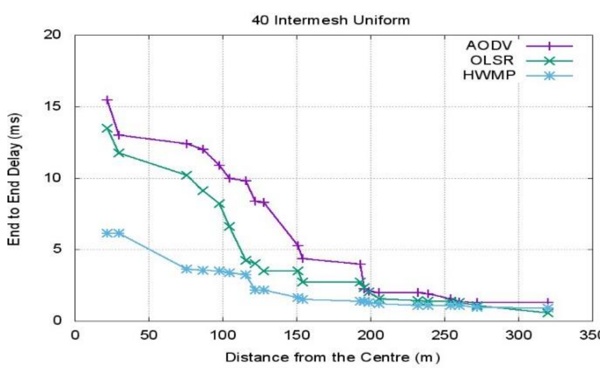
b. 100 Node Network



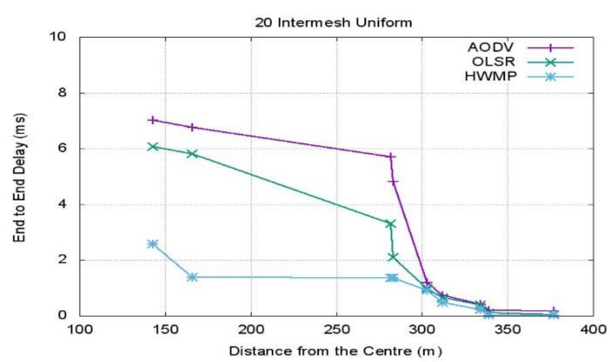
c. 80 Node Network



d. 60 Node Network



e. 40 Node Network



f. 20 Node Network

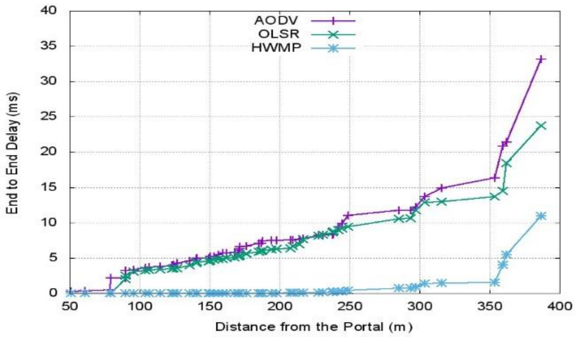
Figure 4.12: End to End Delay vs Distance from Network Centre in Portal-based Uniform Node Distribution

4.3.2 Scenario 2: The Effect of Distance from the Portal

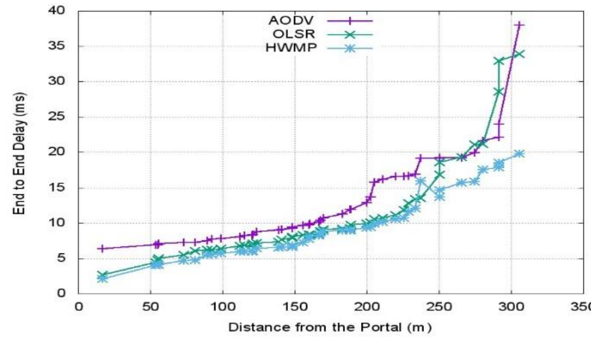
The results obtained when evaluating the Portal-based traffic scenarios in both Uniform and Normal node distributions are presented in this section. The results in Figures 4.13 and 4.14 reveal that the nodes closer to the Portal produce low delays compared to the nodes at the edge of the network. The low delay achieved by the nodes closer to the Portal is due to the data packets having to travel over short paths. For the nodes located far from the Portal, there is a processing delay involved, which is the time required by intermediate nodes to choose which route to forward the packets to. These packets have to wait for the link to be available, while the link is sending other data packets from other backbone nodes.

It is important to note that all three routing protocols show a similar behaviour in all figures. The results indicate that all three routing protocols produce high delays on the nodes far from the Portal. As the distance from the Portal decreases, the node's delay also decreases.

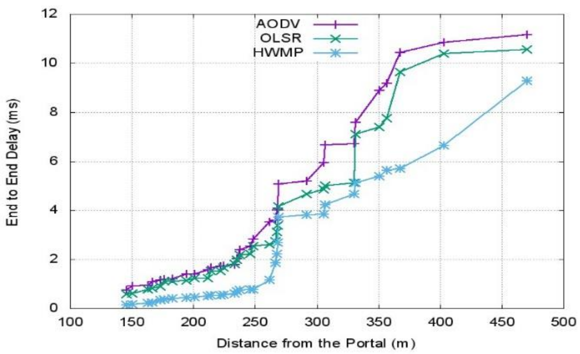
a) Portal-based traffic in Normal Node Distribution



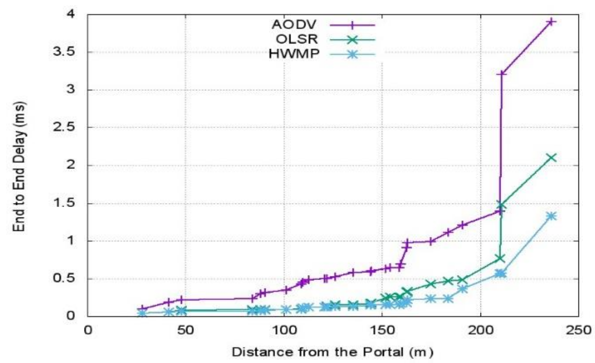
a. 120 Node Network



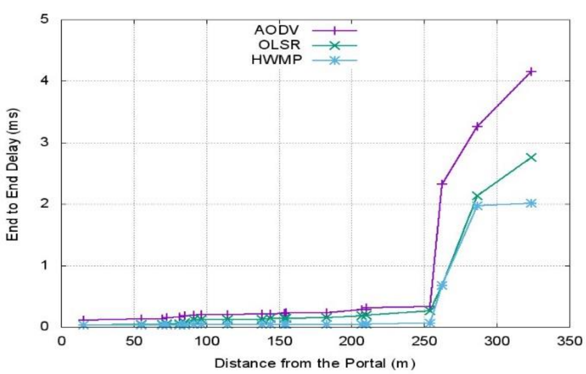
b. 100 Node Network



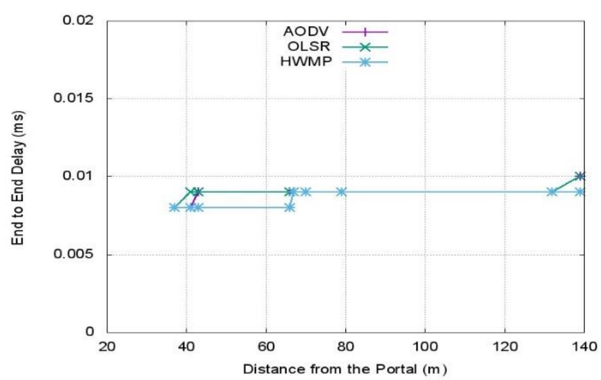
c. 80 Node Network



d. 60 Node Network



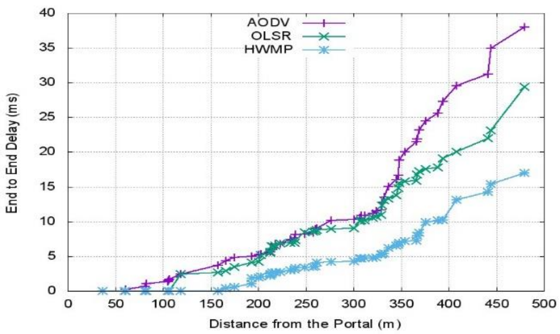
e. 40 Node Network



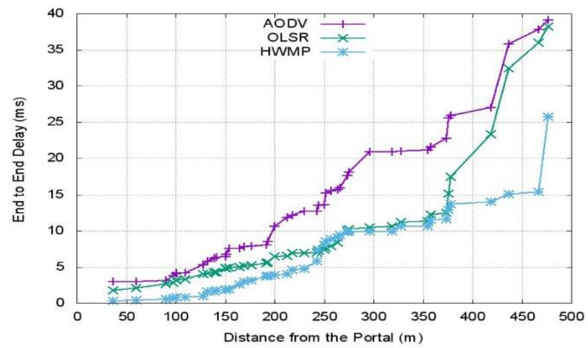
f. 20 Node Network

Figure 4.13: End to End Delay vs Distance from Portal in Portal-based Normal Node Distribution

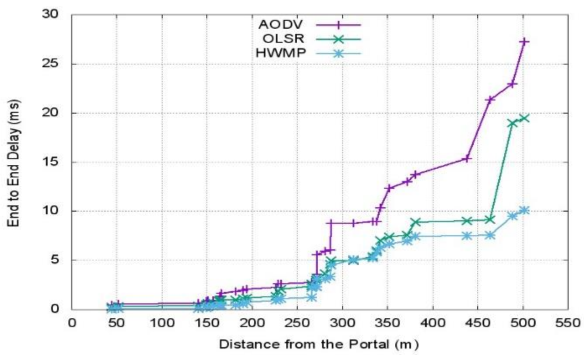
b) Portal-based traffic in Uniform Node Distribution



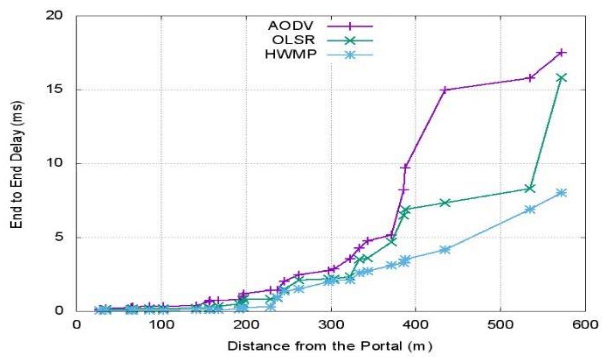
a. 120 Node Network



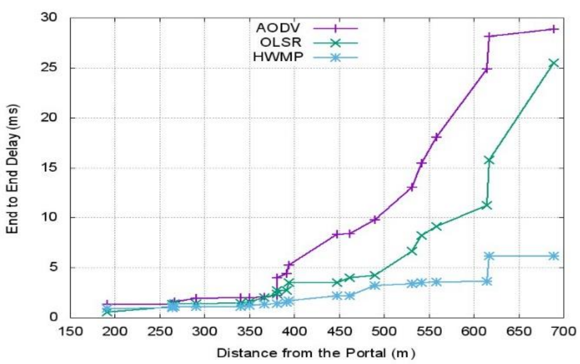
b. 100 Node Network



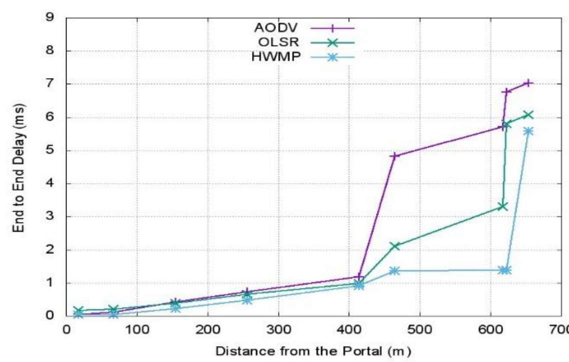
c. 80 Node Network



d. 60 Node Network



e. 40 Node Network



f. 20 Node Network

Figure 4.14: End to End Delay vs Distance from Portal in Portal-based Uniform Node Distribution

The throughput results obtained from individual nodes when using different traffic loads are presented in the next section.

4.4 Experiment 3: Throughput

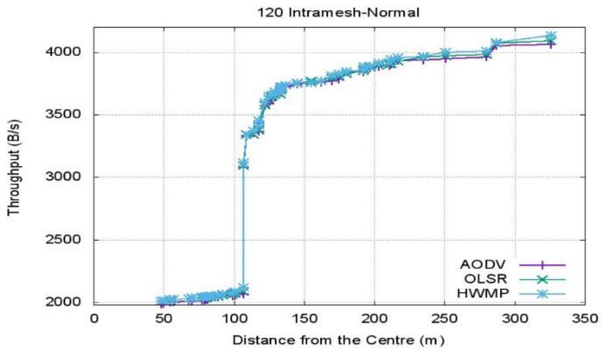
4.4.1 Scenario 1: The Effect of Distance from the Network Centre

This section describes the throughput experiments which were done in order to investigate the rate at which data packets successfully moved from source to the intended destination at a given time period. This gives an indication of the QoS level offered by the network. Both the intramesh and Portal-based traffic scenarios were considered for the simulation. The effect of node location relative to the network centre in both uniform and normal node distribution was also measured.

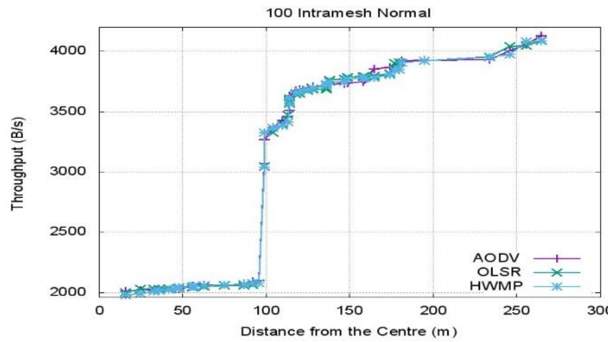
Figures 4.15 – 4.18 depict the results obtained from comparing AODV, OLSR and HWMP routing protocols with different network size. The line graph used in figures 4.15 (a-f) – 4.18 (a-f) clearly shows that the nodes closer to the network centre experience lower throughput than the nodes at the edge of the network. The low throughput obtained by the nodes closer to the network centre is influenced by how data packets are transmitted, as shown in figure 4.1 and 4.2, where most of the network nodes try to send data packets via the centrally located nodes. This causes delays as these nodes are subjected to high traffic volumes.

The performance of all three routing protocols is almost constant, with the AODV slightly underperforming.

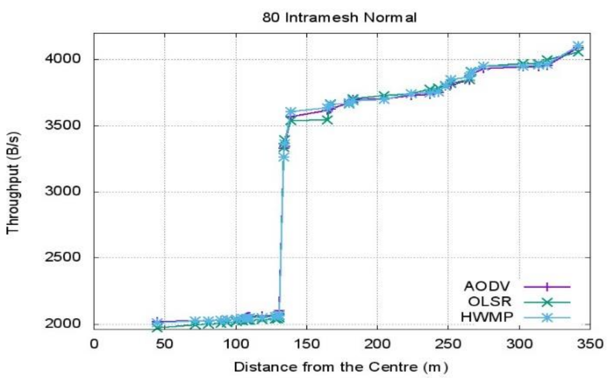
a) Intramesh traffic in Normal Node Distribution



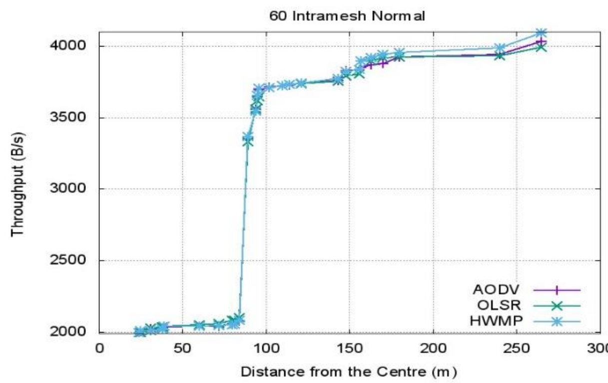
a. 120 Node Network



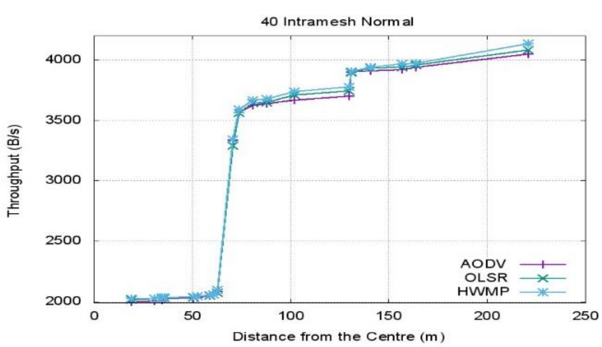
b. 100 Node Network



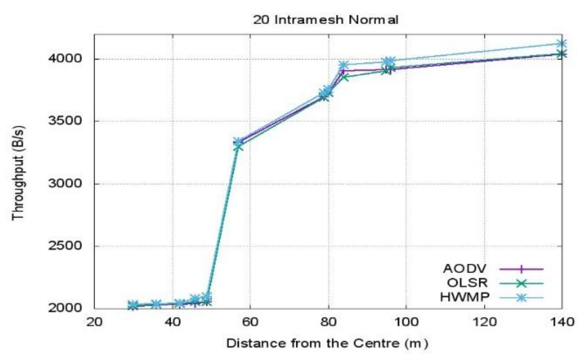
c. 80 Node Network



d. 60 Node Network



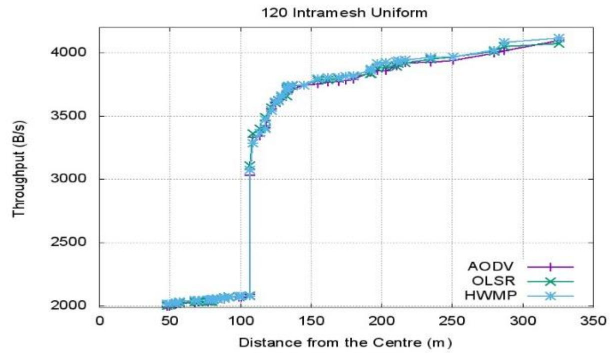
e. 40 Node Network



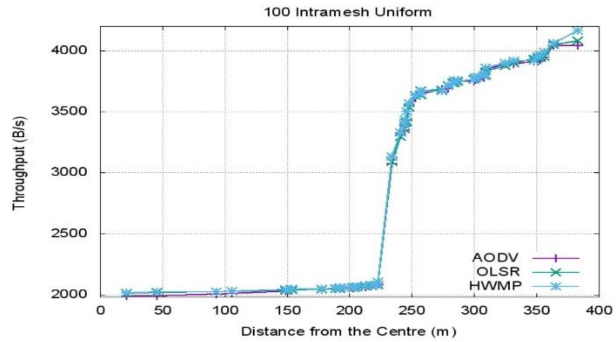
f. 20 Node Network

Figure 4.15: Throughput vs Distance from Network Centre in Intramesh Normal Node Distribution

