THE OPTIMISATION AND PERFORMANCE EVALUATION OF ROUTING PROTOCOLS IN COGNITIVE RADIO BASED WIRELESS MESH NETWORKS

by

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DISSERTATION

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DEDICATION

This dissertation is dedicated to my beloved family:

To my mother, Meriam Kola

To my late daddy, Madimetja Kola

To my beloved sisters, Raesetja, Ntitah and Nape Kola

To all my niece and nephews….

DECLARATION

I hereby declare that this dissertation titled: THE OPTIMISATION AND PERFORMANCE EVALUATION OF ROUTING PROTOCOLS IN COGNITIVE RADIO BASED WIRELESS MESH NETWORKS submitted for the degree of Master of Science at the University of Limpopo is my own original work and has not previously been submitted to any other institution of higher education. I further declare that all sources cited or quoted have been indicated and acknowledged by means of a comprehensive list of references.

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Full Names **Date**

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ABSTRACT

The notion of ubiquitous computing, Internet of things (IoT), big data, cloud computing and other emerging technologies has brougt forward the innovative paradigms and incredible developments in wireless communication technologies. The Wireless Mesh Networks (WMNs) technology has recently emerged as the promising high speed wireless technology to provide the last mile broadband Internet access and deliver flexible and integrated wireless communication solutions. The WMNs has the potential to enable people living in rural, peri-urban areas and small businesses to interconnect their networks and share the affordable Internet connectivity. The recent multimedia applications developed, such as voice over Internet protocol (VoIP), online gaming, cloud storage, instant messaging applications, and video sharing applications require high speed communication media and networks. These applications have witnessed enormous growth in the recent decade and continue to enhance communication amongst the users. Hence, the WMNs must have adequate capacity to support high bandwidth and real-time and multimedia applications.

While the wireless communications networks are dependent on the radio frequency (RF) spectrum, the traditional wireless technologies utilise the RF spectrum bands inefficiently, resulting in sporadic and underutilisation of the RF spectrum. This inefficient usage of RF spectrum calls for novel techniques to leverage the available RF spectrum amongst different players in the wireless communication arena. There have been developments on integration of the WMNs with cognitive ratios to allow unlicensed users of RF spectrum to operate in the licensed portions of spectrum bands. This integration will provide the required bandwidth to support the required high speed broadband communication infrastructure.

In this dissertation, we focus our research on the routing layer in a multi-hop wireless network environment. We addressed the routing challenges in both the WMNs and the cognitive radio based wireless mesh networks (CR-WMNs). The primary focus was to identify the routing protocols most suitable for the dynamic WMN environment. Once identified, the routing protocol was then ported to the CR-WMN environment to evaluate its performance given all the dynamics of cognitive radio environment.

We further proposed the routing protocol called the extended weighted cumulative expected transmission time (xWCETT) routing protocol for the CR-WMNs. The design of our proposed xWCETT routing protocol is based on the multi-radio multi-channel architecture as it gives the base framework matching the cognitive radio environment. The xWCETT integrates features from the Ad-hoc On-demand Distance Vector (AODV) routing protocol and the weighted cumulative expected transmission time (WCETT) routing metric. The xWCETT was implemented using the Cognitive Radio Cognitive Network (CRCN) patch ported in network simulator (NS2) to incorporate the shared and dynamic spectrum access features. We compared the performance of our proposed xWCETT routing protocol with the AODV, dynamic source routing (DSR), the optimised link source routing (OLSR), Destination Sequences Distance Vector (DSDV), and the CRCN-WCETT routing protocols. The extensive simulation and numerical results show that the proposed xWCETT protocol obtained on average, around 10% better performance results in the CR-WNNs as compared to its routing counterparts. The comparative analysis and evaluation was performed in terms of the average end-to-end latency, throughput, jitter, packet delivery ratio, as well as the normalised routing load. The performance results obtained indicates that the proposed xWCETT routing protocol is a promising routing solution for dynamic CR-WMNs environment.

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LIST OF ABBREVIATIONS

AODV	Ad-hoc On-demand Distance Vector
AODV-MR	Multi-Radio Ad-hoc On-Demand Distance Vector
AP	Access Point
BATD	Bottleneck Aware Transmission Delay
BATMAN	Better Approach To Mobile Ad-hoc Network
CBR	Constant Bit Rate
CCC	Common Control Channel
CRAHNs	Cognitive Radio Ad-Hoc Networks
CRCN	Cognitive Radio Cognitive Network
CRNs	Cognitive Radio Networks
CR-WMNs	Cognitive Radio Wireless Mesh Networks
DSDV	Destination Sequences Distance Vector
DSR	Dynamic Source Routing
DYMO	Dynamic MANET On-demand
EFW	Expected Forwarded Counter
EPBW	expected path bandwidth
ERS	Efficient Route Selection
ETT	Expected Transmission Time
ETX	Expected Transmission Count
FTP	File Transfer Protocol
GPS	Global Positioning System
HWMP	Hybrid Wireless Mesh Protocol
iBADT	improved bottleneck aware transmission delay
IEEE	Electrical and Electronics Engineers
ISM	Industrial, Scientific and Medical
JMM	Joint Multi-channel and Multi-path
MAC	Medium Access Control
MANET	Mobile Ad-hoc Network

MIC	Metric of Interference and Channel Switching
MPR	Multi Point Relays
MRMC	Multi-Radio Multi-Channel
NRL	Normalised Routing Load
NS-2	Network Simulator 2
OLSR	Optimised Link State Routing
OS	Operating System
PCs	Personal Computers
PDAs	Personal Digital Assistants
PDR	Packet Delivery Ratio
Pus	Primary Users
QoS	Quality of Service
RERR	Route Error
RF	Radio Frequency
RREP	Route Reply
RREQ	Route Request
RTT	Round Trip Time
TCL	Tool Command Language
TORA	Temporary Ordered Routing Algorithm
TTL	Time to Live
UDP	User Datagram Protocol
WCETT	Weighted Cumulative Expected Transmission Time
WHAT	Weighted Hop Spectrum-Awareness and Stability
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Networks
WMAPs	Wireless Mesh Clients
WMGs	Wireless Mesh Gateways
WMN	Wireless Mesh Networks
WSNs	Wireless Sensor Networks
xWCETT	extended Weighted Cumulative Expected Transmission Time

CHAPTER 1

1. INTRODUCTION

The recent developments in wireless communication technologies have evolved into an important wireless network technology known as Wireless Mesh Networks (WMNs). This technology, WMN, has gained an increased attention in wireless communications arena because of its flexible architecture and its capability to provide integrated communication services without the wired infrastructure. Different from a network formed by wired backbone, WMN is a completely wireless network formed by self-configuring nodes interconnected by wireless links to form mesh topology. The network normally encompasses a combination of stationary and mobile wireless nodes that interconnect to form a multi-hop wireless network [1]. The absence of wired connectivity provides a number of benefits such as simplicity, low up-front deployment cost, lower cost deployment and maintenance, network robustness and extended coverage [1, 2].

Realisation of WMN technology presented a potentially attractive solution to provide wireless communication services and last-mile broadband connectivity for different applications such as home and community broadband networking, neighbourhood gaming, transportation systems and wireless enterprise backbone networks. Extending broadband and wireless communication services to rural and remote villages presents a crucial solution to dismiss the long existing digital divide and build the digital-born society.

The primary benefits of WMN technology include its ability to self-configure, self-heal, and form a robust connectivity amongst network nodes. The technology integrates seamlessly and works in harmony with different wired and wireless technologies such as the Institute of Electrical and Electronics Engineers (IEEE) 802.11, IEEE 802.15, IEEE802.16, the cellular network technology as well as the Wireless Sensor Networks (WSNs). The traditional IEEE 802.11-based and 802.15-based WMNs are constrained to operate in the Industrial Scientific and Medical (ISM) spectrum band which is an unlicensed spectrum band. This spectrum band is greatly utilised by a number of different devices in high dense urban settings, resulting in noisy channels and limited bandwidth availability. The constraints suffered by traditional WMNs resulted in limited overall performance, hence poking the industry and academic research community to pursue new technological developments to meet the future demands anticipated in the wireless network environments. As a result, cognitive radio technology offers a new communication paradigm for the next-generation wireless applications. These cognitive radios are referred to as fully programmable wireless devices that are capable of sensing their operating environments and intelligently adapting their transmission parameters to provide good network and application performance [3, 4]. Cognitive radio technology aims to increase radio frequency spectrum utilisation by allowing unlicensed users to sense and dynamically access licensed spectrum bands, on the condition that licensed primary users are not affected. Hence, adapting WMNs to use cognitive radio technology promises a substantial performance gain in terms of efficient spectrum band utilisation and increased network capacity. Application of cognitive radio technology in wireless multi-hop networks results in the next-generation of intelligent, frequency-shifting and autonomous mesh networks.

Architecturally, the nodes in WMNs are categorised and grouped into three main categories, namely: the wireless mesh gateways (WMGs), wireless mesh access points (WMAPs) and wireless mesh clients (WMCs). Figure 1-1 gives a pictorial illustration of typical WMNs with mesh nodes arranged into their categories.

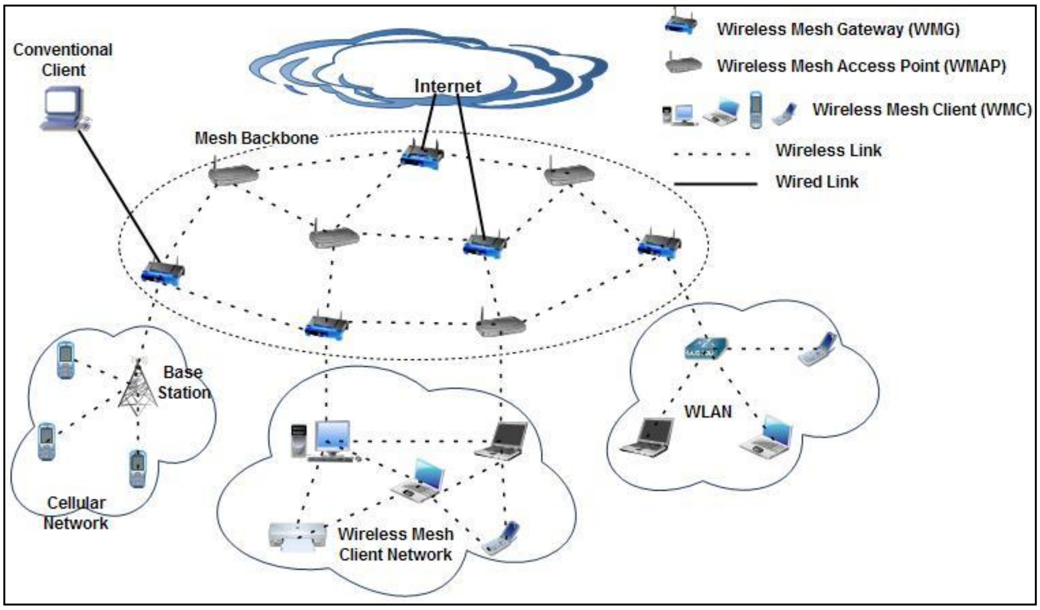

Figure 1-1: An illustration of typical WMNs [5]

In WMNs, WMCs normally include different types of devices that have transmitter and receiver components fitted. The WMCs include the personal computers, laptops, tablets, and mobile phones. These client nodes are normally resource constrained and thus dependent on the backbone and mesh routers for services. The backbone of WMNs is formed by wireless routers, base stations of cellular networks, or any special hardware device compatible with a set of radio technologies used in WMNs. The backbone nodes have powerful resources and capabilities in terms of the power source, computational capabilities and the radio coverage radius. The hardware devices connecting to WMAPs should have the ability to work properly with each type of technology integrated in the WMN architecture. In contrast to WMCs, WMAPs are usually much more powerful in terms of processing and communication capabilities. They are static and form a reliable infrastructure which supplies connectivity to WMCs. The third category of mesh nodes is formed by routers which have the capability to extend connectivity of WMN to the external wired networks or the Internet [6, 7].

Due to the nature of the WMNs, communication amongst the devices in the network depends on the robust connectivity amongst them. On the other hand, roust connectivity depends on the efficiency and effectiveness of a routing strategy employed in the network. In multi-hop WMNs, the client nodes form an important part of cooperative routing decision in the network. These client nodes are normally non-stationary devices which enter and leave the network infrequently, thus introducing the connectivity issues that affect the performance of WMNs. Therefore, optimization and implementation of efficient routing protocols remains a critical part of WMN environment.

1.1. Problem Statement

In the recent literature, a number of routing protocols and routing metrics have been proposed for wireless ad-hoc networks. These routing metrics and protocols were later adapted and deployed in the WMNs and multi-hop cognitive radio network (CRN) environments. However, they do not provide the required level of performance due to the lack of the core features distinguishing the ad-hoc network from WMNs and CRNs. There is a need to investigate and identify the routing protocols and routing metrics that work efficiently in the WMNs and the multi-hop CRNs.

The multi-hop based wireless networks suffer the low bandwidth utilization, reduced throughput due to interference, and increased routing overhead and limited scalability due to the current design of routing protocols. The throughput rate decreases considerably as the number of hops increase, resulting in reduced performance for real-time and delay sensitive traffic. A very closely related problem encountered in multi-radio based WMNs is the incurred routing recovery and channel switching delays caused by routing protocols. The recent research studies in the wireless multi-hop mesh network environments discovered a number of routing protocols tailored to improve the quality and performance of WMNs. Our research focus is centred on the issues and challenges of the traditional and novel multi-hop wireless networks. A set of questions are formulated to simplify our understanding of the underlying causes to these problems.

1.2. Research Aim and Objectives

The primary aim of this research work is to evaluate different routing metrics and routing protocols designed for the conventional WMNs in view of optimising the current performance of WMNs. We also aim to identify the candidate routing protocols that may be directly applied in Cognitive Radio Wireless Mesh Networks (CR-WMNs). Our goal is decomposed into the following research objectives:

- To survey and evaluate the performance of candidate routing protocols designed for the conventional wireless ad-hoc network environment.
- To survey and evaluate the performance of candidate routing protocols designed for cognitive radio network environment.
- To identify the best performing routing protocols in WMN and evaluate their performance in the shared spectrum cognitive radio based WMN environment.
- To propose the spectrum-aware, spectrum-agile and interference-aware routing protocol for CR-WMNs.

1.3. Research Questions

Given the current challenges encountered in multi-hop wireless networks, a set of questions are formulated to guide our research investigation and understand the factors that influence the performance of both traditional and cognitive-radio based

WMNs. What differentiates cognitive-radio WMNs from traditional WMNs is mainly the intelligent and dynamic nature of accessing the radio frequency (RF) spectrum. Hence, we formulated a set of questions aid our research investigation as follows:

- What are the current routing challenges encountered in WMNs?
- Which routing protocols amongst the existing protocols are considered the best for WMNs?
- Which of the existing routing protocols designed for multi-hop WMNs can be seamlessly applied to cognitive-radio based WMNs?
- How much performance gain or drop can be obtained by employing cognitive radios in WMNs?
- What design criteria should be applied when designing the ideal spectrum-agile and interference-aware routing protocol for CR-WMNs?

1.4. Motivation

This research study is motivated by the need to integrate the current wireless networks with cognitive radios for efficient utilisation of RF spectrum. The current IEEE 802.11 and 802.15 based wireless networks are restricted to operate ISM spectrum band, which is heavily utilised. This restriction puts a limit on the potential and capabilities of WMN technology. Designing efficient routing protocols for such multi-hop wireless networks will only improve their performance but does not take away the current limitation of the bounded RF spectrum band.

The current propagation of multimedia applications requires that WMNs must have adequate capacity to support high bandwidth and real-time applications. This calls for novel approaches to integrate WMNs with intelligent radios for dynamic support of shared RF spectrum bands. There have been developments on integration of mesh networks with cognitive ratios [3, 4, 6, 7] that allow secondary unlicensed users of RF spectrum to utilise the licensed portions of spectrum bands without causing any harmful interference to the licenced users. While license-exempt techniques and dynamic spectrum access are being extensively explored in South Africa, successful implementation of license-exempt wireless broadband networks in other countries [8] is the driving force motivating this research work.

1.5. Dissertation Outline

The remainder of the dissertation consists of five chapters structured as follows: Chapter 2 presents the survey and background of multi-hop wireless networks and the routing techniques applied in such environments. In this chapter, we identify and select candidate routing protocols most suitable for WMNs and cognitive radio based mesh network environment. Chapter 3 presents literature review in which critical analysis of the selected routing protocols is performed. Chapter 4 presents the overall research methodology which covers the design of our proposed routing protocol, the system models, experimental simulation parameters and the performance metrics employed. The experimental simulation scenarios are designed and presented in this chapter. Chapter 5 presents the results and discussion. Chapter 6 concludes the research study with the summary of findings and recommendations for future work.

CHAPTER 2

2. ROUTING IN MULTI-HOP WIRELESS NETWORKS: BACKGROUND

2.1. Introduction

The Internet and wired networks are formed by fixed and stationary nodes with fewer or no changes in network topology. They are usually equipped with powerful central nodes which manage the network and control coordination with other nodes in a point-to-point or point-to-multipoint mode. On the other hand, wireless ad-hoc networks [1, 9] are formed by non-stationary nodes that communicate with each other in a multi-hop fashion through wireless links. This multi-hop communication in wireless ad-hoc networks makes routing a crucial task for nodes to communicate with one another effectively. Unlike in wired networks, there exists no central administration node to handle the task of gathering all possible paths to reach all the nodes in the network [10]. In multi-hop wireless ad-hoc network, the nodes communicate with each other through a number of intermediate nodes which relay packets on behalf of other nodes in the network. Hence, selection of suitable intermediate routes to relay packets is crucial and influences performance of the overall network [11].

Routing in multi-hop wireless ad-hoc network is conducted in a distributed manner where each node in the network cooperatively shares its information with the neighbouring nodes within its coverage. In turn, the neighbour node shares the collected topology information back to its neighbours. In this distributed fashion, each node in the network becomes aware of all possible routes to reach any other node in the network [12].

The routing algorithms for multi-hop networks compute set of source-destination routes frequently or only when a source desires to communicate with some target node in the network [12]. Computed routes are then stored in node's cache memory and maintenance of such connectivity is done by broadcasting occasional topology updates. Any change in network topology or connectivity is propagated to all other nodes in the network as soon as it occurs. Hence, most routing protocols designed especially for wired network environments are not well suited to multi-hop network environments. There exists routing issues and challenges hindering a good level of performance in the multi-hop networks and these challenges have seen a vast amount of research work to improve the overall performance of the multi-hop networks, particularly at the network layer [13 -14].

Although WMNs demonstrate to be maturing with huge improvements in wireless technologies, the performance of WMNs is influenced by several factors such as reliability, quality of service (QoS) provisioning, node mobility and scalability. The design of optimal routing protocol should take these factors into consideration to improve the performance of WMNs. In the next section, we briefly give an account of how the performance of routing protocol is likely to influence the overall performance of WMNs.

2.2. Routing in Mobile Ad-hoc Networks, Wireless Mesh Networks and Wireless Local Area Networks

In wireless ad-hoc networks such as Mobile Ad-hoc Networks (MANETs) and WMNs, the topology changes are frequent primarily because of the presence of mobile client nodes and the impaired nature of shared wireless medium. These networks end up with intermittent connection and require the routing layer to adaptively re-establish and maintain communication paths amongst the network nodes [15, 16]. Unlike in wired network environments where routing protocols proactively establish and maintain routing tables by central administration, the connectivity between the source and destination node is computed and maintained by the nodes in a distributed manner through multi-hop meshed network graph [17].

The architecture of WMNs is formed by combining characteristics of the two widely adopted wireless technologies, namely: the Wireless Local Area Network (WLAN) and MANETs. The traditional WLAN is formed by interconnecting wireless access points through a wired backbone network at the network edges. The user devices (client nodes) are equipped with Wireless Fidelity (Wi-Fi) adapters. The user devices are then associated with WLAN wireless access points to establish connectivity in a single-hop mode. To extend coverage in WLAN, a large number of fixed wireless access points must be installed with appropriate wiring to the backbone, resulting in costly undertaking for a large-scale WLAN [18].

In MANETs, the network is formed by interconnecting mobile wireless nodes in an ad-hoc mode without any central administration node or the fixed infrastructure. Each node in the network has the capability of relaying the traffic on behalf of its adjacent nodes. The nodes in MANETs normally exhibit high mobility, causing a highly dynamic network topology.

Being classified as a special type of ad-hoc networks, the WMNs adopted most of the routing protocols from the wireless ad-hoc network domain. Hence, designing routing protocols purely for WMNs has seen a slow development due to the nature of its architecture [19]. The WMNs routing techniques have been derived and adapted from the existing MANET and WLAN routing protocols. The primary differences between the three wireless technologies (MANETs, WMNs and WLAN) have been identified by authors in [19, 20] in terms of routing as follows:

2.2.1. Network topology

A static wireless backbone differentiates the WMNs from the MANETs which do not have any dedicated infrastructure. In both WMNs and MANETs, the end-to-end communication is performed through multi-hop wireless transmission whereas in WLAN the end-to-end communication is performed through a fixed wired backbone. The network topology is fixed in WLANs, semi-static in WMNs and highly dynamic in MANETs because of frequently moving network nodes.

2.2.2. Traffic pattern

In WLANs, the network traffic is exchanged between users (client nodes) and access points in a single-hop mode. In MANETs, the network traffic normally flows between any pair of nodes with each node relaying packets on behalf of other nodes until the target node is reached. In WMNs, the network traffic is exchanged primarily between the client nodes and network gateway nodes through the intermediate routers. The network traffic may also be relayed among client nodes in a hybrid or client WMNs.

2.2.3. Channel diversity

The recent development of multi-radio equipped commodity access routers has driven wireless technologies to take advantages of multiple radio and channel to improve overall bandwidth and capacity of the network [21- 23]. The routers in WMNs are usually equipped with several radios that may be tuned to multiple RF spectrum channels. The multi-radio multi-channel techniques can significantly reduce channel interference while increasing the overall throughput [24, 25]. To improve the performance of the wireless radios, the researchers and industry professionals are studying and exploring the advanced technologies such as cognitive radios, software defined radios, and reconfigurable radios [26 – 27]. Some of these radio technologies are being improved to reach the implementation levels and due to their flexible and dynamic control capabilities, they are promising to provide better communication platforms in the ever changing multi-hop wireless communication environment. However, the routing process remains one of the fundamental issues in the multi-radio multi-hop wireless networks. The factors that influence the performance of routing protocols in the multi-hop multi-radio network environments are described in the next section.

