AN ENHANCED MULTICAST-BASED OPTIMIZED LINK STATE ROUTING FOR WIRELESS COMMUNITY NETWORK

BY

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ABSTRACT

Wireless community networks (WCNs) are a solution for people who are living in some areas facing difficulties for accessing the Internet because no Internet service providers (ISPs) are providing them with the service due to the long distance, the high cost of infrastructure, and the less number of people in these areas. The current routing protocols for WCNs have two performance issues. The first issue is routing stability. Because of the heterogeneous characteristics of links, link quality should be considered as one of the main metrics used to control the routing of packets. However, current routing techniques depend on the shortest path as the main metric to control the routing of packets which results in non-stable routes. Non-stable routes affect communication speed which is a main requirement for large scale of real time applications. The second issue is routing scalability. The scalability is more challenging in the presence of both large number of nodes and mobility. As current routing protocols are inefficient when faced with the dynamic changes and poor links that occur in real-life and self-managed deployments. This results in too much overhead during communications due to flooding as most of the current routing protocols uses unicast traffic. In this research, the ad hoc routing protocol, optimized link state routing (OLSR) is selected and enhanced so that it can meet the standards of efficiency in terms of stability and scalability. OLSR is enhanced through three phases. The first phase is the multicasting expansion where Multicast traffic is expanded to the OLSR routing protocol in WCNs in order to decrease the overhead caused by flooding as OLSR uses unicast traffic. The second phase is the multipoint relay (MPR) selection based on analytical hierarchical process (AHP). Multiple criteria are taken into account simultaneously in the Multi-Criteria Decision Making (MCDM) method to create a flexible decision making process. Multiple metrics can be weighted according to MCDM: AHP. Each node establishes an MPR set based on a single cost determined with the given metrics. The third phase is a composite metric for optimal route selection. The composite metric is proposed using multiple parameters in order to ensure good knowledge of the status of links that can guarantee picking the most stable links in the network. The aim of the new proposed metric is to make finding the best routes extremely easier with the dynamic topology of WCNs. In addition, it aims to avoid the use of hop count metric which is used in the OLSR protocol and is not suitable to the dynamic link characteristics of WCNs. The new proposed routing protocol is developed using C++ programming language under the NS-2 simulator. The performance of the proposed routing protocol is measured using four performance metrics: average end-to-end delay, network control overhead (NCO), packet delivery ratio (PDR), and energy consumption in terms of network density and traffic load with varying mobility speeds. The proposed routing protocol outperforms the OLSR protocol in terms of average end-to-end delay, NCO, and PDR by 5%, 11%, and 12% respectively. While, the energy consumption for the proposed routing protocol is approximately similar to the standard OLSR protocol.

خلاصة البحث

تعد شبكات المجتمع اللاسلكية (WCNs) حلاً للأشخاص الذين يعيشون في بعض المناطق التي تواجه صعوبات في الوصول إلى الإنترنت نظرًا لعدم توفر مزودي خدمة الإنترنت (ISP) لهم بالخدمة بسبب المسافة الطويلة والتكلفة العالية للبنية التحتية وقلة عدد الأشخاص في هذه المناطق. بروتوكولات التوجيه الحالية لشبكات WCN لها مشكلتان في الأداء. المشكلة الأولى هي توجيه الاستقرار. بسبب الخصائص غير المتجانسة للروابط، يجب اعتبار جودة الارتباط كأحد المقاييس الرئيسية المستخدمة للتحكم في توجيه الحزم. ومع ذلك، تعتمد تقنيات التوجيه الحالية على أقصر مسار باعتباره المقياس الرئيسي للتحكم في توجيه الحزم مما يؤدي إلى مسارات غير مستقرة. تؤثر المسارات غير المستقرة على سرعة الاتصال التي تعد مطلبًا رئيسيًا لنطاق واسع من التطبيقات في الوقت الفعلي. المسألة الثانية هي توجيه التوسع. تعد قابلية التوسع أكثر صعوبة في وجود عدد كبير من العقد والتنقل. نظرًا لأن بروتوكولات التوجيه الحالية غير فعالة عند مواجهة التغييرات الديناميكية والروابط الضعيفة التي تحدث في عمليات النشر الواقعية والمدارة ذاتيًا. ينتج عن هذا الكثير من الحمل الزائد أثناء الاتصالات بسبب الفيضانات لأن معظم بروتوكولات التوجيه الحالية تستخدم حركة مرور أحادية الإرسال. في هذا البحث، تم تحديد بروتوكول التوجيه المخصص وتوجيه حالة الارتباط المحسن (OLSR) وتحسينه بحيث يمكنه تلبية معايير الكفاءة من حيث الاستقرار وقابلية التوسع. يتم تحسين OLSRمن خلال ثلاث مراحل. المرحلة الأولى هي توسيع الإرسال المتعدد حيث يتم توسيع حركة الإرسال المتعدد إلى بروتوكول توجيه OLSR في شبكات WCN من أجل تقليل الحمل الناتج عن الفيضانات حيث يستخدم OLSR حركة مرور أحادية الإرسال. المرحلة الثانية هي اختيار الترحيل متعدد النقاط (MPR) بناءً على عملية هرمية تحليلية (AHP). يتم أخذ معايير متعددة في الاعتبار في وقت واحد في طريقة اتخاذ القرار متعدد المعايير (MCDM) لإنشاء عملية صنع قرار مرنة. يمكن ترجيح المقاييس المتعددة وفقًا لـ MCDM: AHP. تنشئ كل عقدة مجموعة MPR بناءً على تكلفة واحدة محددة باستخدام المقاييس المحددة. المرحلة الثالثة هي مقياس مركب لاختيار المسار الأمثل. يُقترح القياس المركب باستخدام معلمات متعددة لضمان معرفة جيدة بحالة الروابط التي يمكن أن تضمن اختيار الروابط الأكثر استقرارًا في الشبكة. الهدف من المقياس الجديد المقترح هو جعل العثور على أفضل المسارات أسهل للغاية باستخدام الهيكل الديناميكي لشبكات WCN. بالإضافة إلى ذلك، تهدف إلى تجنب استخدام مقياس عدد القفزات المستخدم في بروتوكول OLSR وغير مناسب لخصائص الارتباط الديناميكي لشبكات WCN. تم تطوير بروتوكول التوجيه الجديد المقترح باستخدام لغة برمجة C ++ ضمن محاكي NS-2. يتم قياس أداء بروتوكول التوجيه المقترح باستخدام أربعة مقاييس للأداء: متوسط التأخير من طرف إلى طرف، والتحكم في الشبكة (NCO)، ونسبة تسليم الحزمة (PDR)، واستهلاك الطاقة من حيث كثافة الشبكة وحمل المرور مع التنقل المتنوع سرعات. يتفوق بروتوكول التوجيه المقترح على بروتوكول OLSR من حيث متوسط التأخير من طرف إلى طرف و NCO و PDR بنسبة 5٪ و 11٪ و 12٪ على التوالي. بينما، فإن استهلاك الطاقة لبروتوكول التوجيه المقترح مشابه تقريبًا لبروتوكول OLSR القياسي.

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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It is my utmost pleasure to dedicate this thesis to my beloved parents.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchical Process
AODV	Ad Hoc On-demand Distance Vector
AoI	Age of Information
AOLSR	Airborne Optimized Link State Routing
Aps	Access Points
AWMN	Athens Wireless Metropolitan Network
B4RN	Broadband for the Rural North
BGP	Border Gateway Protocol
BMX6	BatMan-eXperimental version 6
BW-OLSR	BandWidth Optimized Link State Routing
CBR	Constant Bit Rate
Cc	Closeness centrality
CPU	Central Processing Unit
DAT	Directional AirTime
DIY	Do-It-Yourself
DSP	Dynamic Shortest Path
D-WCETT	Dynamic- Weighted Cumulative Expected Transmission Time
EFW	Expected ForWarding counter
ELARM	Energy-Load Aware Routing Metric
EM-OLSR	Energy and Mobility Optimized Link State Routing
ETX	Expected Transmission Count
FFDN	Federation French Data Network
FIFO	First In First Out
FON	Fiber Optic Network
GB	GigaByte
GHz	GigaHertz

HWMP	Hybrid Wireless Mesh routing Protocol
IANA	Internet Assigned Numbers Authority
IFQ	InterFace Queue
IHU	I Heard You
IP	Internet Protocol
IPv6	Internet Protocol version 6
ISPs	Internet Service Providers
JEFW	Joint Expected Forwarding Counter
LCR	Link Change Rate
L-OLSR	Localization technology Optimized Link State Routing
MAC	Media Access Control
MACT	Multicast ACTivation
MANETs	Mobile Ad hoc NETworks
MB	MegaByte
MBA-OLSR	Multipath Battery Aware Optimized Link State Routing
MCDM	Multi-Criteria Decision Making
MD	Minimum Delay
MEFW	Minimum Expected Forwarding Counter
MID	Multiple Interface Declaration
ML	Minimum Loss
MOLSR	Modified Optimized Link State Routing
MP-OLSR	MultiPath Optimized Link State Routing
MPR	MultiPoint Relay
NCO	Network Control Overhead
NGO	NonGovernmental Organization
NHDP	NeighborHood Discovery Protocol
NPC	Node Performing the Computation
NS-2	Network Simulator V2.35
NS-3	Network Simulator Version 3

NWNP	Nepal Wireless Networking Project
OGM	OriGinator Messages
OLSR	Optimized Link State Routing
OPNET	OPtimized Network Engineering Tools
PDR	Packet Delivery Ratio
PPO	Packet Priority-Oriented
PP-QoS	PPO-Quality of Service
QoS	Quality of Service
RFC	Request For Comment
RP	RePort
RREP	Route REPly
RREQ	Route REQuest
RSSI	Receive Signal Strength Indicator
Rxcost	Link Cost
SDN	Software Defined Networking
TakNet	Tanzania Knowledge Network
TB	Terabyte
TC	Topology Control
TCP/IP	Transmission Control Protocol/Internet Protocol
TLVs	Type Length Values
TTL	Time To Live
UDP	User Datagram Protocol
VoIP	Voice over Internet Protocol
WCETT	Weighted Cumulative Expected Transmission Time
WCNs	Wireless Community Networks
WiFi	Wireless Fidelity
WMN	Wireless Mesh Network
W-OLSR	Weighted Optimized Link State Routing

CHAPTER ONE

INTRODUCTION

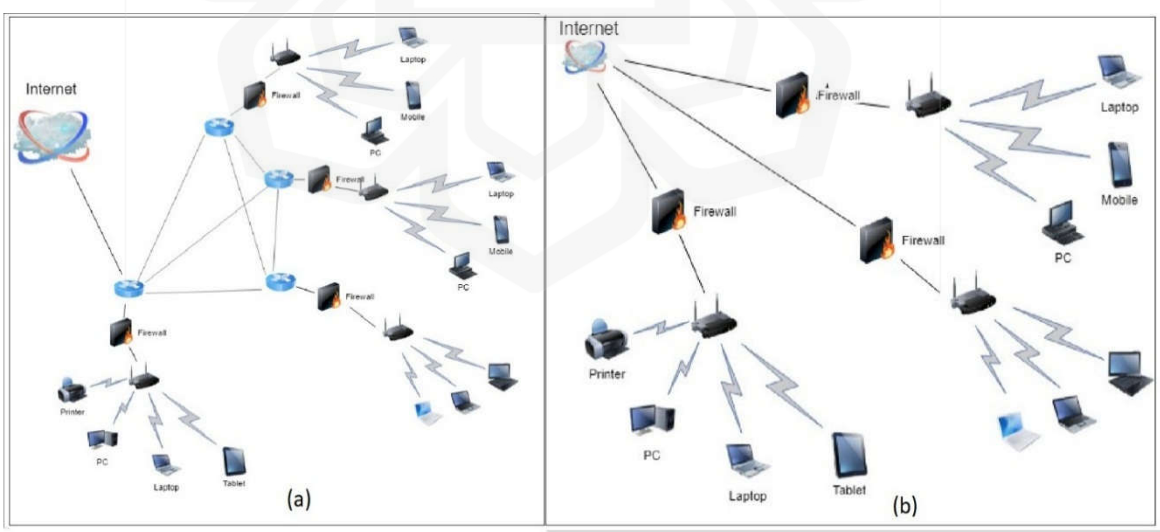
1.1 RESEARCH BACKGROUND

Wireless Community Networks (WCNs) are considered as another form for ownership of Internet Protocol (IP) networks, where community members manage and own every piece of equipment in a decentralized way, and routing for traffic is done in a cooperative manner. These networks are determined to beat on the gap between Internet access and the weak coverage of Internet Service Providers (ISPs) in rural areas. WCNs have been widely spreading in many countries as time went on; access to the Internet becomes more necessary for individual and collective participation in society (Neumann et al., 2015).

From technical perspective, WCNs are considered large-scale networks as it consists of numerous nodes, links, content, and services. In addition, they are distributed and decentralized systems. There is a mix of wired and wireless connectivity, diverse routing mechanisms, and a wide range of applications and services in these decentralized networks. As a consequence of this, they have a very active and diversified nature. These networks are governed by an open peering agreement that removes any obstacles for joining the network (Picopeer.net, 2018). The network's governance, ownership, and knowledge are all open. Therefore, the decentralization, self-management, and self-ownership are characteristics of WCNs. Furthermore, WCNs are considered as self-growing networks especially in links, capacity, and services provided (Om, 2021). Due to the Do-It-Yourself (DIY) approach in WCNs, there is a need for a robust routing protocol to deal with topology changes and frequent breakdowns (Braem et al., 2015). Furthermore, the internal structure of WCNs obligates the routing to be highly scalable and distributed. Moreover, the routing must allow for continuous connections and reconfiguration for new, broken or congested links by using self-adaptive algorithms.