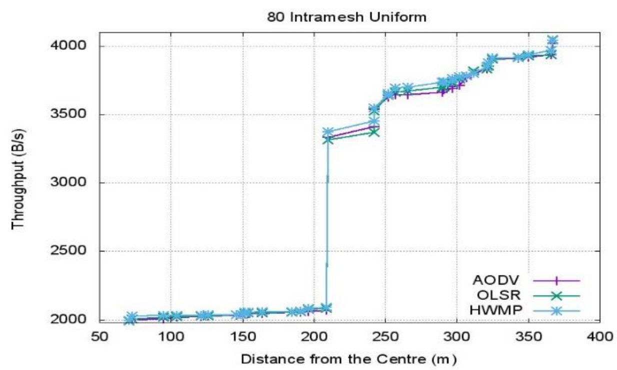
b) Intramesh traffic in Uniform Node Distribution



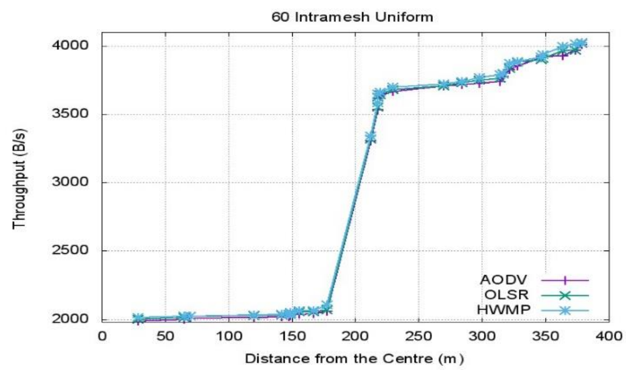
a. 120 Node Network



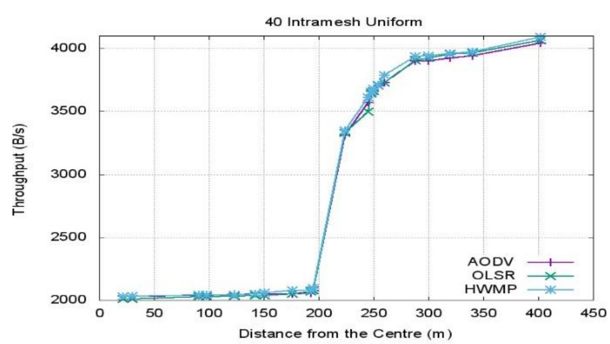
b. 100 Node Network



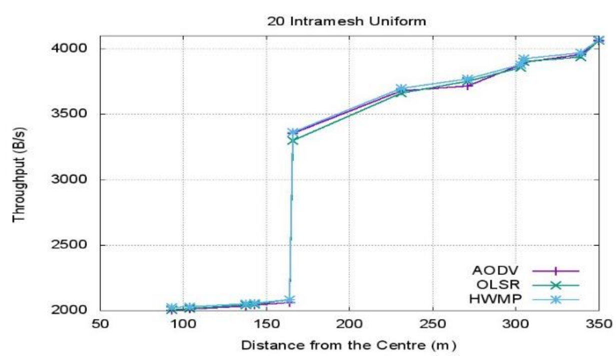
c. 80 Node Network



d. 60 Node Network



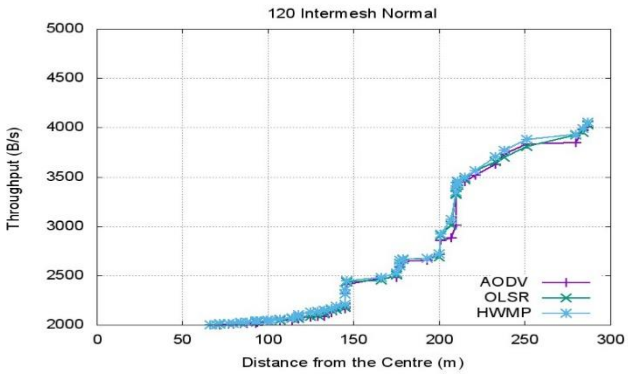
e. 40 Node Network



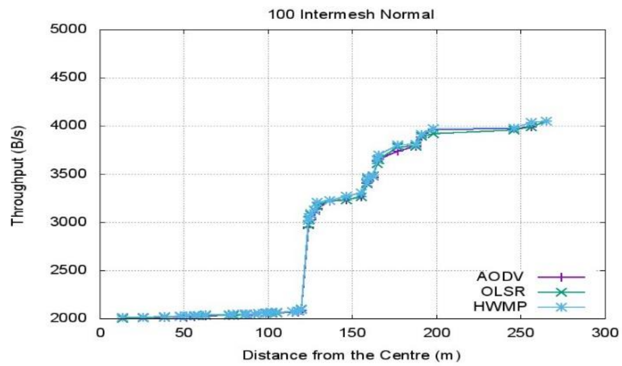
f. 20 Node Network

Figure 4.16: Throughput vs Distance from Network Centre in Intramesh Uniform Node Distribution

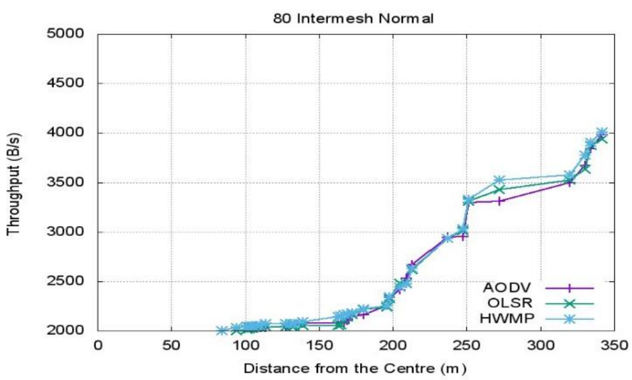
c) *Portal-based traffic in Normal Node Distribution*



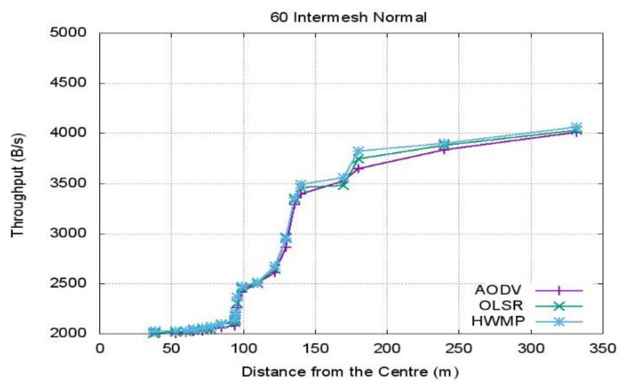
a. 120 Node Network



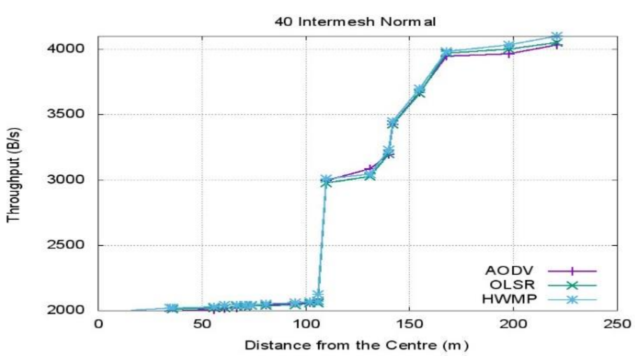
b. 100 Node Network



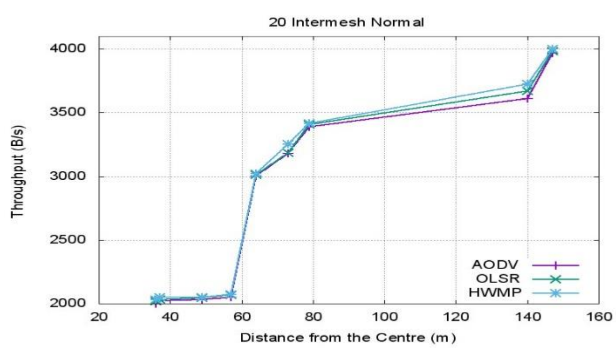
c. 80 Node Network



d. 60 Node Network



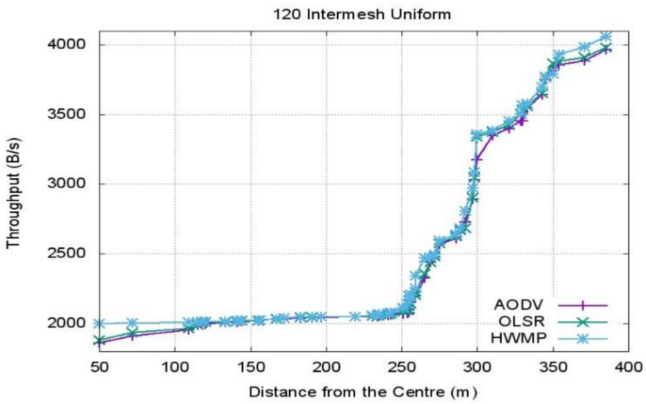
e. 40 Node Network



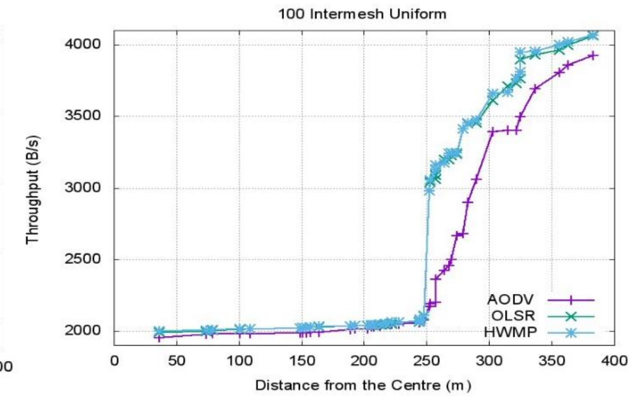
f. 20 Node Network

Figure 4.17: Throughput vs Distance from Network Centre in Intramesh Normal Node Distribution

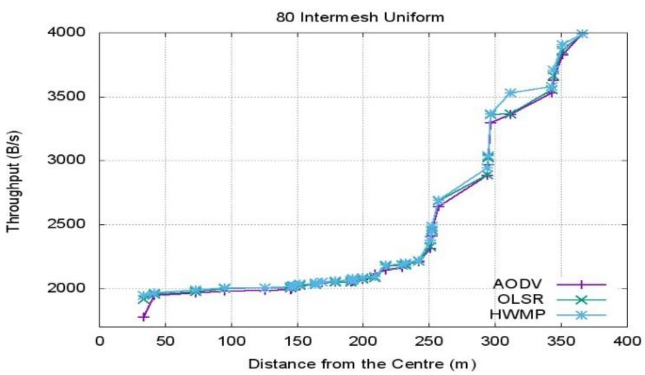
d) Portal-based traffic in Uniform Node Distribution



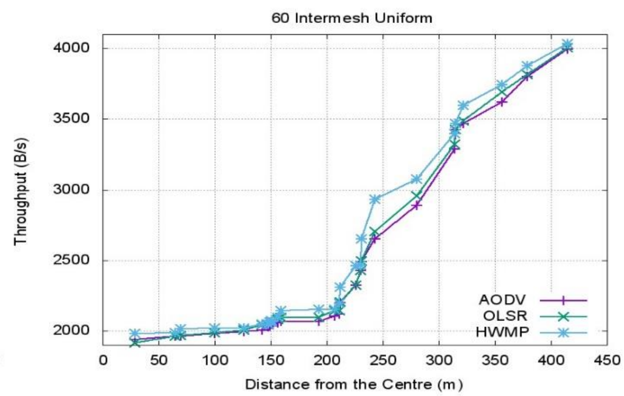
a. 120 Node Network



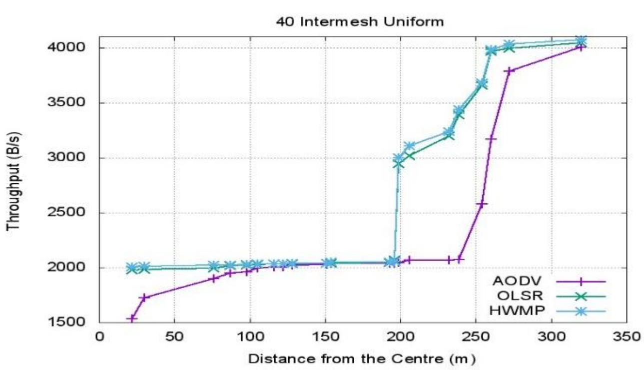
b. 100 Node Network



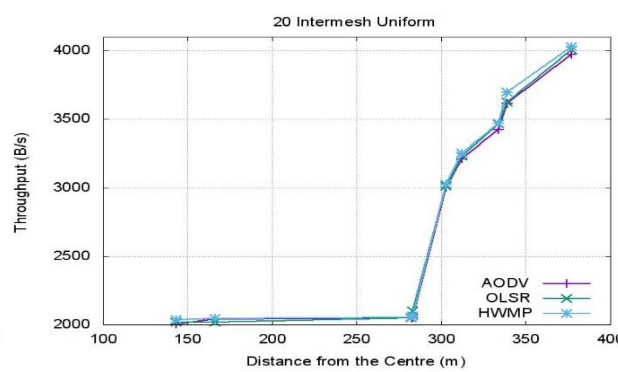
c. 80 Node Network



d. 60 Node Network



e. 40 Node Network



f. 20 Node Network

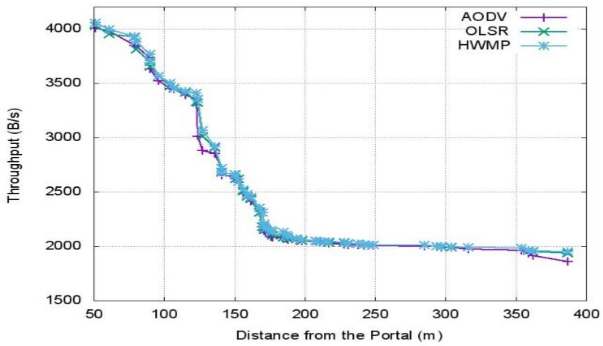
Figure 4.18: Throughput vs Distance from Network Centre in Portal-based Uniform Node Distribution

4.4.2 Scenario 2: The Effect of Distance from the Portal

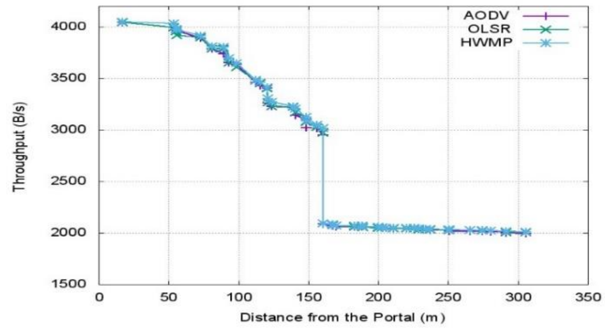
The results obtained when evaluating the Portal-based traffic scenarios in both Uniform and Normal node distributions are presented in this section .The observation from Figure 4.19 and 4.20 is that the throughput for nodes located near the Portal is high compared to the throughput of the nodes located far from the Portal. Throughput depends on the number of hops a packet has to travel between source and destination. The variation also depends on the network size. A throughput drop is expected for nodes far from the Portal, since data packets travel many hops before reaching the intended destination.

Throughput degrades as the number of hops increase. The probability of link failure and packet loss also increase. This means that the throughput for longer paths suffers. The data packets sent from nodes located far from the Portal have more clashes on the medium access, thus causing an increase in collision and packet loss, therefore decreasing throughput. Packet loss may be caused by transmission errors, or if the link to the destination is broken or no longer available. It can also be caused by congestion on the network. The effect of these causes are associated with the network context, which could be total connections or traffic load. When the network has too much traffic, the performance drops significantly. Possible congestion occurs on nodes when data packets arrive at a greater rate than is possible to forward. When congestion occurs, packets must be discarded by the backbone node. This reduces the number of data packets sent, hence throughput degrades for nodes located far from the Portal.