2.3. Factors influencing the routing protocol performance in Wireless Mesh Networks

2.3.1. Reliability

The routing protocol is responsible for the establishment and maintenance of the paths between the source and the target node. The routing protocol must be aware of the dynamics of network topology and must be able to find alternative path to the destination node in case of connectivity failure, broken links and unreachable gateways. It should be able to maintain network connectivity and redistribute the orphaned client nodes among other gateways in case a gateway goes out of reach. Hence fast reconfiguration and support of multiple gateways is also considered a necessity in WMNs.

2.3.2. Quality of Service

The architecture of WMNs is different from the traditional ad hoc networks. Most of the target applications and services in WMNs are broadband based and have different types of QoS requirements. The routing protocol should offer the possibility to route different traffic classes over different established routes such that the delay and time sensitive traffic may be assigned high priority and be routed over best established routes.

2.3.3. Node mobility

In the hybrid WMNs architecture, the client nodes may often be subject to frequent mobility which means the network may encounter intermittent connectivity breakage and change in network topology. The resulting dynamic topology introduces more challenges in the network layer (routing layer) to maintain network connectivity and optimal routing performance when client nodes are non-stationary.

2.3.4. Scalability

Scalability is considered as one of the critical requirements of multi-hop wireless networks. The performance of the network degrades considerably when the network increases in size (i.e. the number of nodes in the network increases) [28]. For example, routing protocols may establish a set of possible source-destination routes but fail to find the most reliable routing path. Hence, inefficient routing protocol may cause the MAC protocol to obtain significant throughput reduction. The routing protocol design must take the scalability feature into consideration.

2.4. The routing metrics in multi-hop wireless ad-hoc networks

The architecture of a good routing solution for multi-hop wireless networks must consider a number of elements such as reliability, decentralized control, self-configurability and scalability. In the current communication era, such a routing solution must be able to provide QoS due to increasing number of multimedia and real-time applications. To satisfy the required design properties [17], a routing algorithm should be flexible and intelligent enough to adapt to the dynamics and physical characteristics of wireless spectrum [29].

The principal component of the routing algorithms and route selection is the routing metric, which is the quantitative value or cost assigned to each path required to forward the packets from the source node to the target node. The routing algorithm uses the calculated routing metric to choose the optimal route. The metric value reflects the cost of utilizing a particular path with respect to the given constraints such as traffic requirements, optimization objectives, domain specific requirements or the network performance measurements. The best path is chosen on the basis that it satisfies all supplied constraints, if any, and that has the lowest calculated cost.

Deployment of wireless multi-hop networks, particularly WMNs, across different environments requires routing algorithm’s capability to deal with highly unstable RF channel. Hence, the design of the routing solution needs to take into account the quality of each link in the network. The decision for a perfect routing metric that takes into account the environmental conditions plays an important role in WMNs because the environment itself exhibits multiple parameters. Multiple input parameters mean complex routing metric design and increased level of computation. Increased computation means higher route establishment and increased network maintenance delays.

In literature, a number of routing metrics have been developed for wireless multi-hop networks which served as the rudiments for more enhanced routing metrics developed to date [9 - 11]. Most of the earlier designed metrics were adopted [14] because of sufficient network performance they produced, although the actual performance may depend on the traffic type, application requirements, technology standards, or the physical implementation environment. Amongst proposed routing protocols to date, a large number of routing protocols compute the source-destination routes based on minimum hop count or the shortest routes from source to destination node [30 – 32]. The shortest path or minimum hop count is the simplest and popular routing metric which works efficiently in the wired networks. In the multi-hop ad-hoc networks, the shortest path (hop count) metric does not work as efficient and effective as it does in the wired networks because of the interference, mobility, and energy considerations. Hence, the optimal routing metric for multi-hop wireless networks may be formed by combining multiple routing metrics. The resulting routing metric will then provide the routing protocol with flexibility in selecting the best route from source to the target destination node. It is a norm to compromise between various performance metrics such as end-to-end latency, delay variations, the throughput, the energy consumption, packet loss ratio, packet delivery ratio, network load or routing overhead [33 - 36]. The researchers and industry professionals in the WMNs environment have adopted the routing metrics from ad-hoc network to work in the WMNs environment. The routing adopted routing metrics are covered in section 2.4.1 through section 2.4.7.

2.4.1. The Hop Count

The hop count metric is regarded as the simplest routing metric used by traditional routing protocols in both the wired and wireless network environments. It uses the shortest path calculation criteria to select the most optimal path to forward the network traffic packets to reach target node. One assumption for this metric is that the network maintains connectivity or connectivity is lost altogether. In real communication environment, this assumption has proven partially true since wireless links may have variable link qualities [38]. The path weight for this metric is equated to the total number of links traversed by a packet in one direction. A simple and obvious benefit of the hop count is its simplicity. On the other side, its primary drawbacks include inability to consider the link quality parameters such as packet loss ratio, transmission rate, or estimated available bandwidth. The authors in [39, 40] have proven that using the hop-count as a primary criteria to compute the shortest path is inadequate for WMNs because the most favoured routes are often the weakest links. Hence, this metric may lead to the most congested areas of the network.

2.4.2. The Expected Transmission Count

The expected transmission count (ETX) metric [41] computes its value by projecting the expected number of MAC layer transmissions. The packet loss rate is measured by estimating the probability of dropping the packets in both the forward and reverse direction. It is one of the early metrics proposed by authors in that considers the link quality during path selection. It is one of the earliest metric developed for multi-hop wireless networks and other metrics have been extended from it. This metric is computed for each individual link by each node in the network. The forward delivery ratio (*pf)* is the probability that the packets are received successfully by the destination node and the reverse delivery ratio (*pr)* is the probability that source node receives the packets successfully. To calculate the ETX value, each node broadcasts the control packet each second and measures the estimate for packet loss. Each node contains the total count of control packets received from its adjacent and neighbouring nodes in the previous 10 seconds. Given the count of control packets, a node then calculates the loss rate of control packets on the links in both directions towards neighbouring nodes. According to the authors in [2, 3], the ETX performs well in the single-radio environments but performs poorly in the heterogeneous multi-radio network environments. The ETX is calculated as:

$$ETX = \frac{1}{(pf\ x\ pr)} \qquad (2\text{-}1)$$

where *pf* refers to the forward delivery ratio and *pr* is the reverse delivery ratio. The (*pf x pr)* computes the probability that a packet is successfully delivered to the target node and that the source node successfully received an acknowledgement. The resulting computed value is the ETX of a single link. To compute the ETX of the entire path *(p)* from source to the target node, the following formula is applied:

$$ETX\ (p) = \sum\nolimits_{link\ l\ \in p} ETX\ l \qquad (2\text{-}2)$$

Most of the contemporary routing metrics that are based on the quality of link state are adapted from the ETX routing metric. This ETX routing metric combines the characteristics of the link quality rates, the irregularities in the uplink and downlink loss rates as well as the interference among adjacent and continuous links of a path [9, 10]. Hence, the ETX metric accounts for the true states of the quality of links in the network. Being considered as the basis from which many routing metrics were developed, the ETX has the benefits of improved link throughput because it considers the quality and effects of each link. The ETX avoids selecting the paths with low throughput caused by the intra-flow interference and this result in the ability to compute paths with high throughput rates. On the other hand, the disadvantages of ETX are the lack of support for channel diversity, it does not integrate link load and transmission rates, and it yields degraded performance in a highly mobile single radio environments [14].

2.4.3. The Expected Transmission Time

The Expected Transmission Time (ETT) metric improves the ETX metric by integrating the transmission rates of each link in the network. The size of packets and bandwidth are included in computing routes in ETT. It computes the transmission time required by the MAC layer to forward a packet over a link, which is identical to the transmission latency. Similar to the ETX, ETT is not designed to take into consideration the radio and channel diversity of modern multi-hop networks. It finds the best route with less channel diversity. ETT is calculated as:

$$ETT \; = ETX \left(\frac{s}{b}\right) \qquad (2\text{-}3)$$

where *s* denotes the packet size and *b* denotes the bandwidth of a link.

2.4.4. The Round Trip Time

The round trip time (RTT) metric of a path refers to the total time taken by a probe packet to traverse from the source node to the destination target node and return back to the sender node. This RTT reflects the end-to-end delay of a path in both the forward and reverse direction. To measure the RTT, a unicast control packet carrying a timestamp is forwarded timeously to its neighbour nodes and each neighbouring node returns the control packet immediately. The source node computes RTT value upon neighbours responding to control packets. The path RTT is calculated as the sum of each individual link RTT values over all links in the source-destination path. The shortcoming of RTT metric is load-dependency since it includes the channel contention, propagation and queuing delays.

2.4.5. The Efficient Route Selection metric

The authors in [42] proposed a novel Efficient Route Selection (ERS) metric aimed at addressing the inefficiencies of ETX. Their approach selects routes with minimal self-traffic and interference. A cross-layer solution is employed in which the routing (network) layer periodically sends the probe packets to the MAC layer to compute the total amount of time a node requires to actively pass the packet. This transmission time ratio (TTR) is computed by using the formula:

$$TTR \; = \frac{Time\ spent\ in\ Transmission\ state}{Total\ Time} \qquad (2\text{-}4)$$

Following this above formula, ERS is computed as a product of ETT, hop count and TTR as:

$$ERS = ETT * HopCount * \; TTR \qquad (2\text{-}5)$$

ERS metric captures and accounts for intra-flow interference present in the traffic. This result in ERS metric that improved the inefficiencies of ETX and ETT metrics by considering the length of the route and the time spent at MAC layer in transmission. The two factors (hop count and RTT) were integrated as additional parameters and the performance was improved as compared to that of ETX and ETT.

2.4.6. The Weighted Cumulative Expected Transmission Time

The Weighted Cumulative Expected Transmission Time (WCETT) metric [43] integrates the radio and channel diversity into the already existing RTT to enhance its performance. It combines the hop count, path radio and channel diversity as well as the transmission data rates to form a single routing metric. The WCETT metric considers the links that operates on the same channel but it does not take into consideration the location of the links. When two or more links are tuned to the same channel but positioned outside each other's interference range, the WCETT metric does not capture the interference. The WCETT metric simply presumes that all the links of the chosen path tuned to the same channels cause interference with each other's transmissions, which can lead to WCETT routing metric selecting non-optimal path. Thus, the WCETT routing metric captures the link quality (based on link loss rates), capacity and further improves the performance by considering the channel diversity.

2.4.7. The Metric of Interference and Channel Switching

The Metric of Interference and Channel Switching (MIC) routing metric was initially proposed by [44] to improve the performance of the network by decreasing the interference levels and reducing the channel switching delays. The MIC is based on the minimum expected transmission time, the utilisation of radio interface and the channel switching cost. The minimum ETT represents the transmission rates between wireless interfaces. The resource utilization is calculated based on ETT of multiple neighbouring nodes. The transmission of one link could result in interference of the adjacent links because the sensing (transmission) range always exceeds transmission range. The one disadvantage of MIC routing metric results from its likelihood of calculating unrealistic metric value because the transmission of one link may interfere with another link tuned to the same channel.

We present a comparative evaluation and analysis of the routing metrics designed for multi-hop wireless network in Table 2-1. The table compares the six multi-hop routing metrics with respect to the hop count, link quality and capacity, the channel diversity, the capability for load balancing as well as the interference.

Table 2-1: The Comparative Analysis of Routing Metrics for Multi-hop Wireless Networks

	Hop Count	**ETX**	**RTT**	**ETT**	**WCETT**	**MIC**
Number of Hops	Yes	No	No	No	No	No
Link Capacity	No	No	No	Yes	Yes	Yes
Link Quality	No	Yes	No	Yes	Ye	Yes
Channel Diversity	No	No	No	No	Yes	Yes
Load Balancing	No	No	No	No	Yes	No
Intra-flow Interference	Yes	No	No	No	Yes	Yes
Inter-flow Interference	No	Yes	Yes	Yes	Yes	Yes

2.4.8. Other integrated routing metrics for wireless ad-hoc networks

The routing metrics discussed above can choose the best path by evaluating and estimating the hop count, queuing and switching latencies, interference levels, quality of links, packet delivery ratio, the packet loss probability, and other dynamics in wireless medium. In multi-hop networks, it is a challenge for a single routing metric to assess all the dynamics inherent in multi-hop wireless network concurrently while computing the perfect source-destination path. This challenge has steered the research community to focus on combining the multiple routing metrics and in order to arrive at the most optimal route. Multiple metric values serve as a parameter input to a single routing algorithm. The following metrics were developed in the quest to integrate multiple routing metrics to find the best route using the value computed from other metrics in ad-hoc networks.

a) The Expected Forwarded Counter metric

The Expected Forwarded Counter (EFW) metric is a cross-layer metric developed by the authors in [45] which selects a path with the highest packet delivery rate. The EFW takes into account the link quality state of wireless links and reliability of network nodes. The latter, reliability, is influenced by how the nodes in the network nodes behave. The metric combines routing and the MAC layer information. The resulting metric value considers the packet dropping caused by mesh routers in the network which exhibits the selfish behavior. These selfish nodes may drop the packets sent by neighbor nodes at the network layer after successfully receiving such a packet frame. The source node automatically assumes packet loss if no acknowledgement is received and hence increases the packet loss probability. This results in lower data-link layer reliability.

b) The Bottleneck Aware Transmission Delay metric

The Bottleneck Aware Transmission Delay (BATD) is an innovative routing metric proposed by authors in [39] which addresses the inefficiencies of WCETT and MIC metrics. The BADT deals with intra-flow interference by capturing the different transmission rates, link loss rates and intra-flow interferences within a path. The performance of the selected path is assessed based on the transmission latency time on the bottlenecked channel. A channel is considered a bottleneck if it has the largest transmission delay time. The comparative analysis of this routing metric with traditional routing metrics (Hop Count, ETX, ETT and WCETT) shows that the BADT achieves better performance in terms of the end-to-end throughput. The authors in [46] further improved the BATD metric and came up with a better iBATD metric which enhanced the performance of multi-radio WMNs in terms of throughput and average latency.

c) The Expected Path Bandwidth

In multi-hop WMNs, an optimal routing strategy should aim to maximize the network throughput. Throughput is severely affected by intra-flow and inter-flow interferences. The expected path bandwidth (EPBW) metric is proposed in [47], where the varying link rate and dynamic link load are considered. The variation in link rate is caused by wireless link quality and variation in link load is mainly due the inter-flow and intra-flow interference. From the performance of EPBW metric, the authors further proposed a distributed routing protocol called EPBWR. The performance of the proposed channel quality and load aware routing strategy presented was analyzed and compared to the traditional AODV, DSR and DSDV protocols. The EPBW metric and EPBWR outperformed the traditional ETX and ETT metrics as well as selected traditional routing protocols.

d) The weighted hop, spectrum-awareness and stability metric

The weighted hop, spectrum-awareness and stability (WHAT) metric [48] was proposed to select the end-to-end path based on spectrum awareness and activities. The concurrent computation of optimal path and monitoring of primary user activities based on time-varying or location-varying spectrums poses a challenging task. The WHAT metric considers opportunistic spectrum access and path stability by integrating the channel switching frequency, the length of the path as well as usage patterns of licensed channels. This helps the WHAT metric to evaluate the overall quality of end-to-end path. One added advantage of WHAT metric is that it satisfies the two key properties of a routing metric design being monotonicity and isotonicity. The monotonicity means the path cost does not decrease when the path is extended while isotonicity preserves the path relationship in terms of cost between two nodes from the same source node [12].

2.5. The Classification of Routing Protocols in Wireless Mesh Networks

The multi-hop ad-hoc wireless networks classify the routing protocols into the number of categories [49, 50] according to topological, geographical or resource-based information [51, 52]. The topology-based routing protocols calculate and choose the paths based on information such as link state between nodes or the connectivity amongst network nodes. The position-based routing protocols calculate and choose the paths based on geographical information. The algorithms in position-based routing may employ services provided by Global Positioning System (GPS). Resource-based routing protocols are classified according to the availability of resource information such as battery or the level of energy for each network node.

The topology-based routing protocols can be further divided into three categories, namely: the reactive, proactive, and hybrid routing protocols [30, 35, 40]. Proactive routing protocols build a routing table and update routing information at regular intervals. Reactive routing protocols construct routing information only when one node wishes to communicate with another node. On the other hand, hybrid routing protocols partitions the network and apply the two routing strategies in different parts of the network. The Figure 2.1 shows a pictorial illustration of routing classification as well as candidate routing protocols for ad-hoc networks. These routing protocols have been selected as a result of their suitable candidacy for WMN environment.

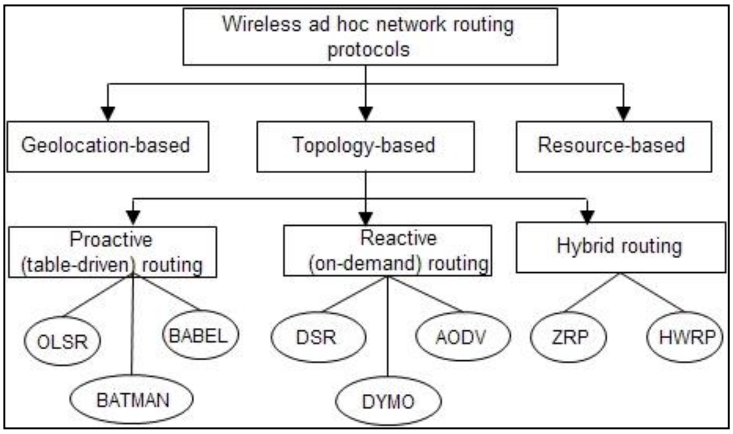

Figure 2-1: Categorization of routing protocols in wireless ad-hoc networks [52]

2.5.1. Table-driven routing protocols

In table-driven (proactive) routing protocols, the route from each node is pre-established to any other node in the whole network. It is table-driven approach as nodes frequently update each other about their existence [29]. Thus, large tables are maintained on each node and the size of tables increase linearly with the number of nodes in the entire network. When a source node wants to transmit the packets to the target node, there is no need to establish the path because all the possible paths to reach any node in the network are pre-established and cached by each node. The entries in routing tables are updated frequently in order to maintain valid table entries. The frequently updated information ensures that all the nodes in the network are able to reach other nodes at any given point in time [53].

The large tables maintained by proactive routing protocols present challenges in keeping routing information fresh while avoiding counting to infinity problem. One viable solution is to add a special value to all the nodes in the network. This special value is incremented every time a node detects changes in its transmission range. A node with higher special value shows that the node has recently refreshed its table entries. Based on the updated information, each node's routing table continually contains valid routes [54]. On the other hand, exchanging of larger routing tables has a negative impact on the network performance as well as the network convergence time.

One approach that makes proactive routing approach unattractive is the periodic flooding of routing updates in the network. These frequent updates consume significant part of available network bandwidth. However, one advantage of proactive protocols is that nodes maintain fresh information about other nodes in the network and a path to any destination node can be quickly established.

According to the authors in [52], proactive routing protocols are more suitable and efficient for high dense networks with bursty traffic and frequently changing topology. MANET [29, 32] is a good example of such network environment. Dozens of routing protocols in this family has been developed in literature. We select three proactive routing protocols from a pool of prominent ad-hoc network protocols to serve as candidates for WMNs. The selected candidate routing protocols are Destination sequenced distance vector (DSDV), Optimized Link State Routing (OLSR) [55] and Better Approach To Mobile Ad-hoc Network (BATMAN) [59]. These routing protocols are much popular in literature because of the performance benefits they yield as compared to other proactive routing protocols.

a) The Optimized Link State Routing protocol

The Optimized Link State Routing protocol (OLSR) protocol [55] is a table-driven routing protocol which uses the routing table to generate the routes from a source to destination. It maintains these tables to update information about the network. Each node shares the content of its routing table with other nodes in the network. The routing table entries are broadcasted to all the nodes in the network. Each node entry contains the node's link state information to all other nodes in the network. The protocol updates and maintains information in two-hop neighbor table and routing table. The OLSR protocol creates multi point relays (MPR) which broadcasts control packets during the route discovery process. Instead of all the network nodes flooding the network with control messages, the MPR nodes exchange the control messages amongst other MPR nodes. When a non-MPR node in the network sends a packet, all of its neighboring nodes receives the packet but only the MPR node is responsible to forward the packet. Therefore flooding overhead is reduced [56].

b) The Babel Routing Protocol

The babel protocol [57] was proposed as a reliable and efficient distance-vector routing protocol designed for both wired networks and WMNs. It was initially designed for wireless ad-hoc networks which makes it extremely robust in the presence of mobile nodes. Its design is based on Destination-Sequenced Distance-Vector Routing (DSDV) routing protocols. In Babel, the control packets are attached to the UDP datagram. The Babel node frequently broadcasts the Hello messages to its neighboring nodes which in turn, propagate the I Heard You (IHU) message to every neighbor. The nodes utilize information exchanged from the Hello and IHU messages to compute the cost of each link in the network [58].

c) The Better Approach to Mobile Ad-hoc Network

The BATMAN [59] is a table-driven routing protocol designed for the multi-hop ad-hoc mesh networks. All nodes periodically broadcast hello packets to its neighbours. The hello messages are known as originator messages (OM). The structure of the originator message is constituted by the originator address, a unique sequence number, and the forwarding node’s address. Upon receipt of the message, each neighbouring node alters the forwarding address to its own address and rebroadcasts the message. Each node also checks the bidirectional link to verify that each link can be used in both directions. The unique sequence number verifies the freshness of the current message. In BATMAN routing protocols, all the nodes along the source-destination route only captures and maintains the information about the succeeding link maintaining the full route to the destination [60]. Hence, the amount of routing overhead is reduced.

2.5.2. Reactive (on-demand) routing protocols

In reactive routing protocols, nodes become aware of the topology and existence of other nodes only when communication session is taking place. The routing table is constructed on request by propagating the network with route request (RREQ) messages. The routes are established each time two nodes need to communicate. The routing module reacts to the demands of the source node which must find a route to the target node for sending data. [54]

The route discovery process is started when one node wishes to communicate with another node, thus requiring a route to the destination node. The route discovery process then terminates when the path to the destination has been found or no path becomes available after examination of all the possible routes. In contrast with the table-driven routing protocols, the one advantage of on-demand routing protocols is that the amount of routing overhead is minimized but with a compromise of slightly higher end-to-end delay during route discovery.