1.1.1 Classification of WCNs Design Schemes

There are two approaches to constructing a WCN. The first approach is called Wireless mesh-based WCN which is based on cautiously constructing a multi-hop network with nodes in specific locations and directional antennas in order to design high-quality radio links. This type of network structure results in fine connectivity and high throughput. However, it requires well-coordinated groups with technical expertise. This scheme is used often in WCNs that have arisen from private initiatives. Figure 1.1 (a) shows nodes with multi-interface that build a wireless mesh, where some other nodes work as gateways to the public Internet. These gateways can be reached through the wireless backbone (Navarro et al., 2016). The second approach is Hotspot-based WCNs. Figure 1.1 (b) shows that clients directly connect to individuals operating “hot-spot” Access Points (APs). This type of network structure doesn’t provide high coverage such as multi-hop networks. However, no much coordination to deploy and operate is required. This network scheme is usually intended for roaming users who use wireless hotspots to connect to the Internet. This structure is often used by Municipality-initiated WCNs (Navarro et al., 2016).



(a) A wireless mesh architecture (b) hotspot-based architecture

Figure 1.1 WCN design approaches (Navarro et al., 2016)

1.1.2 Architecture and Technologies

1. **Node Types**: There are two kinds of nodes that form the WCN (Navarro et al., 2016). First, the backbone nodes are those who construct the backhaul of the network. They run routing software and often have more than two network interfaces. They function as APs. Moreover, they operate omnidirectional antennas. Second, the client nodes which is the "leaves" of the network. These client nodes can be connected to those APs and to benefit from the network's services.
2. **Links**: The network backbone is relying on directional point-to-point links. Links for long distances that assisted by directional antennas are being set up by using IEEE802.11, while it is designed for local communication as a broadcast protocol. Initially, IEEE802.11b is the decided protocol for the backbone; however, it is replaced with IEEE802.11a in order to minimize interference and contention from APs and clients. APs still use IEEE802.11b.
3. **Services and applications**: WCNs can provide many services in addition to the Internet access. The most common services are community-wide Voice over Internet protocol (VoIP) and file sharing.

1.1.3 Representative WCN Examples

In recent years, WCNs have sparked a great deal of excitement due to the promise that they hold of providing low-cost and participatory connectivity solutions for citizens. Such solutions can be especially helpful in developing nations or in secluded areas that have been neglected by public institutions or private network providers. Concurrently, there has been a rise in both the use of wireless devices as well as interest in them as a result of the development of low-cost laptops and mobile devices that come pre-equipped with wireless fidelity (WiFi) access. As a logical progression, a multitude of non-profit projects have emerged in recent years to construct WCNs in order to provide internet access (Neumann, 2017). These WCNs are intended to serve as an alternative to traditional internet service providers (ISPs).

- Freifunk in Germany (freifunk).
- Athens wireless metropolitan network (AWMN) in Greece (AWMN).
- FunkFeuer in Austria (Funkfeuer).
- Guifi.net in Spain (guifi.net).
- Ninux org in Italy (Ninux).
- Nepal wireless networking project (NWNP) in Nepal (NWNP).
- Broadband for the rural north (B4RN) in England (B4RN).
- Federation French data network (FFDN) in France (FFDN).

1.1.4 Routing Protocols

Since routing decides the route that each packet has to follow to reach its destination, it is a crucial function in WCNs. It is insistent that a routing protocol for a community network must be capable of adapting to network changes continuously (Neumann, 2017). Where, any WCN organically grows, with several hops and community members are doing the network administration in a decentralized manner.

As mentioned earlier, the fact that WCNs are made up of a number of layer 2 devices means that they form a network of nodes. The connectivity between the various nodes is not guaranteed and the stability of links may change over time. Therefore, some WCNs use mesh routing protocols for Mobile Ad hoc NETworks (MANETs), while others use the traditional routing protocols. In certain networks, numerous routing protocols are used at the same time. It is possible, for example, that they employ a mesh network within each island and use traditional routing protocols to link them altogether.

1.2 PROBLEM STATEMENT

Since routing decides the route that each packet has to follow to reach its destination, it is a crucial function in WCNs. It is insistent that a routing protocol for a community network must be capable of adapting to network changes continuously (Neumann, 2017). Where, any WCN organically grows, with several hops and community members are doing the network administration in a decentralized manner. Routing in WCNs have investigated to propose a more stable and scalable routing technique.

Links of WCNs always have heterogeneous characteristics. Therefore, link quality is one of the main factors that affect routing stability. Current routing protocols such as optimized link state routing (OLSR) depend on the shortest path as the main metric to control the routing of packets (Barz et al., 2015). Shortest paths are not always the optimal paths as it can suffer from high packet loss and instability (Abdel-Nasser, Mahmoud, Omer, Lehtonen, & Puig, 2020). Therefore, beside the shortest path metric, routing techniques should also consider the quality of the paths (links) during the communication lifetime (Saldana et al., 2016).

In addition, the scalability is more challenging in the presence of both large number of nodes and mobility. As current routing protocols are inefficient when faced with the dynamic changes and poor links that occur in real-life and self-managed deployments. This results in too much overhead during communications due to flooding as most of the current routing protocols uses unicast traffic.

Many researches and extensions for OLSR routing protocol have been proposed to solve the problems of stability and scalability. However, to my knowledge, none of the current researches presents a complete, integrated, and coherent prototype to solve all the problems of WCNs. According to all previously mentioned reasons, an enhanced routing protocol is proposed to achieve optimal routing performance. This protocol is designed to consider the heterogeneous characteristics of WCNs to produce more efficient routing technique in terms of stability and scalability.

1.3 RESEARCH QUESTIONS

This section describes the research questions to be answered in this research work. The research questions are as follows:

1. What are the main factors which affect the performance of common routing protocols in WCNs?
2. How to enhance the current routing protocols in terms of stability and scalability?
3. How to evaluate the performance of the enhanced routing protocol?

1.4 RESEARCH OBJECTIVES

The main aim of this research work is to propose an enhanced routing protocol for WCNs that considers the heterogeneous characteristics of WCNs in order to produce more stable and scalable networks. Therefore, to achieve this aim, the following objectives are set

1. To investigate the various routing protocols that used for WCNs to identify the main factors that affect the performance of these protocols.
2. To design an enhanced routing protocol for WCNs in terms of stability and scalability.
3. To implement and test the proposed routing protocol using NS-2 simulator.
4. To evaluate and analyze the proposed routing protocol with the OLSR routing protocol.

1.5 RESEARCH SIGNIFICANCE

The Internet has made the world a little community in recent years, linking millions of people, organizations, and equipment for different purposes. Sometimes WCNs become a popular solution for people who can't access the Internet services directly from ISPs (M

Kadhim & A Oglah, 2021). WCNs are large, heterogeneous, dynamic, and decentralized networks. Such complex characteristics raise different challenges, such as the effect of wireless communications on the performance of networks and routing protocols (Abdel-Nasser et al., 2020). Therefore, a fast communication over WCNs should be provided. This is achieved by considering the changes occur during the communication. Accordingly, providing a routing technique that takes into account the links stability during routing can help to provide fast communication. This is a main requirement of large scale of real time applications. Furthermore, it should be guaranteed that WCNs users are able to access the network easily regardless of the network size. Therefore, the proposed lightweight scalable routing protocol can help to minimize the communication cost and optimize the usage of the available bandwidth in this imperative type of networks.

This research work contributes to solve the mentioned drawbacks that critically affect the performance of the network. It also helps to provide better internet connection to fit the high demand on mobile Internet-connected devices used in many areas such as; health care, emergency systems, video conferencing, education, military, and business.

1.6 RESEARCH SCOPE

This thesis aims to develop an enhanced routing protocol which guarantee the efficient performance of the network in terms of stability and scalability. This research focuses on WCNs. Among the five layers of Transmission Control Protocol/Internet Protocol (TCP/IP) model, this work focuses on layer 3 (network layer) only. In this thesis, security is not taken into consideration. The implementation and evaluation is based on simulation using Network Simulator v2.35 (NS-2).

1.7 THESIS ORGANIZATION

This thesis is organized as follows:

Chapter 1 is an introductory chapter that discusses the problem statement, the research questions, the objectives of the research, the research significance, the scope of the research, and the organization of the thesis.

Chapter 2 consists of the literature review that investigates the current routing protocols which are commonly used for WCNs. Furthermore, the focus is given on highlighting the strengths and limitations of these routing protocols aiming at identifying and determining the main factors that affect the performance of several routing protocols in WCNs.

Chapter 3 consists of the research methodology of the thesis in order to achieve the objectives of the research. It explains and discusses how this research work is carried out. Moreover, the evaluation metrics are illustrated to measure the degree of improvements between the original OLSR routing protocol and the proposed routing protocol. Finally, the core functionality of OLSR protocol, including node addressing, various information repositories, control traffic, flooding mechanism of MPR, multiple interfaces, neighbor discovery, link state declaration, route calculation, and an overview of OLSR information repositories relations are presented.

Chapter 4 proposes an enhanced routing protocol for WCNs that meets the standards of efficiency in terms of stability and scalability. It shows the components of the proposed routing protocol according to multicasting expansion, MPR selection based on Analytical Hierarchical Process, and composite metric for optimal route selection respectively.

Chapter 5 presents the main findings of this research work and forms the essence of this thesis. The results of the simulation scenarios are conducted to explore the reliability and efficiency of the proposed routing protocol in comparison with OLSR routing protocol.

Also, the chapter discusses the simulation environment and parameter settings to guarantee a fair direct comparison of all simulation scenarios.

Chapter 6 provides a conclusion and summarizes the main findings of this thesis. An outlook regarding promising directions for future research is also outlined in this chapter.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Modern information and communication technologies have the potential to significantly enhance the lifestyle of people in sparsely populated regions. This is accomplished through linking them to the international community, enhancing their access to community resources, and promoting their participation in policy decisions. Unfortunately, a significant number of rural regions don't have enough access to any kind of electronic data, which puts residents, especially those living in poverty, at risk of lagging further behind the large urban world. In addition, the installation of communication networks takes significant financial expenditures. As a result, major telecommunications companies have chosen to focus their efforts on urban regions, because these regions have larger paying capacity and higher density of population. Therefore, it is vital to develop technologies that allow rural communities to build up low-cost communication networks in order to achieve the aim of linking everyone to the Internet (M Kadhim & A Oglah, 2021).

The use of a wireless network in rural areas extends well beyond just accessing the Internet. A network of this kind may be made available by a local government on a non-profit basis for the purposes of education or for the collection of information such as comments on civic services. Therefore, WCNs are used in many applications such as but not limited to media libraries, e-governance, telecommunication, telemedicine, community webs and radio broadcasting, and support network for NonGovernmental Organization (NGO) (Abdel-Nasser et al., 2020).

WCN is a wireless mesh network that is developed using a bottom-up methodology. In a WCN, a particular small number of users establishes an alternate, self-managed, community-based networking infrastructure for themselves and their peers. WCN is often utilized for two primary purposes: facilitating inter-user communications (such as messaging, conversing, and sharing) and providing Internet connection where it isn't already accessible. In today's world, there is a variety of inexpensive equipment available on the market that may be used to establish wireless connections across a range of up to tens of kilometers. It is possible to share a small number of Internet connections over a relatively wide region by using a strategy known as "multi-hop" (Abdel-Nasser et al., 2020).

The use of WCNs have an organic growth because of the existence of a large number of nodes that can use readily manual (decentralized) control. In this research, we focus on the routing layer of WCNs. Nodes of these networks can benefit from the well-established MANETs routing protocols. The reason is that these protocols are able to provide self-adaptation to the network changes and good determination of the routing path for messages end-to-end delivery throughout the network (M Kadhim & A Oglah, 2021). For WCNs, there have been several research studies in the area of routing protocols proposals and performance evaluations, which are listed and discussed below. The table which summarizes the reviewed papers will be mentioned at the end of the literature review.

This chapter undertakes to investigate the current routing protocols which are commonly used for WCNs. Furthermore, the focus is given on highlighting the strengths and limitations of these protocols aiming at determining their effectiveness and quality in good determination of the routing path for messages end-to-end delivery throughout the network. Some recommendations and future work directions have been drawn for helping researchers to explore the unsolved problems related to WCNs routing protocols.

2.2 WCNS AROUND THE WORLD

In recent years, WCNs have sparked a great deal of excitement due to the promise that they hold of providing low-cost and participatory connectivity solutions for citizens. Such solutions can be especially helpful in developing nations or in secluded areas that have been neglected by public institutions or private network providers. Concurrently, there has been a rise in both the use of wireless devices as well as interest in them as a result of the development of low-cost laptops and mobile devices that come pre-equipped with Wireless Fidelity (WiFi) access. As a logical progression, a multitude of non-profit projects have emerged in recent years to construct WCNs in order to provide Internet access. These WCNs are intended to serve as an alternative to traditional ISPs.

Hundreds of WCNs are active all over the world, in both rural and urban areas, as well as in rich and poor regions. WCNs are present in practically everywhere such as in Fiber Optic Network (FON), which works in worldwide. In the north of America, there are many WCNs such as (SeattleWireless), (NYCwireless), (Philadelphia), (MadMesh), (Afanasyev, Chen, Voelker, & Snoeren, 2010), (Rhizomatica), and (LaCurts & Balakrishnan, 2010). In Europe, there are many WCNs that reach thousands of nodes such as (Djurslands.net), (AWMN), (freifunk), (Czfree.net), (guifi.net), (B4RN), and (FFDN). Additionally, there are many other European WCNs, including (Free2Air), (Consume), (Leiden), (Funkfeuer), and (Ninux). In Africa, (Zenzeleni.net), (Nguyen, 2015), and (Geerdts, Gillwald, & Enrico Calandro, 2016) are an example of these networks. While, (NWNP) and Tanzania Knowledge Network (TakNet) are famous WCNs in Asia. A summary of the world's most notable WCNs are concluded in Table 2.1.