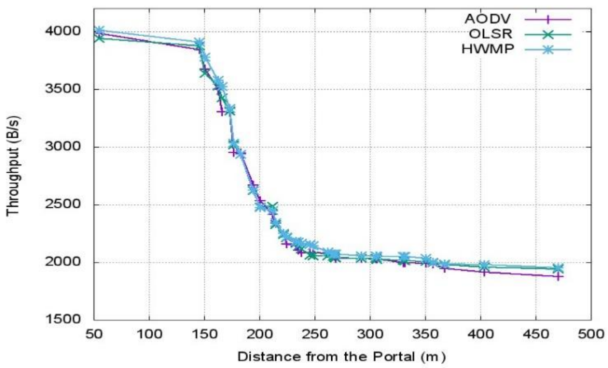
a) ***Portal-based traffic in Normal Node Distribution***



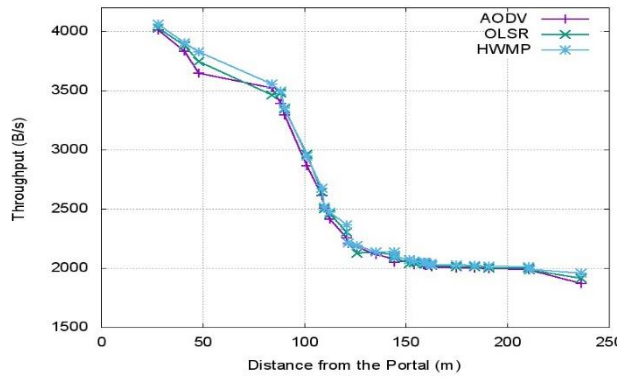
a. 120 Node Network



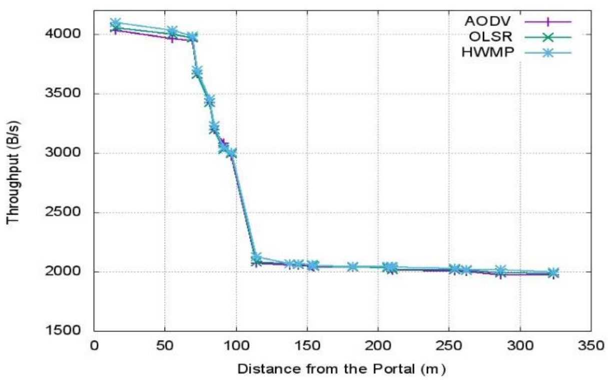
b. 100 Node Network



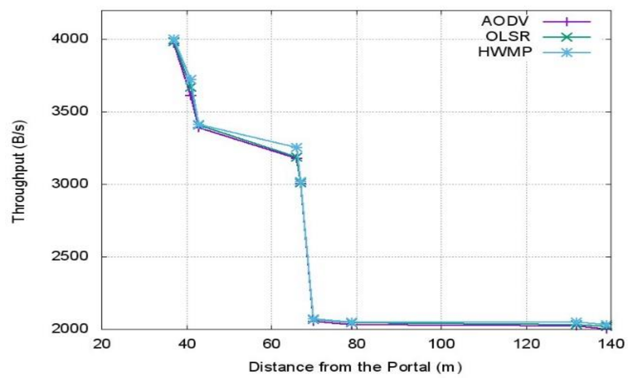
c. 80 Node Network



d. 60 Node Network



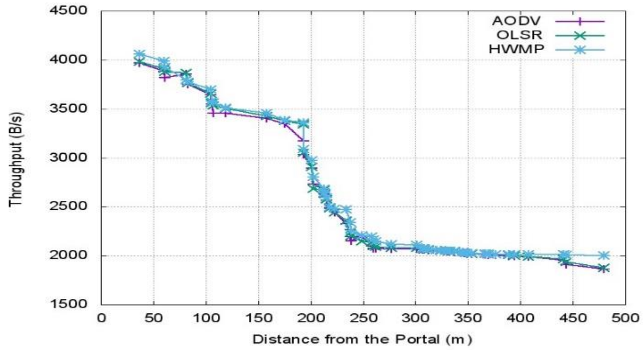
e. 40 Node Network



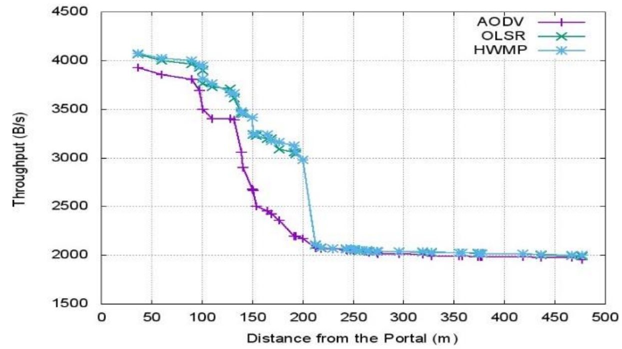
f. 20 Node Network

Figure 4.19: Throughput vs Distance from Portal in Portal-based Normal Node Distribution

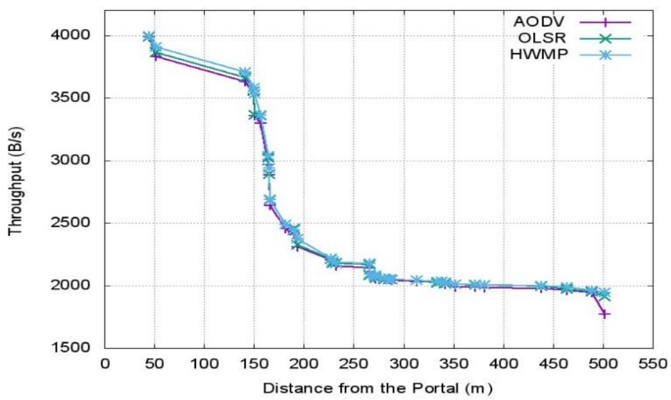
b) ***Portal-based traffic in Uniform Node Distribution***



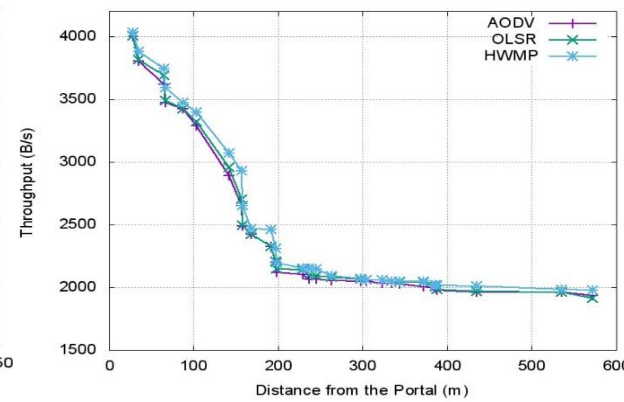
a. 120 Node Network



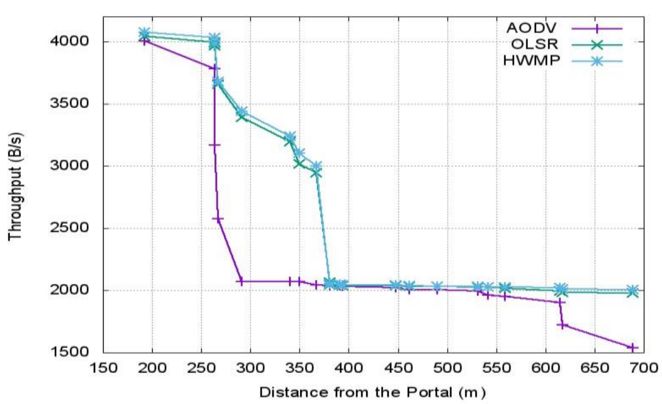
b. 100 Node Network



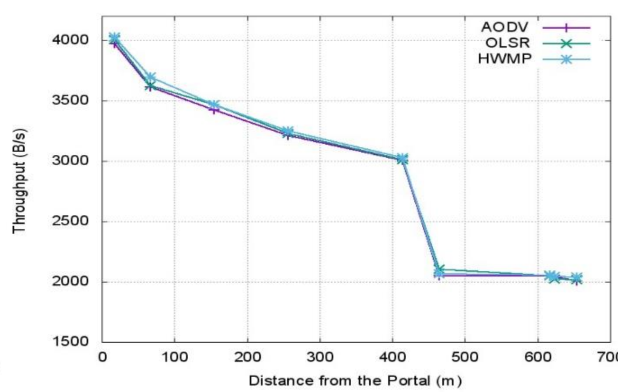
c. 80 Node Network



d. 60 Node Network



e. 40 Node Network



f. 20 Node Network

Figure 4.20: Throughput vs Distance from Portal in Portal-based Uniform Node Distribution

Summary of the Results

A common trend is observed on the nodes located near the network centre, whereby these nodes experience high delays. The packet delivery ratio experienced by nodes close to the network centre is higher than nodes far from the network centre. Low throughput is experienced on the nodes closer to the network centre.

When examining the results of the effect of distance from the Portal, the overall observation was that the throughput of nodes located closer to the Portal is higher than the throughput of edge nodes. High packet delivery ratio is achieved by nodes closer to the Portal. Low delays are also realised on the nodes closer to the Portal.

In all three performance parameters HWMP is the best performing routing protocol, and AODV the worst. This is due to the reactive nature of AODV in maintaining the routes. The reactive mode of HWMP was also found to be the worst performing compared to the proactive mode, when compared in terms of throughput, average end-to-end delay and average jitter. This discovery was made by Bari *et al.* (2012) after doing an evaluation of the HWMP using different applications. The HWMP still delivered the highest number of packets, even in the case where the nodes are far from the centre.

The overall PDR results achieved in the evaluations are almost the same for both Normal and Uniform node distributions. The overall end-to-end delay for Normal node distribution was better than the Uniform end-to-end delay. The overall throughput for Normal node distribution was better than the throughput of the Uniform node distribution. This has also been established and confirmed by Barolli *et al.* (2015a), Barolli *et al.* (2015) Matsuo *et al.* (2015), and Oda *et al.* (2014), where the studie performed an analysis of different WMN architecture using Normal and Uniform node distributions. The studies considered the delay, PDR and throughput as performance metrics and only used OLSR as the routing protocol. Their conclusion correlates with the findings of this study.

5. CHAPTER 5

5.1 Results Analysis of the Realistic Topologies

This section introduces the Berlin and Leipzig node distributions, which are realistic topologies created using the NPART tool. The section then presents the findings of the experiments in the sub-sections that follow. The simulation results are categorised into two scenarios:

Scenario 1: focuses on the effect of distance from the network centre for the Intramesh and Portal-based node distributions.

Scenario 2: focuses on the effect of distance from the Portal, on the Portal-based node distribution only.

The x-axis represents the effect of distance from the network centre, and the effect of distance from the portal, respectively. The y-axis represent the different matrics used. In the Portal-based traffic scenarios both the effect of distance from the network centre and the effect of distance from the portal were measured. In the Intra-mesh traffic scenario, only the effect of distance from the network centre was measured. The results are presented in terms of the performance metrics, namely, packet delivery ratio, end to end delay, and the throughput achieved by individual nodes.

The experiments done and the results obtained are detailed and explained in the next section.

5.2 Experiment1: Packet Delivery Ratio (PDR)

This section presents the results analysis of the Packet Delivery Ratio obtained from individual backbone nodes. The performance was measured against node location relative to the network centre and node location relative to the Portal, in both Intra-mesh and Portal-based traffic scenarios. AODV, OLSR and HWMP routing protocols were used the Berlin and Leipzig node distributions, respectively. It was established in Section 4.1.1 that there is a high rate of traffic being transmitted by backbone nodes located at the centre of the network. The high rate of traffic passing through the backbone nodes located around the network centre can have a negative influence on the performance of the network. Figures 5.1 – 5.6 show the results of PDR obtained from individual backbone nodes, with different network sizes.

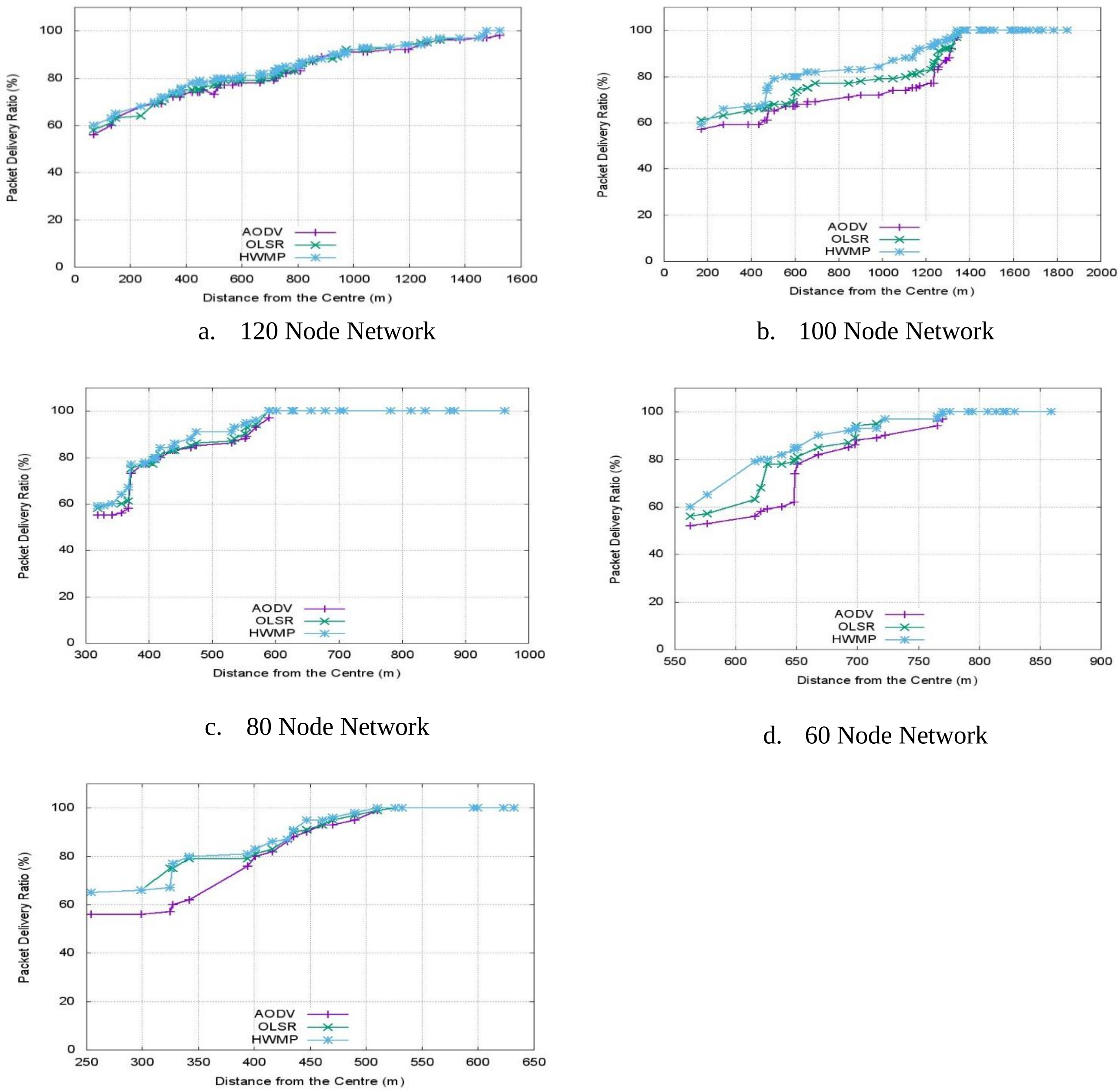
The observation from Scenario1 is that the Packet Delivery Ratio obtained by the backbone nodes located closer to the network centre achieve lower delivery ratio while the inverse is experienced in Scenario 2, where the backbone nodes located closer to the Portal obtain a higher delivery ratio. This can be attributed to the justification established in Section 4.1.1. For Scenario 1, since most traffic is passing through the centre, the backbone nodes experience a lot of traffic, leading to traffic jams, packet drops, and packet delay.

It is also evident in Scenario 2 that the backbone nodes located near the Portal obtain a high packet delivery ratio, which is caused by fewer hops being used by these backbone nodes when sending data to the Portal. Consequently, packet loss or packet drop is significantly reduced, and thus the delivery rate is high in these backbone nodes. In both scenarios, the same trend is observed across all network sizes. The results obtained using realistic topologies compare favourably with the results obtained using random topologies, although there is an improvement in the results obtained using realistic topologies.

The improved rate of packet delivery ratio is due to the nature of realistic topologies, which contain many bridges, allowing the traffic to transmit data packets to the correct location. The numerous bridges in realistic topologies do not allow unnecessary traffic, resulting in realistic topologies experiencing a better packet delivery ratio in all network sizes.