According to the authors in [53], reactive routing protocols are most suitable and efficient for low dense networks with static traffic patterns such as WMN environment. A number of routing protocols in this category has been developed in literature. We select three reactive routing protocols from a pool of prominent ad-hoc network protocols to serve as candidates for WMNs. The selected candidate routing protocols are Dynamic Source Routing (DSR), Ad-hoc On-demand Distance Vector (AODV) and Dynamic MANET On-demand (DYMO).

a) The Ad-hoc On-demand Distance Vector routing protocol

The Ad-hoc On-demand Distance Vector routing protocol (AODV) [37] is an on-demand routing protocol that builds the source-destination paths only when one node wants to communicate with another node in the network. The routes are maintained for that session only. The AODV does not maintain the routes that are not active during the communication session. The functionality of AODV routing protocol is based on the distance vector which enables dynamic and on-demand multi-hop route discovery and maintenance between the wireless nodes. Mesh nodes obtain routes to new destinations quickly while also providing quick response to link breakages and changes in network topology. It allows fast network convergence and it is capable of providing faster link adaptations, optimal bandwidth utilization and faster processing of overheads. The route discovery and maintenance process used by AODV protocol results in reduced routing overhead and efficient network resources utilization.

b) The Dynamic Source Routing protocol

The Dynamic Source Routing protocol (DSR) [62] falls in the category of on-demand routing protocols. It was designed for the ad-hoc networks where nodes in the network are not static. It was designed to support the self-configuring, self-organising and self-healing network environments without requiring any infrastructure or the central node responsible to administer the network. The protocol is made up of the route discovery and route maintenance mechanisms which allow nodes to discover and maintain routes between source-destination set of nodes in a multi-hop wireless network. The protocol includes guaranteed loop-free routing and fast recovery when network topology changes.

2.5.3. Hybrid routing protocols

The hybrid routing protocol combines together the basic properties of table-driven and on-demand routing protocols, resulting in a protocol that behaves both proactively and reactively [63, 64]. The network is divided into clusters and wireless nodes are grouped and assigned to each cluster. Each group of nodes may employ a different routing strategy altogether, which may be a flat, hierarchical, topology-based, location-based or resource-based routing. The hybrid routing protocols take advantages of the features of category by overcoming their noticeable disadvantages.

WMNs employ diverse routing protocols in different parts of its layered architecture. Proactive routing protocols are often employed in the backbone portion of WMNs while reactive routing protocols are employed in mesh clients. A noticeable advantage of hybrid routing protocols [50] is that they reduce the routing overhead of table-driven protocols and reduces the end-to-end latency generated by the route discovery process in on-demand routing protocols. Recently developed IEEE 802.11s standard [65] defines a default routing protocol for WMNs called Hybrid Wireless Mesh Protocol (HWMP) although the standard permits vendors to operate using alternative protocols.

Candidate routing protocols for WMNs in this category of routing are HWMP [53] and Zone Routing Protocol (ZRP) [66].

2.6. The characteristic comparison of candidate routing protocols for WMNs

Table 2-1 summarises the characteristics of each routing protocol presented in section 2.4 in terms of how they react to the node's desire to transmit packets, the routing metrics used to compute best path, the ability of routing protocol to distribute traffic load in the network, ability to avoid congestion, ability to support node mobility and the throughput pattern generated by each routing protocol.

Table 2-1: The characteristic evaluation of on-demand versus table-driven routing protocols in WMNs

	AODV	**DSR**	**DYMO**	**OLSR**	**BATMAN**	**BABEL**
Type	On-demand	On-demand	On-demand	Table-driven	Table-driven	Table-driven
Routing approach	Fastest & shortest route	Shortest route	Shortest route	Shortest route	Shortest route	Hop count (shortest route)
Mobility support	Yes	Yes	Yes	Yes	Yes	Yes
Scalability	No	No	Scales better than AODV	No	Scales better than OLSR	Scales better than OLSR
Load balancing	No	No	No	No	No	No
Congestion control	Yes	Yes	Yes	No	Yes	Yes
Throughput	Decreases with number of mobile nodes	Decreases as mobility increases	Decreases with increase in nodes. Better that AODV	Better compared to DSDV	Better compared to OLSR	Better compared to OLSR
Loop free	Yes	Yes	Yes	Yes	Yes	Yes

2.7. Conclusion

In summary, the architecture and protocols designed for ad-hoc networks have been realised to yield degraded performance when applied in WMNs. The primary reason being that ad-hoc networks have been designed to support high mobility and collaborative exchange of traffic amongst all nodes. On the other hand, WMNs are designed for static or limited mobility with mesh routers capable of acting as central administration. In this chapter, we presented the routing protocols and routing metrics applied in both MANETs and WMNs, highlighting their merits and shortcomings. We noted that differences in MANETs and WMNs do influence the performance of routing protocols and consequently the overall performance of network. The performance variation of routing protocols stems from the design and architecture of routing metric, routing algorithm and the environment in which it operates.

CHAPTER 3

3. LITERATURE REVIEW

3.1. Background of Routing in Multi-hop Wireless Network

The major obstacles in providing the guaranteed quantifiable QoS in MANETs and WMNs involve a number of factors including, but not limited to improper utilisation of available bandwidth resources, power limitations especially in resource stripped MANETs, inefficient cross-layer inter operations, ineffective routing strategies and routing optimizations. Most routing optimization techniques endeavour to compute the most optimal routes between communicating source and destination nodes in multi-hop mesh networks. Effective, robust and reliable routing requires proper design of routing protocol according to the domain of operation. In the past decade alone, a lot of research was done focusing on the design of optimal routing protocols for WMNs. This has resulted in an increased number of routing protocols designed for the multi-hop ad-hoc networks [67]. These protocols include reactive, proactive and hybrid routing protocols such as AODV [38], DSR [62], OLSR [55], BATMAN [59], BABEL [57], HWRP [65] and ZRP [64] just to name a few. These routing protocols, initially designed and proposed for MANETs are suitable for application in WMNs because of the similarities between the two networks.

The overall performance analysis of routing protocols is normally based on quantitative performance metrics such as end-to-end latency, throughput, packet loss ratio, packet delivery ratio, jitter, and routing overhead amongst others. Routing protocols are usually designed with the target optimization and performance objective such as minimising the end-to-end delay, minimising routing overhead, minimising the packet loss ratio, maximising throughput and packet delivery ratio. Measuring or setting the optimal performance level in ad-hoc wireless networks is a challenging task because there is usually a trade-off between performance metrics depending on the application or traffic type. Throughput may be deemed important performance metric in most applications along with end-to-end delay; thus maximising the throughput obtained under delay constraint becomes more useful than the throughput itself when defining the network capability. In [68], the authors present the multi-objective routing framework for the wireless ad-hoc networks to better understand the network behaviour and performance when multiple criteria must be satisfied.

A lot of research work has recently been undertaken in both MANETs and WMNs suggesting different results on the performance of proactive and reactive routing protocol [60, 67, 69, 70]. Most researchers subjected their conclusions on mobility of network nodes as the primary key performance element. In this research work, we aggregate related results drawn by different researchers on the performance of routing protocols in static and dynamic wireless environment. In order to understand the behaviour of selected routing protocols in static and dynamic wireless environment, the following two assumptions are drawn to constitute the basis for comparative analysis:

i. The on-demand (reactive) routing protocols perform better in a dynamic topology (highly mobile) wireless environment. This case favours the MANETs and client WMNs.
ii. The proactive (table-driven) routing protocols perform better in a static or less mobile wireless environment. This case favours the infrastructure WMNs.

3.2. Routing in Multi-hop Cognitive Radio Network

The multi-hop CRNs differ from the traditional multi-hop wireless networks such as MANETs, WMNs and wireless sensor networks (WSNs). The traditional wireless networks are based on fixed network resource allocation while CRNs are based on the dynamic network resource allocation. The primary difference lies in the availability of RF spectrum and allocation of resources. Routing becomes an important consideration during the design of the routing algorithm in order to attain good performance. However, any good routing solution needs to be coupled with the functionalities of other layers, especially the MAC layer so that routing decisions are accurate. Coupling the routing layer with MAC layer ensures that the dynamic changes occurring at the lower layers such as availability of channels are accounted for. Also, the information such as high quality and stable routes becomes easy to communicate in a cross-layer fashion [71].

In the multi-hop CRNs, the performance of the network is influenced by the activities of PUs which results in a dynamic topology. Also, the routing metric should be computed with considerations of dynamic topology, the quality of each link in the network, availability of channels, the stability of each link in the network, the estimated activities of primary users (PUs), as well as the transmission rates. Hence, the routing process has the added role of concurrently maintaining the connectivity amongst secondary user (SU) nodes while monitoring the PU activities. It becomes quite a challenging task to calculate the most optimal path from the source node to the target node. For mobile SU nodes, another challenge introduced is the lack of computational and energy resources [72]

The other important element to consider in multi-hop CRNs is the knowledge about the spectrum and the entire network configuration. The multi-hop CRNs use the local spectrum knowledgebase techniques to gather information about the surrounding and share it amongst each node in the network. The information from one cognitive radio node to another node is normally shared through the channels common to the two or more nodes. This means the network nodes must have a common channel where they are both connected to so that they can start exchanging the control signal messages and data traffic. The channel is called common control channel (CCC) and is used to discover the neighbour nodes as well as for source-destination route establishment [73, 74]. Each node in the network may be equipped with more than one radio to enhance the network performance and increase the bandwidth utilisation. However, it becomes more costly to deploy more than one radio on each node in the network. Also, attaching two or more radios to a single node introduces the interference problem whereby the signal transmitted on one radio may interfere with the signal reception on the other radio [75].

A number of routing protocols have been proposed for both the traditional multi-hop wireless networks and CRNs. We present the classification of the most notable routing protocols in each domain in Figure 3-1. Figure 3-1a shows routing protocols for the traditional wireless networks and Figure 3-1b shows the routing protocols designed for CRNs. Unlike the traditional multi-hop network, most routing protocols tailored for CRNs incorporate the dynamic nature of RF spectrum band.

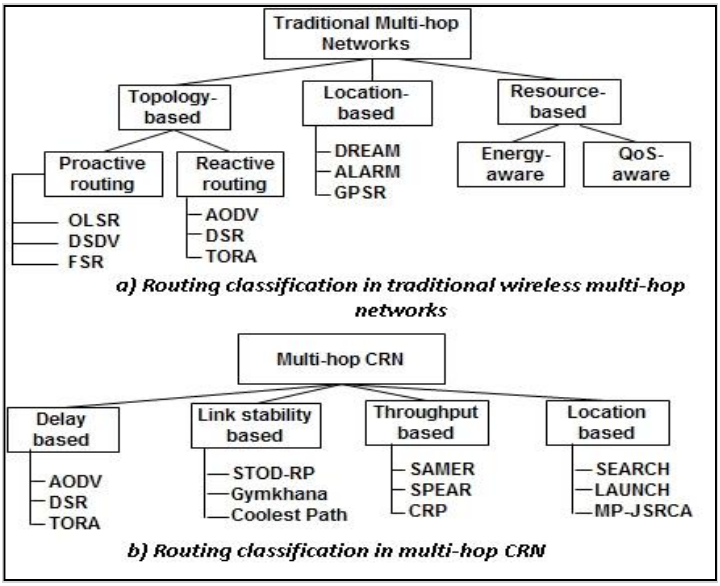

Figure 3-1: Classifying the multi-hop traditional and CRN routing protocols [76, 77]

In Figure 3-1a, the routing protocols are categorised into different groups according to the location, available resources or the topological information obtained from the network. This classification results in the three categories common to the traditional multi-hop wireless networks such as MANETs, WMNs, and WSNs. The routing protocols have been developed with the design objectives of each routing category. Figure 3-1b further depicts those routing protocols designed for the multi-hop CRNs. These protocols have been designed according to the requirements of the four categories based on latency, throughput, link stability and geographical location information. As it can be observed from the Figure 3-1, some routing protocols such as AODV, DSR, and OLSR (to mention a few) can be employed in both the traditional and novel networking paradigms. In the next section, we evaluate the performance of the candidate routing protocols in the WMNs environment.

3.3. The Performance Analysis and Evaluation of Routing Protocols for Wireless Mesh Networks

The authors in [67] compare the ad-hoc network and the WMNs environments and evaluate the performance of table-driven OLSR routing protocol against the on-demand AODV and DSR routing protocols. To study the effect of the three selected routing protocols in WMNs, each routing protocol was tested in an experimental simulation scenario. The experiments were conducted in 1 km x 1 km topography with number of nodes ranging from 15 to 60. The architecture of WMN considered was client WMN type. The data rate considered for simulation scenarios was 11 Mbps with IEEE 802.11 MAC and the performance metrics used for analysis are end-to-end delay, throughput and network load. It must be noted that these three performance metrics were considered critical for the provision of guaranteed end-to-end QoS. The constant bit rate (CBR) traffic type was generated for all the scenarios.

In a small and medium scale client WMNs scenarios (15 and 30 nodes respectively), OLSR achieved the highest (peak) average throughput, followed by AODV, while DSR attained the lowest throughput. For average end-to-end delay, OLSR and AODV achieved relatively similar results with the lowest average delay. Again, DSR performed poorly by yielding higher average latency. The maximum average latency of above 24 milliseconds was observed with DSR protocol which may hamper the performance of real-time and delay sensitive applications. Similar results were observed in a large-scale network (having 60 nodes) in terms of the end-to-end latency and throughput.

Performing the same scenario in similar network environment, the OLSR outperforms the DSR and AODV routing protocols with the worst performance results obtained by the DSR. However, a good performance demonstrated by OLSR compensate for traffic overhead generated and flooded in the network. Being a proactive routing scheme, OLSR frequently floods the network with topology control packets to maintain connectivity amongst network nodes. An optimised version of OLSR employs the MPR nodes to propagate routing updates in the network on behalf of group nodes in its connectivity range. MPR nodes are used to avoid unnecessary broadcast of packet transmissions. Therefore, the proactive OLSR routing protocol attains better performance than the reactive routing protocols in static WMN environment with large-scale concentrated network.

The authors in [78] investigate the performance of proactive BATMAN and OLSR routing protocols in WMN testbed as a function of throughput, packet loss rate and delay. The testbed consists of 49 stationery nodes arranged in a 7 x 7 grid topology and the Wi-Fi nodes are close to one another. The testbed was set to operate on 2.4 GHz RF band. The performance results of the experiment are presented in terms of routing overhead, throughput and end-to-end delay. The results obtained indicate that OLSR generate less routing packets because of its strict rules to forward HELLO and topology control (TC) messages. The authors observed that as the number of nodes increase, the OLSR is more likely to generate more routing packets than the BATMAN, resulting in increased routing overhead. The philosophy of BATMAN is based on the objective of increasing the chances of packet delivery. Unlike the OLSR routing protocol, the BATMAN only checks the existence of a link without checking the quality. This means the BATMAN will forward all the packets as long as the link is active. The BATMAN archived the overall better performance results in terms of end-to-end latency and throughput. Hence, the authors conclude that the novel BATMAN routing protocol offers better performance as compared to OLSR in a static WMN environment in terms of better throughput, less delay and lower routing overhead.

It has been noted that OLSR does not produce reliable routing as the number of nodes become very large (i.e. in a large scale mesh networks of over 300 nodes). Hence, the researchers have proposed better routing protocols such as BABEL [57] and BATMAN [59] in order to overcome the shortcomings of OLSR.

In [79], the authors compared the performance of OLSR, DYMO and MP-OLSR (multipath extension of OLSR) in a dynamic MANET environment on the basis of QoS provisioning. They evaluate these routing protocols based on traffic generated by Voice over Internet Protocol (VoIP), the file transfer protocol (FTP) and hypertext transfer protocol (HTTP) applications. Simulation experiment was considered with 60 mobile nodes distributed uniformly in 1000m x 1000m grid. The initial positions were assumed in the beginning of each simulation scenario. The 802.11b radios were used. The two-ray propagation model was used and 2.4 GHz RF spectrum band was considered.

The evaluation criterion was based on changing the number of nodes in the network, the ratio of static to mobile nodes, and the number of connections. The end-to-end latency, throughput, jitter and power consumption were used as performance metrics. The simulation results obtained in the study provided evidence that reactive DYMO routing protocol obtained the best latency, throughput and energy consumption when compared to the OLSR protocol. This outcome validated the assumption that on-demand routing protocols perform much better than table-driven routing protocols in a dynamic topology.

The research studies [80, 81] proposed the DYMO protocol as an improvement of the existing AODV and this has led to a number of modifications to DYMO routing protocol. When compared to DSR and the AODV, DYMO protocol provides better performance in wireless ad-hoc network environment with mobile nodes.

Based on the AODV standard routing protocol, the authors in [82] proposed an enhancement of AODV which exploits the local connectivity relationship between each node in the network with its neighbouring nodes. This improvement reduces the amount of routing overhead as well as the latency incurred during the route establishment phase. During the path establishment, the source node broadcasts a route request (RREQ) control packet to its neighbours. Any intermediate node that has a valid path to reach the target node, responds by generating a route reply (RREP) packet on behalf of the target node. This process reduces the size of the routing tables at each node, resulting in reduced routing table lookup time when sending the packets to the destination node.

The authors in [83] proposed load balancing and interference aware protocol (LBIARP) at routing layer to improve performance of IEEE 802.11 based WMNs. The proposed protocol reduces flow interference in the selected routing path by selecting non-overlapping channels for adjacent links and by assigning low-weights for non-interfering adjacent nodes. Comparing results obtained by the LBIARP with the traditional reactive AODV routing protocol, they managed to obtain smaller end-to-end delay and improved throughput in both single-radio and dual-radio WMN environment. Though the proposed LBIARP protocol was not subjected to delay-sensitive or real-time traffic, it offers a good platform for load balancing and interference avoidance technique for WMNs. LBIARP algorithm enhances performance for traditional single-radio and multi-radio WMNs with static frequency spectrum bands and channels. To achieve similar results in cognitive multi-hop networks where the available frequency band and channels change with respect to time and location is a challenging task. We aim to achieve similar or improved performance metrics in a cognitive radio based WMNs.

To deal with QoS strict traffic and applications in multi-hop wireless networks, multi-path routing approaches have been widely employed in WMNs and other wireless multi-hop networks. The authors in [84] propose a QoS-aware robust multi-path routing technique for WMNs which establishes a set of multiple disjoint paths from the source to the destination node. The multiple control packets are transmitted concurrently between the source and destination pairs along all possible paths. Upon receipt of control packets, the destination node computes the estimated cumulative bandwidth as well as the average delay for all paths. This information is then transmitted back to the source node which in turn selects a robust best path among multiple paths. Any change in quality that violates the specified traffic QoS requirements is detected and the traffic flow is rerouted using an alternative best path retrievable from the node’s cache memory. Traditional WMN routing protocols compute a set of available non-interfering frequency channels from unlicensed fixed spectrum band and candidate multi-path routing protocols select the best paths from this pool of orthogonal channels. This technique requires source nodes to maintain large cache memory for calculated array of multiple paths. Increased memory becomes a drawback for resource stripped mobile nodes in the network and invalidation of a single path may affect validity of other paths.

Other techniques to improve performance of traditional multi-radio WMNs require the routers to access multiple channels dynamically and opportunistically [85, 86]. The authors in [87] proposed a routing scheme called JMM that combines the multi-channel link layer with the multi-path routing. The proposed protocol takes advantage of the multiple channels and multiple paths in WMNs and exploits this benefit in terms of the end-to-end packet delivery ratio. The proposed scheme divides time slots and facilitates the channel usage amongst the divided time slots and transmits the packets on more than one source-destination path. Comparing the proposed JMM protocol with the popular single-path based AODV and DSR routing protocols, the proposed JMM scheme obtained good performance in terms of efficient bandwidth utilisation, network robustness, end-to-end latency and the end-to-end average throughput rate.

3.4. Conclusion

In this chapter, we presented the background of routing in multi-hop wireless network environments with special focus on MANETs, WMNs and CRNs. We selected and surveyed six routing protocols that are suitable for application in WMNs based on extensive analysis and evaluation conducted by several studies in the recent literature.

CHAPTER 4

4. RESEARCH METHODOLOGY

In this research work, we adopted a quantitative experimental approach whereby the experiments are performed using the network simulation package. In our experiments, several routing protocols from a wireless mesh and cognitive radio wireless mesh network environments are simulated and the performance results are recorded and analysed. The simulation experiments are conducted using the open source object-oriented discrete-event network simulation software called network simulator (NS-2) version 2.31 [88]. The NS-2 simulator is configured to run on Ubuntu 12.04 distribution of the Linux operating system (OS). The cognitive radio wireless mesh simulation experiments are performed on NS-2 platform with cognitive radio cognitive network (CRCN) [89] patch which enables the cognitive radio capabilities on NS-2.

Other utilities such as AWK programming language, perl scripting, python scripting and Gnuplot plotting utility were used for data manipulation, analysis and graphical representation of the results. We performed a number of experimental simulation scenarios based on two network environments. The first set of scenarios were based on a dynamic wireless mesh network environment and the second set of simulation scenarios were based on a dynamic cognitive radio wireless mesh network environment. In the first scenario, we evaluated the performance of four (4) routing protocols designed for wireless ad-hoc networks, namely AODV, OLSR, DSR and DVDV. The performance of the selected four routing protocols is evaluated and analysed. The best routing protocol amongst the four is selected to be a candidate protocol in the cognitive radio based wireless mesh network environment. In the second scenario, we evaluate the performance of the three (3) routing protocols, namely: AODV, WCETT, and xWCETT in CR-WMNs.

We present the design of our proposed routing scheme in the next section, followed by the system model and simulation environment for the two scenarios. The network performance metrics used to evaluate the routing protocols in both the simulation scenarios are also presented in the last section of this chapter.

4.1. Proposed Routing Scheme: The xWCETT Routing Protocol

Having investigated a number of routing metrics and protocols in the wireless ad-hoc network environment, their weaknesses and strength, advantages and disadvantages, we propose a routing scheme called the extended Weighted Cumulative Expected Transmission Time (xWCETT). The proposed routing scheme considers the merits obtained by the AODV routing protocol as well as the merits obtained by the multi-radio based WCETT routing metric. It combines the benefits of the AODV protocol with WCETT metric to form a new enhanced routing scheme. We intend to measure the throughput of each link in the network, the end-to-end latency, the stability of each link, the usage of each channel per link in the network, as well as the primary user (PU) activities. We integrate the data transmission rates, determine the bandwidth requirements of each traffic, assess the quality of each link, assess the state of each channel per link, and measure the PU spectrum channel occupancy.