Table 2.1 WCNs around the world

WCN Name	Location	Found	Size	Environment	Internet	Network Technology
Free2Air	London, England	1999	--	Urban	yes	wired, WiFi
Consume	Clink St., London, England	2000	> 200 nodes	Urban	yes	WiFi
SeattleWireless	Seattle, Washington, USA	2000	> 80 nodes	Urban	yes	WiFi, VoIP
Djurslands.net	Djursland, Denmark	2000	> 27000 households	Rural	yes	WiFi
NYCwireless	New York, USA	2001	> 145 nodes	Urban	yes	WiFi
AWMN	Greece	2002	> 2473 nodes	Urban, Rural	yes	WiFi
Freifunk	Germany	2002	> 41000 nodes	Urban, Rural	yes	fiber, WiFi
Wireless Leiden	Leiden, Netherlands	2002	> 300 nodes	Urban, Rural	yes	WiFi
Czfree.net	Prague, Czech Republic	2002	> 2000 transmitters	Urban, Rural	yes	WiFi
Funkfeuer	Austria	2003	> 300 nodes	Urban, Rural	yes	wireless

Ninux	Italy	2003	> 352 active nodes	Urban, Rural	no	WiFi
NWNP	Nepal	2003	> 150 villages	Rural	yes	WiFi
Guifi.net	Catalonia, Spain	2004	> 37534 nodes	Urban, Rural	yes	fiber, WiFi
FON	Worldwide	2006	> 23 million hotspots	Urban, Rural	yes	WiFi
Wireless Philadelphia	Philadelphia, USA	2007	> 350 kilometer^2	Urban	yes	WiFi
MadMesh	Madison, USA	2007	> 250 nodes	Urban	yes	WiFi
Google WiFi	California, USA	2008	> 500 nodes	Urban	yes	WiFi
Rhizomatica	Oaxaca, Mexico	2009	> 700 nodes	Rural	yes	wireless
B4RN	Norfolk & Suffolk, England	2011	> 7000 homes	Rural	yes	fiber
FFDN	France	2011	28 WCNs	Urban, Rural	yes	WiFi, fiber
Cisco Meraki	California, USA	2012	> 1407 nodes	Urban,Indoor	no	wireless
TakNET	Tak province, Thailand	2013	> 2000 homes	Rural	yes	WiFi
Zenzeleni.net	Eastern Cape, South Africa	2013	> 60 kilometer^2	Rural	yes	WiFi, VoIP public phone
Mesh Bukavu	Bukavu, Congo	2015	> 15 nodes	Urban	yes	WiFi
Home of Compassion	Cape Town, South Africa	2015	> 20 active Aps	Urban	yes	WiFi

2.3 ROUTING PROTOCOLS COMMONLY USED IN WCNS

Since routing decides the route that each packet has to follow in order to reach its destination, it is a crucial function in WCNs. It is insistent that a community network's routing protocol must be capable of adapting to network changes continuously (Neumann, 2017). Where, any WCN organically grows, with several hops and community members are doing the network administration in a decentralized manner.

As mentioned earlier, WCNs are a mesh of nodes as they are constituted of probably various layer 2 devices. Since the connectivity between the various nodes is not assured and the stability of links may vary over time, several WCNs employ mesh routing protocols that are previously used for MANETs to overcome this. Modified versions of OLSR protocol are used by a large number of WCNs (Abdel-Nasser et al., 2020; Benjbara, Habbani, & Mouchfiq, 2021). It has been extended with the Expected Transmission Count metric (ETX) as well as some other features to be used in WCNs. Some WCNs become using the OLSRv2 which is the second version of OLSR protocol (Barz et al., 2015). Furthermore, another routing protocol that is used for WCNs is Better Approach To Mobile Ad hoc Networking (B.A.T.M.A.N.) advanced (Fehnker, Chaudhary, & Mehta, 2018). It is a routing protocol for the second layer, so it creates a bridged network. Moreover, it provides error-free roaming of clients between wireless nodes. The Internet Protocol version 6 (IPv6) is the basis for the BatMan-eXperimental version 6 (BMX6) protocol. Moreover, BMX6 attempts to develop the social structure of WCNs (L. Liu, Liu, Qian, & Zhu, 2018). Babel is an additional distance-vector routing protocol used for WCNs that avoids loops and documented in Request For Comment (RFC) 6126 (Carvalho, Westphall, & Machado, 2022).

In this chapter, a taxonomy of routing protocols used for WCNs has been designed. The WCNs routing protocols have been classified into five classes, namely: Babel, BMX6, OLSR, OLSRv2, and other routing protocols applied on WCNs as summarized in Figure 2.1. Firstly, a review is made of the basic problem that the researchers identify in their research work. Secondly, the research methodology that these researchers use to solve problems is presented. Finally, the strengths and limitations of each method are discussed to determine its effectiveness and quality in WCNs. Therefore, the above-mentioned routing protocols are explained in the following sections as well as the used mechanisms including the neighbor discovery and topology dissemination. Table 2.2 summarizes the differences between Babel, BMX6, and OLSR in terms of reducing overhead, minimizing convergence time, dissemination mechanism, and sending data. While, Table 2.3 summarizes the comparison of OLSR and OLSRv2 in terms of flexibility, packet format, neighborhood discovery, extensions for security, and selection of shortest routes. Furthermore, the comparison between MultiPoint Relay (MPR) selection approaches based on the improved OLSR routing protocols is summarized in Table 2.4. Also, some major techniques with a discussion of strengths and limitations are described in Table 2.5.

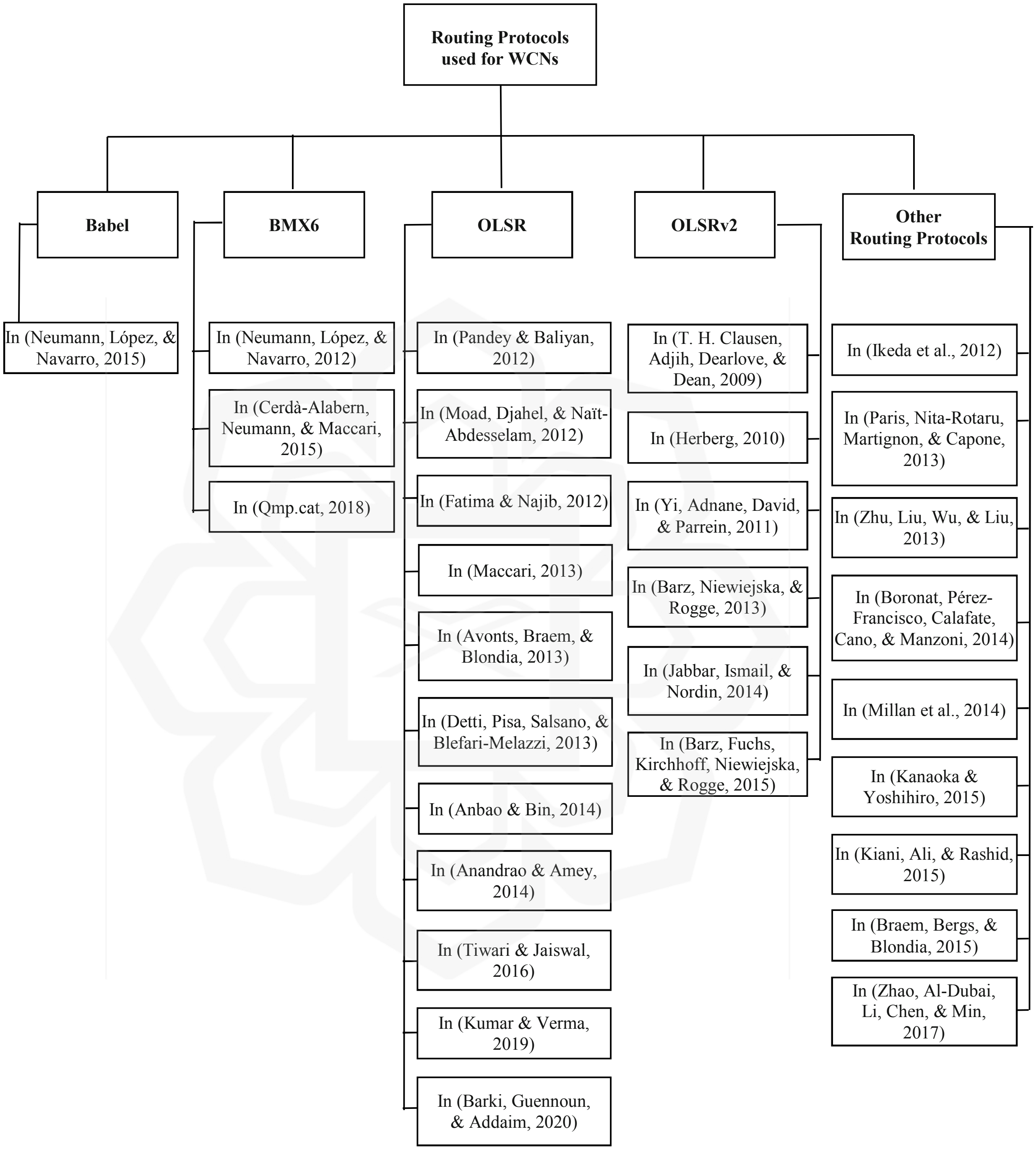


Figure 2.1 A taxonomy of routing protocols used for WCNs

2.4 BABEL ROUTING PROTOCOL

2.4.1 Protocol Overview

Babel is a kind of proactive and distance vector routing protocol. Furthermore, it is based on the Bellman-Ford protocol. Moreover, it focuses on limiting routing pathologies like black holes or routing loops. In order to achieve its concern, it does two functions. Firstly, it uses a good feasibility condition to filter the received routing updates and determine which to consider seconds (von Ehren, Andre, & Wiedner, 2021). A feasible routing update for a route should have a smaller metric than any other routing updates for this route. Secondly, the destination node generates a sequence number to be added to a routing update. This sequence number advertises and decides the routing changes that can be compared to the metric. The similar sequence numbers has same information (Carvalho et al., 2022).

- **Neighborhood discovery**

  Hello message and I Heard You (IHU) message are two types of messages that are exchanged by Babel nodes for discovering their neighborhood seconds (von Ehren et al., 2021). Hello message is a multicast message which assists nodes for neighborhood discovery as well as rating the link cost (rxcost). Its sequence number is increasing internally with every Hello message. Babel nodes exchange Hello messages every 4 seconds. The main purpose of the IHU messages is sharing the rxcost with the neighborhood as well as identifying the bi-directionality of a link. IHU messages are theoretically unicast; however, they are transmitted to a multicast address in order to combine multiple messages in one packet. They are sent by default every 12 seconds (von Ehren et al., 2021). Figure 2.2 shows a typical neighborhood discovery for Babel routing protocol.

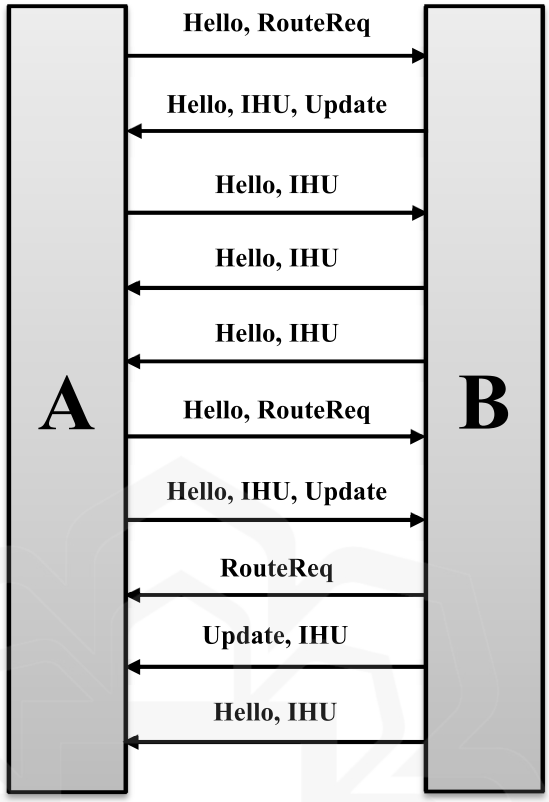


Figure 2.2 A typical neighborhood discovery for Babel routing protocol

- **Topology distribution**

  Babel nodes exchange periodic update messages, so that they can discover their indirect neighbors seconds (von Ehren et al., 2021). The route update message carries a routing table that includes a route and its own related cost. Furthermore, Babel forces nodes to perform unscheduled route updates if any significant topology change happened like a considerable metric change or a route retraction. On the other hand, when an update is received by any node, the node checks the feasibility of it. If the update is feasible, then the node calculates the cumulative metric by merging the update metric with the cost of the link that transfers the update seconds (von Ehren et al., 2021). Figure 2.3 shows Babel topology distribution mechanism.