5.2.1 Scenario 1: The effect of Distance from the Network Centre

a) Intramesh traffic in Berlin Node Distribution



a. 120 Node Network

b. 100 Node Network

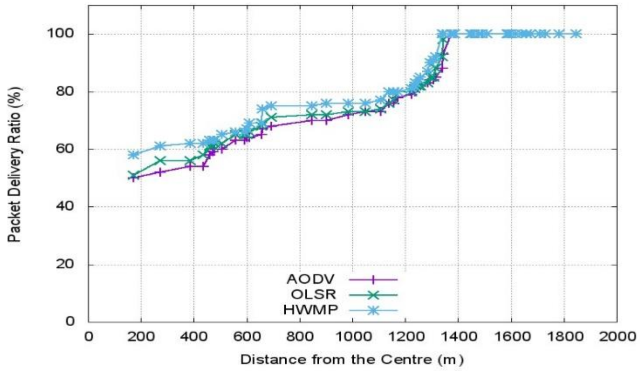
c. 80 Node Network

d. 60 Node Network

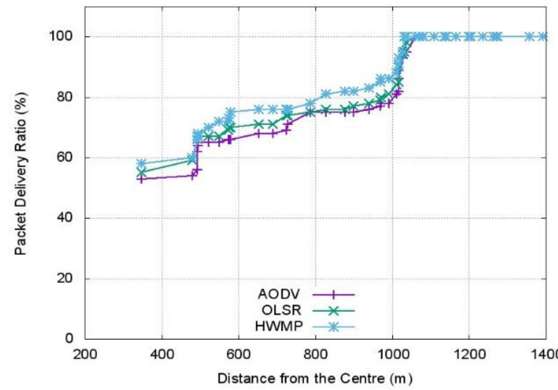
e. 40 Node Network

Figure 5.1 : Packet Delivery Ratio vs Distance from the Network Centre in Intramesh Berlin Node Distribution

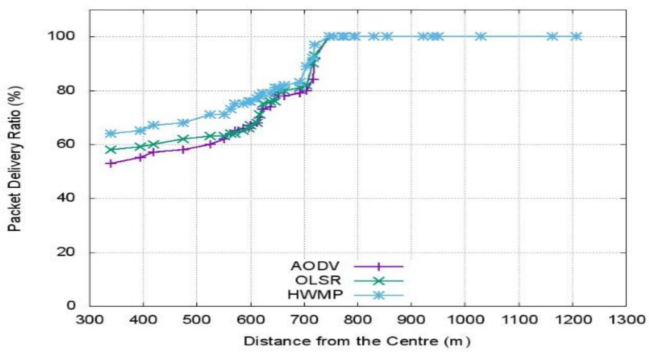
b) Intramesh traffic in Leipzig Node Distribution



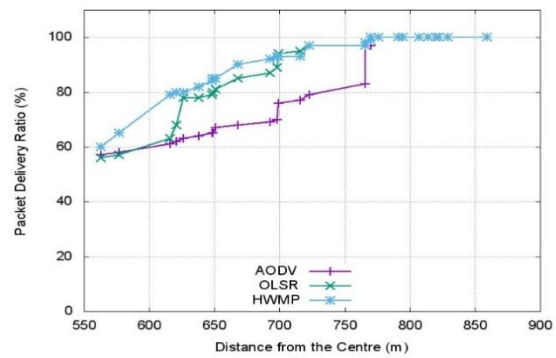
a. 120 Node Network



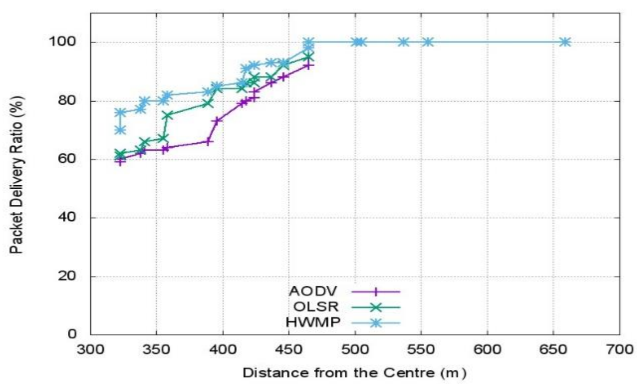
b. 100 Node Network



c. 80 Node Network



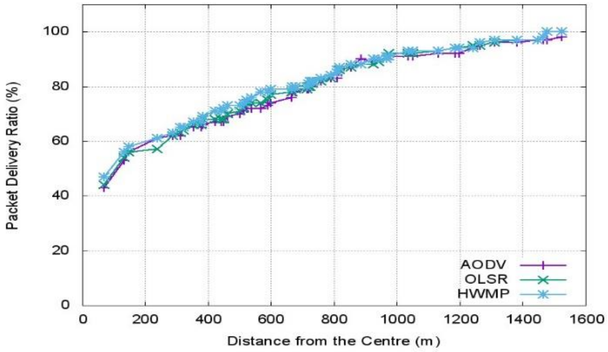
d. 60 Node Network



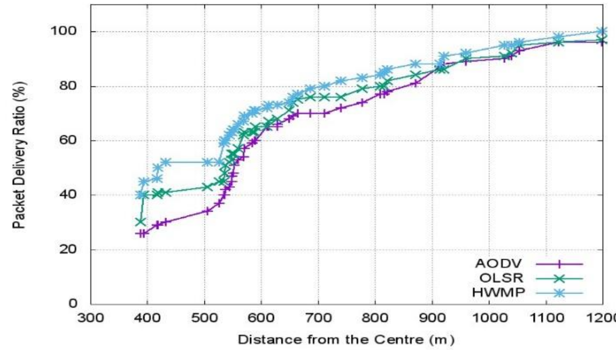
e. 40 Node Network

Figure 5.2: Packet Delivery Ratio vs Distance from Network Centre in Intramesh Leipzig Node Distribution

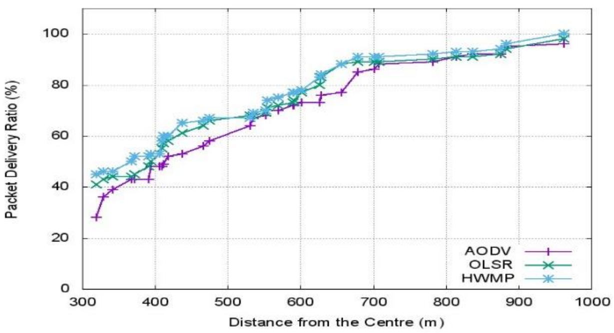
c) Portal-based traffic in Berlin Node Distribution



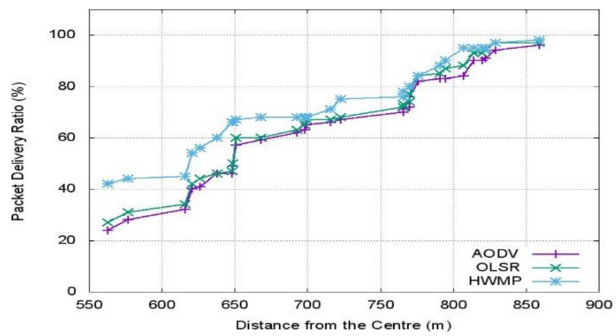
a. 120 Node Network



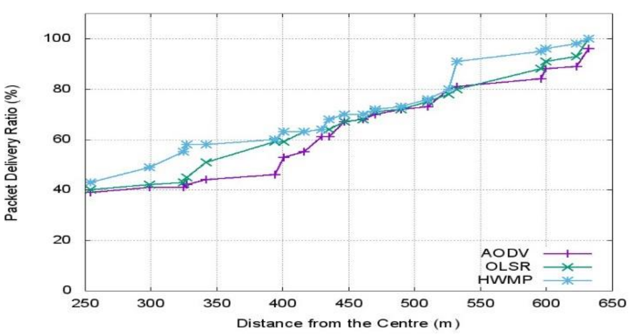
b. 100 Node Network



c. 80 Node Network



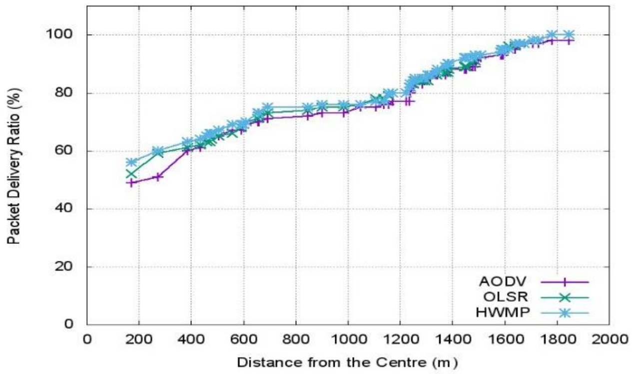
d. 60 Node Network



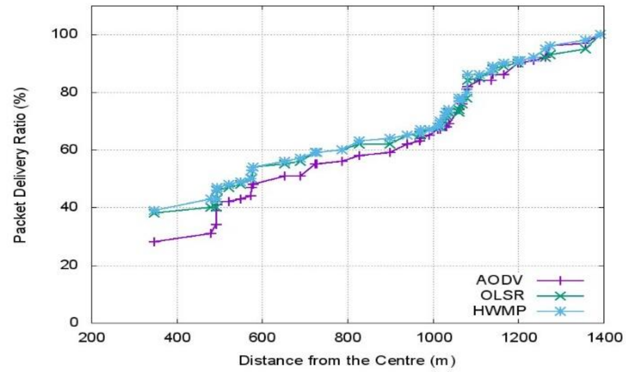
e. 40 Node Network

Figure 5.3: Packet Delivery Ratio vs Distance from Network Centre in Portal-based Berlin Node Distribution

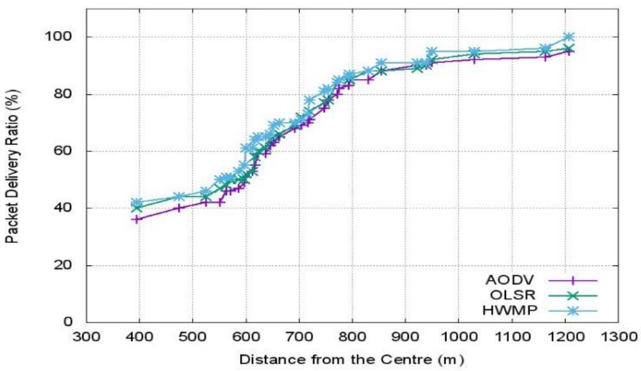
d) Portal-based traffic in Leipzig Node Distribution



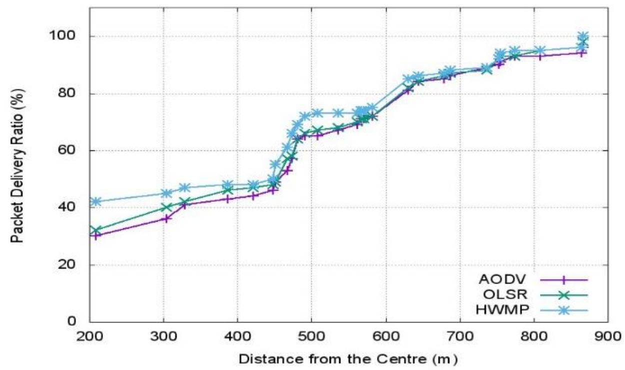
a. 120 Node Network



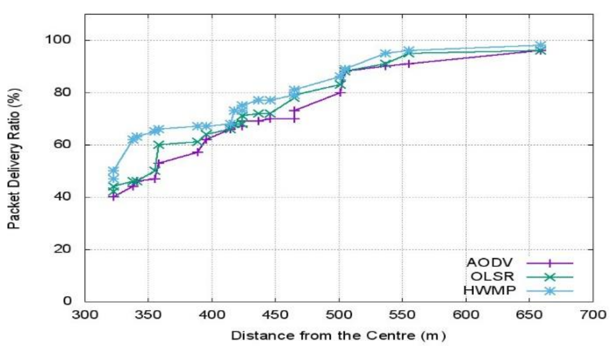
b. 100 Node Network



c. 80 Node Network



d. 60 Node Network

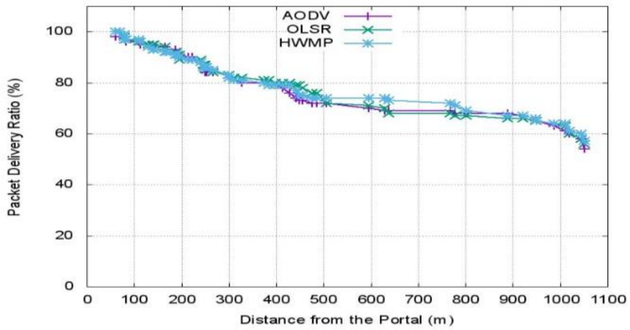


e. 40 Node Network

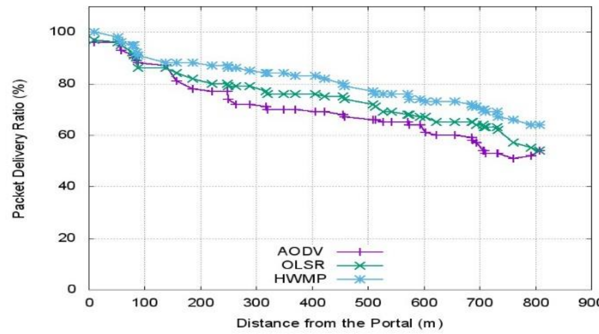
Figure 5.4: Packet Delivery Ratio vs Distance from Network Centre in Portal-based Leipzig Node Distribution

5.2.2 Scenario 2: The Effect of Distance from the Portal

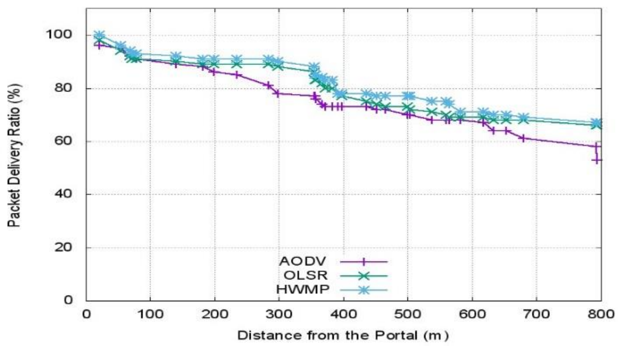
a) Portal-based in Berlin Node Distribution



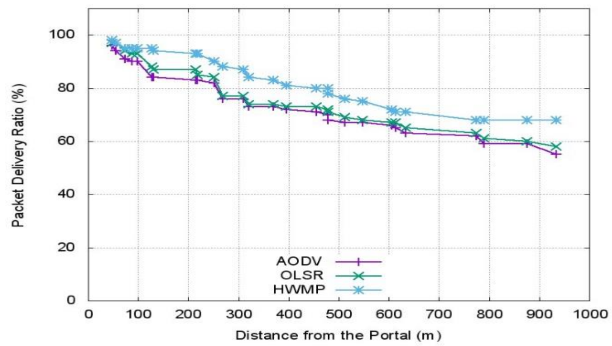
a. 120 Node Network



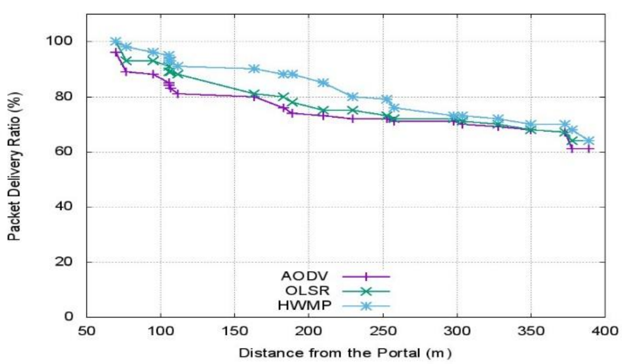
b. 100 Node Network



c. 80 Node Network



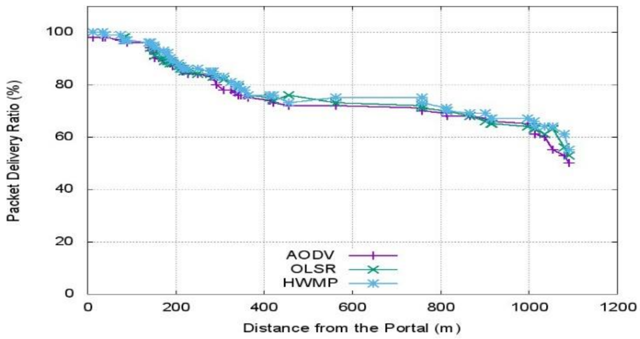
d. 60 Node Network



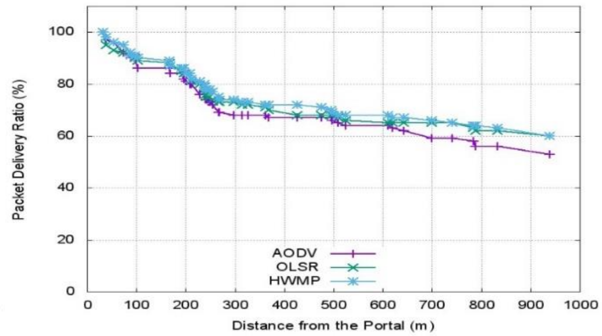
e. 40 Node Network

Figure 5.5: Packet Delivery Ratio vs Distance from the Portal in Portal-based Berlin Node Distribution

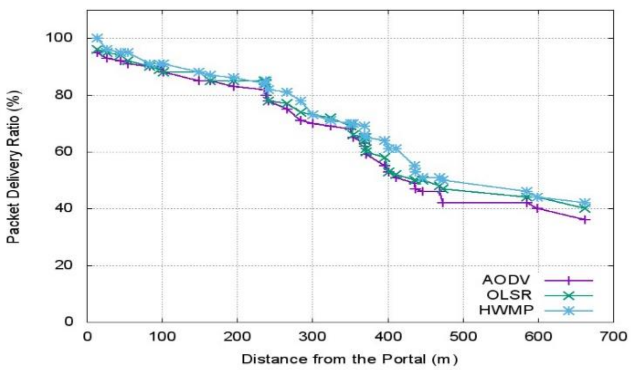
b) Portal-based traffic in Leipzig Node Distribution



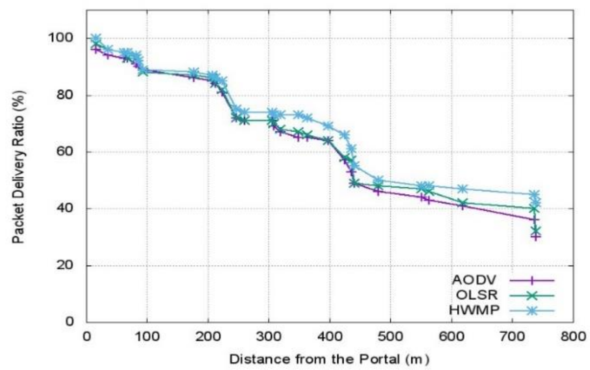
a. 120 Node Network



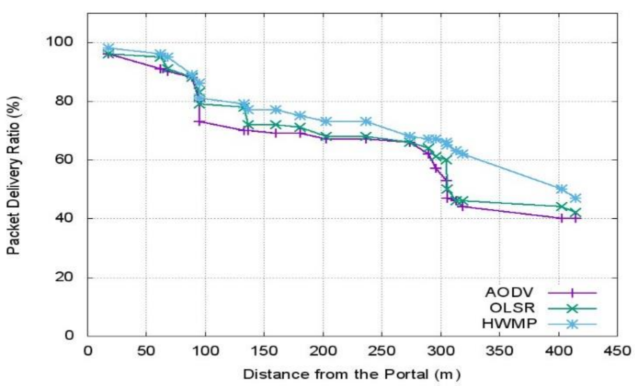
b. 100 Node Network



c. 80 Node Network



d. 60 Node Network



e. 40 Node Network

Figure 5.6: Packet Delivery Ratio vs Distance from the Portal in Portal-based Leipzig Node Distribution

5.3 Experiment 2: End-to-End Delay

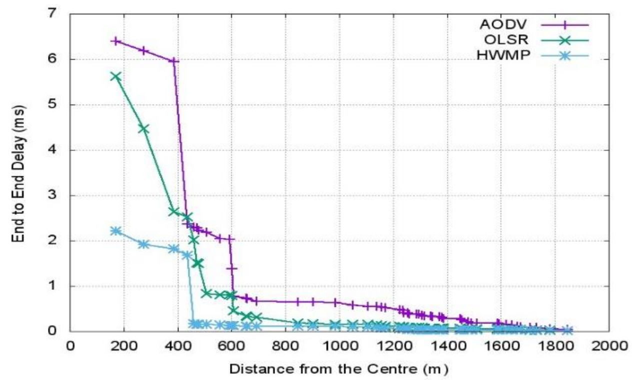
The aim of the investigation was to determine the time take taken by data packets being transmitted form source to destination. In most applications, delay is usually used to measure the network performance.. The delay is calculated from the sent time, when the packet leaves the source, and the received time, when the packet reaches the intended destination. The delay is measured in milliseconds (ms). The network must achieve as low a delay as possible in order to be considered a best- performing network. Consequently, a lower value of delay of the routing protocol indicates better performance of the network.