Our proposed xWCETT routing scheme is based on a distributed local spectrum knowledge whereby each node in the network is responsible for constructing information about its immediate surroundings. The local knowledge information is shared amongst the neighbouring nodes through the common control channel (CCC). We assumed that all the nodes are tuned to the CCC to avoid broadcasting the control messages through all the channels, which reduces the amount of routing overheads. This means that the AODV protocol’s route request (RREQ) and route reply (RREP) messages are communicated through the CCC. The source node generates a RREQ message and pushes it to its neighbouring nodes through the CCC. The nodes receiving the RREQ message processes the message by checking if the message’s destination IP address matches their own. If the node receiving the RREQ message is not the destination node, it rebroadcasts the message. If the RREQ message’s IP address is matched, the receiving node then generates the unicast RREP message and sends it back to the source node through the path traversed by the former RREQ message. Upon receiving the RREP message, the source node searches for the best available channel in its channel availability table and start to transmit the message on that channel. The local channel availability records in the channel availability table are sorted according to the usage patterns. The best available channels always float atop of the channel availability table. The first channel in the table is selected for data transmission. All the intermediate nodes follow the same process of selecting the best channel in the channel availability table and forward the message.

The routing metric used to compute the optimal source-destination path is adapted from the expected transmission count (ETX), expected transmission time (ETT) and WCETT routing metrics. The ETX component measures the packet loss rate by estimating the number of MAC layer transmissions expected to successfully transmit the packet from source to destination node. We calculate the ETX of each link (l_i) in the network as follows:

$$ETX\ (l_i) = \frac{1}{(df.dr)} \qquad (1)$$

The *df* estimates the packet delivery ratio from the node to its neighbouring nodes and the *dr* estimate the ratio of packet delivery from the neighbouring node back to the node (i.e. the reverse delivery ratio). Hence, the quality of each node in the network is computed in both directions. The complete source-destination path is then computed from equation (1) as follows:

$$ETX\ (p) = \sum_{link\ l\ \in p} ETX\ l \qquad (2)$$

The ETT routing metric was initially designed to improve the performance of the ETX metric by integrating the link transmission rates into path cost calculation. The ETT metric is calculated as follows:

$$ETT(l_i)\ = ETX\ \left(\frac{s}{b}\right) \qquad (3)$$

From equation (2), the *s* represents the size of each packet and the *b* represents the bandwidth of each link.

The multi-hop CRN environment is attributable to multiple available SU spectrum channels. We denote the total of available SU channels by $C\ (c_1, c_2, ..., c_n)$ and then define a variable X_c to estimate of transmission time of each channel along the given path as:

$$X_c = \sum_{i\ \in\ C} ETT\ l_i \qquad (4)$$

where $1 \leq c \leq C$. The third component of the routing metric is the WCETT metric which is calculated as follows:

$$WCETT\ (p) = (1 - \alpha) \sum_{i=1}^{n} ETT\ l_i + \alpha \max_{1 \leq c \leq C} X_c \qquad (5)$$

This routing metric is formulated by combining the two terms that are considered a trade-off between the end-to-end latency as well as the throughput. The variable α is an adjustable parameter used to set the preference between the path length and the channel diversity (i.e. the total number of channels available). From the equation (5), we introduce the probability variable, P_c to estimate the availability of channels from the channel availability table. The P_c computes the estimated probability that a channel is unavailable for the SUs due the PU activities. This result in the following metric:

$$xwcett\_metric = (1 - \alpha) \sum_{i=1}^{n} ETT\ l_i + [(1 - P_c)\ \alpha \max_{1 \leq c \leq C} X_c] \qquad (6)$$

The P_c represents the estimated probability that the channel *c* in a given *C* set of channels is unavailable for the SUs because of the PU activities. We made an assumption that each SU node is able to monitor and calculate the probabilistic availability measure of a channel based on the local knowledge of PU channel usage statistics. In the real scenario, this assumption would mean that each node will share its knowledge about the spectrum environment with its neighbours. As the nodes share their spectrum information, a global knowledge about availability of spectrum channels would be known by all the nodes in the network. Give the PU channel usage statistics derived from the channel availability table, this routing metric prioritizes stable source-destination routes by avoiding to select the channels with a higher probability of being occupied by the PUs.

The proposed xWCETT routing protocol implements the xwcett_metric to select the best routes from the source node to destination node. The route establishment and maintenance process is similar to the AODV [27] protocol whereby the RREQ and RREP control messages are exchanged to establish communication. Our system model employs two radios per SU node in CRN where one radio is meant to constantly monitor availability of channels and the second radio switches amongst available channels for data transmission. Every time the source node wants to communicate with some destination node, the source node generates RREQ message and propagates it through multiple available channels. The RREQ packets are only broadcast on available channels to ensure non-interference with PUs. During route discovery process RREQ probe packet is checked whether the packet is new or it’s being received previously. For new RREQ packets, a corresponding RREP packet is generated based on available channels. Otherwise, intermediate CR nodes compute a reverse path BACK to the sender using the same set of channels deemed available per link. The route error (RERR) probe packets are generated and propagated on a new set of channels whenever a channel is invalidated by PU action, thus notifying its neighbours about invalid channels [29][30]. At any point in time, each SU node monitors PU activities on a set of allocated channels and associates appropriate probability values for each channel based on PU activities. In each case during the route establishment process, RREP packet is generated based on the routing metric in (6). The lowest metric value is used to determine the best route and therefore, data packets are transmitted on the selected path.

The xWCETT routing protocol is implemented based on the design of multi-radio multi-channel architecture illustrated in Figure 4-1. The TCL script is used to configure the number of radios and channels needed for simulations. In our case, the number of radios was set to two and the number of channels was set to four. The primary idea is to create multiple radios and multiple channels through the TCL library by invoking several copies of link layer (LL), queue, MAC, network interface (NetIf), and channel-set for each radio in C++ library.

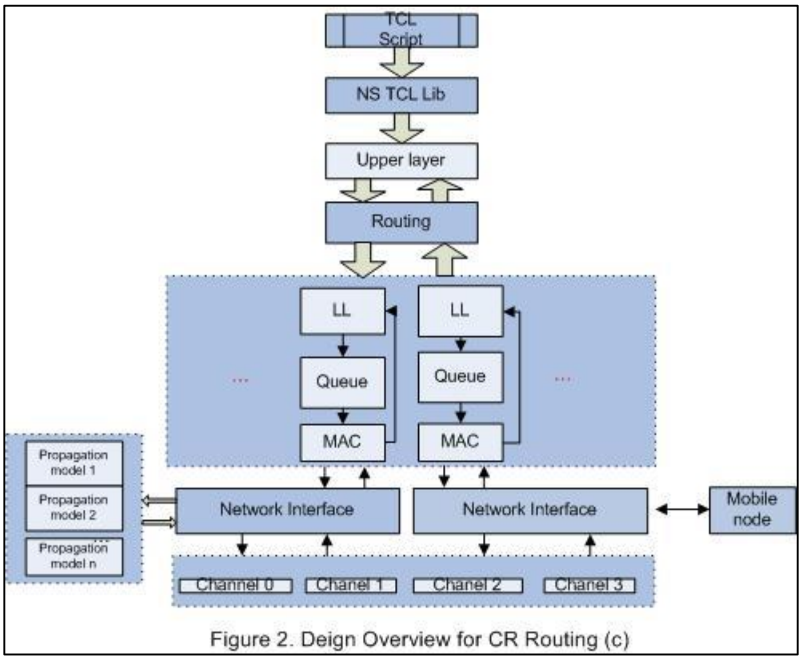

Figure 4-1: Design overview of multi-radio multi-channel routing architecture [88]

4.2. Wireless Mesh Network System Model and Simulation Environment

In our first simulation experiments, we considered a small-to-medium wireless mesh network consisting of two types of nodes, namely: wireless mesh routers and client nodes. The mesh routers serve primarily as the backbone to provide connectivity and access point to the client nodes. The connection is initiated and terminated by client nodes. Each node in the network is equipped with two radios, one radio connecting the routers in the backbone and the other radio serves as the access point to service the client nodes. Client nodes were equipped with a single radio to interface with mesh routers. Both the mesh routes and client notes are free to change position at random, creating the dynamic topology.

In wireless mesh network environment, we performed a total of three (03) experiments. The network nodes were varied from ten (10) to fifty (50) with nodes randomly positioned in a 1000m by 1000m grid. In each simulation, communication was initiated by a single client node seeking to communicate with another client node through a number of mesh routers. This means traffic was always taking place between the client nodes via number of mesh routers. The traffic source generated and transmitted Constant Bit Rate (CBR) packets with User Datagram protocol (UDP) at the transport layer. Other simulation parameters were configured according to Table 4-1. The specifications of the machine used to perform simulation experiments were: Intel(R)

Core(TM) i5-5200 with 2.20 GHz processor and 8.00 GB Random Access Memory (RAM) over Linux Ubuntu 12.04 Precise Pangolin.

Table 4-1: Wireless Mesh Network Simulation Parameters

Parameter	**Value**
Topography	1000 m x 1000 m
Number of nodes	10, 30, 50, 70
Mobility model	Random Waypoint
Mobile speed	1 m/s – 15 m/s
Transmission range	200 m
MAC	IEEE 802.11b
RF Propagation Model	Two Ray Ground reflection
Antenna type	Omni-directional
Traffic type	CBR
Packet size	1500 bytes
Data rate	11 Mbps
Routing protocols	AODV, DSR, OLSR, DSDV
Simulation time	300 s

For the above wireless mesh based simulation scenario, the performance data was recorded in NS-2 trace files. The performance data was analysed and results are presented in Chapter 5.

4.3. Cognitive Radio Wireless Mesh Network System Model and Simulation Environment

The second set of our simulation experiments were based on CR-WMN. The CR-WMN was configured with two (2) types of nodes, namely: the primary users and cognitive nodes. The primary users represent the licensed user having authority over its assigned set of channels. The cognitive users on the other side need to sense the availability of licensed channels and only utilize available channels without causing interference to the primary users. The cognitive nodes are equipped with two radios. The first radio is for controlling channel and the second radio is for data transmission. The control radio is responsible for scanning and maintaining the set of available channel where each node maintains a table of available channel and spectrum information. The data transmission radio constantly switches from one channel to the other channel based on the channel availability information. The network size was varied between twenty (20) and hundred (100) nodes distributed in an area of 1000 m *x* 1000 m. The communication is initiated by one cognitive node seeking to communicate with another cognitive node in the same network. The cognitive nodes are allowed to have variable mobility rate, changing from one position to a different position. The traffic source generated and transmitted CBR packets over UDP transport layer. Other simulation parameters were configured according to Table 4-2.

Table 4-2: Cognitive Radio based Wireless Mesh Network Simulation Parameters

Simulation Parameter	**Assigned Value**
Topography	1000 m x 1000 m
Primary users	4
Secondary users	20, 40, 60, 80, 100
Cognitive radio mesh interfaces	2
Mobility model	Random Waypoint
Mobile client node speed	1 m/s – 10 m/s
Number of primary users	0, 1, 2
Transmission range	200 m
Medium access control	IEEE 802.11b MACCON
RF Propagation Model	Two Ray Ground reflection
Antenna type	Omni-directional
Traffic type	CBR
Packet size	1500 bytes
Packet rate	2, 4, 6, 8, 10 (packet/s)
Data rate	11 Mbps
Routing protocols	AODV, WCETT, xWCETT
Simulation time	300 s

The set of simulation scenarios for cognitive radio based network environment were each configured as follows: Scenario 1 had network size of twenty (20) cognitive radio nodes and two (2) primary users. Scenario 2 had network size of forty (40) cognitive radio nodes and two (2) primary users. Scenario 3 had network size of sixty (60) cognitive radio nodes and two (2) primary users. Scenario 4 had network size of eighty (80) cognitive radio nodes and two (2) primary users. Finally, Scenario 5 had network size of hundred (100) cognitive radio nodes and two (2) primary users. The results are analysed and presented in Chapter 5.

4.4. Performance Metrics

In each of the simulation scenarios conducted, we monitored and recorded the results of each simulation scenario and how each routing protocol performed. We collected the network performance data and the performance parameters used to analyse the network performance are outlined as follows:

4.4.1. The end-to-end latency

The end-to-end delay measures the average amount of time it takes for the packets to traverse the selected route from the source node to the target node. In multi-hop cognitive radio mesh networks, the routes from source node to the target node may be asymmetric, i.e. a route traversed by a packet from source to reach the destination node may be different from the target node back to the source node. This is mainly because of the dynamic nature of the network environment where the available channels fluctuate due to the activities of the primary users. Hence, the average end-to-end delay helps to measure performance of the network under such dynamics of the cognitive radio mesh networks.

4.4.2. The end-to-end throughput

The average end-to-end throughput defines the average number of packets that are generated by the source node and successfully received by the destination node per unit time. This is obtained by adding the total number of packets received by the destination node and dividing by the simulation time. Hence, rate of this end-to-end packet delivery efficiency plays a vital role in the overall performance of the network.

4.4.3. The end-to-end Jitter

Jitter can be defined as the delay deviation or variation of the received network packets. In our research work, we measured these variations in delay which may be caused by a number of factors such as primary user activities, congested network links, or interference causing the source node to incur higher variations in latency. This metric may affect the overall network performance especially when subjected to real-time traffic applications.

4.4.4. Packet Delivery Ratio

This performance metric quantifies the rate of total number of packets generated by the source node to the total number of packets received by the target node. It is a simple metric to measure the amount of packet loss in the network. We measure the percentage of packet delivery ratio generated by each routing protocol, which in turn gives an indication of how each routing protocol loses traffic packets.

4.4.5. The normalized routing overhead

We also considered the routing overhead metric as the amount of additional traffic generated by the selected routing protocols. The routing overhead is computed as the difference in total number of network control packets (in bytes) and the total number of data packets generated by the network. The normalized routing overhead is used as an important measure to compare the performance of routing metrics implemented by each routing protocol. This measures the effective scalability of routing protocol and the efficiency of the protocol given different parameters in the network environment. For the research study, we measure the impact that routing overhead has on the overall network as a result of the increased routing packets roaming the network.

4.5. Conclusion

This chapter presented the design of our proposed xWCETT routing protocol whose architecture is based on the AODV routing protocol and WCETT routing metric. This protocol integrates the features of AODV protocol and WCETT routing metric and further incorporates the three dynamics of multi-hop CRN environment, namely: the dynamic spectrum channels, dynamic topology and intermittent PU activities. This trio makes our proposed xWCETT routing protocol spectrum-agile (as it caters for dynamic topology), spectrum-aware (as it exploits the dynamic availability of channels) and interference-aware (as it avoids the active PU channels).

We further discussed in details the simulation environment, system models, simulation parameters and network performance metrics employed in the simulation scenarios. Two sets of simulation scenarios were performed based on a dynamic WMNs and CR-WMNs. The setup and simulation parameters of each set of simulation scenarios are outlined. The results, analysis and discussion of results are presented in Chapter 05.

CHAPTER 5

5. RESULTS AND DISCUSSIONS

In Chapter 04, we described the methodology and simulation environments carried out in our study. Two sets of simulation scenarios were performed based on the parameters stipulated in Table 4-1 and Table 4-2. In the first set of simulation scenarios, we evaluated the performance of AODV, OLSR, DSR and DSDV routing protocols in a dynamic WMNs setting. In the second set of simulation scenario, we simulated the performance of our proposed xWCETT routing protocol (presented in Chapter 03) against the AODV and WCETT routing protocols. The second set of scenarios was based on the CR-WMNs setting. The results and discussions for both simulation environments are presented in this chapter. We present the results obtained for WMNs and CR-WMNs environment in section 5.1 and 5.2 respectively.

5.1. Wireless Mesh Network Scenario Results

We performed a total of three (3) simulation scenarios varying the number of mesh routers in each experiment. We started the simulation scenarios with ten (10) node network configuration and increased the number of nodes by twenty (20) for the remaining two scenarios. The results and analysis are presented in the next section.

5.1.1. Scenario 1: Ten (10) Node Wireless Mesh Network Configuration

a) The end-to-end latency results

Figure 5-1 to 5-3 presents the end-to-end latency performance results obtained for simulation scenario one. Figure 5-1(a) through 5-1(d) presents the end-to-end latency performance results obtained by each of the four routing protocols (AODV, DSR, OLSR and DSDV). Figure 5-2 shows the comparative end-to-end latency results obtained by the four protocols and Figure 5-3 presents the average latency comparative results.

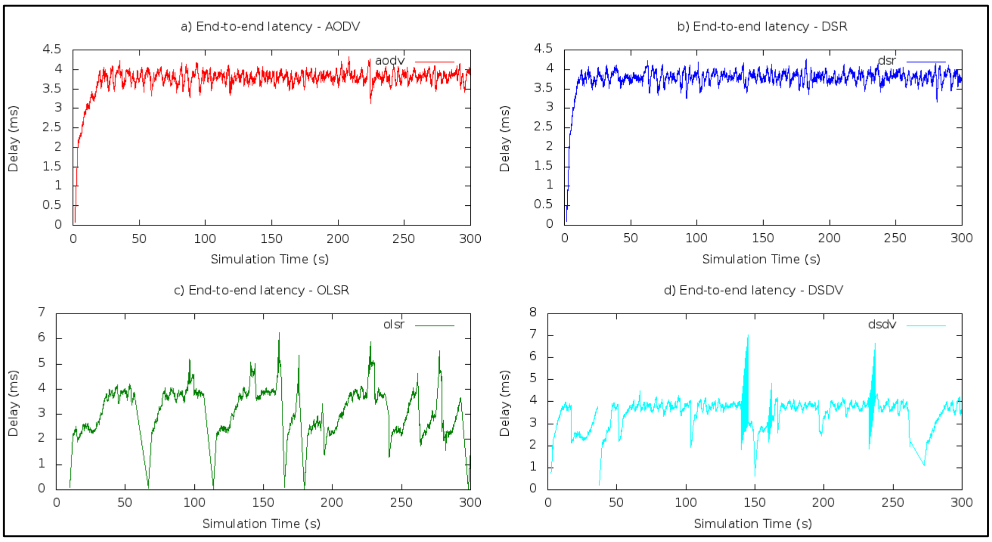

Figure 5-1: The end-to-end latency performance results for 10 node network configuration

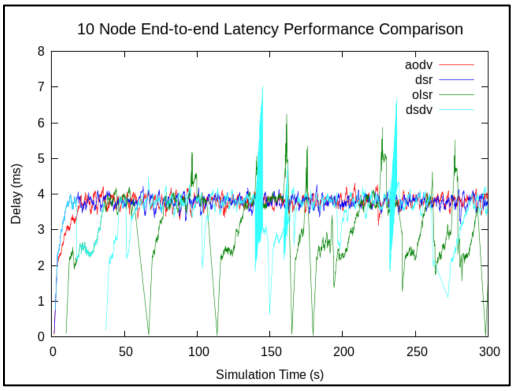

Figure 5-2: The end-to-end latency comparative results

The end-to-end latency performance results presented in Figure 5-1 shows a distinct behaviour between the two categories of routing protocols, i.e. reactive and proactive routing category. The AODV and DSR represent the reactive routing protocols whereas OLSR and DSDV represent the proactive routing protocols. We observe that the reactive AODV and DSR are able to maintain a constant and stable performance throughout the simulation period. They are more flexible and robust in semi-static to dynamic network environment. On the other hand, the performance of OLSR and DSDV is dependent on routing table which is constructed and maintained frequently by periodically broadcasting the probe packets on the common control channel. The proactive OLSR and DSDV protocols lack the ability to maintain constant performance in terms of end-to-end latency because the nodes in our configuration are mobile. Hence the proactive OLSR and DSDV result in frequent route breaks that triggers route repair and this process affects the overall network performance.

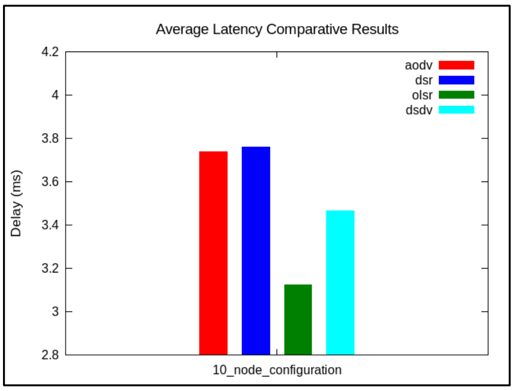

Figure 5-3: The average latency comparative results

Figure 5-2 presents the end-to-end comparative results obtained by the four (4) routing protocols representing the two (2) classes of routing protocols. The proactive OLSR and DSDV obtained low average end-to-end delay as compared to the reactive counterparts. In a low dynamic or semi-static network environment, this behaviour is expected because the established routes do not change until the nodes move out of the signal coverage, causing the network to break. The average results depicted in Figure 5-3 indicate insignificant performance difference as the average end-to-end latency results range from 3.10 ms to 3.76 ms, resulting in the average performance difference below 0.6 ms. Thus, a more robust and stable end-to-end performance in terms of latency may be more desirable than the fluctuating and unreliable average performance. The AODV and DSR routing protocols are able to provide such a robust performance as depicted in Figure 5-2. Hence, the AODV obtained better performance latency results.

b) The end-to-end jitter results

The end-to-end jitter performance results are presented in Figure 5-4 to 5-6. Figure 5-4(a) through 5-4(d) presents the end-to-end jitter performance results obtained by each of the four (4) routing protocols (AODV, DSR, OLSR and DSDV). Figure 5-5 presents the comparative end-to-end jitter results. Figure 5-6 shows the end-to-end average jitter results.

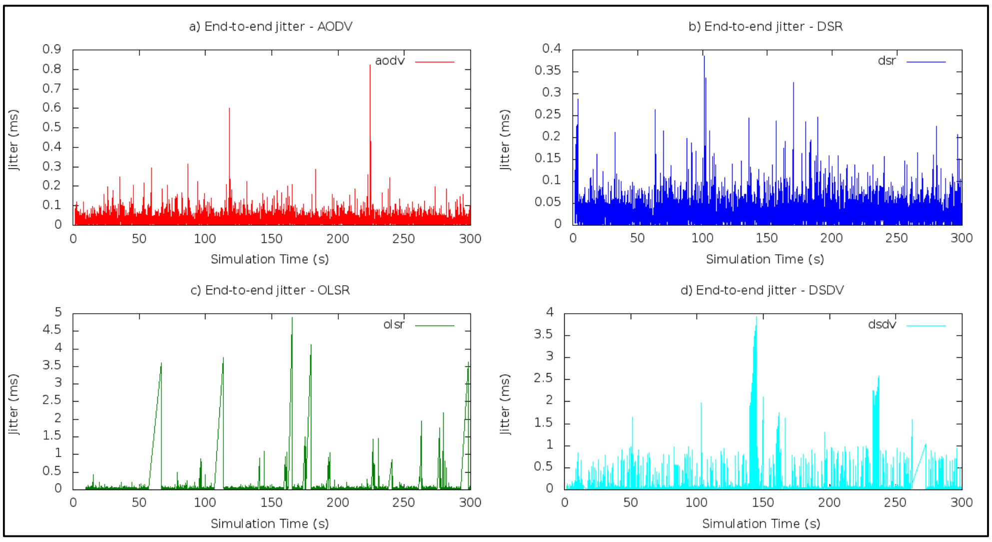

Figure 5-4: The end-to-end jitter performance results for 10 node network configuration

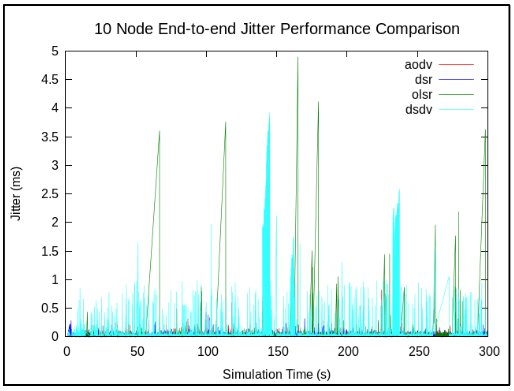

Figure 5-5: The end-to-end jitter comparative results

From the results presented in Figure 5-4, we observe similar performance behaviour between the two (2) classes of routing protocols. The nodes in our network configuration exchange user datagram protocol (UDP) datagrams and the wider delay deviations (higher spikes) on Figure 5-5 indicate the presence of network congestion because we have multiple sets of nodes exchanging packets in the network.