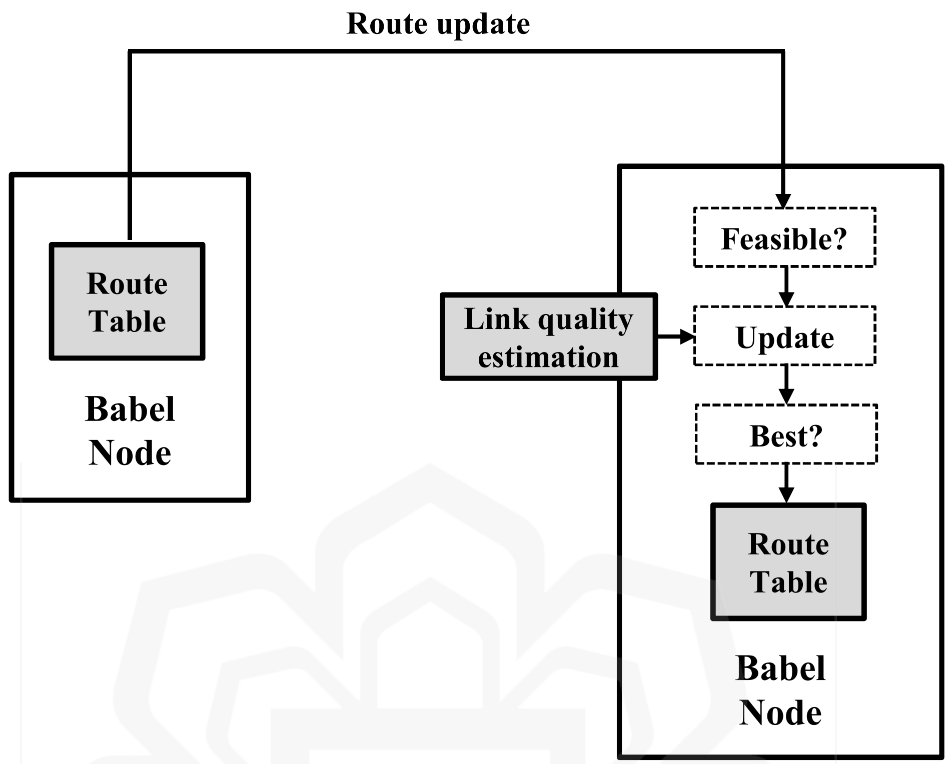


Figure 2.3 Babel topology distribution mechanism

2.4.2 Related Works of Babel

Neumann et al. (Neumann et al., 2015) study the performance of three commonly used proactive routing protocols in WCNs which are BMX6, OLSR and Babel. The study aims to identify which one is better in which condition of the network. The scalability, the performance, and the stability of these protocols are measured through simulation. In low density networks with low stable links, Babel is found the most lightweight protocol with the least memory, Central Processing Unit (CPU), and control-traffic requirements. However, in dense deployments with frequent link changes, OLSR and BMX6 outperform Babel in terms of overhead, stability, and even self-healing capabilities. This is because of their strictly constant rate for sending topology and routing update messages.

2.5 BMX6 ROUTING PROTOCOL

2.5.1 Protocol Overview

The main goal of BMX6 is attaining low routing overhead as well as achieving high reactivity to network changes (Singh, Sharma, Shukla, & Jha, 2021). Therefore, it applies between neighbors stateful-compressed communication for reducing the periodic messages size thus attaining low routing overhead. Stateful communication is done using compact (16 bit) local identifiers. Moreover, the context-specific propagation of local information vs global information and static information vs dynamic information attains high reactivity to network changes (Singh et al., 2021).

On the classification for information, the static information is that implausible to change such as addresses and other details of a node. Those attributes are collected altogether into the node's description. On the other side, link and path costs estimations are dynamic information. Moreover, global versus local separation identifies what information kept locally (such as local identifiers and link costs) and what information is flooded globally throughout the network (such as path costs and node descriptions) (Singh et al., 2021).

- **Neighborhood discovery**

  The neighbor discovery is done in the same manner as Babel as shown in Figure 2.2. Where the Hello messages are sent to a multicast address each 0.5 seconds by default. Furthermore, there is a sequence number that is generated with each new Hello message. On the other hand, RePort (RP) messages are also sent each 0.5 seconds and record the number of Hello messages sent and received by a node, so that a node is able to compute and the cost of transmission and reception for a link (Singh et al., 2021).

- **Topology distribution**

In BMX6, spreading routs through the network is done by OriGinator Messages (OGM) that are flooded over the network by each node (Singh et al., 2021). Each node sends OGM every 5 seconds and then the node which receives it forwards it again. The OGM includes a local identifier of the sender for the originator node. It also includes a sequence number as well as a metric for the cost of reaching the sender to the originator. This metric is calculated by adding the metric included in the received OGM to the cost of the sender link. Then, the node compares the calculated cost with the cost via other neighbors. If the calculated cost is less than the cost of another neighbor, then the node updates the OGM and re-multicasts it. On the other hand, the static information is shared only if the local identifier refers to an unknown node (Singh et al., 2021). Figure 2.4 shows BMX6 topology distribution mechanism.

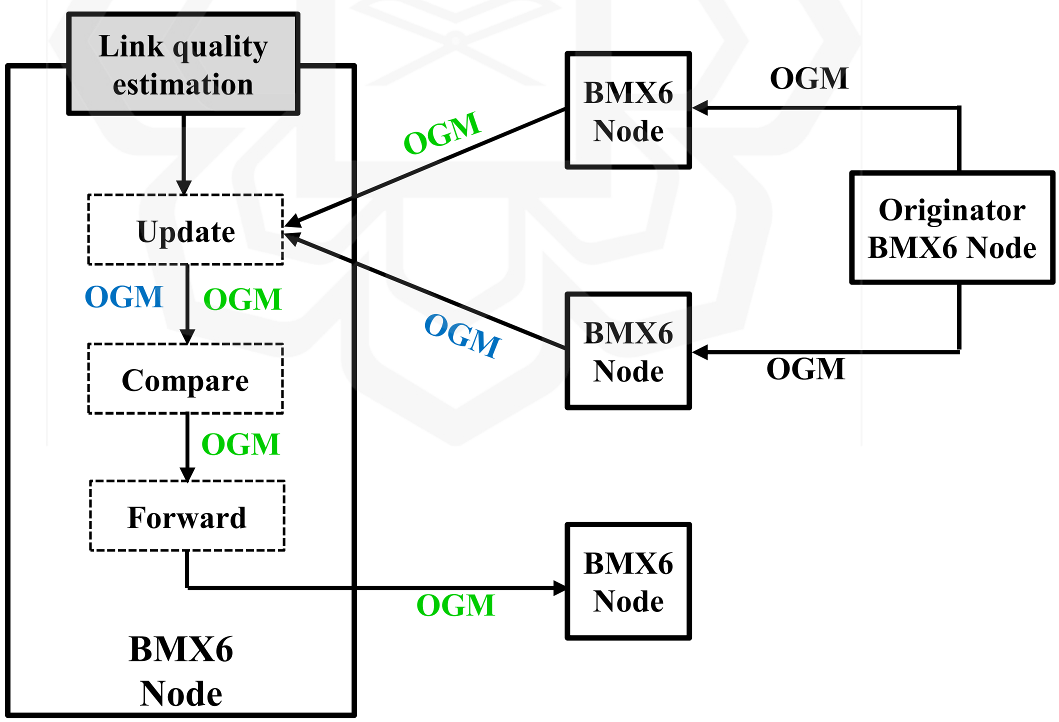


Figure 2.4 BMX6 topology distribution mechanism

2.5.2 Related Works of BMX6

Neumann et al. (Neumann et al., 2012) study and analyze the scalability that is achieved in the WCNs routing using the BMX6. Convergence time and overhead are measured for both BMX6 and OLSR, while increasing the nodes and the network diameter. Results show that BMX6 performance is much better than OLSR with the addition of a new node. Cerdà-Alabern et al. (Cerdà-Alabern et al., 2015) perform experiments on the QMPSU network (Qmp.cat, 2018) to analyze the performance of the routing protocol. Using a well-known conflict-graph model, the expected capacity estimation on some multi-hop paths is derived. These values are compared with the throughput measured experimentally on the same paths. The capability of the BMX6 routing protocol to choose the optimal path is also tested. They find that the paths chosen by BMX6 are best one most of the time. Nevertheless, the available capacity is mostly overestimated by the conflict-graph model, even by providing accurate information on the core network graph.

2.6 OLSR ROUTING PROTOCOL

2.6.1 Protocol Overview

The optimization part of OLSR comes in the flooding mechanism (Nabou, Laanaoui, & Ouzzif, 2021). The main technique that OLSR protocol depends on it is MPRs. Where, broadcast messages are forwarded by only some selected nodes which are called MPRs during the flooding process. Therefore, by using this technique, the traffic overhead is reduced when compared to the original flooding technique, as the broadcast messages are forwarded by all nodes (Nabou et al., 2021)..

- **Neighborhood discovery**

  OLSR performs neighborhood detection by sending periodical Hello messages. The Hello message includes a sequence number that increases internally as well as the links known to the neighbors of the sender and the quality of links. The Hello messages are sent periodically every two seconds (Nabou et al., 2021). Table 2.2 summarizes the differences between Babel, BMX6, and OLSR. Figure 2.5 shows a typical neighborhood discovery for OLSR routing protocol.

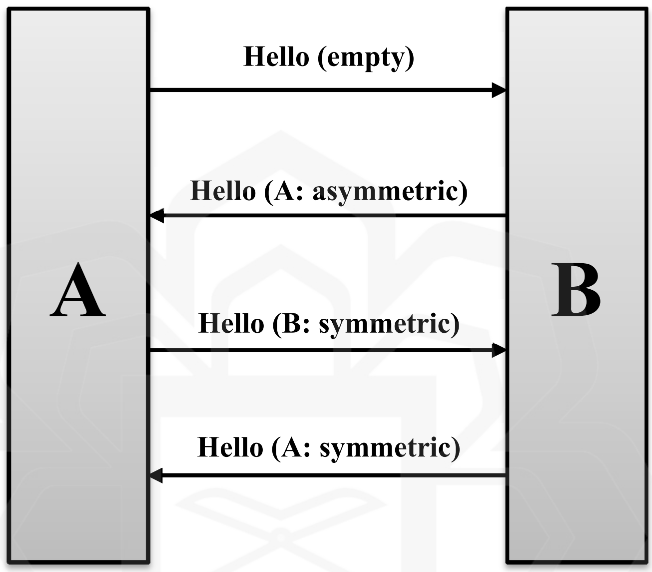


Figure 2.5 A typical neighborhood discovery for OLSR routing protocol

- **Topology distribution**

  OLSR works as other link state routing protocols, where Topology Control (TC) messages are flooded in the network in order to disseminate the partial view of the entire topology to every node in the network. every node in the network generates the TC messages periodically and forward them in the network without any changes. The TC message defines the nodes in the path from the source of the message and the quality of links involved in the path (Nabou et al., 2021). Figure 2.6 shows OLSR topology distribution mechanism.

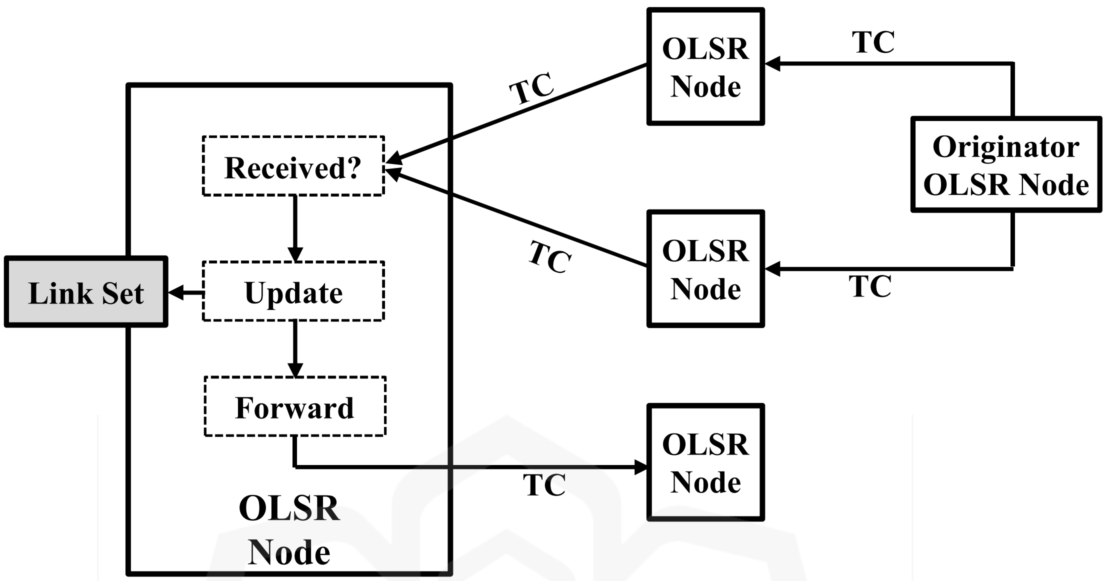


Figure 2.6 OLSR topology distribution mechanism

2.6.2 Related Works of OLSR

Maccari and Leonardo (Maccari, 2013) perform an analysis of the Ninux network to study and illustrate the impact of the routing metrics and the centrality metrics. The ETX metric, the shortest path betweenness centrality, and the Closeness centrality (Cc) are tested on this network which used OLSR as a routing protocol. The analysis shows that Cc metric can be successfully merged with OLSR. Dropping ETX metric allows reintroducing the multipoint relays to save resources. However, without using ETX, bad links are chosen until the moment when they break down. Avonts et al. (Avonts et al., 2013) present the results of a survey sent to different WCN organizations. They aim at showing the differences between most of these networks and indexing their common challenges. Regarding the routing, OLSR comes in the first place as the main routing protocol used by ten networks (53%). In the second place comes Border Gateway Protocol (BGP) used in three networks (16%) and in the third place is BATMAN used in two networks (11%). The remaining four networks use some different types of routing protocols. Detti et al. (Detti et al., 2013) propose to mix the Software Defined Networking (SDN) principles with a Wireless Mesh Network (WMN) that is formed by OpenFlow switches. The data traffic routing is engineered by using the traditional OpenFlow controller.

Table 2.2 The differences between Babel, BMX6, and OLSR

	Babel	BMX6	OLSR
Reducing overhead	By retaining long intervals between periodic updates.	By compacting periodic messages as much as possible.	Updates are shared more frequently with nearby nodes than with far away nodes.
Minimizing convergence time	By sending unscheduled updates when the network changes considerably.	Very frequent exchange of messages.	The time interval between updates is kept small.
Dissemination mechanism	Complete routing table is shared locally.	Every node periodically advertises its existence.	Information concerning every link is shared using MPR technique.
Sending data	Uses history-sensitive route selection.	Each node only maintains the general direction toward the destination and relays the data to the best next-hop neighbor.	Uses hop count for routes selection process.