The delay results depicted in Figures 5.7 to 5.12 were obtained from both scenarios, for Berlin and Leipzig node distributions. The results show that there is a decrease of delay on the backbone nodes located far from the network centre. Delays are introduced, especially because when the backbone nodes transmit data packets they compete for channel access. Depending on the priority mechanism used, some data packets may have to wait longer before being transmitted. As section 4.1.1 mentioned that there are high traffic volumes experienced at the network centre, and bottlenecks are expected to happen, causing delays. The length of delay starts to improve on the nodes located far from the network centre.

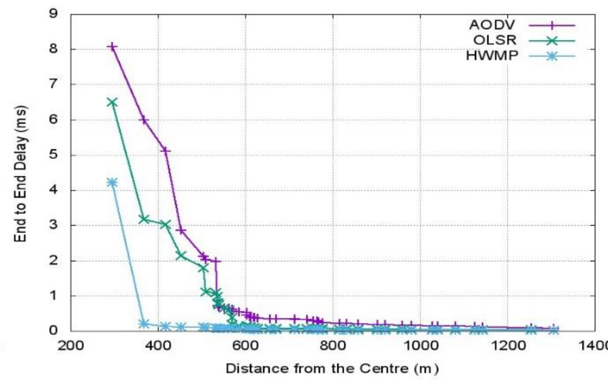
Furthermore, the delay of the backbone nodes located near the Portal is lower than the delay of backbone nodes located far from the Portal. There is a positive correlation between the results obtained by realistic topologies and random topologies. When creating a realistic topology, the topology that is generated is fully connected, planned and has low average node degree, allowing the network to be well-connected. In this way, backbone nodes have many possible routes to the intended destination, eliminating unnecessary delays.

5.3.1 Scenario 1: The Effect of Distance from the Network Centre

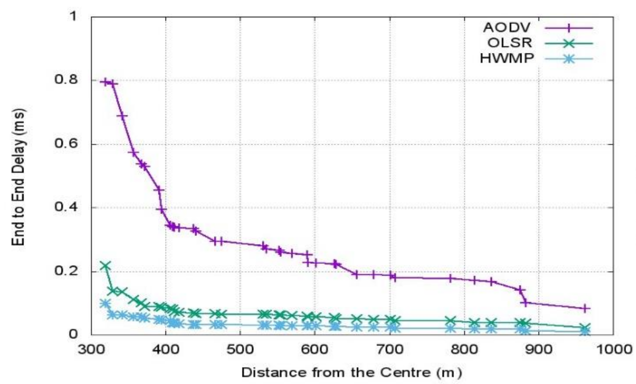
a) Intramesh traffic in Berlin Node Distribution



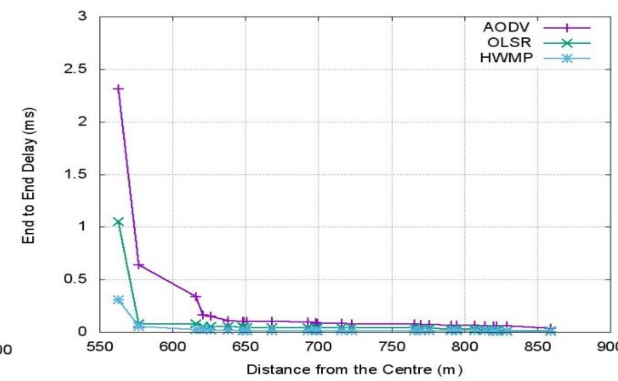
a. 120 Node Network



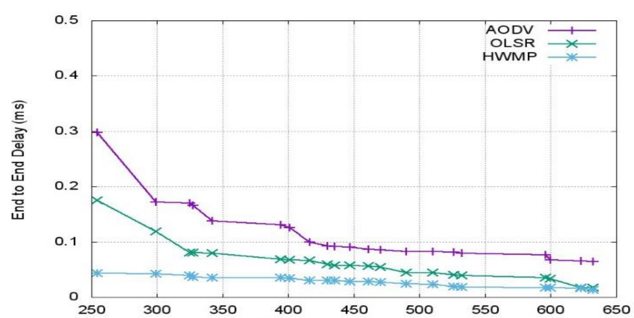
b. 100 Node Network



c. 80 Node Network



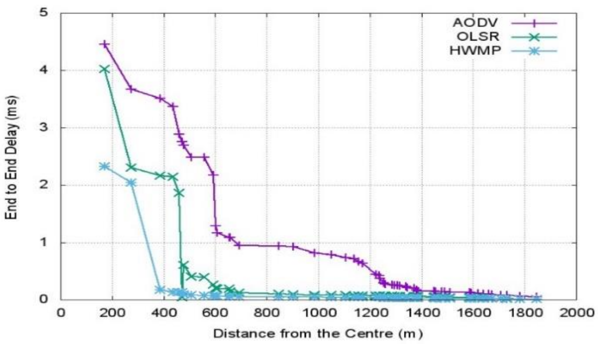
d. 60 Node Network



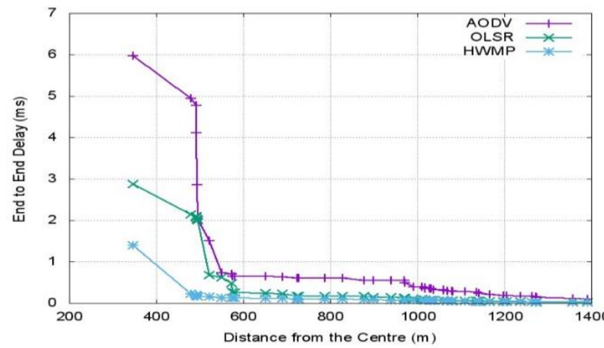
e. 40 Node Network

Figure 5.7: End-to-end delay vs Distance from Network centre in Intramesh Berlin Node Distribution

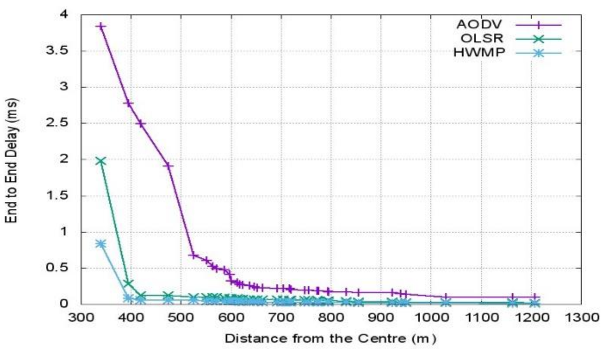
b) Intramesh traffic in Leipzig Node Distribution



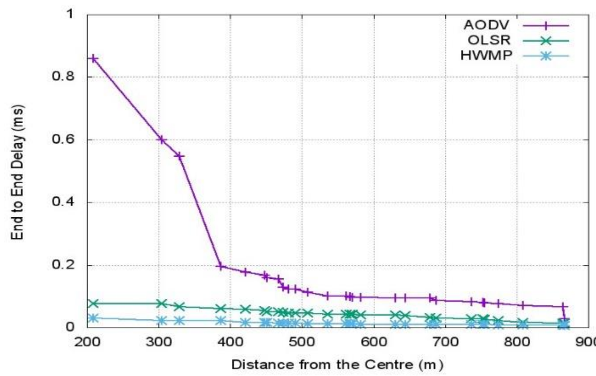
a. 120 Node Network



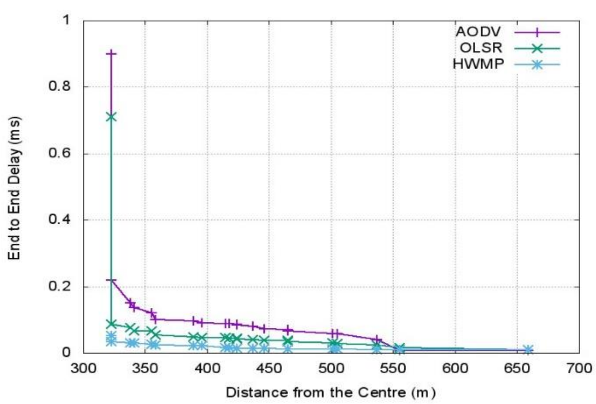
b. 100 Node Network



c. 80 Node Network



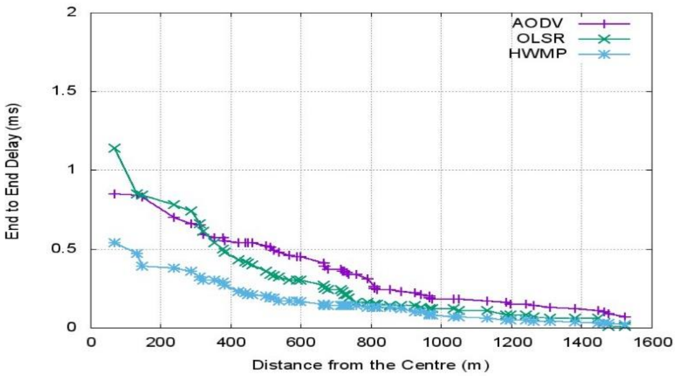
d. 60 Node Network



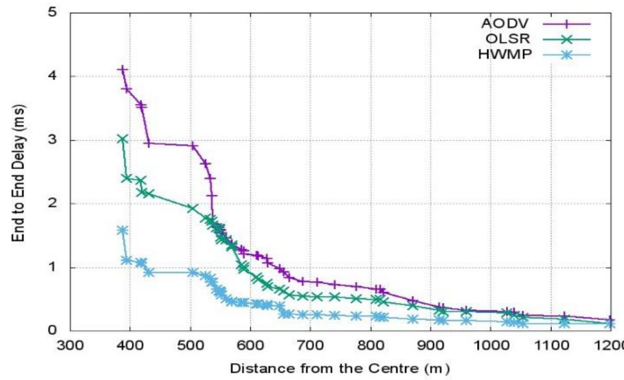
e. 40 Node Network

Figure 5.8: End-to-end delay vs Distance from Network centre in Intramesh Leipzig Node Distribution

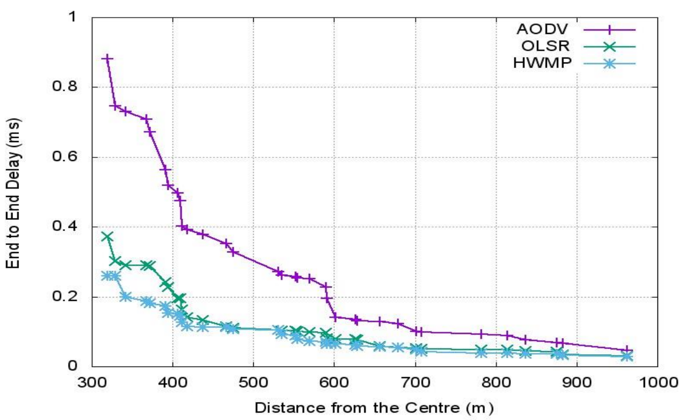
c) Portal-based traffic in Berlin Node Distribution



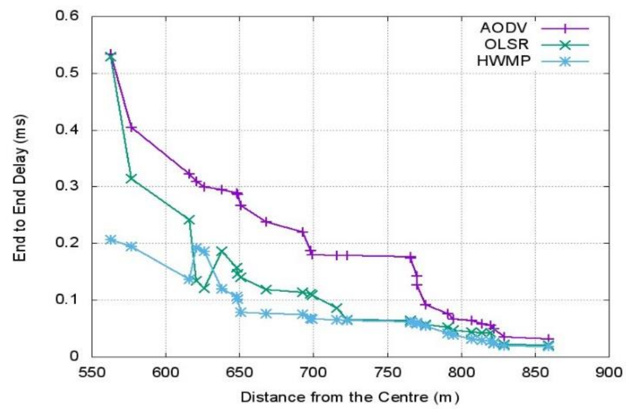
a. 120 Node Network



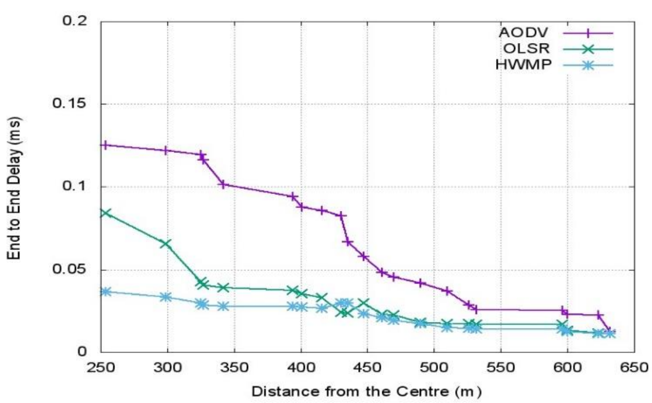
b. 100 Node Network



c. 80 Node Network



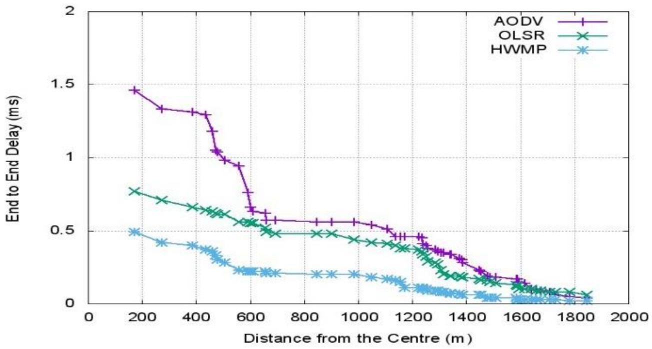
d. 60 Node Network



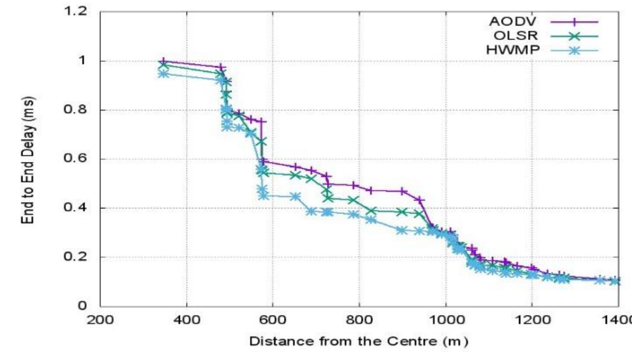
e. 40 Node Network

Figure 5.9: End-to-end delay vs Distance from Network centre in Portal-based Berlin Node Distribution

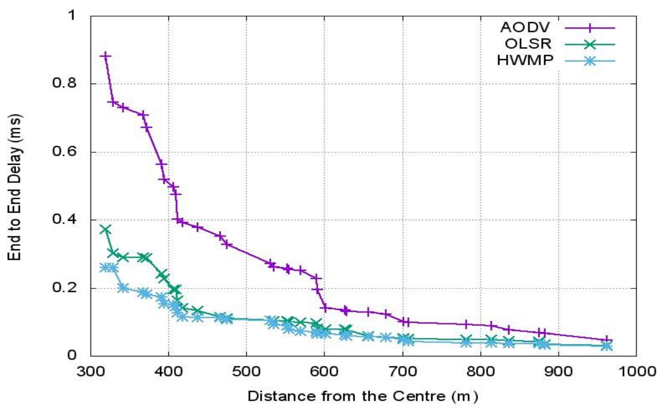
d) Portal-based traffic in Leipzig Node Distribution