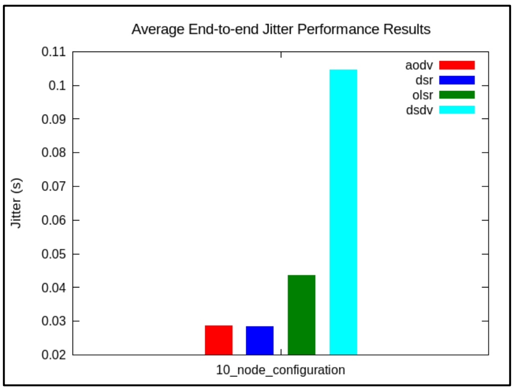

Figure 5-6: The average jitter results

From the Figure 5-6, we observe that the reactive AODV and DSR obtained lower end-to-end jitter results. The two (2) protocols obtained stable and robust end-to-end latency results as depicted in the end-to-end latency results (Figure 5-1 and 5-2). Stable and constant end-to-end latency performance yields lower delay variations (jitter). The performance favours the reactive AODV and DSR.

c) The end-to-end throughput results

We present the throughput performance results obtained by the four (4) routing protocols in Figure 5-7 through 5-9. Figure 5-7(a) through 5-7(d) presents the end-to-end throughput performance results obtained. Figure 5-8 illustrate the comparative end-to-end throughput results obtained and Figure 5-9 presents the comparative average throughput results obtained in this scenario.

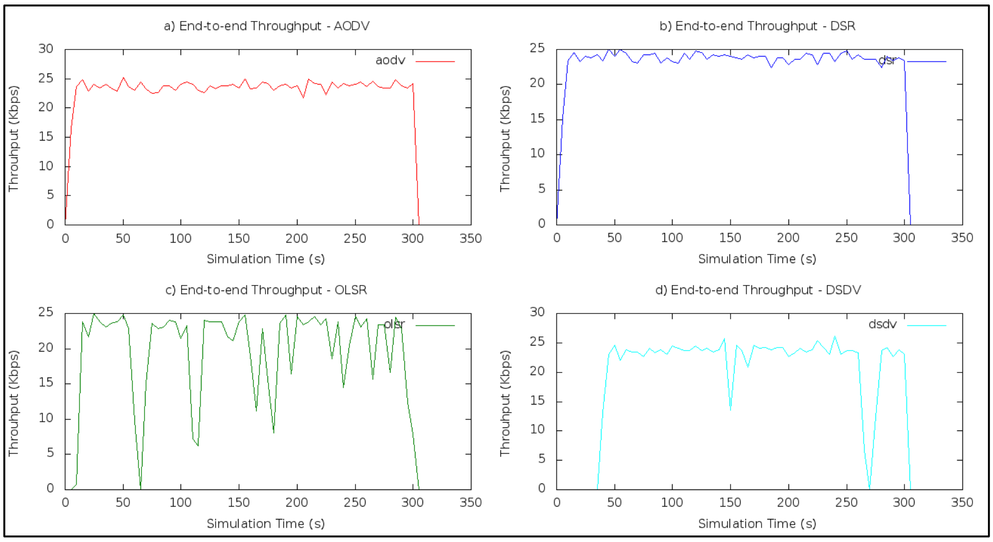

Figure 5-7: The end-to-end throughput performance results for 10 node network configuration

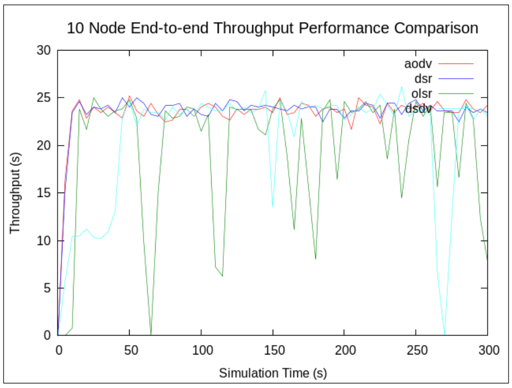

Figure 5-8: The end-to-end throughput comparative results

In Figure 5-7 and 5-8, we see a constant throughput maintained by the reactive AODV and DSR. In all the figures, Figure 5-7(a) through 5-7(d), each protocol attained a peak throughput of 25 Kbps. The first two (2) reactive protocols are stable while the proactive OLSR and DSDV fail to maintain stable throughput. The degraded performance of OLSR and DSDV is attributed to frequent breakage of network links as the nodes change positions due to mobility, causing the nodes to rebuild their routing tables for fresh connectivity.

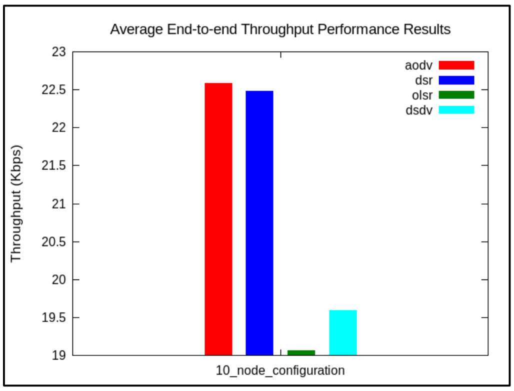

Figure 5-9: The average throughput comparative results

The average throughput results depicted in Figure 5-9 shows that AODV achieved the highest throughput, followed by DSR. The OLSR and DSDV have attained lower throughput as compared to AODV and DSR. Therefore, the performance favoured the two (2) reacting routing protocols with AODV yielding the highest performance.

d) The packet delivery rate results

Figure 5-10 presents the end-to-end packet delivery rate (PDR) results obtained in this scenario.

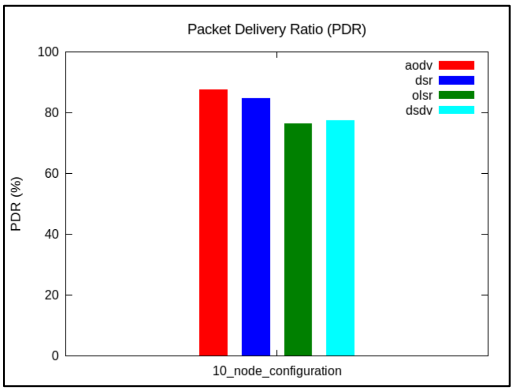

Figure 5-10: Packet delivery ratio (PDR) results obtained by the four routing protocols

The performance of the four (4) routing protocols in terms of the PDR (illustrated in Figure 5-10) shows the percentage of packets successfully delivered from the source node to the destination node. We observe that the highest percentage of packet delivery is obtained by the AODV due to its flexibility in establishing the path and recovering from route failures. The higher throughput obtained by AODV (shown in Figure 5-9), maintained end-to-end latency (shown in Figure 5-2) and low average jitter (shown in Figure 5-6) provide a clear indication that fewer packets are lost during transmission. From the PDR results obtained, we see that AODV protocol provides better performance.

e) The normalized routing overhead results

In Table 5-1 and Figure 5-11, we present the routing load and normalised routing load (NRL) analysis of the four (4) routing protocols.

Table 5-1: The routing load and normalised routing load (NRL) analysis of the four routing protocols

Routing protocol	Routing load	NRL
AODV	7068	0.17
DSR	8227	0.20
OLSR	10031	0.25
DSDV	9038	0.23

We observe from Table 5-1 that the routing load and NRL generated by reactive routing protocols (AODV and DSR) is less in comparison to the proactive routing counterpart (OLSR and DSDV). In the reactive routing class, routing protocols generate and propagate the routing packets only when the nodes want to communicate. Once the connection between two nodes has been established, the bandwidth is reserved for data transmission. This results in better bandwidth utilization because more bandwidth is reserved for data transmission.

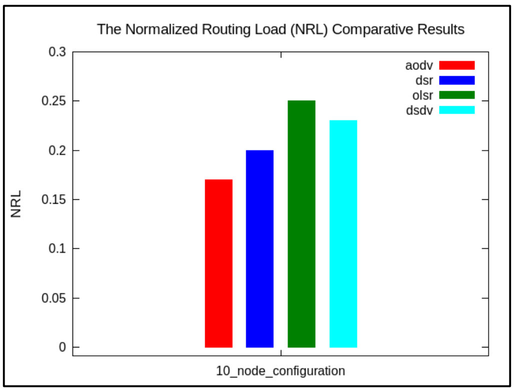

Figure 5-11: The NRL analysis results of the four routing protocols

From the Figure 5-11, we observe that the AODV generated less NRL as compared to the three (3) counterparts, achieving better performance in terms of network resource utilisation. On the other hand, the higher NRL value generated by proactive OLSR and DSDV indicates inefficient bandwidth utilization which affects the packet delivery rate and throughput.

5.1.2. Scenario 2: Thirty (30) Node Wireless Mesh Network Configuration

In simulation scenario two (2), we increased the number of the mobile nodes in the network to thirty (30) and the other simulation parameters were not changed. The end-to-end and average performance results obtained for this scenario are presented in Section 1.1 of Appendix A.

5.1.3. Scenario 3: Fifty (50) Node Wireless Mesh Network Configuration

In simulation scenario three (3), we increased the number of the mobile nodes in the network to fifty (50) and the other simulation parameters were not changed. The end-to-end and average performance results obtained for this scenario are presented in Section 1.2 of Appendix A. The overall results obtained in this section have shown that the AODV is the best performing protocol. On the basis of these results, the AODV routing protocol was selected and its performance was compared with the performance of the WCETT and xWCETT in the next section. The next section presents the results obtained for the simulation scenario based on CR-WMNs environment. A total of five (5) set of scenarios were performed, varying the number of cognitive radio nodes from twenty (20) to hundred (100) nodes. The results are presented below.

5.2. Cognitive Radio Wireless Mesh Network Experimental Results

5.2.1. Scenario 1: Twenty (20) Node Network Configuration

a) The end-to-end latency results

Figure 5-12 presents the end-to-end latency performance results obtained in scenario one of CR-WMNs. The number of cognitive radio nodes was set to twenty (20) and the number of primary users was set to two (2). In chapter 03, we presented the design of our proposed xWCETT routing protocol. The proposed xWCETT routing protocol was simulated and evaluated against AODV and WCETT. Figure 5-12(a) presents the end-to-end latency performance results obtained by the proposed routing protocols (xWCETT). Figure 5-12(b) and 5.12(c) present the end-to-end latency performance results obtained by AODV and WCETT respectively. Figure 5.12(d) presents the end-to-end latency comparative results obtained by the three (3) routing protocols.

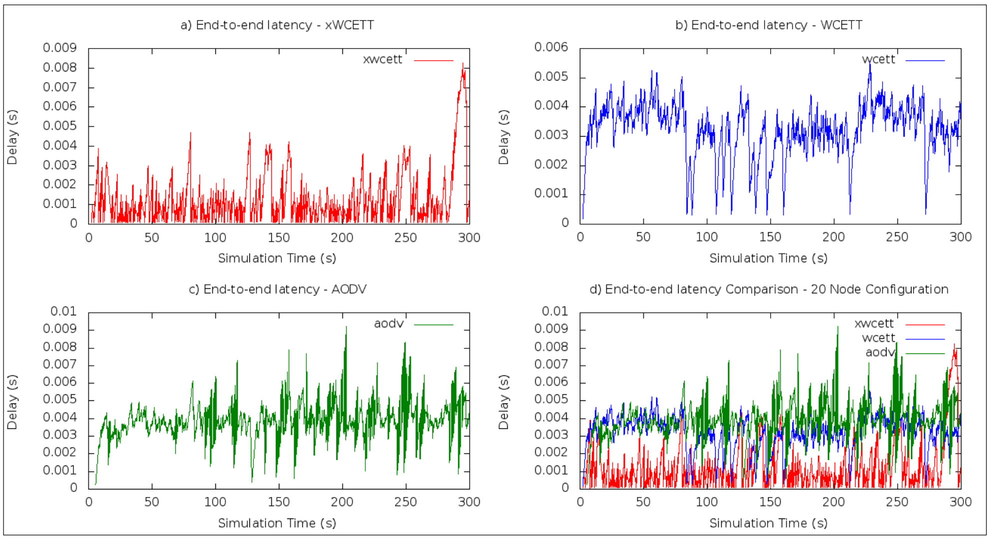

Figure 5-12: The end-to-end latency performance results of 20 node network configuration

From the results presented in Figure 5-12, we observe that the xWCETT is able to maintain a stable and minimal end-to-end latency in comparison to AODV and WCETT. This behaviour indicates a stable and robust performance in a multi-hop CRN environment where the random and intermittent PU activities are likely to destabilise network connectivity and degrade network performance. The performance of AODV and WCETT protocols is primarily affected by the dynamic spectrum availability caused by intermittent presence of PUs. The secondary nodes movement also has a negative impact of the performance of AODV and WCETT protocols, thereby increasing the end-to-end latency obtained.

Figure 5-13 presents the end-to-end average latency results obtained by the three (3) routing protocols (xWCETT, WCETT and AODV).

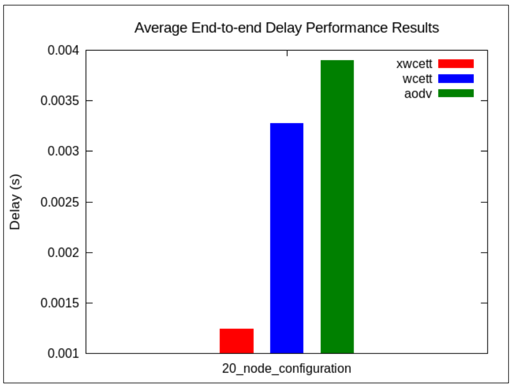

Figure 5-13: The average latency performance results

From Figure 5-13, we observe that the latency obtained by xWCETT is minimal on average as compared to AODV and WCETT. The AODV and WCETT routing protocols obtained the latency higher than xWCETT primarily because the protocols are not designed for the cognitive radio environment. The WCETT protocol was designed for multi-channel multi-radio architecture which may be partially comparable to the cognitive radio architecture. Thus, the WCETT routing protocol obtained a lower average latency compared to the AODV routing protocol. However, the performance of both AODV and WCETT suffers due to dynamically changing environment resources (such as availability of spectrum).The sporadic availability of PU activities causes WCETT and AODV to suffer increased delays.

In Figure 5-14 and 5-15, we present the end-to-end jitter performance results obtained by the three (3) routing protocols. Figure 5-13(a) through 5.13(c) present the end-to-end jitter performance results obtained by xWCETT, WCETT and AODV respectively. Figure 5.13(d) and 5-14 presents the comparative end-to-end jitter and average jitter results.

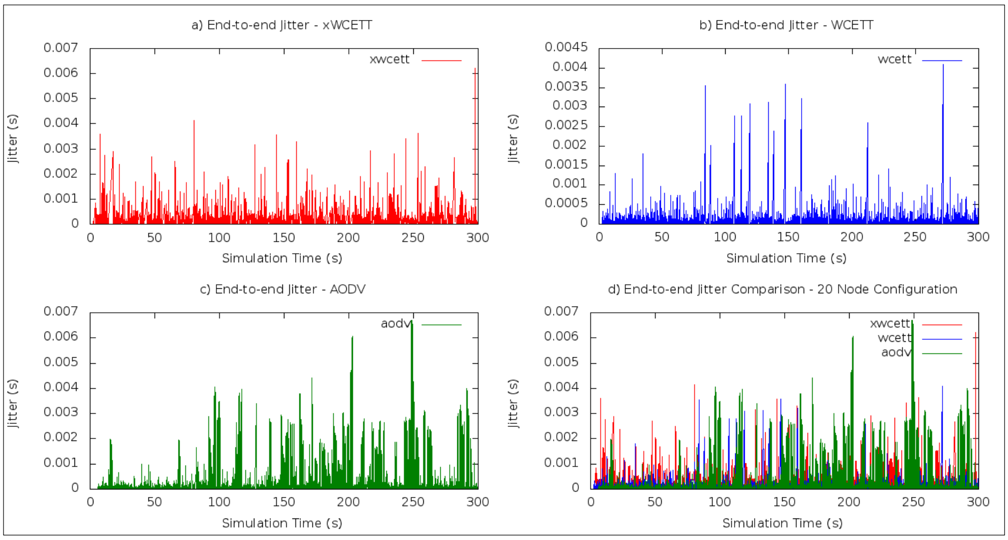

Figure 5-14: The end-to-end jitter performance results of 20 node network configuration

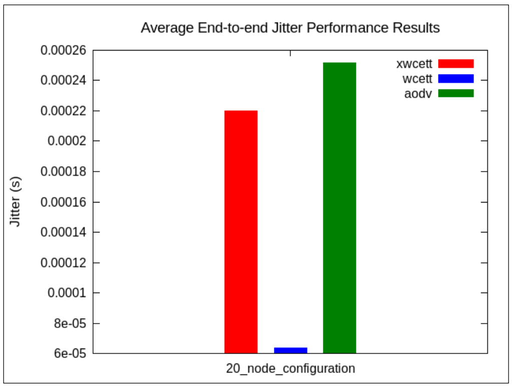

Figure 5-15: The average jitter performance results

The end-to-end and average jitter performance results obtained in Figure 5-14 and 5-15 indicate that the performance of xWCETT protocol suffers delay variations per packet delivery. The AODV and xWCETT obtained higher average jitter results as compared to the WCETT routing protocol. This behaviour is attributed to the topology and spectrum dynamics. The WCETT routing protocol obtained best results in terms of jitter performance when compared to the proposed xWCETT protocol. Each node in the network maintains the channel availability table refreshed and updated whenever the PU activity is detected. The ordering of the cost values in the channel availability table slightly increase the network repair time and results in an increased average jitter.

In the following figures, we present the throughput performance results obtained by the three (3) cognitive radio based routing protocols in Figure 5-16 and 5-17. Figure 5-16(a) through to 5-16(c) we present the end-to-end throughput performance results. Figure 5-16(d) shows the end-to-end comparative throughput results while Figure 5-17, presents the average throughput results.

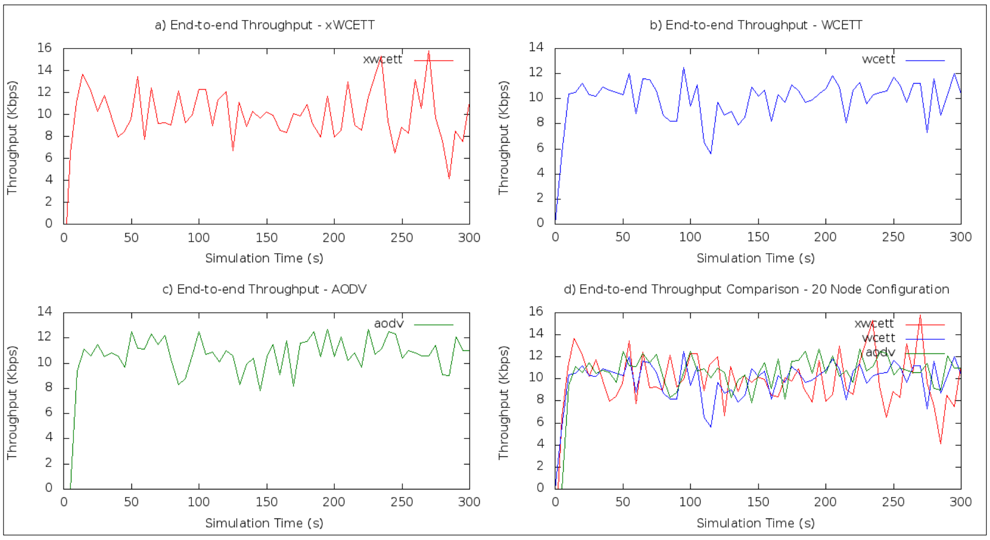

Figure 5-16: The end-to-end throughput performance results of 20 node network configuration

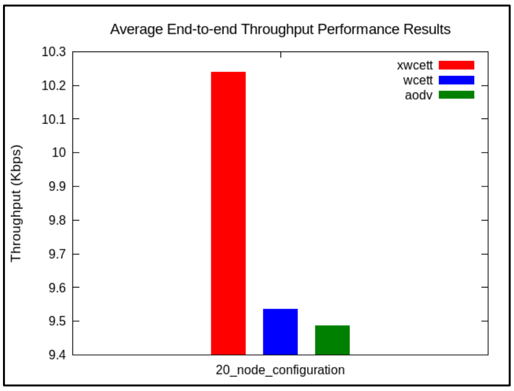

Figure 5-17: The average throughput performance results

The end-to-end throughput results presented in Figure 5-16 demonstrate unsteady performance in all three (3) routing protocols. The xWCETT protocol obtained the highest achievable throughput when compared to AODV and WCETT. The AODV protocol obtained the lowest average throughput as depicted in Figure 5-16. The higher throughout rate obtained indicate efficient utilization of the bandwidth as more packets are transmitted per unit time. This means the xWCETT routing protocol is able to utilise network resources more efficiently than AODV and WCETT protocols.

Figure 5-18 presents the end-to-end PDR results. The results show that xWCETT achieved the highest percentage of packet delivery rate. This shows that xWCETT protocol loses fewer packets when compared to the WCETT and AODV routing protocols. The longer source-destination path re-establishment during route breaks affect packet delivery rate in the AODV and WCETT routing protocols. The xWCETT is able to recover much quicker than its two (2) counterparts.