2.7 OLSRV2 ROUTING PROTOCOL

2.7.1 Protocol Overview

The second version of OLSR protocol is OLSRv2 that is defined in RFC7181. OLSRv2 has the same key features for OLSR such as MPRs as well as including other improvements like modularity and flexibility (Barz et al., 2015). As shown in Table 2.3, OLSRv2 differs from OLSR in several respects:

1) Firstly, regarding packet format, Hello and TC messages in OLSR have the same packet format. However, the general MANET packet format which is defined in

RFC5444 is used in OLSRv2. Furthermore, OLSRv2 uses Type Length Values (TLVs) that specified in RFC5497 as well as message jitter which is specified in RFC5148 (Barz et al., 2015).

2) Secondly, concerning neighborhood discovery, hello messages are used in OLSR to get information about neighbors. However, the NeighborHood Discovery Protocol (NHDP) (Barz et al., 2013) is used in OLSRv2 for discovering the neighbors.
3) Thirdly, about the shortest routes selection, OLSR uses hop count but OLSRv2 uses link metric. Minimum hop count is not always the best metric as it doesn't guarantee the quality of links (Barz et al., 2015).
4) Finally, regarding security, OLSRv2 has extensions for security as signatures can be attached with packet/message TLVs. However, the fixed packet/message format of OLSR brings signature problems (Barz et al., 2015).

2.7.2 Related Works of OLSRv2

Clausen et al. (T. H. Clausen et al., 2009) find that the traffic of the binary format of OLSR is less than the traffic of the flexible RFC5444 packet format of OLSRv2. Herberg and Ulrich (Herberg, 2010) aim to enhance the performance of the routing through speeding up shortest path calculation algorithm. This is achieved by decreasing the required CPU time using a Dynamic Shortest Path (DSP) calculation algorithm. Results show that DSP requires less time to calculate the shortest paths, especially for networks with high density. Barz et al. (Barz et al., 2013) evaluate the OLSRv2. In case of IPv6 only setup, the traffic of the routing process for OLSRv2 is less than OLSR for high density networks. Barz et al. (Barz et al., 2015) add a new metric called the Directional AirTime (DAT) to deal with the heterogeneity of links in WCNs. This metric is based on a proposed architecture for the node which is called hybrid node design. This design separates between the radio terminals of the node and the router terminal. The DAT value is calculated as the fraction of successfully received frames according to the value of the link speed. Results show that a more stable route selection process and improved throughput values are achieved. The new

DAT metric produces good network paths more consistently and the enhanced OLSRv2 outperforms OLSR in many situations.

Table 2.3 Comparison of OLSR and OLSRv2

	OLSR	**OLSRv2**
Flexibility	Not modular	More modular and more flexible
Packet format	Binary packet format (fixed format)	TLV packet format defined in RFC5444 (flexible format)
Neighborhood Discovery	It uses Hello messages to obtain neighborhood information	It uses the (NHDP) for neighbor discovery
extensions for security	Signatures can be attached as packet/message TLVs	fixed packet/message format causes signature problems
Selection of shortest routes	Hop count	Link metric

2.8 OTHER ROUTING PROTOCOLS APPLIED ON WCNS

Ikeda et al. (Ikeda et al., 2012) evaluate the performance of Hybrid Wireless Mesh routing Protocol (HWMP) using Network Simulator version 3 (NS-3) simulator. A basic routing protocol for WMNs is called HWMP, which is based on Ad hoc On-demand Distance Vector (AODV) and tree-based routing. This protocol is described in IEEE 802.11s. There are reactive and proactive components that work together to provide efficient and optimum path selection in mesh networks. Experiments involving the sending of multiple flows at a Constant Bit Rate (CBR) are carried out. According to the findings, real-time applications such as video streaming become more difficult when the transmission rate is increased to higher values and as the number of connections increases to 30. This causes an increase in the amount of delay and jitter.

Paris et al. (Paris et al., 2013) study the problem of selfish nodes in WCNs. Previous routing protocols cannot choose the network paths with the highest rate of delivery when there are intermediate nodes which have selfish forwarding behavior. Therefore, a cross-layer routing metric named Expected ForWarding counter (EFW), and two alternative refinements which are the Minimum EFW (MEFW) and the Joint EFW (JEFW) are proposed. These metrics helps to choice the most efficient path by considering both the Media Access Control (MAC) layer quality of wireless links and the routing-layer forwarding behavior of network nodes. According to the findings, the proposed solutions significantly boost both the throughput of the network and its level of fairness.

The double shortest path routing strategy is proposed by Zhu et al. to minimize traffic congestion (Zhu et al., 2013). This is accomplished by concurrently adopting the routing technique that takes into account the shortest path in both the inter-modules and the intra-module. When the tunable parameters are set appropriately, the proposed routing technique is significantly better than the conventional shortest path routing protocol.

Boronat et al. (Boronat et al., 2014) start comparing a variety of metrics that may be of relevance in practical WCN scenarios. Real topologies derived from a particular WCN, namely "guif.net", are used to execute routing scenarios. The routes that are produced by applying the various metrics are compared in terms of length, capacity, and the alternate paths. According to the findings, the number of routes with low bandwidth may be reduced by half, while network capacity can increase by up to 25% when using metrics based on real link bandwidth. This concludes that routing based on shortest path is not enough. The real link capacity must be also considered.

For the Funkfeuer WCN, Millan et al. (Millan et al., 2014) perform a link quality analysis and prediction. This is an important issue to be considered in routing because of the unreliability nature of the wireless medium. In order to get an accurate estimation of the link quality in the routing layer for real-world WCNs, time series analysis is performed. The results that are acquired from a number of different learning algorithms indicate that the link quality values which are calculated by time series algorithms produced accurate predictions in WCNs. It has been noticed that one of the most important factors in achieving high accuracy of predictions is the size of the training data set. The error rate tends to decrease over time, and this trend is inversely proportional to the size of the data set.

Kanaoka and Yoshihiro (Kanaoka & Yoshihiro, 2015) study the delay on the multi-channel WMNs which use dynamic metrics. A combination of the speedy local decision of forwarding channels with dynamic metrics is proposed to complement the delay drawback. In multi-radio multi-channel WMNs, the findings indicate that combining local link switching with dynamic metrics works effectively.

New routing metric named Energy-Load Aware Routing Metric (ELARM) for HWMNs is proposed by Kiani et al (Kiani et al., 2015). ELARM determines the optimal route depending on the stability of the link and the network load conditions. In addition, the energy conditions of the receiving node are used for evaluating link stability. A number of simulations are tested in order to make a direct comparison between the proposed metric and two of its most promising predecessors, namely weighted cumulative expected transmission time (WCETT) and Dynamic-WCETT (D-WCETT). Scenarios are simulated with high mobility to represent the instability of links. Results show marked improvement in the packet delivery ratio and the average network latency with a slight increase in routing overhead.

Braem et al. (Braem et al., 2015) study the BGP behavior of WCNs. This is accomplished by estimating dumps of BGP messages coming from the AWMN and Guifi networks. The results of this evaluation are then compared with data obtained from the public Internet. This comparison shows that WCNs are significantly less stable, while the public Internet shows a significantly higher ratio of update messages over withdrawal messages.

In order to provide the most efficient routes for real-time applications, Zhao et al. (Zhao et al., 2017) develop a model for selecting a cross layer relay node of the routing protocols. Two routing metrics are proposed which are the Packet Priority-Oriented (PPO) routing metric and the PPO-Quality of Service (PP-QoS) routing metric. Simulations confirm the superiority of the proposed model against a number of existing counterparts.

2.9 ENHANCED VERSIONS OF THE OLSR PROTOCOL

As the focus in this research is on enhancing the performance of OLSR routing protocol. Therefore, in this section, we focus on the previous work done on OLSR routing protocol and applied on different types of wireless networks. Table 2.4 summarizes the comparison between MPR selection approaches based on the improved OLSR routing protocols (Barki et al., 2020).

Yi et al. (Yi et al., 2011) propose MultiPath OLSR (MP-OLSR) routing protocol. It is based on OLSRv2 and is a hybrid multipath routing protocol. It also is intended to enhance QoS, load balancing, and energy conservation. In addition to including a significant modification to the Dijkstra algorithm, it makes use of the MPR mechanism to flood the network with control traffic information. The proactive behavior of the OLSR is changed into an on-demand route calculation by the MP-OLSR, which also transforms the OLSR into a source routing protocol with two cost functions that may generate several disjoint or non-disjoint paths. For packet transmission, the number of hops is used as the link cost metric. The cost of all connection between the source and destination is initially set to "1", which might either cause congestion on a particular path or an increase in the amount of energy that is expended by particular intermediary nodes.

Pandey and Baliyan (Pandey & Baliyan, 2012) attempt to compare the three different versions of OLSR, which are referred to ETX, Minimum Loss (ML), and Minimum Delay (MD). In light of the fact that OLSR-ETX is based on the quality of the link regards to the ability to send and receive Hello messages. This is accomplished by carrying out the probability calculation (ratio of the number of messages that are sent from X to Y to the total number of messages that are received by Y from X) for every node, and the ETX formula is calculated as follows: ETX = 1 / P (X) * P (Y). For this reason, while selecting the route with the shortest path, we take into consideration the path that has the sum of the smallest ETX. ETX is calculated using OLSR-ML. This product is termed PLINK = P (X) * P (Y), and it is designed to discover the link with the lowest lost packets. The routing table is used to compute the transmission delay that occurs between nodes in OLSR-MD. The path with the smallest delay is considered to be the shortest path. It is clear from the comparison of these versions that OLSR-ETX provides higher levels of satisfaction in regards of evaluation parameters (end-to-end delay, Throughput, etc.) (Barki et al., 2020).

The BandWidth OLSR (BW-OLSR) protocol (Moad et al., 2012) is an improved version of the RFC3626 (T. Clausen & Jacquet, 2003). The authors modify the MPR selection algorithm, so that they take into consideration the bandwidth as a parameter for path computation between the source and destination node. There is only one path to take among the possible paths that the OLSR calculates through the MPRs of the Node Performing the Computation (NPC) node. This is the path that contains the maximum number of nodes that have the widest bandwidth without necessarily being the shortest. The simulation that has been conducted on OPtimized Network Engineering Tools (OPNET) for OLSR version and BW-OLSR version indicates that the BW-OLSR provides a number of MPRs bigger than those computed by OLSR, which resulted in a considerable increase in rate across the network.

In Energy and Mobility OLSR (EM-OLSR) (Fatima & Najib, 2012), the value of the willingness parameter is calculated based on two metrics, called as the energy and mobility of the node, which helps the OLSR protocol to reinforce its selection of MPRs. Each node computes its own residual energy and its own movement speed, and then it deduces from these two values the value of willingness, which may be one of three different values WillignessDefault, WillignessLow or WillignessHigh depending on the outcome of the following algorithm:

Algorithm 1: Willingness parameter

```
if(life_time > EnergyThreshold && MobilitySpeed > MobilityThreshold or
   energy < EnergyThreshold && MobilitySpeed < MobilityThreshold)
        willingness = WillignessDefault
if(energy < EnergyThreshold && MobilitySpeed > MobilityThreshold)
        willingness = WillignessLow
if(energy > EnergyThreshold && MobilitySpeed < MobilityThreshold)
        willingness = WillignessHigh;
```

In terms of throughput, the number of lost packets, and the amount of energy consumption, the simulation experiments conduct on the NS-2 simulator indicate that the EM-OLSR version provides superior results in comparison to the OLSR standard protocol.

In (Jabbar et al., 2014), they make use of the multipath Dijkstra algorithm . Nevertheless, the preliminary link cost of every link is determined depending on the remaining battery capacity of both nodes. In order to take use of the topological information in the OLSR and MP-OLSR, they change the Hello and TC messages for Multipath Battery Aware OLSR (MBA-OLSR) and add the node's remaining energy information to them. Additional TLV may be added for remaining battery information using the TLV method of OLSRv2. Because of these improvements, other nodes in the network are aware of the information about the amount of battery energy that is still remaining in the local node.

Anbao & Bin (Anbao & Bin, 2014) proposes a version of OLSR called node Localization technology OLSR (L-OLSR), where the MPR selection algorithm take into consideration the angle between two lines, one composed of the NPC node and the node with the highest level of accessibility (L-OLSR), and the other composed of NPC node and a potential candidate for the MPR (NA and NC, respectively) in their version of OLSR (L-OLSR). This node is considered MPR for the NPC node if the angle is near to 90, 180, or 270 degrees. The following formula can be used to determine the NC-NPC-NA angle from the node coordinates to determine the distances NPC-NA, NPC-NC, and NA-NC:

$$x = \text{arcos}\ ([(NPC - NA)^2 + (NPC - NC)^2 - (NA - NC)^2] / 2 * (NA - NC)) \qquad (2.1)$$

The result of the simulation run on NS-3 demonstrates that the number of packets transmitted by standard OLSR is significantly higher than the number of packets transmitted by L-OLSR. On the other hand, the number of packets received is almost similar for both versions of OLSR; consequently, the number of missing packets encountered by L-OLSR is significantly lower than that encountered by OLSR. As a result, this proposed solution requires a large amount of CPU power, which is not appropriate for smart devices with limited computing capacity and battery power.

Weihgted OLSR (W-OLSR) is an extended version that has been created from the standard OLSR because the author intends to add a new parameter to the process of selecting MPRs (Anandrao & Amey, 2014). This new parameter is called weihgted-MPR, and it is derived from residual energy, signal strength, and transmission delay using the following formula:

$$\text{Weighted MPR} = X*\text{Residual Energy} + Y*\text{Signal Strength} - Z*\text{Transmission delay} \qquad (2.2)$$

If the weighted-MPR of the node is less than the weight_threshold, then the node is regarded to have an MPR. X, Y, and Z are constants. The Hello message is transmitted together with the value of the remaining energy and the transmission time at the node that is considered to be the source. The quality of this link (poor or excellent) is evaluated during reception by evaluating the amount of residual energy, the delay in transmission, and the strength of the signal. According to the findings of a comparison between the standard OLSR and W-OLSR, the latter is more effective than the OLSR in regards of throughput and the number of lost packets. However, the average energy consumption increases with node density and node speed.