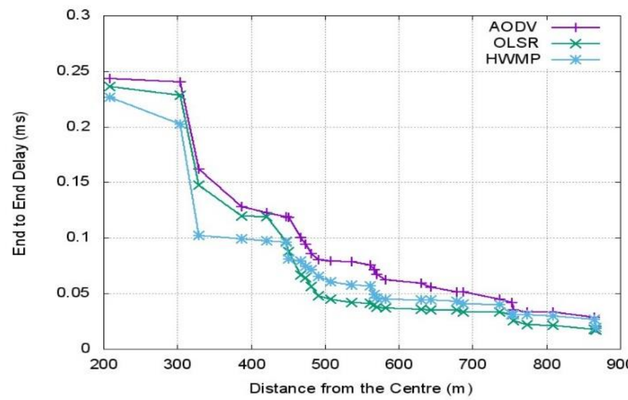
a. 120 Node Network



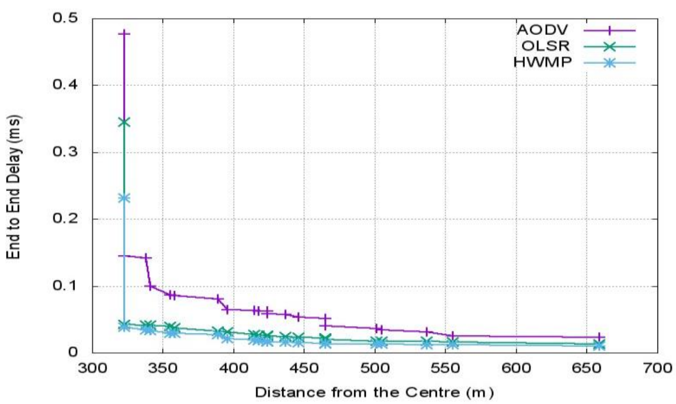
b. 100 Node Network



c. 80 Node Network



d. 60 Node Network

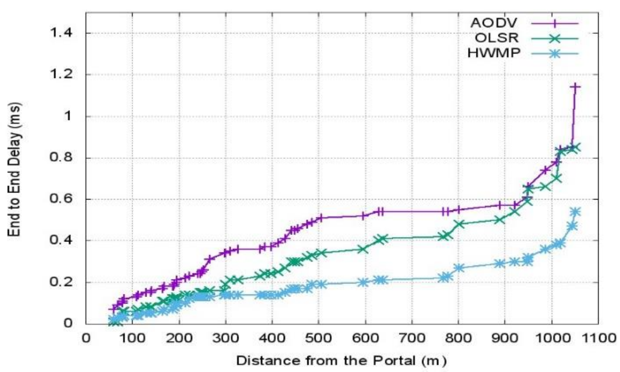


40 Node Network

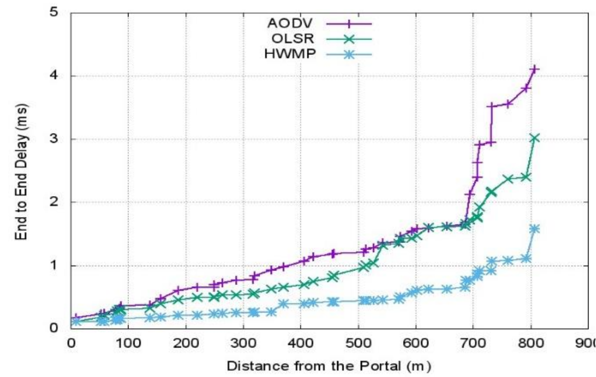
Figure 5.10: End-to-end delay vs Distance from Network centre in Intramesh Leipzig Node Distribution

5.3.2 Scenario 2: The Effect of Distance from the Portal

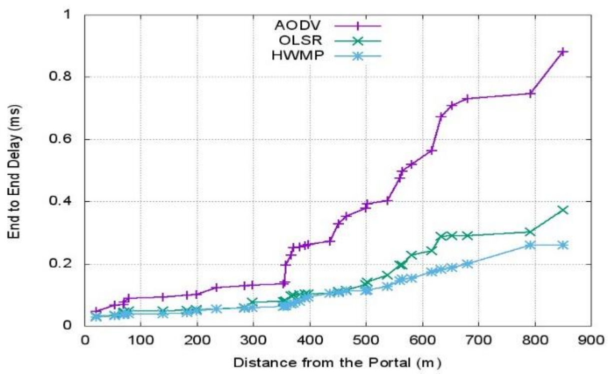
a) Portal-based traffic in Berlin Node Distribution



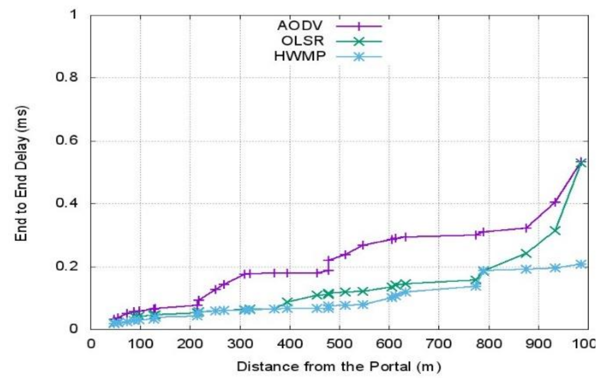
a. 120 Node Network



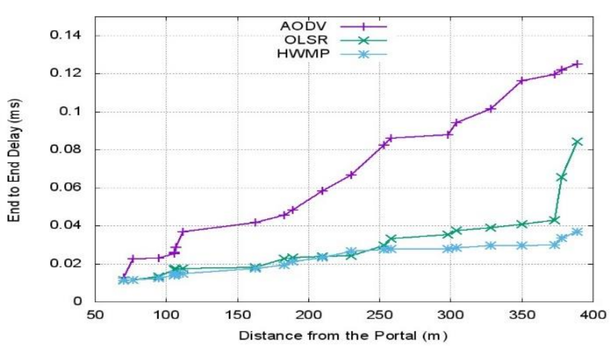
b. 100 Node Network



c. 80 Node Network



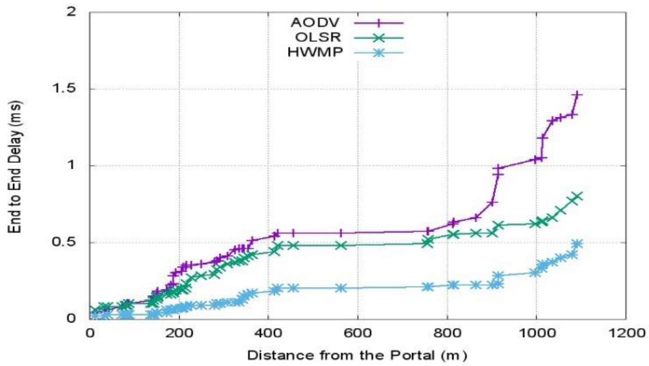
d. 60 Node Network



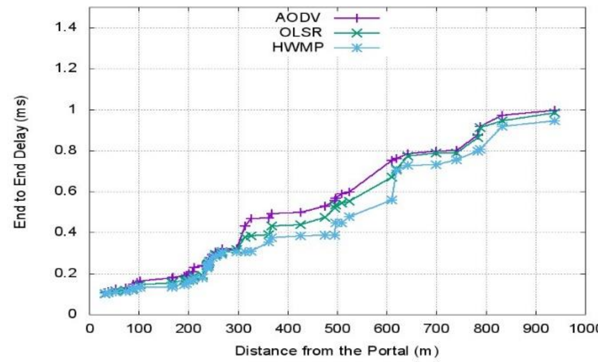
e. 40 Node Network

Figure 5.11: End-to-end delay vs Distance from Portal in Portal-based Berlin Node Distribution

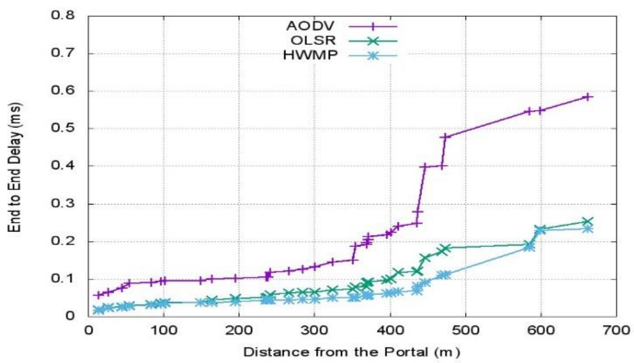
b) Portal-based traffic in Leipzig Node Distribution



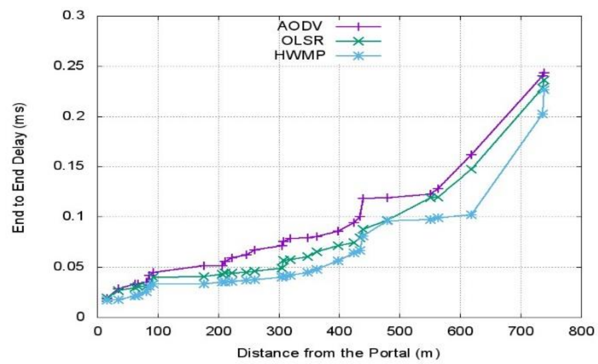
a. 120 Node Network



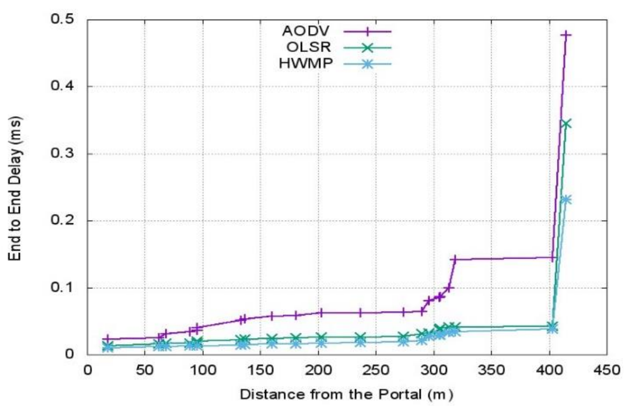
b. 100 Node Network



c. 80 Node Network



d. 60 Node Network



e. 40 Node Network

Figure 5.12: End-to-end delay vs Distance from Portal in Portal-based Leipzig Node Distribution

5.4 Experiment 3: Throughput

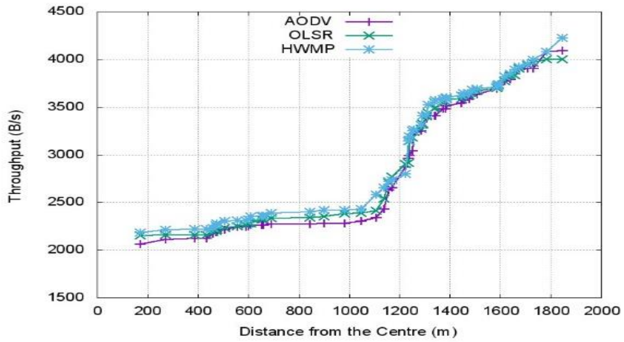
Throughput is the amount of data received over a period of time. High throughput achieved indicates that QoS requirements are being met. Figures 5.15 – 5.20 indicate throughput results obtained from individual backbone nodes in Berlin and Leipzig node distributions. Both Intramesh and Portal-based traffic were evaluated with node location relative to the network centre and the Portal. The results show that the nodes located closer to the network centre achieve lower throughput compared to the backbone nodes and the verge of the topology area. The low throughput achieved by these nodes can be attributed to high traffic volumes in the network centre, whereby the centrally located nodes are an easy target when other nodes try to send their data packets.

Throughput degrades as the number of hops increase. Hence, throughput decrease is expected to on backbone nodes located far from the Portal. The data packets from backbone nodes located far from the Portal have to pass through a number of hops before reaching the Portal. As the data packets are transmitted over many hops packets can get lost or dropped along the transmission, thus causing a decrease in the throughput. Even though these results follow the same trend as the results obtained in random topologies, realistic topologies have much better improved throughput results.

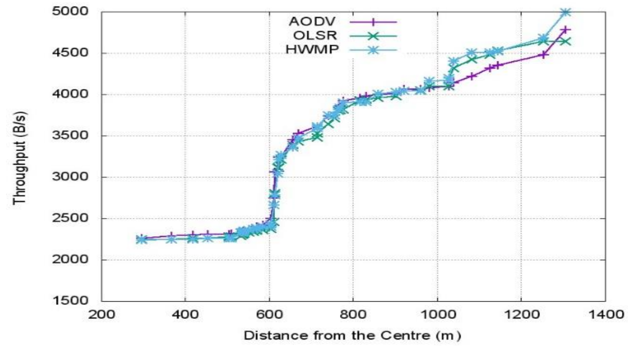
Realistic topologies use low average node degree, allowing the level of interference to be projected. The parameters involved in designing a realistic topology were shown in Tables 3.2 and 3.3. These tables show that realistic topologies use a large number of links. This reduces network congestion and, as a result, the traffic can be redirected to available links should one link become unusable.

5.4.1 Scenario 1: The Effect of Distance from the Network Centre

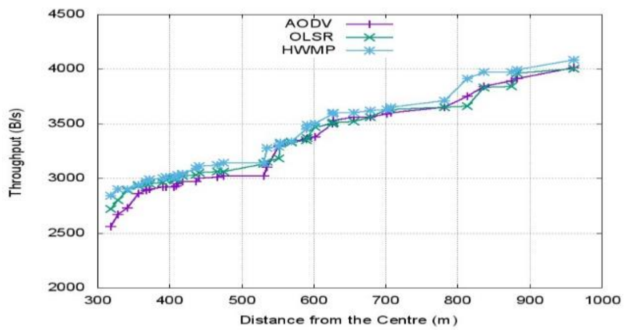
a) Intramesh traffic in Berlin Node Distribution



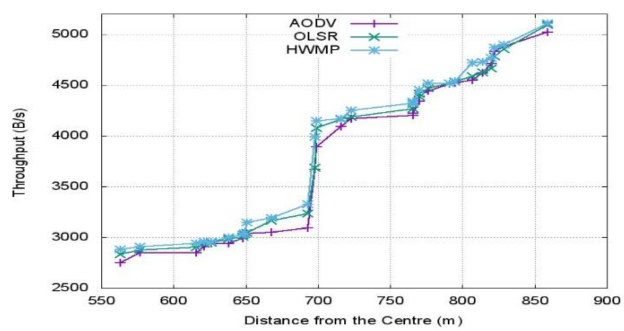
a. 120 Node Network



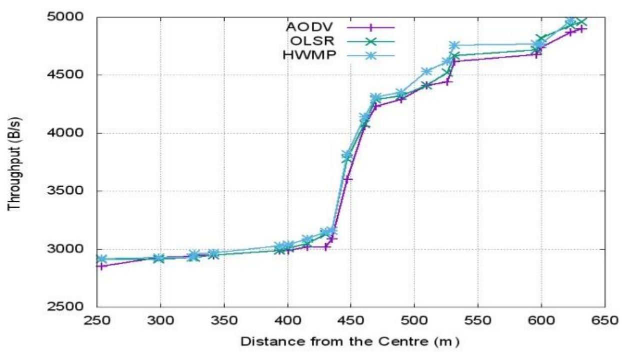
b. 100 Node Network



c. 80 Node Network



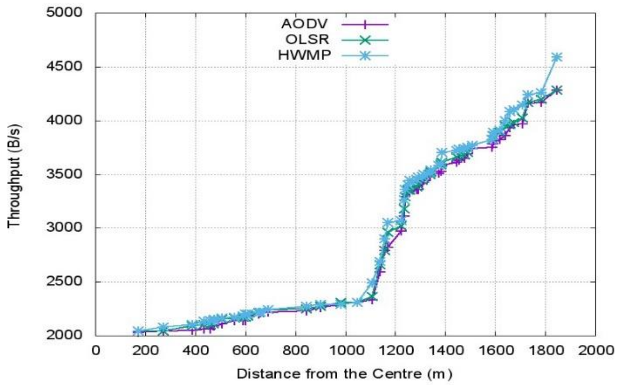
d. 60 Node Network



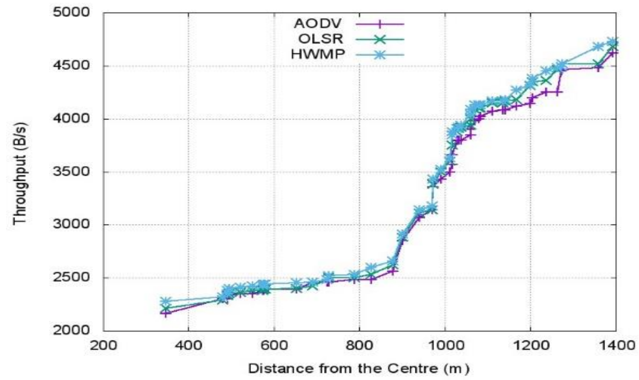
e. 40 Node Network

Figure 5.13: Throughput vs Distance from network centre in Intra-mesh Berlin Node Distribution

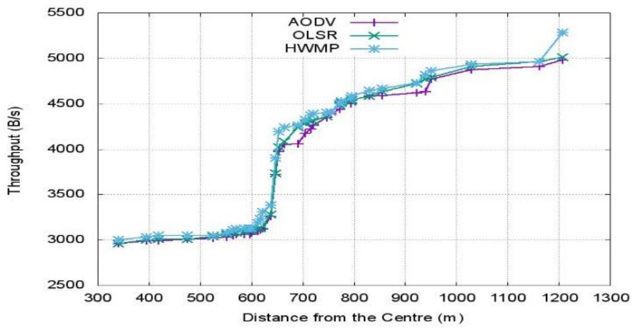
b) Intramesh traffic in Leipzig Node Distribution