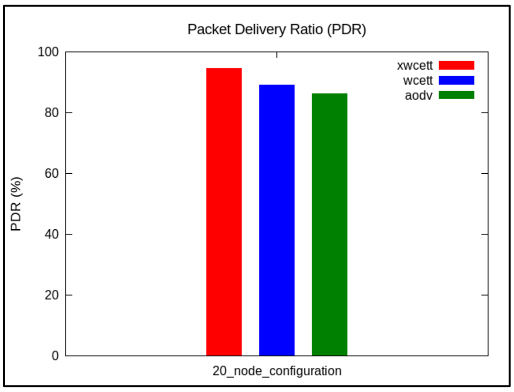

Figure 5-18: Packet delivery ratio (PDR) results obtained by three routing protocols

The final set of results obtained for the first scenario in cognitive radio environment focused on the number of hops traversed by the packets, the routing load as well as the normalised routing overhead. The results are presented in Table 5-2 and Figure 5-19 respectively.

Table 5-2: Total hop count, average hop count, routing load and normalised routing load (NRL) analysis for the three (3) routing protocols

Routing protocol	**Total hop count**	**Ave hop count**	**Routing load**	**NRL**
AODV	134256	20	8068	0.27
WCETT	148192	23	7527	0.25
xWCETT	140512	22	7031	0.21

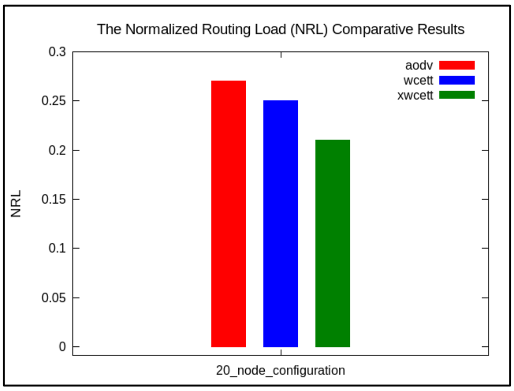

Figure 5-19: The NRL analysis results of the three routing protocols

We observe in Table 5-2 that AODV obtained the less number of hops and has a lower average hop count as compared to xWCETT and WCETT routing protocols. The AODV protocol uses Dijkstra's shortest path algorithm to compute the best paths from source to destination. This result in fewer number of hops the packets traverse to reach the destination node. However, we observe in Figure 5-19 that AODV protocol does not give the better performance in terms of NRL. During route establishment and data transmission, AODV broadcasts the routing packets on all available channels which results in high routing overhead. High routing overhead consumes the network resources and results in inefficient bandwidth utilization. In WCETT and xWCETT protocols, packets traverse longer paths to reach destination. However, WCETT and xWCETT provide better and more improved performance (as depicted in Figure 5-19) in terms of NRL because they are optimized to consider the channel diversity. The xWCETT protocol obtained the lowest routing load because it improves the mechanisms to establish the best path in cognitive radio environment, taking into account the presence of PUs.

5.2.2. Scenario 2: Forty (40) Node Network Configuration

In simulation scenario two of the cognitive radio environment (CR-WMNs), we increased the number of cognitive radio nodes to forty (40). The rest of the simulation parameters were not changed. The end-to-end and average performance results are comparable to the ones obtained in the scenario one. The results are therefore presented in Section 1.1 of the Appendix B.

5.2.3. Scenario 3: Sixty (60) Node Network Configuration

In simulation scenario three of the cognitive radio environment (CR-WMNs), we increased the number of cognitive radio nodes to sixty (60) and other simulation parameters were not changed. The similar pattern of average and end-to-end performance results was observed. The results are presented in Section 1.3 of the Appendix B.

5.2.4. Scenario 4: Eighty (80) Node Network Configuration

In simulation scenario four of the cognitive radio environment (CR-WMNs), we repeated the same CR-WMNs experimental scenario with an increased number of cognitive radio nodes to sixty (60). The similar pattern of average and end-to-end performance results was observed. The results are presented in Section 1.4 of the Appendix B.

5.2.5. Scenario 5: One hundred (100) Node Network Configuration

Finally, in the last cognitive radio based simulation scenario, we increased the size number of cognitive radio nodes to one hundred (100). The other simulation parameters remained fixed. The average and end-to-end performance results for this scenario are presented in Section 1.5 of the Appendix B. The performance patterns observed in the CR-WMNs scenario indicate that the network performance degrades gradually as the number of nodes (network size) increase. The network performance analysis and evaluation considered the end-to-end and average latency, jitter, throughput, PDF and routing overhead. The next section concludes the CR-WMNs scenario with the comparative performance analysis and results.

5.3. Cognitive Radio Wireless Mesh Networks Comparative Performance Analysis

We analysed the performance of each of the three CR-WMNs routing protocols (xWCETT, WCETT and AODV) by varying the number of cognitive radio nodes. The primary objective of varying the size of the network was to investigate the effect of network size on the actual performance of each routing protocol. Figure 5-20 through 5-23 present the end-to-end average comparative results obtained. The Figure 5-20 and Figure 5-21 present the latency and jitter comparative performance results obtained respectively.

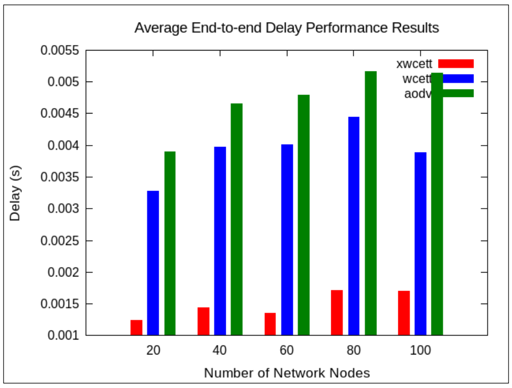

Figure 5-20: The average latency versus the number of cognitive radio nodes

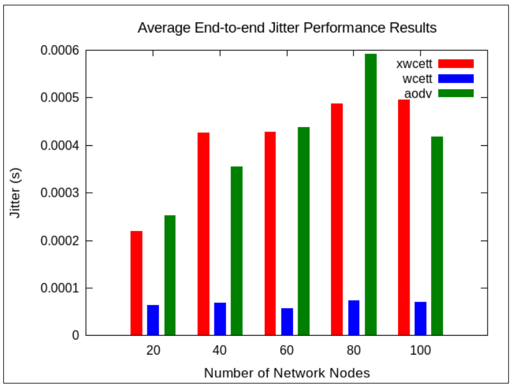

Figure 5-21: The average jitter versus the number of cognitive radio nodes

The results presented in Figure 5-20 show a direct proportionality between latency and network size. Increasing the number of network nodes increases the average end-to-end latency. The same behaviour was observed in the case of jitter results, presented in Figure 5-21. The xWCETT protocol performed well in terms of the latency but its performance was poor in terms of the average jitter results. The performance of xWCETT protocol is affected by the frequent updates and ordering of the channel availability table entries.

The next two figures, Figure 5-22 and Figure 5-23 presents the comparative throughput and PDR respectively. From the latency and jitter results, we observed that the performance of the CR-WMNs scales down gradually as the network increases in size. This pattern was also observed in the average throughput and packet delivery ratio as shown in Figure 5-22 and 5-23 respectively. Figure 5-22 indicates the higher throughput values obtained with fewer nodes in the network and the throughput values drops as the network grows larger. The PDR results presented in Figure 5-23 shows the gradual decrease in the average delivery rate with more packets dropped as the network grows larger in size. When simulating the CBR traffic over the UDP transport in a multi-hop network environment, this observation is not surprising because of the best effort strategy employed by the UDP.

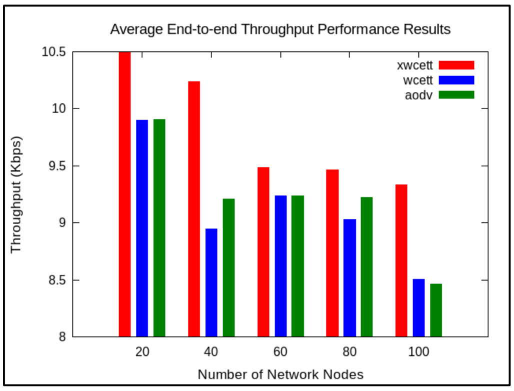

Figure 5-22: The average throughput versus the number of cognitive radio nodes

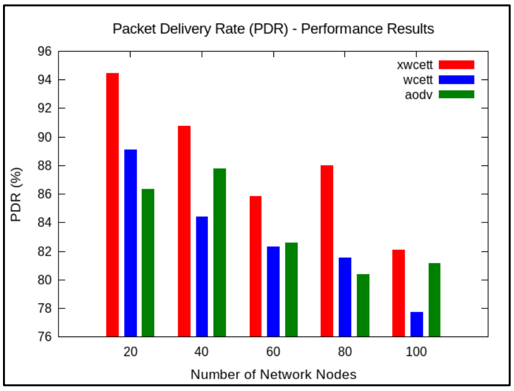

Figure 5-23: The end-to-end packet delivery rate versus the number of cognitive radio nodes

The end-to-end comparative results presented in Figure 5-20 to 5-23 illustrated that the overall end-to-end performance of a multi-hop cognitive radio network depends largely on the performance of routing criteria implemented by the routing protocol. We observed significantly improved results obtained by the proposed xWCETT protocol in comparison to the AODV and WCETT routing protocols. When the size of the network was increased, the performance xWCETT remained stable and continued to improve as compared to the AODV and WCETT routing counterparts. However, the WCETT protocol achieved the best delay variations (jitter) results because it transmits data over a set of available channels using the broadcast mechanism. Unlike the WCETT protocol, the xWCETT frequently updates its channel entries, sort them and transmit only on the best selected available channel. The AODV routing protocol's performance was mostly unstable with high end-to-end latency and low throughput rate because of its initial design objectives.

5.4. Summary of Findings

The results presented demonstrated that the AODV routing protocol performs most efficiently and efficiently in a dynamic ad-hoc network environment as it has outperformed the three counterparts, namely: the OLSR, DRS and DSDV routing protocol. Our proposed xWCETT routing protocol has dominated the AODV and the multi-radio multi-channel based WCETT protocol in the cognitive radio based dynamic mesh network environment.

The xWCETT protocol was modified to take cognizance of the dynamic parameters in the CRN environment. The AODV and WCETT protocols were implemented to utilize the hop-count and link quality respectively to compute the optimal source-destination path on a common control channel (CCC). On contrary, the xWCETT protocol employed a dedicated radio (interface) tuned to the out-of-band control channel for control signalling and another radio (interface) switching amongst multiple channels for data transmission. The xWCETT protocol further accounts for the PU activities and avoids interference with the PUs transmissions. The CCC creates performance bottleneck especially in a CRN environment. Hence, a combination of our implemented routing metric and a choice of out-of-band control channel has improved the performance of the xWCETT protocol in terms of end-to-end throughput, latency packet delivery ratio and the routing overhead. These results indicates that the proposed xWCETT routing protocol may be considered a promising routing solution for the dynamic CR-WMNs environment.

5.5. Conclusion

This chapter presented the results obtained by simulating the performance of the selected routing protocols in wireless mesh network and cognitive radio based mesh network environments. The first section presented the simulation results and analysis of AODV, DSR, OLSR and DSDV routing protocols in the dynamic mesh network environment. The second section presented the simulation results and analysis of our proposed xWCETT protocol in comparison with the AODV and WCETT routing protocols in a dynamic cognitive radio based wireless mesh network environment.

The results obtained in the first section (wireless mesh network environment) showed that the AODV outperformed the three routing protocols (DSR, OLSR and DSDV). We observed that the two reactive routing protocols (AODV and DSR) presented better and more improved performance results as compared to the proactive OLSR and DSDV. The AODV routing protocol provided the best results in all the three simulation scenarios which were considered, i.e. varying the number of network nodes from ten (10) to thirty (30) to fifty (50). The AODV was chosen as the candidate in a dynamic wireless mesh network environment on the basis of its good performance.

The results obtained and presented in the second section of this chapter (cognitive radio wireless mesh network environment) showed that the proposed xWCETT protocol is the best performing in terms of end-to-end latency, throughput, packet delivery ratio and the routing overhead. When ranking the performance of these three routing protocols, the xWCETT takes the first position, followed by the WCETT protocol. The AODV stands at the third position. The WCETT protocol’s performance is comparable to xWCETT and it also outperformed xWCETT protocol in terms of end-to-end delay variations (jitter). The AODV protocol suffered high end-to-end latency, low bandwidth utilization, low throughput rate and low packet delivery ratio largely because it was not designed for the multi-radio based network environment.

CHAPTER 6

6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1. SUMMARY

The primary purpose of this study was to evaluate the performance of different routing protocols designed for the traditional and cognitive radio based WMNs in view of optimising the overall performance of the mesh networks. We primarily aimed to identify and optimise the routing protocols that may be directly applied to the CR-WMNs. We surveyed and evaluated the performance of the routing protocols designed for the traditional wireless ad-hoc network as well as the cognitive radio based routing protocols. We then identified the best performing routing protocol in WMN and evaluated its performance in a shared spectrum cognitive radio based WMN environment. We finally proposed a spectrum-aware, spectrum-agile and interference-aware routing protocol for the CR-WMNs.

The overall research work was carried out in two main stages. In the first stage, we evaluated the performance of four routing protocols designed for the mobile ad-hoc networks (MANETs). A total of three of these routing protocols have shown to yield degraded performance when applied to the WMNs primarily because the architecture, algorithmic design and objectives of MANETs is different from WMNs. The architecture of MANETs was designed to support high mobility and collaborative exchange of traffic amongst all the mobile nodes. On the other hand, the architecture of WMNs was designed with limited mobility as an important consideration. We presented the performance of the four candidate routing protocols, namely AODV, DSR, OLSR and DSDV. The numerical and extensive simulation experiments were performed using the NS-2.

In the second stage, we proposed and presented the spectrum-agile, spectrum-aware and interference-aware routing protocol for dynamic CR-WMNs called the xWCETT. The design of the proposed xWCETT routing protocol was based on the multi-radio multi-channel architecture. Having identified the AODV routing protocol as the optimal and more suitable candidate routing protocol for the WMNs, we compared the performance of AODV, the multi-radio multi-channel based WCETT and our proposed xWCETT routing protocols in the CR-WMNs environment. An account of the final research findings and conclusion is given in the next section.

6.2. RECOMMENDATIONS

The research study undertaken in this dissertation has highlighted a number of routing issues and challenges encountered in the cognitive radio based multi-hop networks. A common challenge that influences the performance and behaviour of the CRNs is the technique employed for control signalling. The technique employed in selection of the common control channel (CCC) for neighbour discovery as well as route establishment influences the end-to-end network performance. In our study, we employed a dedicated radio (interface) tuned to the out-of-band CCC for control signalling and another radio (interface) switching amongst multiple channels for data transmission. In the real multi-hop CRN environment, a dedicated control signalling channel may not be available and this will require the network to establish the control and data channels from the given spectrum bands. This will require complex techniques to establish, synchronise and maintain the communication channels. Hence, the future studies might look at the advanced techniques that allow two radios to dynamically partition the available spectrum band into the data and control channels, and concurrently use the bandwidth channels efficiently without causing any interference amongst each other. Given the heterogeneous nature of the multi-hop CRN environment, efficient multi-radio based routing strategy could yield an improved bandwidth utilisation, reduced routing overhead and higher end-to-end throughput.

6.3. FINAL CONCLUSION

In the case of WMNs based simulation scenarios, the results obtained showed that the reactive routing protocols (AODV and DSR) were able to maintain the consistent and stable end-to-end performance throughout all the simulation scenarios performed. A different behaviour was observed in the case of proactive OLSR and DSDV protocols, in which fluctuating performance was observed. The AODV protocol outperformed all the three routing counterparts in terms of the end-to-end latency, jitter, throughput, PDR and normalized routing load. However, the proactive OLSR protocol obtained slightly lower average latency as compared to the AODV protocol because of its robustness to maintain cached source-destination routes until the routes break. This performance difference was insignificant because the more robust and stable end-to-end performance is more desirable than the unreliable and fluctuating performance. Hence, the AODV was considered the best routing protocol for WMNs.

In the case of CR-WMNs based simulation scenarios which formed the core focus of this study, we observed similar behaviour between the xWCETT and WCETT routing protocols. However, the xWCETT protocol outperformed the two routing counterparts (AODV and WCETT) in terms of end-to-end latency, throughput, packet delivery ratio and the normalized routing load. The WCETT protocol obtained results similar to the xWCETT and outperformed its successor xWCETT only in terms of steady end-to-end delay variations (jitter). One notable performance difference between the xWCETT and WCETT protocol lies in the formulation, ranking and maintenance of available list of channels. The WCETT protocol broadcasts it control packets over all available channel-set while the xWCETT protocol selects the best channel for transmission. The xWCETT protocol was able to attain steady and robust performance with no interference caused to the PUs. Hence, in all the CR-WMNs simulation scenarios (i.e. varying the size of the cognitive radio network from small-scale to large-scale), the performance of the proposed xWCETT routing protocol was significantly better than the AODV and WCETT routing protocols.

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APPENDIX A

A. WIRELESS MESH NETWORK SCENARIO RESULTS

1.1 Scenario 2: Thirty (30) Node Network Configuration

1.1.1. The latency results

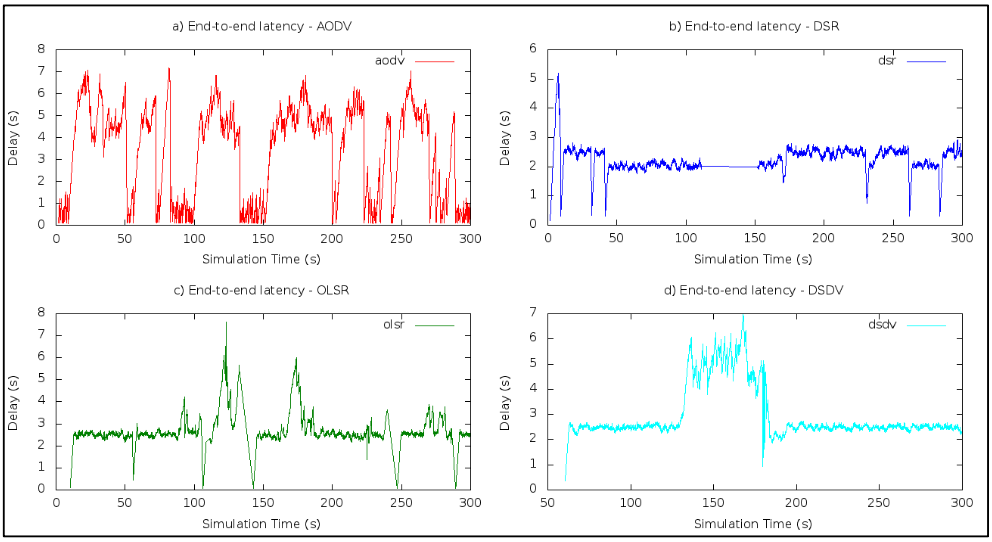

Figure A-1: The end-to-end latency performance results for 30 node network setup

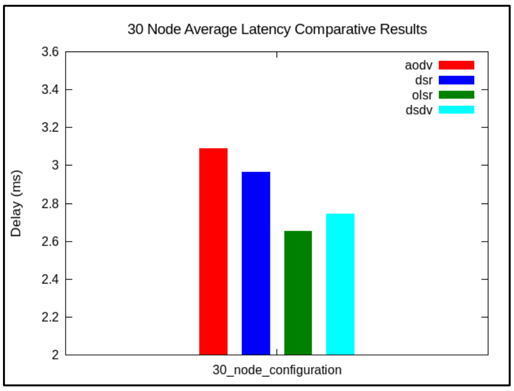

Figure A-2: The average latency performance results

1.1.2. The jitter results

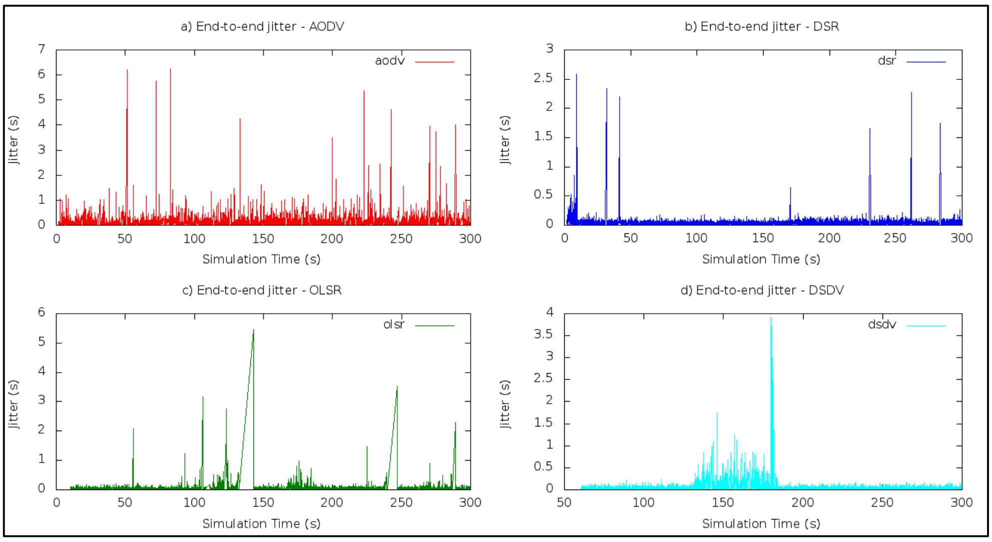

Figure A-3: The end-to-end jitter performance results of 30 node network configuration