In Modified OLSR (MOLSR) (Tiwari & Jaiswal, 2016), OLSR is updated so that every node in the network may select its option of "Update" or "Not update" the Hello and TC messages. This is done in order to reduce the cost of borrowing a path, both in terms of the number of jumps required and the amount of energy required. Depending on the energy capacity of the intermediary nodes, this approach chooses a different path if the threshold is reached. End-to-end delay, overhead routing, and residual energy are just a few of the metrics used to evaluate the effectiveness of this technique. According to the simulation findings, the proposed MOLSR algorithm reduces network load and energy consumption significantly. In addition, the average throughput is slightly reduced.

The MPR selection approach that is used by the OLSR protocol has been optimized, and this improvement serves as the foundation for the Airborne OLSR (AOLSR) protocol that has been presented (Kumar & Verma, 2019). Initially, there are two sets of MPRs for each node: one on the right and one on the left. Then, depending on the location of the destination, the MPRs on either the right side or the left side are utilized for the further rebroadcasting of control and data packets.

Table 2.4 Comparison between MPR selection approaches based on the improved OLSR routing protocols (Barki et al., 2020)

	Energy	**Bandwidth**	**Mobility Node**	**Simulator**	**Path (Link)**	**Security**	**Hello**	**Tc**	**Hard/ Soft**	**Math. Model**	**Control overhead**
OLSR					✓		✓	✓	S		
OLSR-ETX		✓		NS-2	✓		✓		S		✓
OLSR-ML		✓		NS-2	✓		✓		S		✓
OLSR-MD		✓		NS-2	✓		✓		S		✓
BW-OLSR		✓		OPNET	✓				S	✓	
EM-OLSR	✓		✓	NS-2	✓		✓				
L-OLSR				NS-3	✓				S		
W-OLSR	✓		✓		✓		✓		S		✓
MOLSR	✓			NS-3	✓		✓	✓	S		✓

Table 2.5 Summary of previous works for different routing protocols used in WCNs

Reference	Approach	Pros	Cons
(Herberg, 2010)	They decrease the required CPU time by applying DSP algorithm.	DSP uses less CPU time to calculate shortest paths, especially in large networks.	It takes more CPU time to calculate shortest paths, especially in smaller networks.
(Yi et al., 2011)	The proposed MP-OLSR improves QoS, load-balancing, and energy conservation. It uses MPR to flood the network with control traffic and modifies the Dijkstra algorithm.	It improves node lifetime and QoS metrics versus simulation time variance in various models.	MBAOLSR is more effective than MP-OLSR in energy usage and QoS metrics.
(Ikeda et al., 2012)	They evaluate the performance of HWMP using NS-3 simulator	No delay only for low values of transmission rates and less number of connections.	Higher transmission rates and 30 connections increase delay and jitter, complicating real-time applications.
(Neumann et al., 2012)	They analyze the scalability that is achieved in the WCNs routing using the BMX6	The addition of new nodes do not effect BMX6 convergence time or protocol overhead.	OLSR suffers from scalability issues for convergence time and protocol overhead.
(Moad et al., 2012)	Bandwidth is added as a route parameter among source and destination nodes.	There are more MPRs than OLSR calculates, hence it's better than OLSR	Network load is much higher in this scheme than in OLSR standard.
(Fatima & Najib, 2012)	OLSR selects MPRs by computing the Willingness parameter from the node's energy and mobility metrics.	In terms of throughput, packet loss, and energy consumption, it outperforms the OLSR standard protocol.	Need to be compared with MDR based DSR to evaluate the energy behavior of two different topology management strategies
(Pandey & Baliyan, 2012)	They compare the three versions of OLSR, namely ETX, ML and MD.	In terms of the evaluation parameters, OLSR-ETX provides a higher level of satisfaction	OLSR-ML shows the minimum end-to-end delay out of the four protocols.

(Barz et al., 2013)	They evaluate the OLSRv2 using the virtual confine testbed extended by a rician fading model.	With more nodes and IPv6 exclusively, OLSRv2 has lower total traffic than OLSRv1.	OLSRv2's RFC5444 packet format has a higher overhead than OLSRv1's binary format.
(Paris et al., 2013)	The proposed EFW selects network paths with the greatest delivery rate in the presence of selfish intermediary nodes.	Network throughput and fairness are greatly improved by the proposed techniques.	N/A
(Maccari, 2013)	Ninux network analysis to examine routing and centrality metrics.	Dropping ETX metric allows reintroducing the multipoint relays to save resources.	Without ETX, faulty links are utilized until they break down.
(Cerdà-Alabern, Neumann, & Escrich, 2013)	They present an experimental evaluation of QMPSU network through live measurements.	The throughput is good only with less number of hops.	The throughput tends to reduce as the number of hops increases.
(Avonts et al., 2013)	Present the results of questionnaire sent to different WCN organizations.	53% of networks are using the OLSR routing protocol.	16% are using BGP and 11% are using B.A.T.M.A.N .
(Detti et al., 2013)	Integrate the SDN principles to a WMN formed by OpenFlow switches.	SDN improves the user performance in the traditional mesh network with IP forwarding and OLSR routing.	N/A
(Zhu et al., 2013)	The proposed double shortest path routing strategy is to avoid traffic congestion.	The proposed routing method is better than the classic shortest path routing protocol with selecting the appropriate parameters.	The proposed routing method is better than the classic shortest path routing protocol only with selecting the appropriate parameters.
(Boronat et al., 2014)	Some metrics that may be relevant in realistic WCN scenarios are compared.	NA	Routing based on shortest path is not enough. The real link capacity must be also considered.
(Millan et al., 2014)	They perform a link quality analysis and	The greater the quantity of the data set, the less	To make accurate predictions, the size of

	prediction for the Funkfeuer WMCN.	the error degrades over time.	the training data set is a key factor.
(Jabbar et al., 2014)	The initial cost of multiple links is based on the mobile node's remaining battery.	It improves node lifetime and QoS metrics versus simulation time variance in various models.	No modifications in the MPR selection mechanism is considered.
(Anbao & Bin, 2014)	They propose L-OLSR, where the MPR selection method considers angle between two lines.	This strategy aids in the coverage of a scattered region that has not yet been covered.	Due to the difficulty of the computations, the suggested solution is not suited for smart devices with limited CPUs and batteries.
(Anandrao & Amey, 2014)	Weihgted-MPR is a new MPR selection parameter added to the traditional OLSR, based on the residual energy, signal strength, and transmission delay.	In terms of throughput and packet loss, it outperforms OLSR.	The average energy consumption increases with node density and node speed.
(Neumann et al., 2015)	They examine BMX6, OLSR, and Babel routing protocols in WCNs.	In low density networks with low stable links, Babel is found the most lightweight protocol.	OLSR and BMX6, with frequent link changes, outperform Babel in overhead, stability, and self-healing.
(Barz et al., 2015)	They add a new metric called DAT to deal with the heterogeneity of links in WCNs.	New DAT metric produces good network paths, and the enhanced OLSRv2 outperforms OLSRv1 in several situations.	OLSRv2's flexible RFC5444 packet format has greater overhead than OLSRv1's binary format.
(Cerdà-Alabern et al., 2015)	They perform experiments on the QMPSU network to analyze the performance of BMX6.	In the majority of situations, BMX6 is able to select the optimal path.	In conflict-graph models, capacity is overestimated.
(Kanaoka & Yoshihiro, 2015)	They study the delay on the multi-channel WMNs which uses dynamic metrics.	Combination of the local switching of links and dynamic metrics works well in multi-radio multi-channel WMNs.	Little overhead

(Kiani et al., 2015)	They propose a new routing metric called ELARM for HWMN.	Significant improvement in packet delivery and average network latency.	a slight increase in routing overhead.
(Braem et al., 2015)	They study the BGP behavior of WCNs.	N/A	WCNs are significantly less stable, although the public Internet shows a significantly higher ratio of update messages over withdrawal messages.
(Tiwari & Jaiswal, 2016)	Depending on the energy capacity of the intermediary nodes, this approach takes a different route if it crosses the threshold.	A considerable decrease in network messages load and energy consumption is achieved.	The average throughput is slightly reduced.
(Zhao et al., 2017)	They describe a methodology for selecting the best relay nodes for real-time applications using a cross-layer approach.	The proposed model's superiority over a variety of current models.	N/A
(Farmani, Jaseemuddin, & Batarfi, 2017)	In WMNs with stationary nodes, such as community wireless networks, they enhance multicast routing.	The proposed approach has a greater throughput and PDR than PIM-SM because it uses a network with a larger density of multicast receivers.	Little overhead
(Kumar & Verma, 2019)	It optimizes the MPR selection method used in OLSR protocol based on direction of them.	Improved PDR and average end-to-end delay.	It brings greater routing overhead.
(Barki et al., 2020)	Techniques for computing and choosing MPR nodes based on energy, mobility, bandwidth, and link quality are studied.	This study determines the influence of metrics on MPR node selection and calculate best route from source to destination nodes.	Most approaches assess a limited number of metrics for selecting MPR nodes, which is insufficient to make the OLSR protocol comprehensive and efficient.

2.10 OPEN ISSUES AND RESEARCH GAPS

From the above literature review, several researchers provide a variety of contributions in WCNs routing protocols aiming at determining their effectiveness and quality. Therefore, in this section, the results of those protocols and methods are analyzed for explaining and clarifying their strengths and limitations.

WCNs grow organically in a decentralized manner with an already large number of nodes. Therefore, WCNs can make use of routing protocols for MANETs. Where these routing protocols self-adapt to network changes in order to determine the routing paths (Braem et al., 2013).

Babel gives a high performance without consuming memory and CPU and with less traffic overhead in case of a network with steady links and low network density. Nevertheless, if the network is highly dynamic, then Babel protocol results in high control overhead and processing overhead in order to meet the changes in topology through distributing additional route request messages and routing updates. While, in same scenarios, OLSR and BMX6 outperform Babel regarding overhead, stability, and self-healing capabilities, because they update topology and routes in constant rates.

On one hand, the MPR mechanism that is used by the OLSR routing protocol results in the OLSR protocol significantly benefits from the MPR mechanism that causes a proportional increase in overhead as the network grows in links and nodes. On the other hand, the BMX6 routing protocol generally has low control overhead as it hides the state of the local nodes from the widespread information as well as using compact local identifiers. Therefore, when comparing OLSR with BMX6 in terms of convergence time and overhead with network growth in nodes and distance, BMX6 differentiates from OLSR. As both overhead and convergence time in BMX6 doesn’t increase with the growth of the network. However, the convergence time and control overhead grow super linearly. As a result, BMX6 outperforms OLSR in terms of the control overhead in addition to the fast reaction for dynamic link changes. However, BMX6 requires higher memory than OLSR.

OLSR suffers from convergence problems and more traffic. Therefore, OLSRv2 comes with additional features to such as increasing the self-configuration capabilities and dual-stack configuration to overcome the drawbacks of OLSR. While comparing OLSR with OLSRv2, OLSRv2 outperforms OLSR in terms of throughput, jitter, average end to end delay, and loss rate of packets. Where throughput in OLSRv2 is higher than OLSR. Furthermore, the average end to end delay decreases much in OLSRv2 than OLSR. Moreover, regarding jitter, OLSRv2 shows better results than OLSR. Also, the loss rate of packets for OLSRv2 is always lower than OLSR. Hence OLSRv2 protocol provides good results as compared to OLSR. However, the traffic generated by OLSR in IPv4 only setup is significantly lower than using OLSRv2. Due to the fact, the fixed binary packet that used in OLSR doesn't cause high overhead. However, the use of the flexible TLV packet format for OLSRv2 results in high overhead. While the traffic overhead caused by the routing process is less for OLSRv2 than OLSR in case of an IPv6 only setup with a larger number of nodes. From this analysis, we can think in the replacing the flexible TLV packet format used in OLSRv2 with the efficient binary packet format used in OLSR to obtain the best performance of OLSRv2.

Beside the previously mentioned routing protocols, some other routing protocols have been tested on WCNs such as AODV and BGP routing protocols. AODV show high increase in jitter and delay with high network load and more connections. While BGP shows less network stability, however there are significant high ratio of update messages over withdrawal messages in the public Internet.

A wide variety of different optimization techniques for calculating the MPR are presented. The investigation of these approaches enables us to make some findings. Most approaches focus on energy in comparison to other parameters (mobility, security, bandwidth). In addition, we notice that there are no mathematical models used in any of the research that are used. Furthermore, the technique for selecting MPRs and the structures of messages Hello and TC are two key areas where the authors most often make improvements on them. However, it is not taken into consideration to conduct studies on the dependency that exists between the parameters, regardless of the fact that modifying any one of the parameters may have an effect on the others. In addition, in comparison to other types of mobility, such as random direction, Manhattan grid, freeway point, and others, the simulation makes the most frequent use of the random way point type. Furthermore, the simulations are performed with NS-2 tool in comparison to NS-3. As a result of these findings, we can conclude that the OLSR protocol lacks a reaction study by operating on multiple parameters at once.

We can conclude from this discussion that there is a need for an enhanced routing protocol that achieve optimal routing performance with taking in consideration the heterogeneous characteristics of WCNs in order to produce more efficient routing technique in terms of stability and scalability.

There are many challenges and issues in this emerging technology that have to be addressed in order to have an efficient and reliable communication. Below are some open issues related to the performance of WCNs:

- **Power Transmission Level**: Transmission power for WCNs should be more equal or more to that of the current networks(Shahdad, Sabahath, & Parveez, 2016).
- **Provisioning**: This is the process of allocating bandwidth to customers of WCNs.
- **Scalability**: Current routing protocols are not processing IPv4 and IPv6 address types simultaneously, which leads to high overhead (Om, 2021).
- **Stability**: Current routing protocols are not considering the link quality as a metric for controlling the routing of packets. The real link capacity must be also considered to guarantee the stability (Saldana et al., 2016).
- **Efficiency of TCP Protocol**: the use of TCP protocol is inefficient while transmission of data in single-hope network. which worsens in WCNs (Saldana et al., 2016).
- **Security**: WLANs have a wide variety of security mechanisms. However, none of them is appropriate for WCNs. Authentication, privacy, and reliability are all part of these mechanisms (Barz et al., 2015).