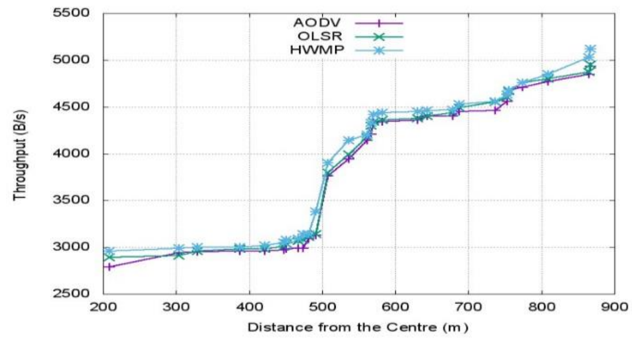
a. 120 Node Network



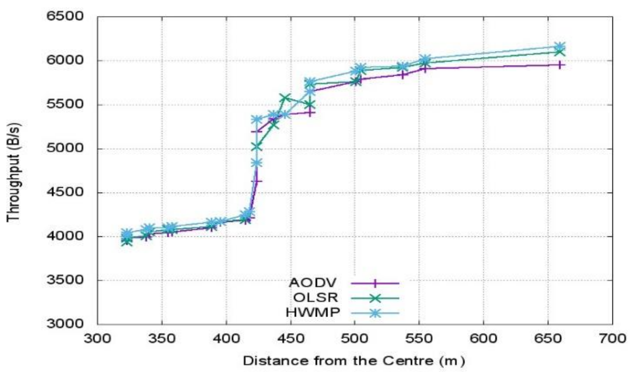
b. 100 Node Network



c. 80 Node Network



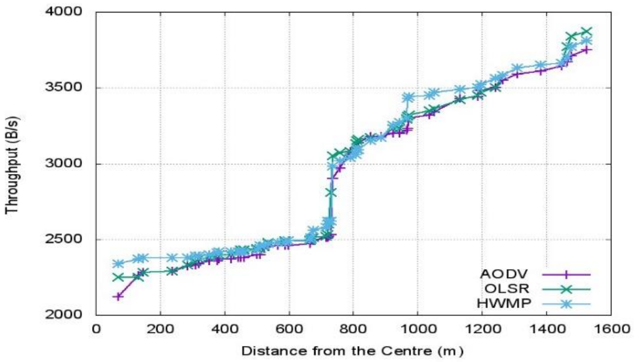
d. 60 Node Network



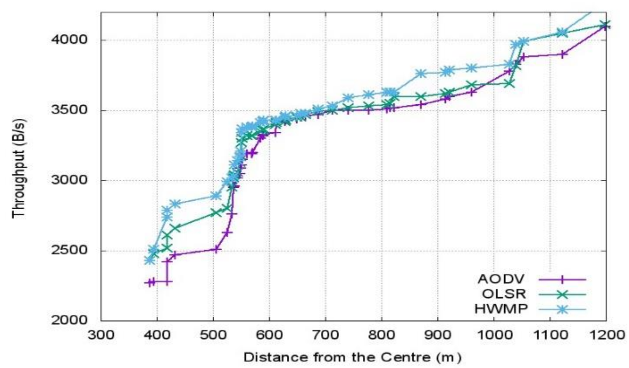
e. 40 Node Network

Figure 5.14: Throughput vs Distance from network centre in Intra-mesh Leipzig Node Distribution

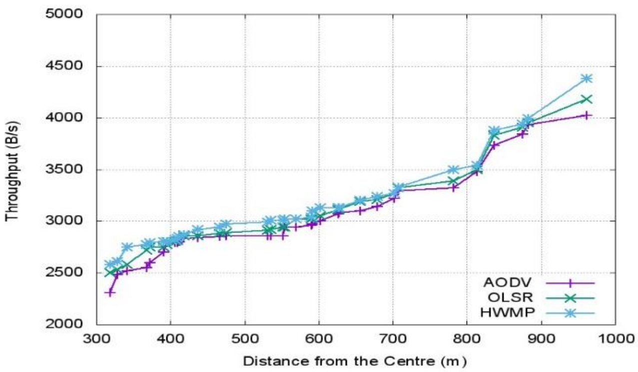
c) Portal-based traffic in Berlin Node Distribution



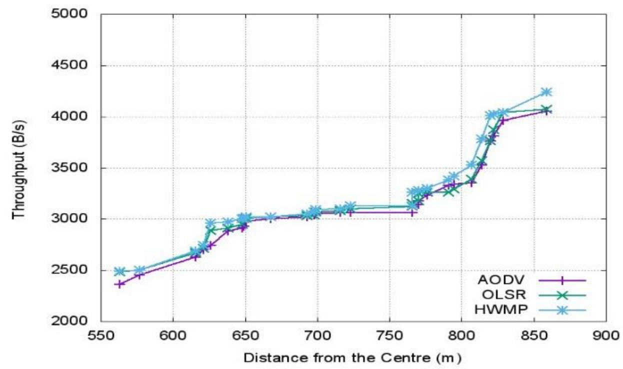
a. 120 Node Network



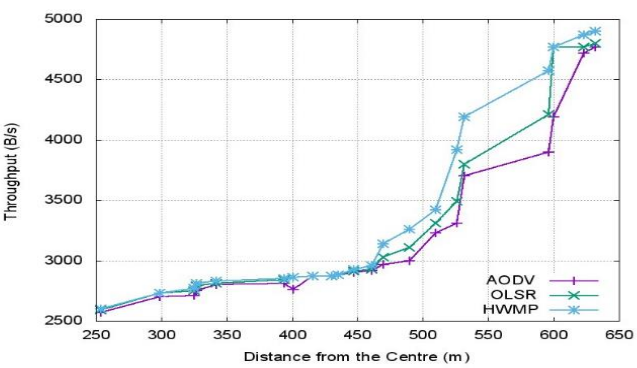
b. 100 Node Network



c. 80 Node Network



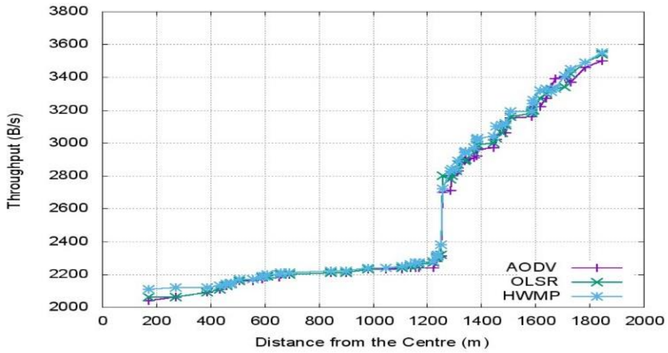
d. 60 Node Network



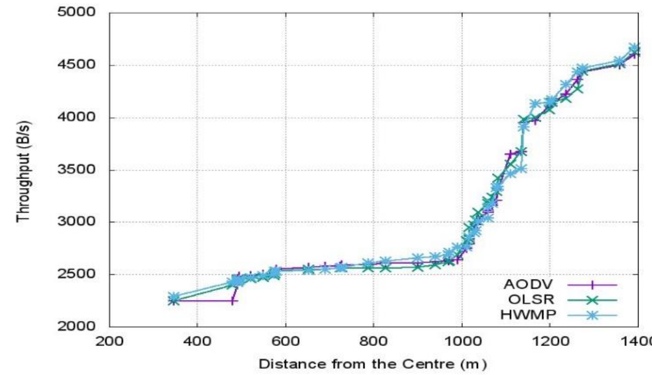
e. 40 Node Network

Figure 5.15: Throughput vs Distance from network centre in Portal-based Berlin Node Distribution

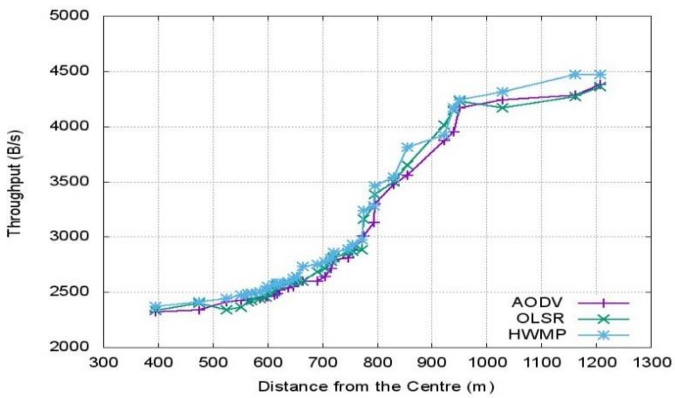
d) Portal-based traffic in Leipzig Node Distribution



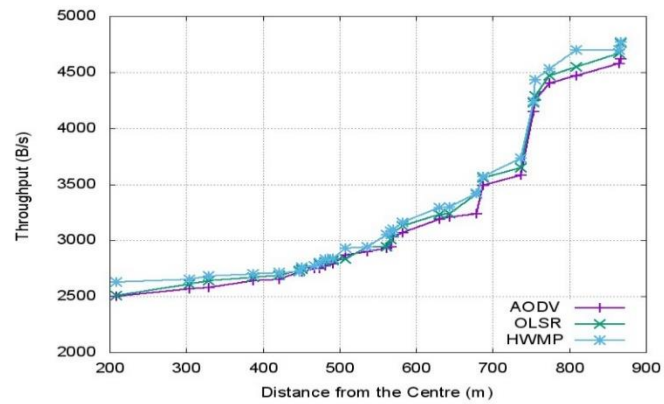
a. 120 Node Network



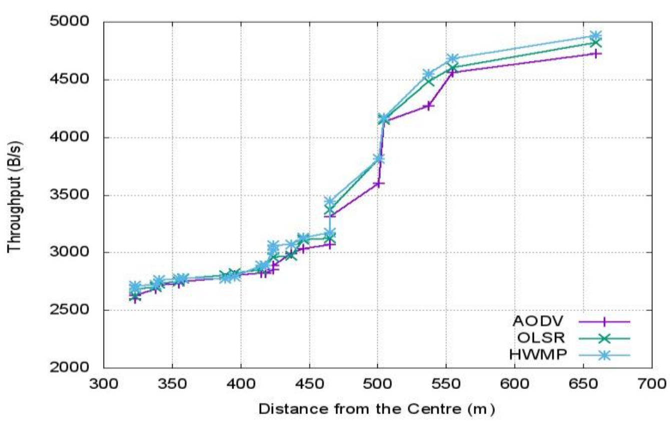
b. 100 Node Network



c. 80 Node Network



d. 60 Node Network

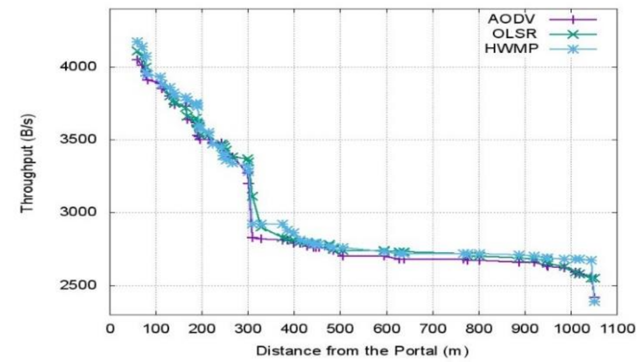


40 Node Network

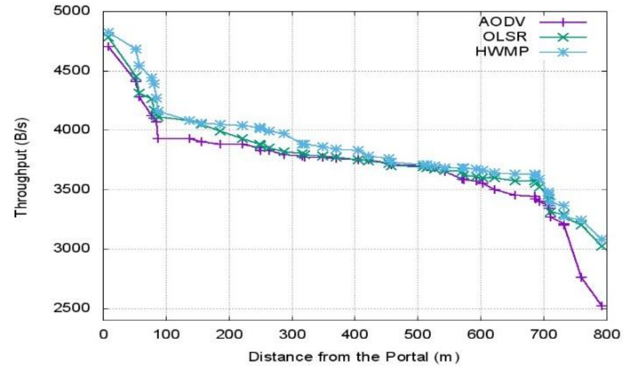
Figure 5.16: Throughput vs Distance from network centre in Portal-based Leipzig Node Distribution

5.4.2 Scenario 2: The Effect of Distance from the Portal

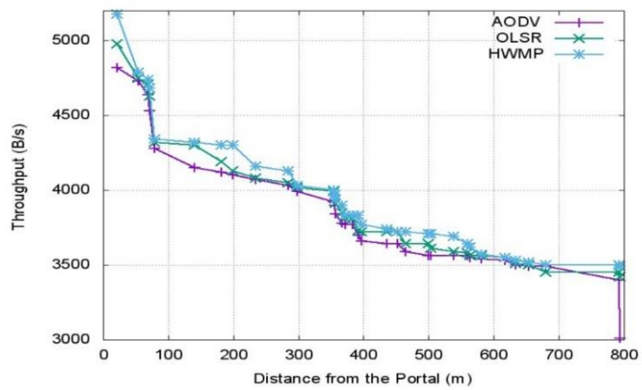
a) Portal-based traffic in Berlin Node Distribution



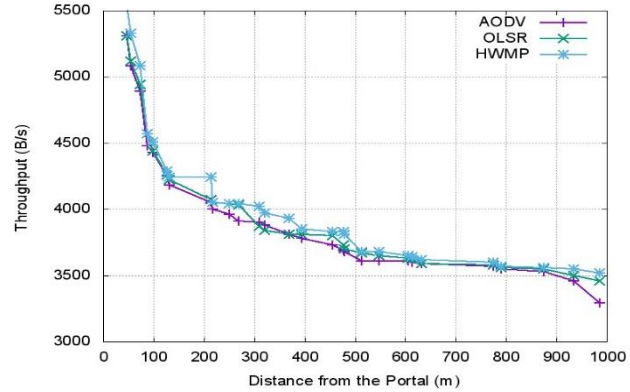
a. 120 Node Network



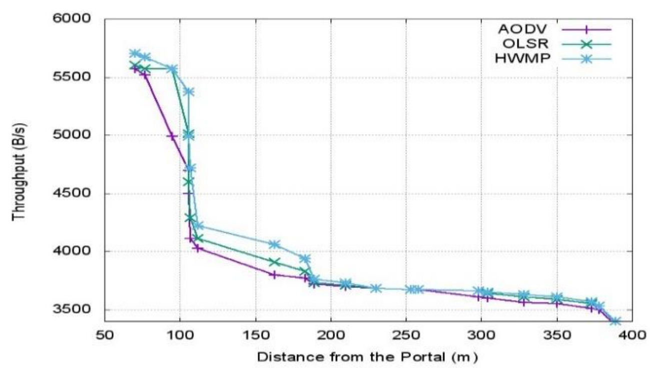
b. 100 Node Network



c. 80 Node Network



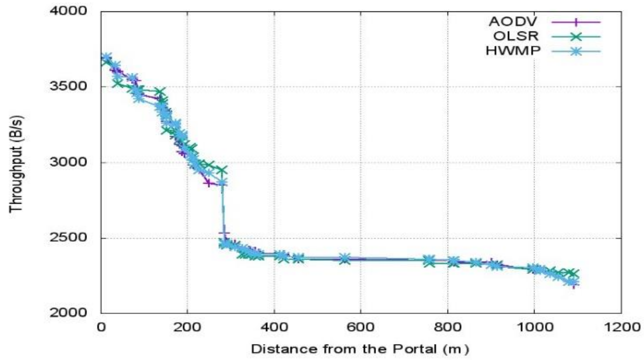
d. 60 Node Network



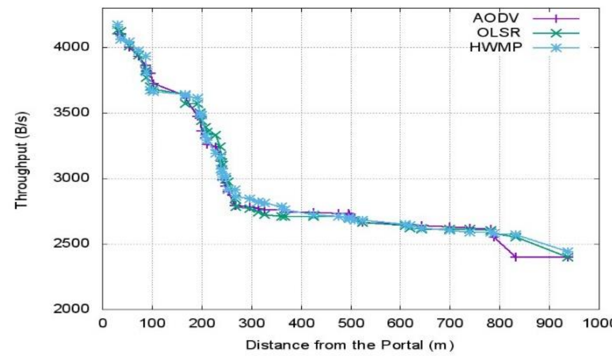
e. 40 Node Network

Figure 5.17: Throughput vs Distance from the Portal in Portal-based Berlin Node Distribution

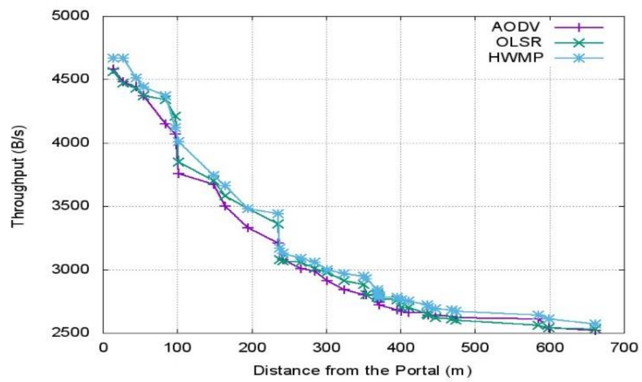
b) Portal-based in Leipzig Node Distribution



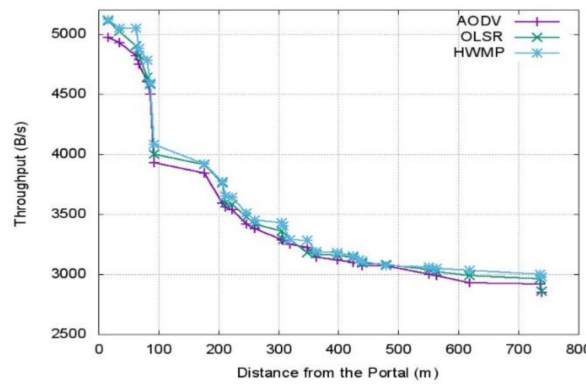
a. 120 Node Network



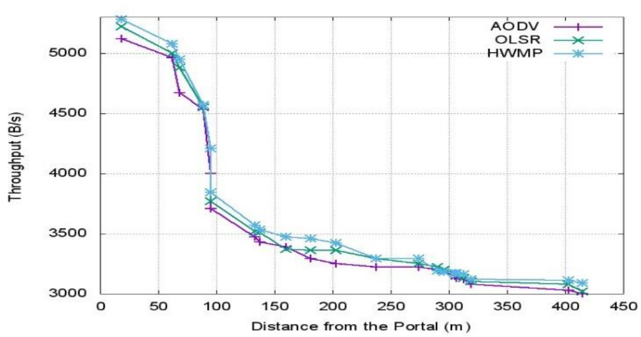
b. 100 Node Network



c. 80 Node Network



d. 60 Node Network



e. 40 Node Network

Figure 5.18: Throughput vs Distance from the Portal in Portal-based Leipzig Node Distribution

Summary of the Results

The previous chapter and this chapter presented the simulation results obtained from Random topologies and Realistic topologies, respectively. It was observed that both results compared favourably, following a similar pattern, with the Realistic topologies producing better performance in terms of packet delivery ratio, end to end delay, and the throughput achieved by individual backbone nodes. These backbone nodes were subjected to distance from the network centre and the distance from the Portal. The experiments were conducted on both Intra-mesh and Portal-based traffic scenarios supported by IWMN.