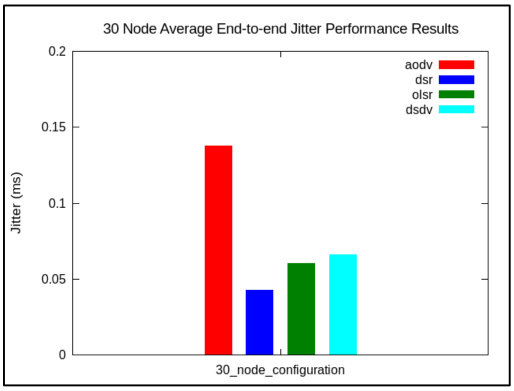

Figure A-4: The average jitter performance results

1.1.3. The throughput results

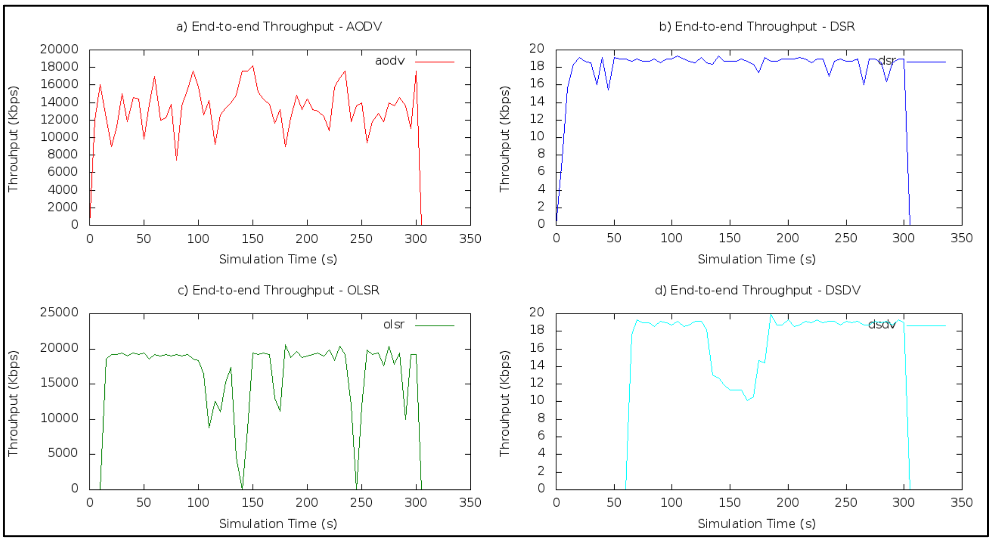

Figure A-5: The end-to-end throughput performance results for 30 node network configuration

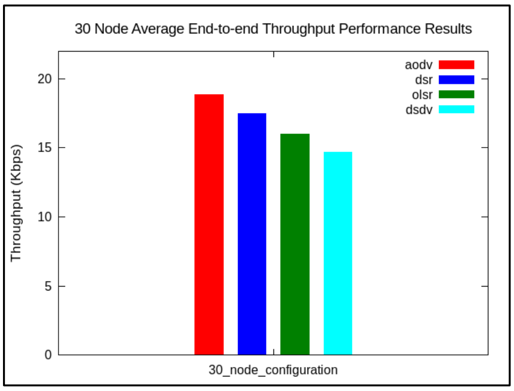

Figure A-6: The average throughput performance results

1.1.4. The packet delivery rate results

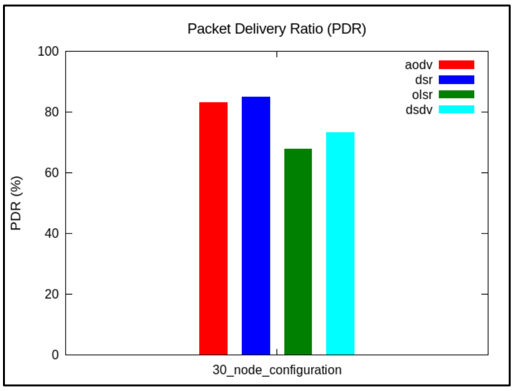

Figure A-7: Packet delivery ratio (PDR) results obtained by three routing protocols

1.2 Scenario 3: Fifty (50) Node Network Configuration

2.7.1. The latency results

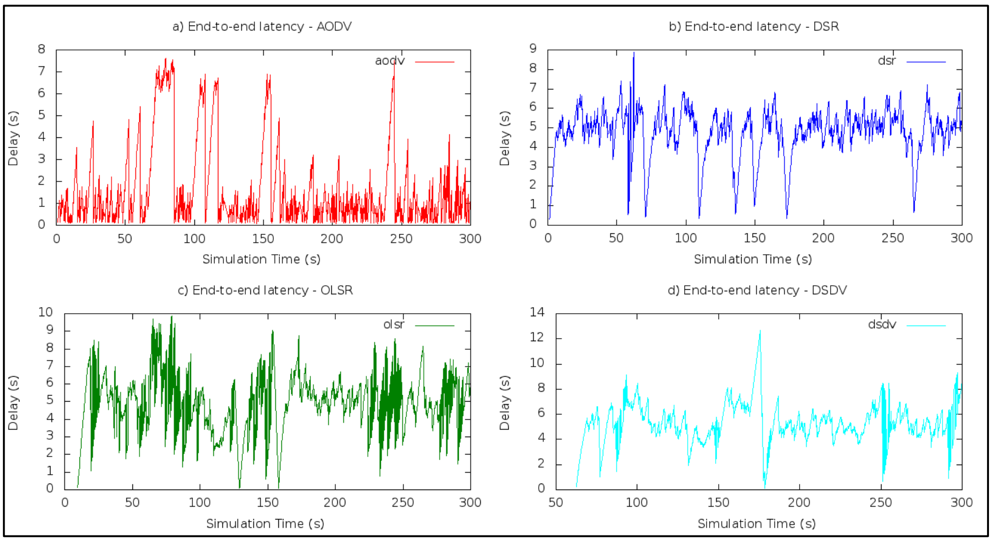

Figure A-8: The end-to-end latency performance results for 30 node network setup

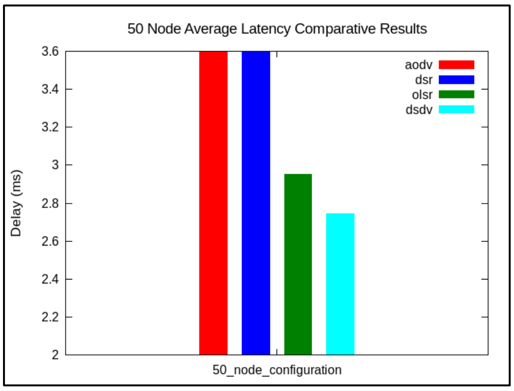

Figure A-9: The average latency performance results

1.2.2. The jitter results

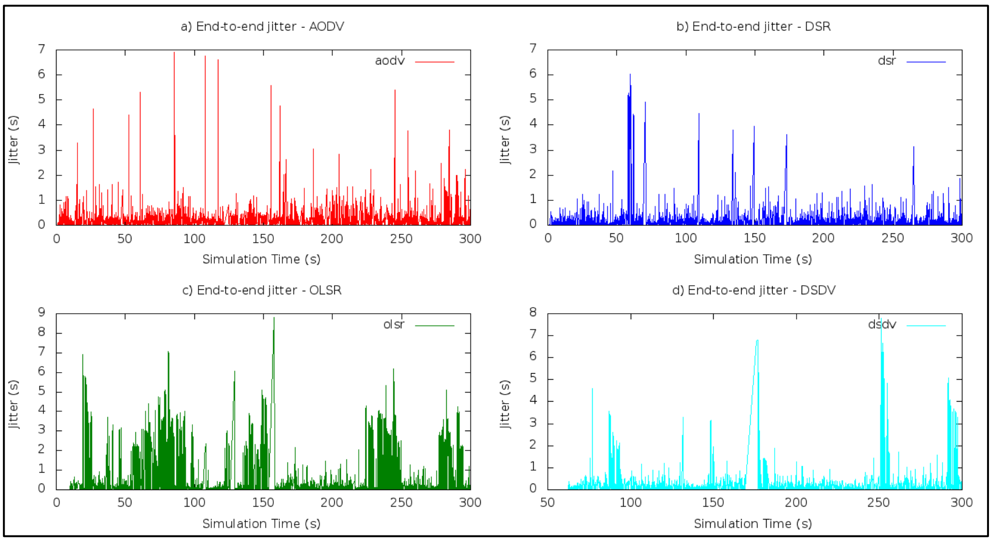

Figure A-10: The end-to-end jitter performance results of 50 node network configuration

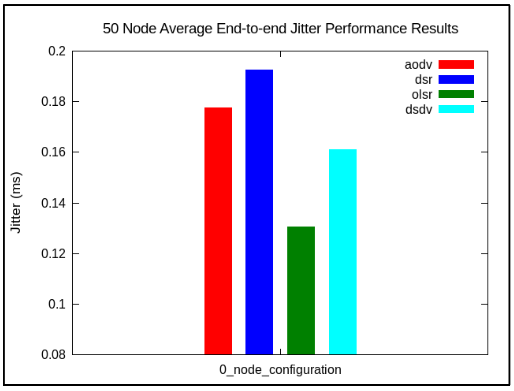

Figure A-11: The average Jitter performance results

1.2.3. The throughput results

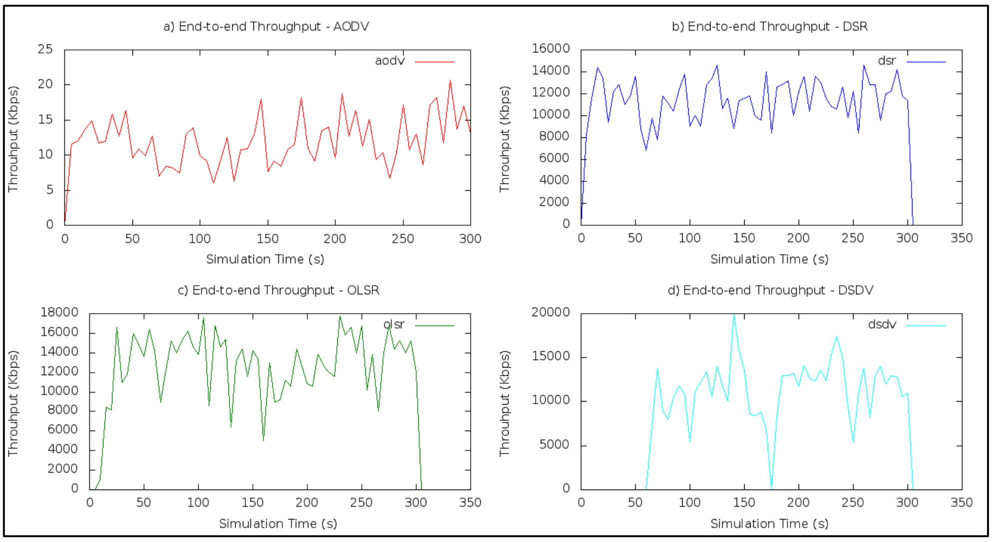

Figure A-12: The end-to-end throughput performance results for 50 node network configuration

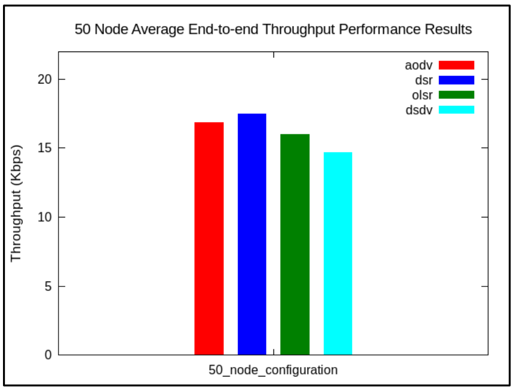

Figure A-13: The average throughput performance results

1.2.4. The packet delivery rate results

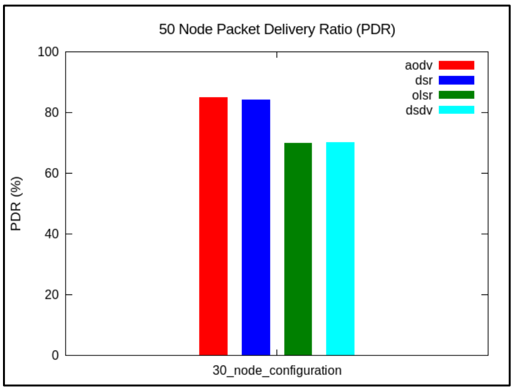

Figure A-14: Packet delivery ratio (PDR) results obtained by three routing protocols

APPENDIX B

B. COGNITIVE RADIO BASED WIRELESS MESH NETWORK SCENARIO RESULTS

1.1. Scenario 2: Forty (40) Node Network Configuration

1.1.1. The latency results

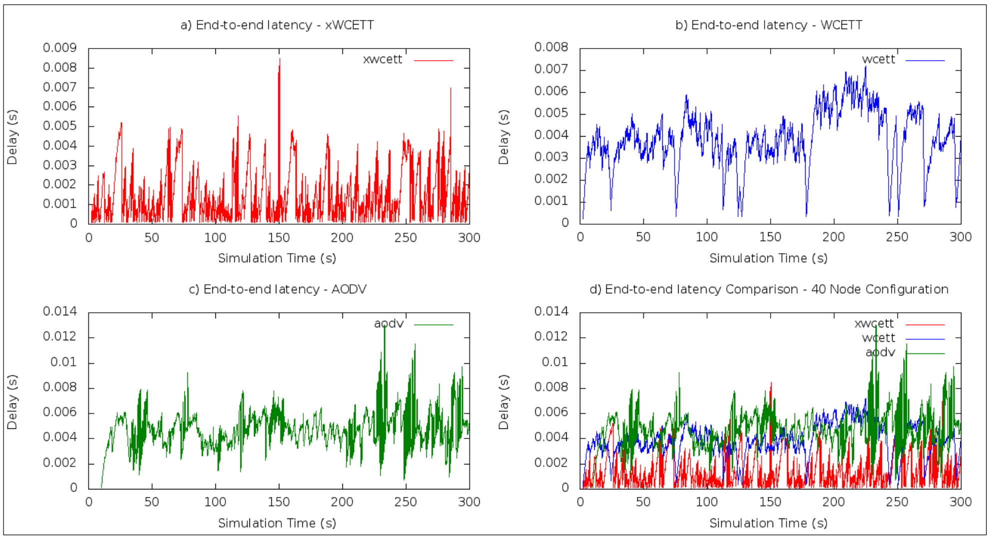

Figure B-1: The end-to-end latency performance results of 40 node network configuration

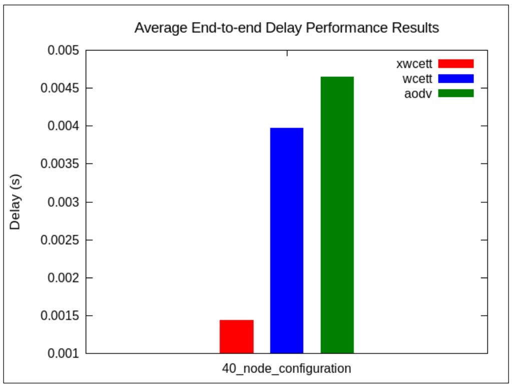

Figure B-2: The average latency performance results

1.1.2. The jitter results

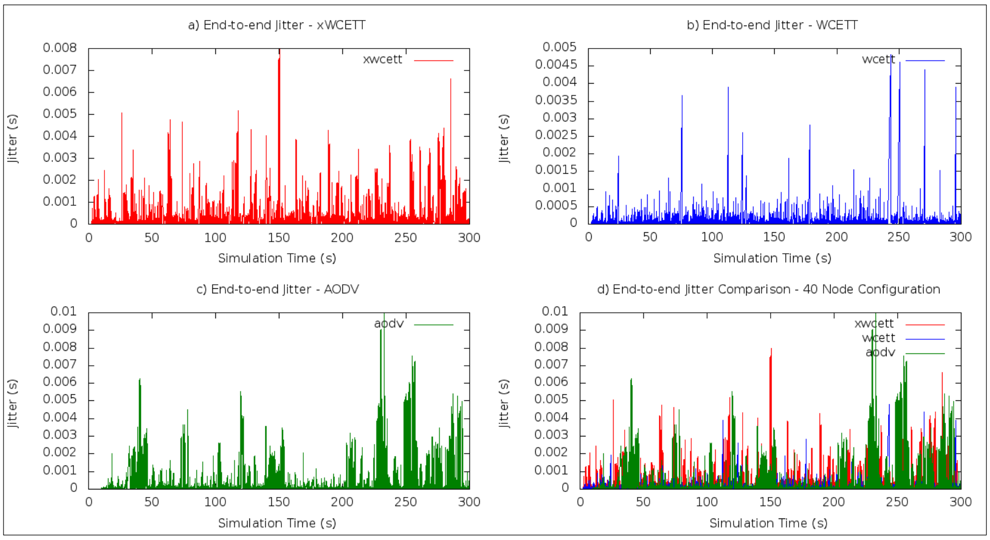

Figure B-3: The end-to-end jitter performance results of 40 node network configuration

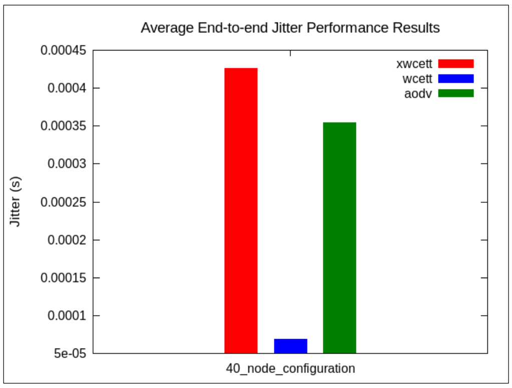

Figure B-4: The average Jitter performance results

1.1.3. The throughput results

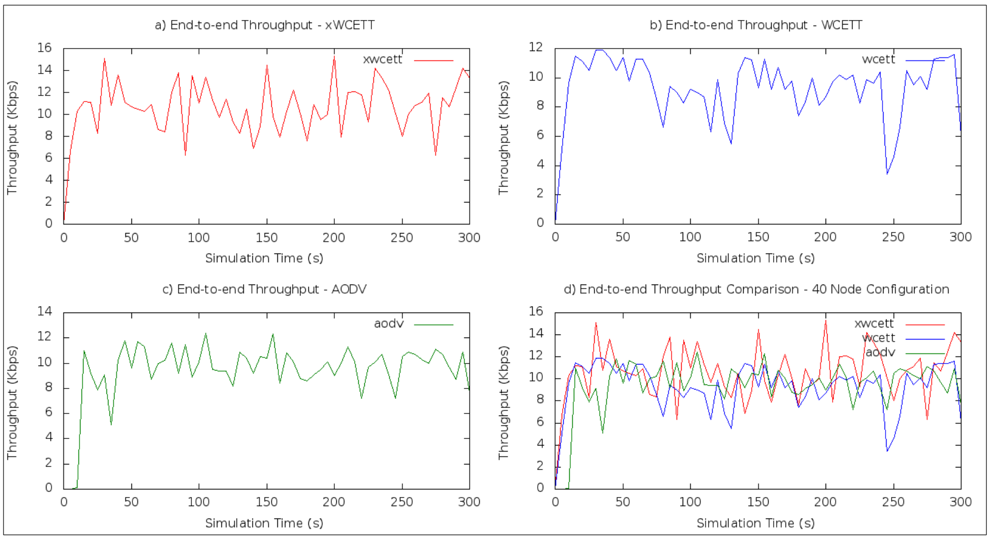

Figure B-5: The end-to-end throughput performance results of 40 node network configuration

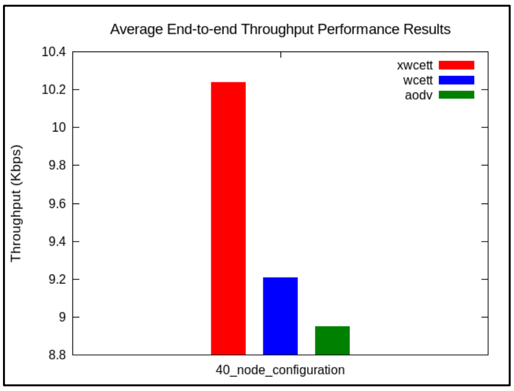

Figure B-6: The average throughput performance results

1.1.4. The packet delivery rate results

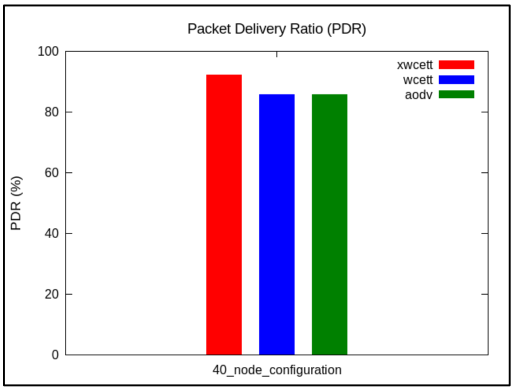

Figure B-7: Packet delivery ratio (PDR) results obtained by three routing protocols

1.2. Scenario 3: Sixty (60) Node Network Configuration

1.2.1. The latency results

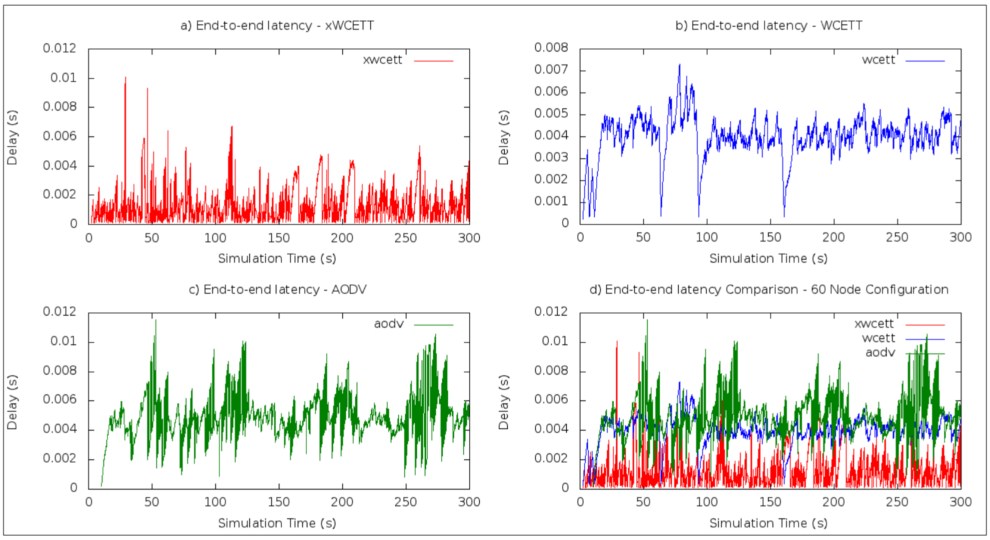

Figure B-8: The end-to-end performance latency results of 60 node network configuration