From these challenges, we focus in this research only on stability and scalability issues of routing protocols used for WCNs.

2.11 CHAPTER SUMMARY

This chapter investigates the current routing protocols which are commonly used for WCNs. A taxonomy of routing protocols used for WCNs has been designed. The WCNs routing protocols have been classified into five classes, namely: Babel, BMX6, OLSR, OLSRv2, and other routing protocols applied on WCNs. Firstly, a review is made of the basic problem that the researchers identify in their research work. Secondly, the research methodology that these researchers use to solve problems is presented. Additionally, the emphasis is on highlighting the protocols' advantages and disadvantages in order to assess their efficacy and quality in good determination of the routing path for messages end-to-end delivery throughout the network. Finally, various recommendations and future study directions have been proposed for helping academics to explore the unsolved challenges related to WCNs routing protocols.

CHAPTER THREE

SYSTEM MODELLING

3.1 INTRODUCTION

This chapter demonstrates and explains the main methodology used in this research study in order to accomplish the research objectives. In addition, it illustrates the performance evaluation metrics which can be used to measure the performance between both the proposed routing protocol and OLSR. Furthermore, it presents the core functionality of OLSR protocol, which is used in this research work. It proceeds as follows: firstly, the methodology of research is discussed in Section 3.2. Secondly, the evaluation metrics are demonstrated in Section 3.3. Finally, a detailed explanation of the core functionality of the OLSR routing protocol is presented in Section 3.4.

3.2 RESEARCH APPROACH

The procedure for conducting the research methodology is illustrated in Figure 3.1:

The first stage in conducting this research work consists of investigating and studying the most relevant literature. WCNs' routing protocols are explained clearly, providing the necessary basic knowledge to understand its difficulties and aspects. The literature review investigates the current existing routing protocols which are commonly used for WCNs. Additionally, the emphasis is placed on illuminating the strengths and limitations of various routing protocols in order to evaluate the efficiency and quality of their performance in WCNs. The investigation of the literature is carried out to discover the possible research gaps and limitations of the current routing protocols that affect the performance of WCNs.

The review covers the various routing protocols that commonly and efficiently used for WCNs. Therefore, an exploratory research has been conducted aiming at:

- Identify the main factors that affects the performance of WCNs.
- Investigate the significance of improving the performance of WCNs.
- Investigate the various routing protocols that commonly and efficiently used for WCNs.
- Find out the weaknesses in the current routing protocols and address research gaps.

The second stage of this research entails undertaking a critical analysis of several proactive routing protocols, with a focus on the routing metrics they employ. The aim of this critical analysis is to determine the drawbacks of the present metrics and discover the potential areas for improvements. Accordingly, this provides a better understanding, identification, and selection of the key design features required for the development of the proposed enhanced routing protocol.

The third stage of the research entails the design of the proposed enhanced routing protocol for WCNs. This enhanced routing protocol covers the gaps found in the current existing routing protocols.

Through this stage, the new proposed routing protocol is developed using C++ programming language, according to the current existing protocol design for the purpose of simulation. The proposed scheme is designed based on OLSR routing protocol. Enhancements of the proposed scheme are multicasting expansion, MPR selection based on the AHP, and a composite metric for optimal route selection. The proposed enhanced routing protocol are designed to:

- Keep the topology of the network robust and stable.
- Guarantee picking the most stable links in the network.
- Find the optimal routes with the existence of the dynamic topology.
- Decrease the overhead caused by the flooding of unicast traffic.
- Avoid waste of bandwidth that is caused by transmission of unicast data packets.

In the fourth stage, the implementation of the proposed enhanced routing protocol is accomplished. The new proposed routing protocol is developed using C++ programming language, according to the OLSR protocol design for the purpose of simulation.

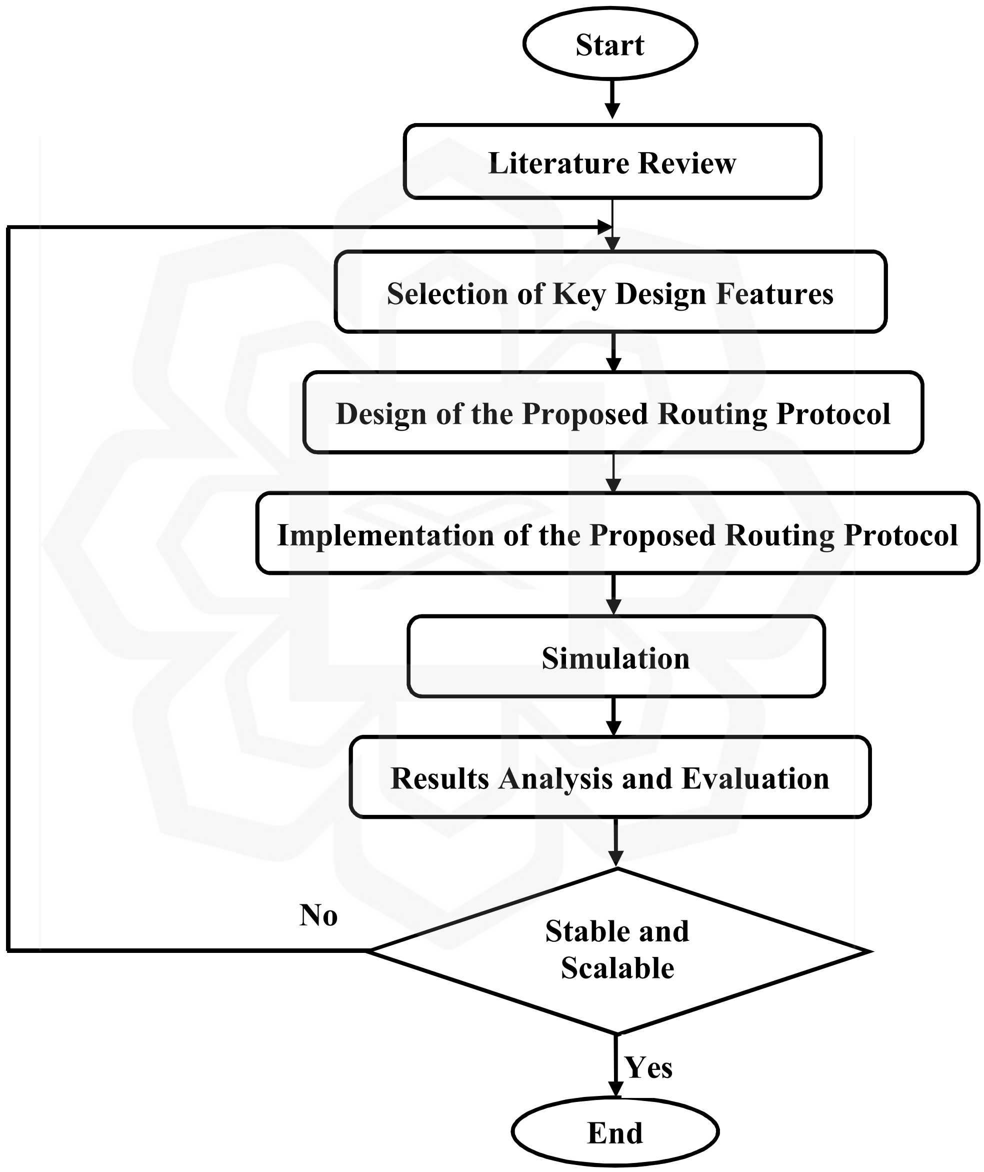


Figure 3.1 Research methodology flowchart

In this research, NS-2 simulator is used to simulate different WCN scenarios. It is an efficient discrete-event object-oriented network simulator which is commonly used in network researches. According to our study of the features of WCNs, various scenarios with different network configurations are designed and generated using this simulator. These scenarios are used for evaluating the performance of the proposed protocol in comparison with original routing protocol. NS-2 is an integrated framework which can be used for identifying data inputs, investigating data output, and reporting the result. The version used is 3.34-allinone along with the X-graph package in order to plot the graphs and charts. NS-2 has been enhanced and used by many researchers over the last three decades. NS-2 is implemented in C++ and Tcl programming languages. The advantages of NS-2 are that it can be used with several other software packages such as Tc/Tk and X-Graph, which may be fitted individually or in combination with NS-2.

In this stage, the performance evaluation of the proposed routing protocol is demonstrated and compared with OLSR routing protocol to verify the efficiency and effectiveness of it. The simulation results obtained for the selected routing protocols are analyzed and compared based on different performance metrics. Table 3.1 outlines how the research questions

Table 3.1 The relation between RQs, ROs, and Methodology

Research Questions	**Research Objectives**	**Methodology**
RQ1	RO1	Literature Review Selection of Key Design Features
RQ2	RO2 & RO3	Design of the Proposed Routing Protocol Implementation of the Proposed Routing Protocol Simulation
RQ3	RO4	Results Analysis and Evaluation

3.3 PERFORMANCE EVALUATION METRICS

In this research, the performance between both the proposed routing protocol and OLSR is evaluated and analyzed in terms of average end-to-end delay, network control overhead, packet delivery ratio, and energy consumption.

3.3.1 Average End-to-End Delay

It is measured in regards to the amount of time that has passed from the data packet is sent from the source to the time that it is received at the destination.

$$P_D = T_{recv} - T_{sent} \tag{3.1}$$

Where P_D represents the packet delay. T_{recv} and T_{sent} are the received and the sent time of each packet respectively.

This metric can be used to measure the efficiency of the proposed routing protocol with different network densities. When the network density increases, the performance decreases significantly as a result of the large time delay involved in determining the optimal route and waiting in the buffer at each node. Due to the fact that a scalable network may include thousands of nodes, the end-to-end delay of data packets is calculated by submitting the delays that occur at each node along the path to the destination. In order for the network to be robust, it is essential to identify any errors that may occur and quickly locate alternative routes (Rath, 2018).

3.3.2 Network Control Overhead (NCO)

NCO refers to the proportion of the total number of control packet that are sent across the network by each node to the total number of data packets that are received by destinations.

Control packets consist of route request packets, route reply packets, and error packets (Lassouaoui, Rovedakis, Sailhan, & Wei, 2016).

$$NCO = \frac{No\ of\ control\ messages\ sent}{No\ of\ data\ received} \tag{3.2}$$

The WCNs' routing protocol scheme's efficiency is proven through the measurement of network control overhead. Furthermore, it helps keeping track of the quantity of control messages that are exchanged inside the network so that it can accurately reflect the stability of the network topology (Lassouaoui et al., 2016).

3.3.3 Packet Delivery Ratio (PDR)

PDR of a network is the proportion of data packets that reach their intended destination successfully in comparison to the total number of packets that are sent by the sender. The PDR may be computed by getting the total number of packets that are delivered and dividing it by the total number of packets that are sent. The aim is to deliver as many data packets as possible to the final destination. Increased PDR results in improved network performance (Kaur & Saxena, 2018).

$$PDR = \frac{\sum_1^N CBR_{recv}}{\sum_1^N CBR_{send}} \tag{3.3}$$

Where N represents the number of data sources. CBR_{recv} refers to the total number of CBR packets that has been received. CBR_{send} refers to the total number of CBR packets that has been sent per source.

This metric is very important because it provides a description of the loss rate that can be experienced by the transport layer, which operates on top of the network layer. As a result, the PDR serves as a reflection of the maximum throughput that the network is capable of supporting (Lassouaoui et al., 2016).

3.3.4 Energy Consumption

We depend on the power-trace mechanism in order to calculate the amount of energy that is being consumed. The power-trace method provides an estimate of the energy consumption that is caused by the use of the CPU as well as activities that occur at the network level, such as the transmission and reception of packets (Lassouaoui et al., 2016).

$$E_i = \frac{(T_{CPU} * I_{CPU} + T_{RX} * I_{RX} + T_{TX} * I_{TX}) * V}{R_{timer}} \quad (3.4)$$

Where V is the battery voltage (3.6V). I_{CPU} = 1.8 milliAmpere hour (mAh), I_{RX} = 20 mAh, and I_{TX} = 17.7 mAh indicate the quantity of current which has been used through the CPU run time T_{CPU}, the radio listen run time T_{RX}, and the radio transmit run time T_{TX} (all expressed in ticks) respectively. R_{timer} refers to the number of ticks that occur every second (32768 ticks/s).

3.4 OLSR - CORE FUNCITIONALITY (BENCHMARK)

The experimental RFC3626 contains documentation of the OLSR protocol, which has been created for mobile ad hoc networks. OLSR is table-driven and proactive, and it makes use of an optimization technique known as MPR to limit the flooding of traffic. The OLSR protocol is broken down into its basic functionality and a collection of auxiliary functions. In a stand-alone MANET, the basic functionality defines a protocol that may enable routing. Additionally, there are a variety of auxiliary functions available, each with its own set of potential scenarios. It is possible to implement any auxiliary function along with the core since all auxiliary functions are compatible with one another. It is also claimed that the protocol may accommodate nodes that implement various subsets of the auxiliary functions in the network.

It is essential to have a solid understanding that OLSR is not responsible for the routing of traffic. It is in no manner accountable for the operation of actually routing traffic via the network. OLSR is more accurately defined as a route maintenance protocol due to the fact that it is in charge of maintaining the routing table which is used for the process of routing packages; nonetheless, protocols of this kind are more often referred to as routing protocols.

3.4.1 Node addressing

An IP address is the unique identification that OLSR use for each node in the network. Because OLSR is developed to be capable of operating on nodes that use various communication interfaces, each node needs to select one IP address which can work as its primary address. The OLSR protocol is compatible with both IPv4 and IPv6. In the scope of an OLSR, the significant variations between IPv4 and IPv6 may be broken down into three categories: the minimum size of messages, the size of the IP addresses that are communicated in control messages, and the address that must be used as the destination for control traffic (Addanki & Kumar, 2022).