For the packet delivery ratio, it was observed that for the Intramesh traffic in all node distributions backbone nodes located near the network centre experience low delays. As the distance from the centre increases, the pdr also increases. In the Portal-based traffic scenario, the pdr decreases as the distance from the portal increases. In terms of the end to end delay, in the Intra-mesh traffic, the backbone nodes located far from the network centre experience lesser delays. The inverse is true when the backbone nodes are subjected to the distance from the Portal.

Examining the throughput results, the backbone nodes located closer to the network centre produced lower throughput compared to the nodes located far from the network centre. This lower throughput result correlates with the low packet delivery ratio experienced by these same backbone nodes, since the end to end delay was also high.

In all the results obtained, the performance of three routing protocols were also considered. It was noted that AODV was the worst-performing routing protocol. This is generally caused by the reactive nature of the protocol. In AODV, the routes are only established when there is a route request. This establishment of routes causes bottlenecks and delay, which results in congestion or packet loss. OLSR achieved better throughput than AODV. OLSR also achieved a higher number of successfully delivered packets compared to AODV, as was shown by Sandhu *et al.* (2012) in their study which evaluated the performance of OLSR and AODV.

HWMP was the best-performing routing protocol. HWMP takes advantage of the proactive and reactive nature of a protocol. The proactive mode uses flooding to minimise the control traffic. The proactive mode employs the MPRs, which prevents messages from being sent to the entire network. Only the MPRs transmit the message instead of all network nodes. This technique significantly reduces the number of transmissions in the flooding procedure. Hence, HWMP performs better that AODV and OLSR.

HWMP has also been proven to perform better in small or large network sizes, which agrees with the findings. This result was established by Ibrahim *et al.* (2013) where the results indicated that HWMP uses less time compared to AODVwhen transmitting data packets. This implies that choosing the best path in HWMP can result in faster data delivery.

6. CHAPTER 6

6.1 Conclusion

IWMNs have several benefits, such as self-healing, self-configuration, and self-organising. The network infrastructure usually comprises stationary nodes, support traffic within the nodes, and Portal traffic. Providing QoS guarantees is a vital objective in WMNs. It is therefore important that the wireless communication supports QoS, since different applications require different QoS requirements such as throughput, packet delivery ratio, and delay. In order to meet different QoS requirements, efficient routing protocols must show good performance in different traffic scenarios and different node distributions. (Akyildiz, 2009).

This dissertation has presented the analysis obtained when investigating the effect of individual node location relative to the network centre as well as the Portal on QoS in IWMNs. The interest stimulated by the investigation revealed that in IWMN the location of a node can influence the performance of the network. The studies focused on the node location relative to the network centre, stating that nodes at the centre of the network are heavily loaded and they forward more traffic than the edge nodes. This resulted in longer delays, low throughput and possibly low packet delivery ratio. Hence, this work purported to investigate the impact of node location relative to the network centre. In addition to that, the work also investigated the node location relative to the Portal.

In order to achieve the research goal, measurable objectives were the mechanism used. The objectives were to study and classify existing QoS in IWMNs, and to also perform a simulation evaluation on node location relative to the network and the Portal. The next section attempts to validate how the research objectives became the tool for realising the goal of the study.

The preliminary investigation conducted discovered that in IWMNs the location of a node can impact the performance of the network. But the investigation was limited in scope to uniform node distribution and Intramesh communication. However, the literature survey revealed that existing node distribution is not limited to uniform distribution and that other distributions such as normal, linear, and grid have not been fully explored. Additionally, there are two types of traffic scenario supported by IWMNs which have not received adequate attention from researchers compared to the Intra-mesh traffic. To this end, this study explored the two types of traffic scenario, called Intramesh and Portal-based, in random (uniform and normal) and realistic (Berlin and Leipzig) topologies, with a view to determining the impact of node location on QoS mechanisms in IWMNs.

The following was the first research objective utilised the literature review:

(i). To conduct a literature survey on the transport layer protocols (TCPs), routing protocols (hybrid, proactive, reactive), node distributions, and traffic scenarios

The outcome from research objective one came as a result of a detailed background study of network QoS mechanisms. The study analysed existing literature in order to understand how different node locations can influence network performance when QoS mechanisms are used as metrics. Arising from the background knowledge gained from the review of related works, relevant research publications were selected for deeper scrutiny. This strategy employed specific QoS metrics as yardstick for identifying the loopholes in the selected published works. The outcome of the survey resulted in the justification for the remaining four objectives of the research, which utilised the simulation method as the evaluation approach.

The objectives were:

(ii). **To evaluate the effect of node distance from the network centre using Random node distribution on Intra-mesh and Portal-based traffic scenarios**

(iii). **To evaluate the effect of node distance from the Portal using Random node distribution on Intra-mesh and Portal-based traffic scenarios**

(iv). **To evaluate the effect of node distance from the network centre using Realistic node distribution on Intra-mesh and Portal-based traffic scenarios**

(v). **To evaluate the effect of node distance from the Portal using Realistic node distribution on Intra-mesh and Portal-based traffic scenarios**

In trying to achieve these objectives, comprehensive simulation experiments were performed. The results from the experiments were analysed. For each experiment, two scenarios were defined for the three performance metrics in Sections 3.4. The performance metrics considered were the packet delivery ratio, the end-to-end delay, and the throughput. Under each scenario, Intra-mesh and Portal traffic were investigated. Furthermore, the normal, uniform, Berlin and Leipzig node distributions were explored. The QoS requirements are fulfilled if the node is able to produce high throughput, low delays and achieve high packet delivery.

In general, the outcome of the evaluation showed that graphs are quite similar in all network sizes, traffic scenarios and topologies. The packet delivery ratio increased on the nodes far from the network centre but decreased on the nodes closer to the Portal. Low throughput was attained by nodes located closer to the network centre whereas the nodes closer to the Portal achieved high throughput. With respect to the delay, nodes closer to the network centre experienced high delays whilst nodes closer to the Portal experienced low delays. It can be concluded that the low throughput, low packet delivery ratio and high delays concur with the previous studies of node location relative to the network centre. Furthermore, and to the best of my knowledge, this is the first time it has been realised that there is a positive impact on the high throughput, high packets delivery ratio and low delays achieved by the nodes closer to the Portal.

.

The Random topologies were subjected to the same topology area. This indicates the need to investigate random topologies in different topology areas. On the oher hand, the topology area for the Realistic topologies is not user-defined. Hence, the performance of Realistic topologies is better than Random topologies. The aim of doing simulations is to find out how the network might behave in real-life implementation, and Realistic topologies give an idea since they have the properties of a real network. Therefore, we can recommend Realistic topologies since they highlighted what can be expected in real life. Furthermore, it would be useful to investigate mobility in Realistic topologies, since the experiments in this study only considered static nodes.

6.2 Limitations and Future work

The limitations and shortcomings emerging from the study are highlighted in this section. The challenges do not invalidate the fact that the problem statement was adequately addressed, even though there is still more that can be done, to fully provide QoS on the network. The following shortcomings of the experimental environment are recognised and are brought to the notice of readers:

i. Traffic file: when creating a traffic file not all the nodes participate (Only about 80% participated in the simulation process).

ii. Simulation life time: while running some simulations some computers were very slow, taking more than two days to generate one tracefile.

iii. Trace file analyser: the analyser could only extract a single piece of information for a single node at a time, consuming a lot of time.

The motivation for using simulations is that the experiments have to be evaluated from small to large network sizes, ranging from 20-120 nodes. In future, a testbed need to be explored, for real-life experiments.

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APPENDIX A

```
#!/usr/bin/perl

# cc Pragasen Mudali, Wireless Mesh Network Research Group, Univ. of Zululand

# Thu 20 Mar 2008 14:42:06

use strict;

use Spreadsheet::WriteExcel;


# Create a new Excel workbook called perl.xls

my $workbook = Spreadsheet::WriteExcel->new("perl.xls");

my $worksheet = $workbook->addworksheet();



# to check the command line option

if($#ARGV<0){

   printf("Invalid Usage: <node placement file> <# of nodes> <X co-ord. of network center> <Y co-ord.
of network center>\n");

   exit 1;

}



# to open the node placement file

open(Trace, $ARGV[0]) or die "Cannot open the node placement file";

#my $node_counter = 0; #counter for the number of nodes contained in the node placement file

#my $node_tx_range = 250; # node transmission range

my $node_id; # stores the identity of the currently processed node

my $x1 = 0;

my $y1 = 0;
```

```
my $x2 = $ARGV[2]; # X coordinate for network center
my $y2 = $ARGV[3]; # Y coordinate for network center
my @node_dist;
my $node_dist_from_center = 0;
#my $counter = 0;


while(<Trace>){ # read one line in from the file                              #
        my @line = split;  #split the line with delimin as space              #
        if($line[3] eq "X_"){                                                        #
                $node_id = $line[1]; printf("The node ID is %d\n", $node_id);    #
                $x1 = $line[4];                                                       #
                push @{$node_dist[$node_id]{"X"}}, $x1;                         #This portion is
                printf("X = %d\n", $x1);                                          #used to extract
        }                                                                             #X and Y vals and
        if($line[3] eq "Y_"){                                                        #store in array for
                $y1 = $line[4];                                                       #further processing
                push @{$node_dist[$node_id]{"Y"}}, $y1;                         #
                printf("Y = %d\n", $y1);                                          #
        }                                                                             #

##################################################### above is fine.

}
close(Trace); #close the file

printf("\n##################################################\n");
```

```
#print ${$node_dist[40]{"X"}}[0]; printf("\n");

#print ${$node_dist[40]{"Y"}}[0]; printf("\n");



for(my $i=0; $i < $ARGV[1]; $i++){

	$node_dist_from_center = 0;

	$x1 = ${$node_dist[$i]{"X"}}[0];				#

	$y1 = ${$node_dist[$i]{"Y"}}[0];				#

	$node_dist_from_center = sqrt((($x1-$x2)*($x1-$x2))+(($y1-$y2)*($y1-$y2)));

	#print($i); print(" is "); print($node_dist_from_center); print("m away from network center");

	$worksheet->write($i,0,$i);

	$worksheet->write($i, 1, $node_dist_from_center);

	#print($i); print(","); print($node_dist_from_center);

	#print("\n");

}

print("See perl.xls for output\n");

get Distance from the Center/Portal
```

Figure 7.1 Perl Script to calculate distance

```
s -t 6.234289345 -Hs 2 -Hd -2 -Ni 2 -Nx 275.79 -Ny 171.26 -Nz 0.00 -Ne -1.000000 -Nl AGT -Nw --- -Ma 0 -Md 0 -Ms 0 -Mt 0 -Is
2.2 -Id 4.0 -It tcp -Il 40 -If 0 -Ii 0 -Iv 32 -Pn tcp -Ps 0 -Pa 0 -Pf 0 -Po 0
r -t 6.234289345 -Hs 2 -Hd -2 -Ni 2 -Nx 275.79 -Ny 171.26 -Nz 0.00 -Ne -1.000000 -Nl RTR -Nw --- -Ma 0 -Md 0 -Ms 0 -Mt 0 -Is
2.2 -Id 4.0 -It tcp -Il 40 -If 0 -Ii 0 -Iv 32 -Pn tcp -Ps 0 -Pa 0 -Pf 0 -Po 0
s -t 6.234289345 -Hs 2 -Hd -2 -Ni 2 -Nx 275.79 -Ny 171.26 -Nz 0.00 -Ne -1.000000 -Nl RTR -Nw --- -Ma 0 -Md 0 -Ms 0 -Mt 0 -Is
2.255 -Id -1.255 -It AODV -Il 48 -If 0 -Ii 0 -Iv 30 -P aodv -Pt 0x2 -Ph 1 -Pb 1 -Pd 4 -Pds 0 -Ps 2 -Pss 4 -Pc REQUEST
r -t 6.235457358 -Hs 36 -Hd -2 -Ni 36 -Nx 276.32 -Ny 175.03 -Nz 0.00 -Ne -1.000000 -Nl RTR -Nw --- -Ma 0 -Md fffffff -Ms 2 -
Mt 800 -Is 2.255 -Id -1.255 -It AODV -Il 48 -If 0 -Ii 0 -Iv 30 -P aodv -Pt 0x2 -Ph 1 -Pb 1 -Pd 4 -Pds 0 -Ps 2 -Pss 4 -Pc REQUEST
r -t 6.235457566 -Hs 34 -Hd -2 -Ni 34 -Nx 241.38 -Ny 114.64 -Nz 0.00 -Ne -1.000000 -Nl RTR -Nw --- -Ma 0 -Md fffffff -Ms 2 -
Mt 800 -Is 2.255 -Id -1.255 -It AODV -Il 48 -If 0 -Ii 0 -Iv 30 -P aodv -Pt 0x2 -Ph 1 -Pb 1 -Pd 4 -Pds 0 -Ps 2 -Pss 4 -Pc REQUEST
r -t 6.235457576 -Hs 15 -Hd -2 -Ni 15 -Nx 264.45 -Ny 102.89 -Nz 0.00 -Ne -1.000000 -Nl RTR -Nw --- -Ma 0 -Md fffffff -Ms 2 -
Mt 800 -Is 2.255 -Id -1.255 -It AODV -Il 48 -If 0 -Ii 0 -Iv 30 -P aodv -Pt 0x2 -Ph 1 -Pb 1 -Pd 4 -Pds 0 -Ps 2 -Pss 4 -Pc REQUEST
r -t 6.235457670 -Hs 13 -Hd -2 -Ni 13 -Nx 239.88 -Ny 261.85 -Nz 0.00 -Ne -1.000000 -Nl RTR -Nw --- -Ma 0 -Md fffffff -Ms 2 -
Mt 800 -Is 2.255 -Id -1.255 -It AODV -Il 48 -If 0 -Ii 0 -Iv 30 -P aodv -Pt 0x2 -Ph 1 -Pb 1 -Pd 4 -Pds 0 -Ps 2 -Pss 4 -Pc REQUEST
r -t 6.235457676 -Hs 4 -Hd -2 -Ni 4 -Nx 179.54 -Ny 146.84 -Nz 0.00 -Ne -1.000000 -Nl RTR -Nw --- -Ma 0 -Md fffffff -Ms 2 -Mt
800 -Is 2.255 -Id -1.255 -It AODV -Il 48 -If 0 -Ii 0 -Iv 30 -P aodv -Pt 0x2 -Ph 1 -Pb 1 -Pd 4 -Pds 0 -Ps 2 -Pss 4 -Pc REQUEST
s -t 6.235457676 -Hs 4 -Hd 2 -Ni 4 -Nx 179.54 -Ny 146.84 -Nz 0.00 -Ne -1.000000 -Nl RTR -Nw --- -Ma 0 -Md 0 -Ms 0 -Mt 0 -Is
4.255 -Id 2.255 -It AODV -Il 44 -If 0 -Ii 0 -Iv 30 -P aodv -Pt 0x4 -Ph 1 -Pd 4 -Pds 4 -Pl 10.000000 -Pc REPLY
r -t 6.235457739 -Hs 27 -Hd -2 -Ni 27 -Nx 157.88 -Ny 168.12 -Nz 0.00 -Ne -1.000000 -Nl RTR -Nw --- -Ma 0 -Md fffffff -Ms 2 -
Mt 800 -Is 2.255 -Id -1.255 -It AODV -Il 48 -If 0 -Ii 0 -Iv 30 -P aodv -Pt 0x2 -Ph 1 -Pb 1 -Pd 4 -Pds 0 -Ps 2 -Pss 4 -Pc REQUEST
```

Figure 7.2: New Trace File Format in NS2

```
NPART(nodes n, communication radius R,
desired degree distribution of network target):

placedNodes = { new node at (0, 0)}
networkArea=( (minX=0, minY=0), (maxX=0, maxX=0) )
repeat
   placementArea = ( (minX-R, minY-R), (maxX+R, maxY+R) )
   minMetricValue = ∞
   repeat
      create candidateNode uniformly random in placementArea
so that candidateNode is connected to placedNodes
      candidateMetric=metric (placedNodes ∪ candidateNode )
      if(candidateMetric < minMetricValue)
            bestCandidate = candidateNode
            minMetricValue = candidateMetric
      endif
   until(retry different node candidates are evaluated)
   placedNodes = placedNodes ∪ bestCandidate
   update networkArea based on bestCandidate location
until(all n nodes are placed)
```

Figure 7.3: NPART algorithm (Milic & Malek, 2012)