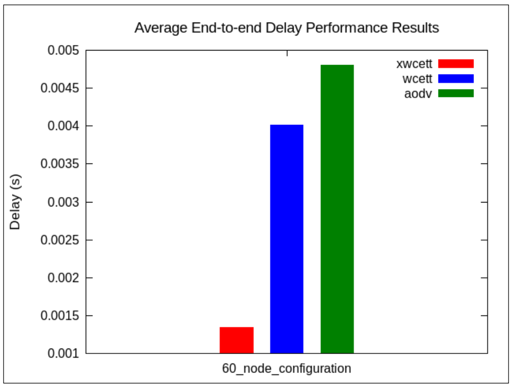

Figure B-9: The average latency performance results

1.2.2. The jitter results

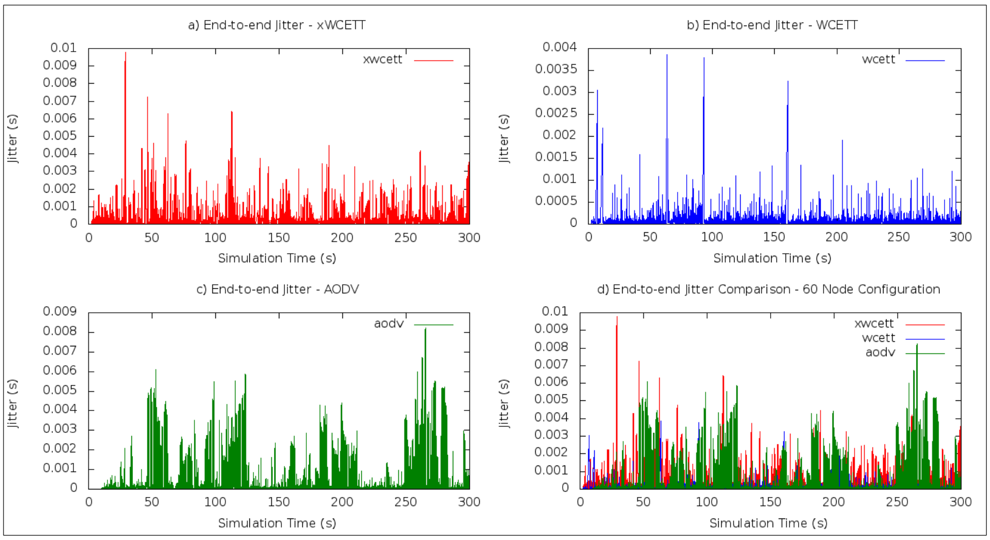

Figure B-10: The end-to-end jitter performance results of 60 node network configuration

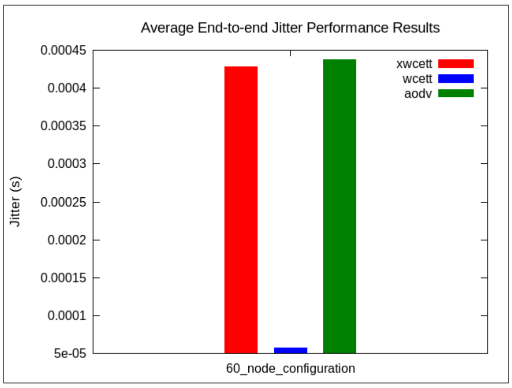

Figure B-11: The average jitter performance results

1.2.3. The throughput results

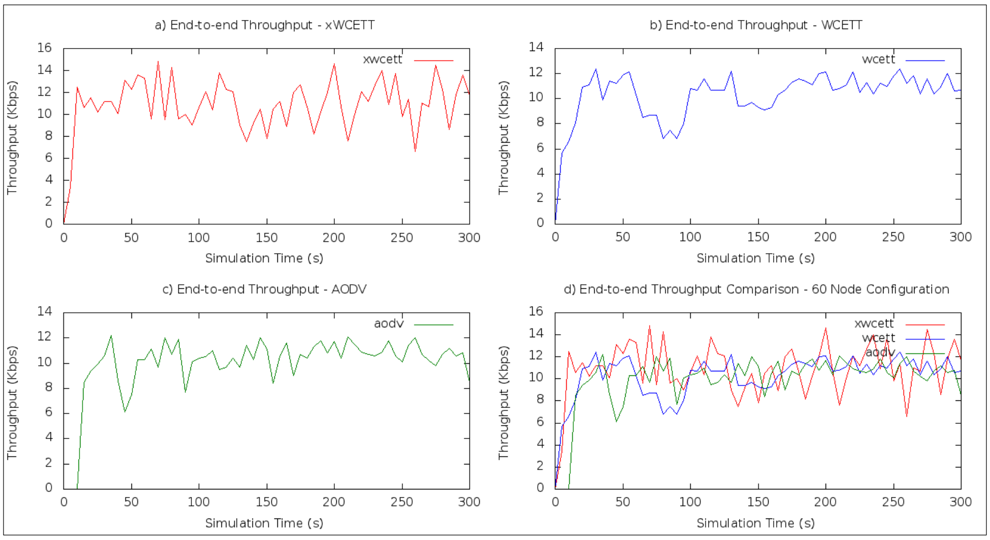

Figure B-12: The end-to-end throughput performance results of 60 node network configuration

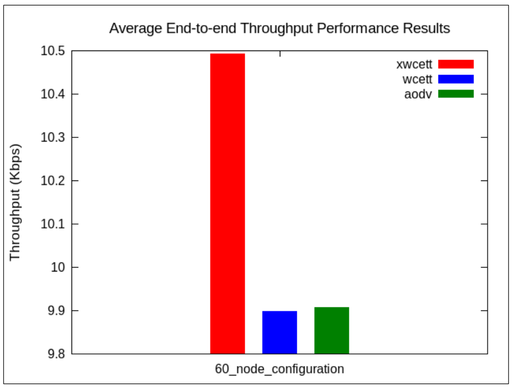

Figure B-13: The average throughput performance results

1.2.4. The packet delivery rate results

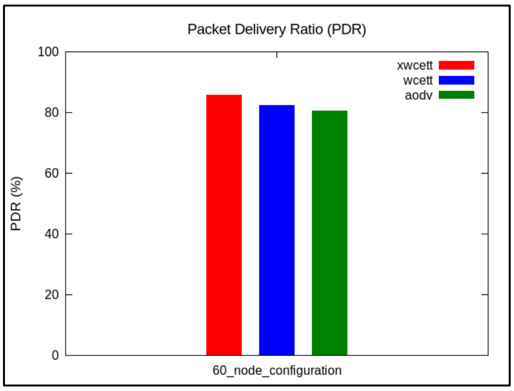

Figure B-14: Packet delivery ratio (PDR) results obtained by three routing protocols

1.3. Scenario 4: Eighty (80) Node Network Configuration

1.3.1. The latency results

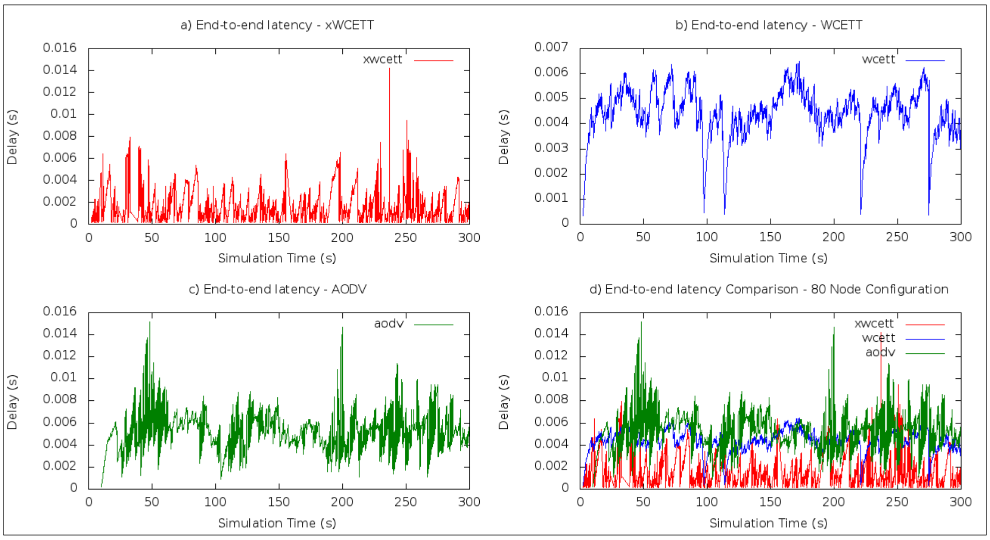

Figure B-15: The end-to-end latency performance results of 80 node network configuration

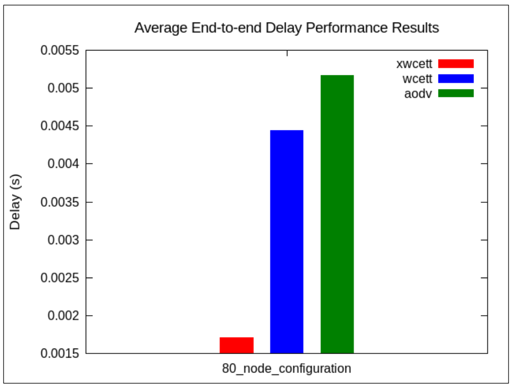

Figure B-16: The average latency performance results

1.3.1. The jitter results

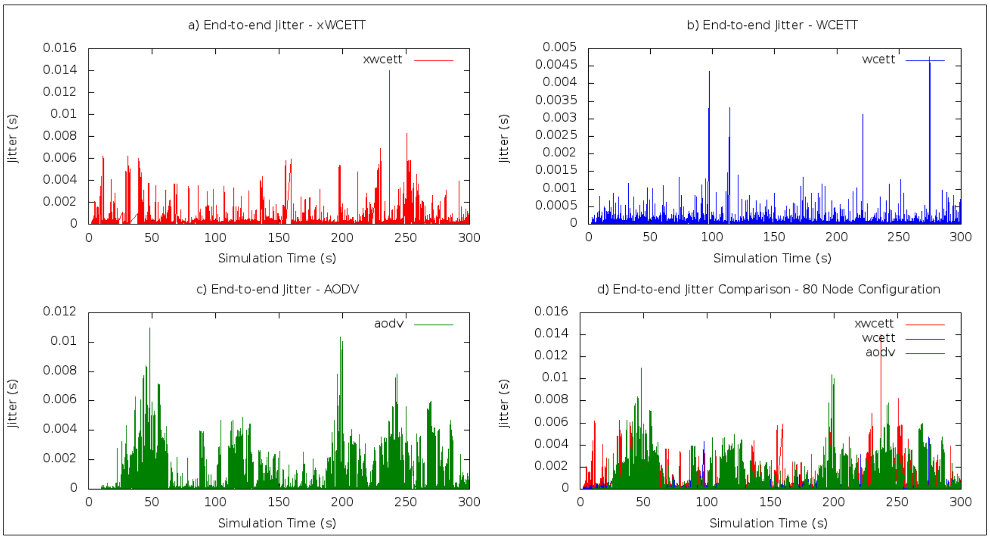

Figure B-17: The end-to-end jitter performance results of 80 node network configuration

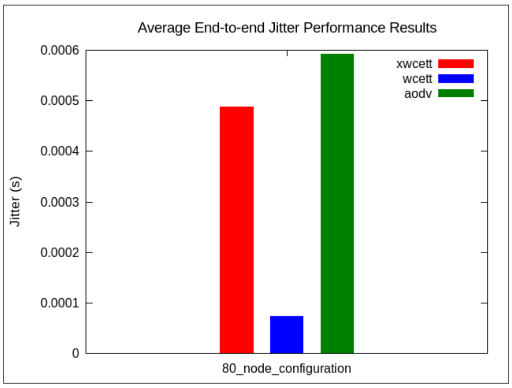

Figure B-18: The average jitter performance results

1.3.2. The throughput results

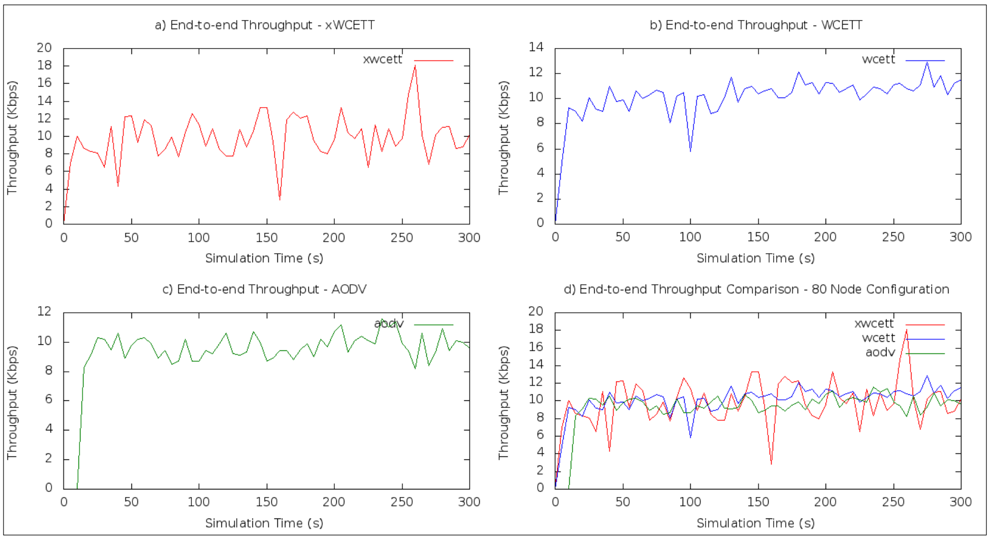

Figure B-19: The end-to-end throughput performance results of 80 node network configuration

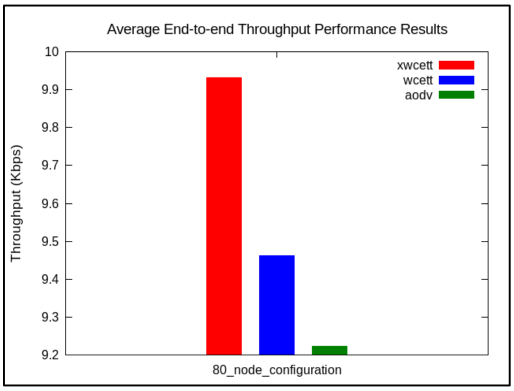

Figure B-20: The average throughput performance results

1.3.3. The packet delivery rate

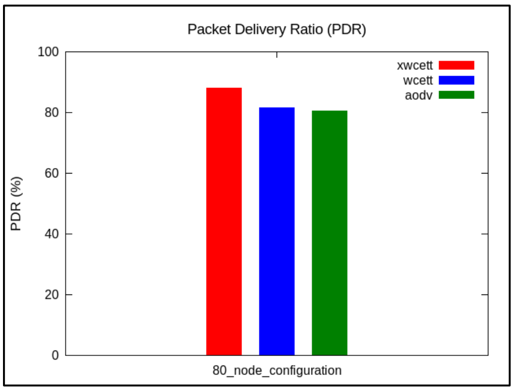

Figure B-21: Packet delivery ratio (PDR) results obtained by three routing protocols

1.4. Scenario 5: One hundred (100) Node Network Configuration

1.4.1. The latency results

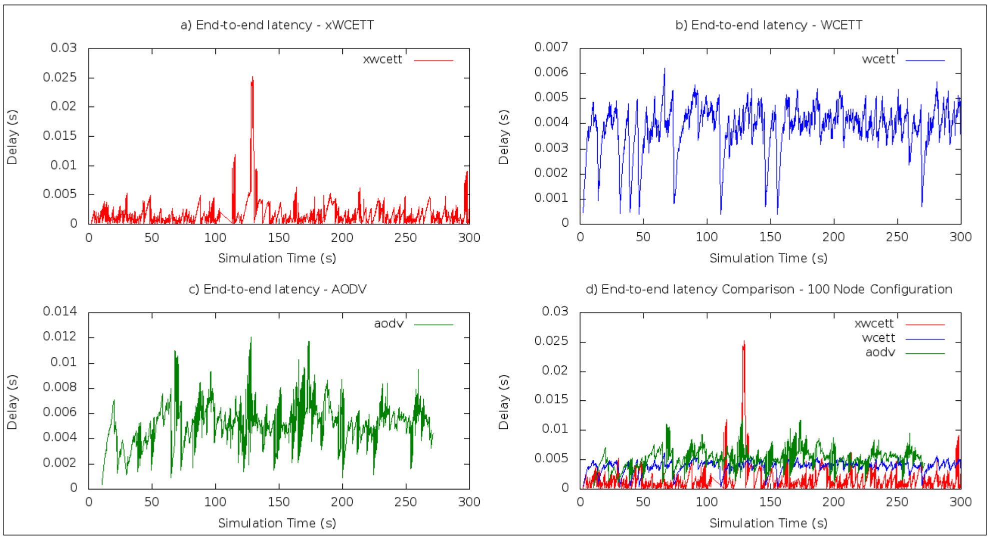

Figure B-22: The end-to-end latency performance results of 100 node network configuration

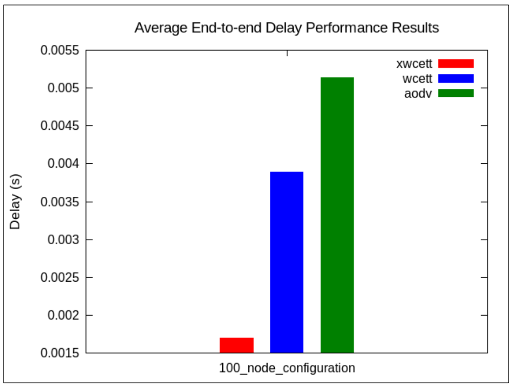

Figure B-23: The average latency performance results

1.4.2. The jitter results

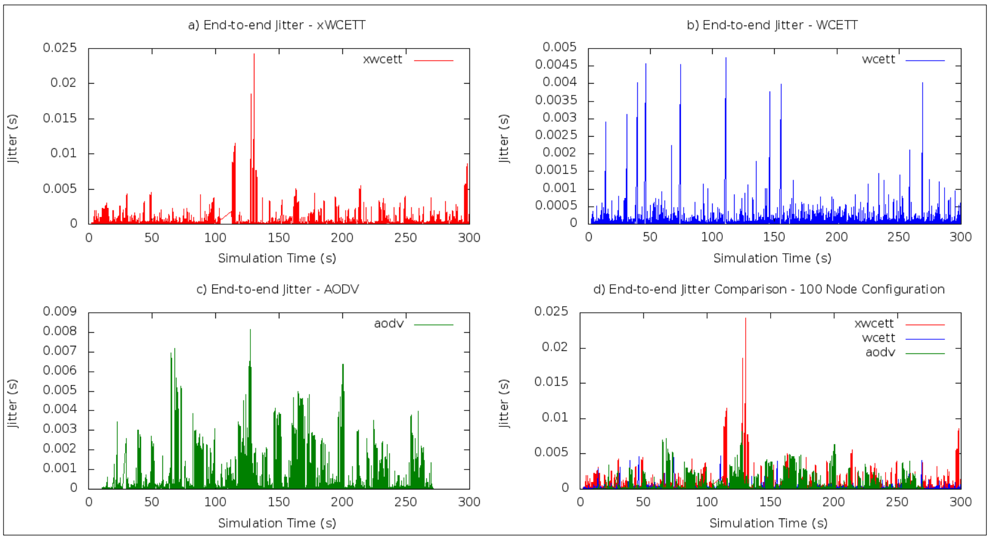

Figure B-24: The end-to-end jitter performance results of 100 node network configuration

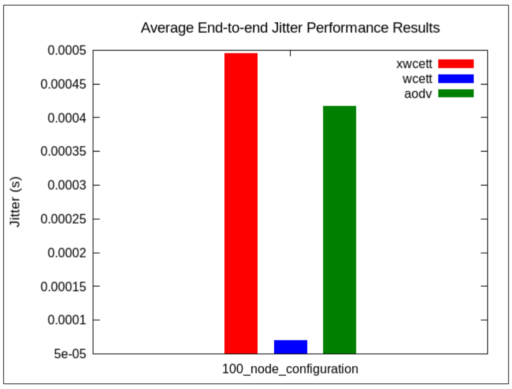

Figure B-25: The average jitter performance results

1.4.3. The throughput results

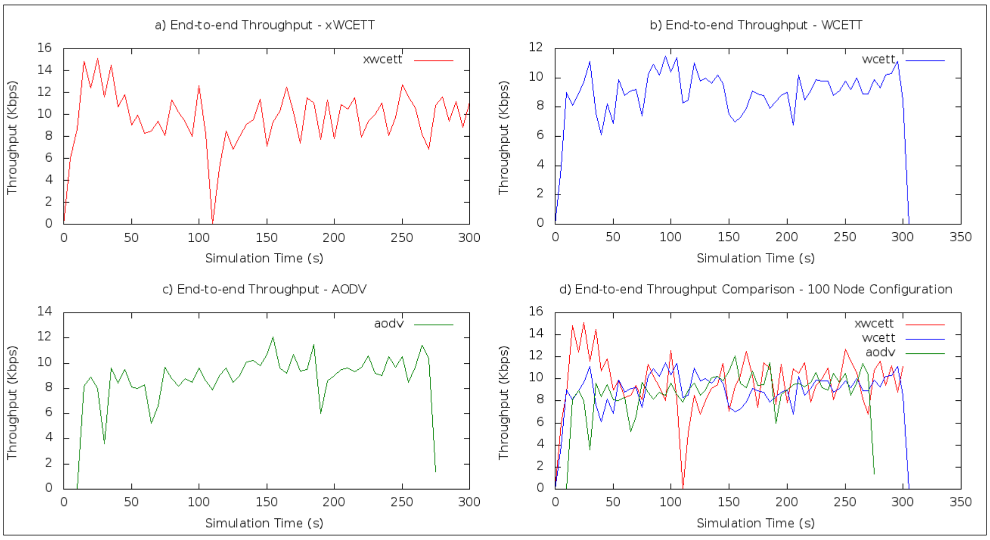

Figure B-26: The end-to-end throughput performance results of 100 node network configuration

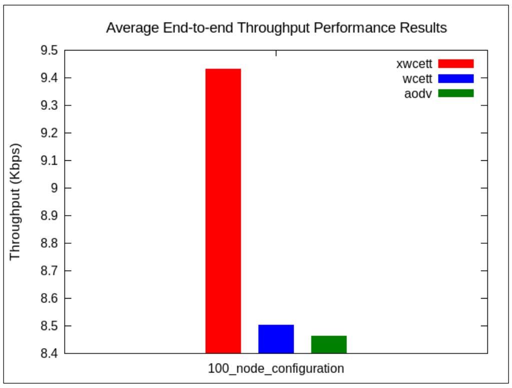

Figure B-27: The average throughput performance results

1.4.4. The packet delivery rate

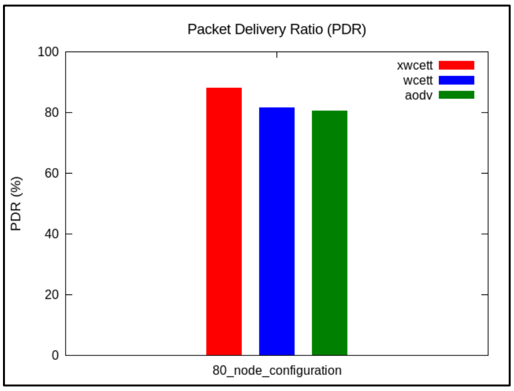

Figure B-28: Packet delivery ratio (PDR) results obtained by three routing protocols