3.4.2 Information repositories

OLSR is a derivation of the traditional link-state method. The traditional link-state method is the basis for the OLSR, which maintains state by storing a variety of information databases. The processing of received control messages causes these information repositories to be brought up to date, and the information that is stored there is employed in the process of creating control messages (Chandan, Kushwaha, & Mishra, 2018). A short look is now taken at the various information repositories that are used by the core of OLSR as follows:

1) **Multiple Interface Association Information Base**

   This dataset includes information regarding nodes that use several communication interfaces. All of the interface addresses of these kind of nodes are recorded in this repository.

2) **Link Set**

   This repository is preserved so that the state of links to neighbors may be calculated. Because it acts on particular interface-to-interface links, this database is the only one that can operate on addresses that are not considered to be primary addresses.

3) **Neighbor Set**

   All one-hop neighbors of registered are stored in this repository. The data is automatically modified depending on the link set's information. Neighbors, whether symmetric or asymmetric, are taken into account.

4) **Two-hop Neighbor Set**

   All of the nodes that are reachable through a neighbor with one-hop are recorded in this repository, with the exception of the local node. It is important to note that there are two-hop neighbor set may also include nodes that are registered in the neighbor set.

5) **MPR Set**

   This repository contains registrations for all MPRs that are chosen by the local node.

6) **MPR Selector Set**

   This repository contains all the neighbors who have chosen this node as an MPR.

7) **Topology Information Base**

   This repository stores information regarding all link-state information that was obtained from nodes participating in the OLSR routing domain.

8) **Duplicate set**

   Information regarding newly processed and forwarded messages can be found in this database.

The majority of the information that is stored in these databases is assigned a timeout when it is registered. This is a number that indicates for how much longer the information that has been recorded is to be regarded valid. This number is established in accordance with a validity time that has been retrieved from the message that was used to most recently update the data. The utilization of a distributed validity time enables individual message emission periods for all nodes in the network. According to the specified timeout, all repository entries are deleted when they are no longer valid (Benjbara et al., 2021).

3.4.3 Control traffic

The User Datagram Protocol (UDP) on port 698 must be used for the transmission of all OLSR control traffic. The Internet Assigned Numbers Authority (IANA) assigns this port to the OLSR. The RFC does not provide a broadcast address, despite the fact that it requires this traffic to be transmitted when IPv4 is used. Because IPv6 does not provide broadcast addresses, it is implicitly known that one must make use of a multicast address whenever this situation occurs, despite the fact that this need is not specifically outlined in the RFC (Nabou et al., 2021).

3.4.3.1 Packet Format

All OLSR traffic data is transmitted via OLSR packets, which have a header and a body, as shown in Figure 3.2 (Chandan et al., 2018). The OLSR packet header has the following fields:

- **Packet Length**
  The entirety of the packet, including the header, is measured in bytes to determine its length.
- **Packet Sequence Number**
  A sequence number that increases by one unit whenever this host sends out a new OLSR message. It is necessary to maintain of a separate packet sequence number for each interface in order to ensure that packets sent over a given interface may be consecutively enumerated.

One or several OLSR messages make up the body of an OLSR packet. Figure 3.2 shows the header used by OLSR messages. This header must be respected by all OLSR messages (Chandan et al., 2018). The header fields include:

- **Message Type**

  There is an integer that indicates the kind of message that is being sent. The range of message types from 0 to 127 is reserved for usage by OLSR, whereas the range from 128 to 255 is referred to be "private" and may be utilized for customized protocol extensions.

- **Vtime**

  This parameter specifies the amount of time after receiving a message that a node can continue to regard the information it contains as valid. A mantissa-exponent format is used to represent the time interval information.

- **Message Size**

  The length of this message measured in bytes, including the length of the message header.

- **Originator Address**

  It refers to the main address of the originator of this message.

- **Time To Live (TTL)**

  The maximum number of hops this message can be forwarded. The radius of flooding may be controlled by using this field.

- **Hop Count**

  It refers to the number of times that the message has been forwarded.

- **Message Sequence Number**

  A sequence number that increases by one unit whenever this host sends out a new OLSR packet.

3.4.3.2 Message Types

The primary functionality of OLSR is responsible for defining the different types of tree message. The processing and generation of these messages is the basis for all of OLSR's core functionality. Nevertheless, the packet format of the OLSR protocol for a broad range of user-defined packets allows to be sent and flooded in accordance with the requirements of the designer. OLSR uses the default forwarding rule to forward unknown packet types. Due to OLSR's usage of MPR optimization, message flooding is now a viable option for anybody in need of ad hoc network traffic broadcasting throughout the whole network (Chandan et al., 2018).

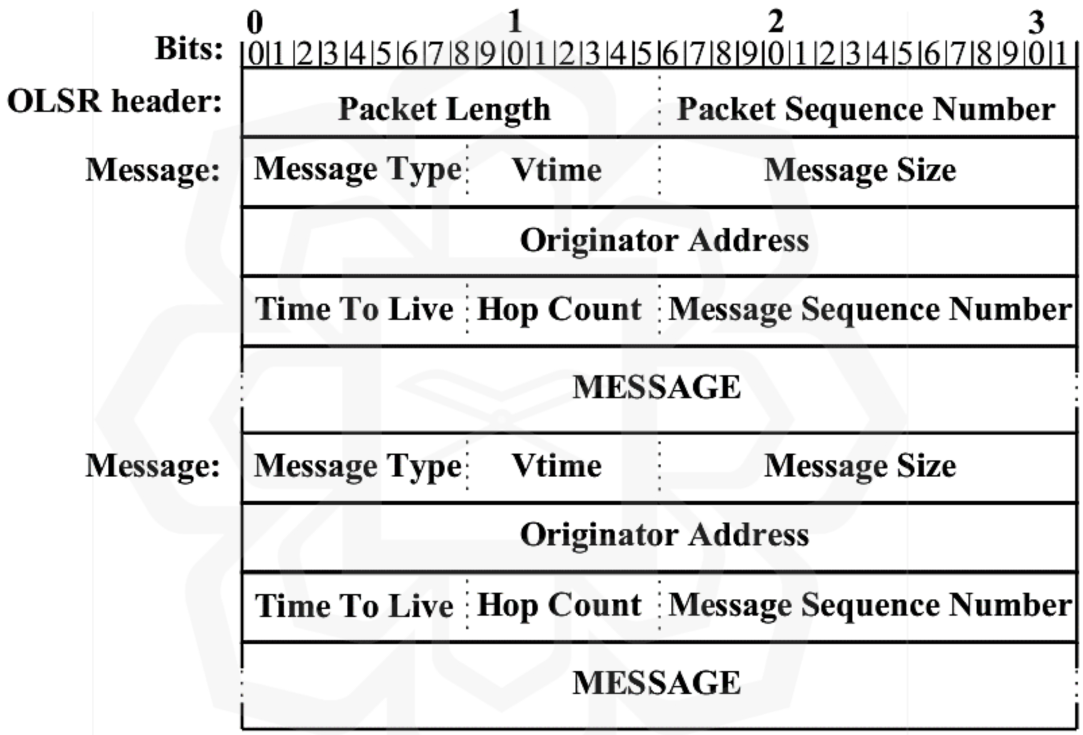


Figure 3.2 OLSR packet format

3.4.4 MPR flooding mechanism

OLSR exploits packet flooding to disseminate network topology information. Flooding is the process in which all nodes in a network retransmit packets they have received. A sequence number is often included in these packets to prevent looping. Receiving nodes are responsible for registering this sequence number in order to guarantee that a packet is only retransmitted one time (Addanki & Kumar, 2022). A packet is not retransmitted if it is received by a node that has a sequence number less or equal towards the sender's last registered retransmitted packet. Other improvements, such as the elimination of retransmission on the interface on which a packet is received, are often implemented in wired networks. Nevertheless, in a wireless multi-hop network, it is absolutely necessary for nodes to retransmit packets via the same interface which it receives. This is because the fundamental structure of wireless multi-hop networks requires it. This again leads each retransmitted for receiving a duplicate packet from each symmetric neighbour which retransmits the packet (Nabou et al., 2021). Figure 3.3 depicts a scenario of wireless flooding. It is clear that each transmission tends to result in the receipt of the same packet. In the Figure 3.2, any node may be the source of the flood.

With employing traditional flooding, the total number of retransmissions required is equal to n - 1, where n is the total number of nodes within the network. In the scenario shown in Figure 3.3, the total number of nodes are 24. It is clear that some kind of optimization can be beneficial for this flooding strategy.

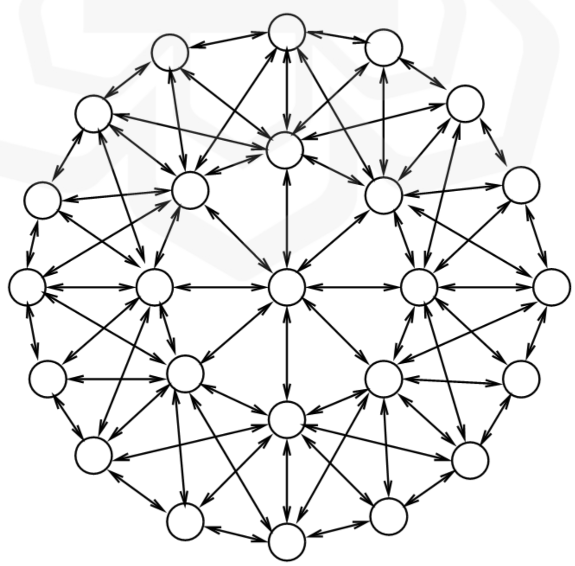


Figure 3.3 Flooding a packet in a wireless multi-hop network. The arrows show all transmissions

3.4.4.1 Multipoint Relaying

MPR aims to minimize the amount of repeated retransmissions during the forwarding of a broadcast packet. This method reduces the number of nodes that are able to retransmit a packet across all nodes to a particular subset of all nodes. The network topology influences the size of this subset in a significant way (Addanki & Kumar, 2022).

This may be accomplished by choosing neighbors to act as MPRs. Each node computes its own set of MPRs mostly as a subset of its selected symmetric neighbor nodes, where all two-hop neighbors is reachable across an MPR (Nabou et al., 2021). This implies that an MPR m must occur for each node n inside the network which can be reachable from the local node through at least two symmetric hops, where n is connected to *m* by a symmetric link, and m is a symmetric neighbor of the local node. Figure 3.4 illustrates a situation where node A chooses the black nodes to act as MPRs. Because of this, it is possible to reach all of the two hop nodes using an MPR. Node B doesn't retransmit traffic from A which is supposed to be flooded (Addanki & Kumar, 2022).

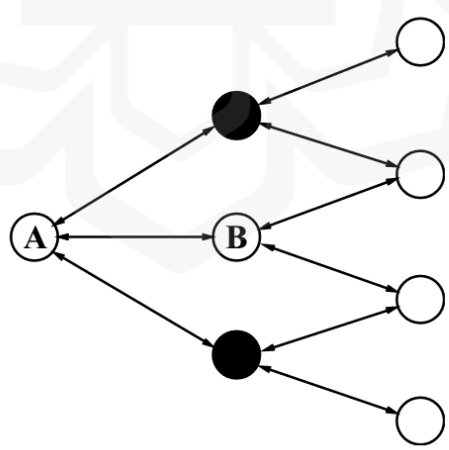


Figure 3.4 The node A has chosen the black nodes to act as its MPRs

Through the use of OLSR, nodes are able to declare their willingness to take on the role of MPR for their neighbors (Nabou et al., 2021). There are eight different levels of willingness, ranging from the lowest value of WILL_NEVER(0) to the highest value of WILL_ALWAYS(7). The value of WILL_NEVER(0), which is the lowest possible value, implies that this node cannot be selected as an MPR. Whereas, the highest value of WILL_ALWAYS(7) implies that this node forever need to be selected as an MPR. Hello messages distribute the willingness, and this information has to be taken into account while computing MPRs (Nabou et al., 2021).

3.4.4.2 Forwarding OLSR Traffic

Flooding in MANETS is made feasible through the transmission of messages (Nabou et al., 2021). In OLSR, a default forwarding algorithm is specified. This method floods packets with information obtained from MPR. However, one is able to set their own regulations for the custom forwarding of their own customized messages. It is, nevertheless, necessary to transmit all the received messages of a type that is not recognized by the local node, using the default forwarding algorithm (Addanki & Kumar, 2022). The algorithm is described as follows:

1) If the link that the message comes on is not thought to be symmetric, the message is quietly rejected. It is necessary to query the link set in order to examine the current state of the links.
2) If the TTL value that is contained in the message header equals to 0, then the message is quietly ignored.
3) The message is automatically ignored if it has really been forwarded. It is necessary to query the duplicate set in order to look for any messages that have already been forwarded.
4) The message is forwarded if the last hop sender, not necessary the originator, has selected this node to act as an MPR. Otherwise, the message is ignored. For the purpose of confirming this, the MPR selector set is inquired.
5) Forwarded messages have their TTLs decreases by one and their hop-counts raises by one before being broadcast on all interfaces.

Because this strategy involves forwarding all unidentified message types that are received, it enables flooding of specific message types, even if these message types are still only recognized to a small subset of the nodes in the network (Nabou et al., 2021).

Figures 3.5 and 3.6 illustrate the several ways in which the paths information are transmitted as it is being spread, firstly via the use of traditional flooding and subsequently through the use of MPR flooding (Nabou et al., 2021). The network topology and the technique used to calculate MPR both have a significant impact on the number of retransmissions that occur during an MPR situation. According to use the same topology as shown in Figure 3.3, a potential MPR computation can cause the black nodes in Figure 3.7 to be selected as MPRs through the center node. Clearly, if the central node is to flood a message across the network, MPR requires four retransmissions, instead of 24 required by traditional flooding (Addanki & Kumar, 2022).

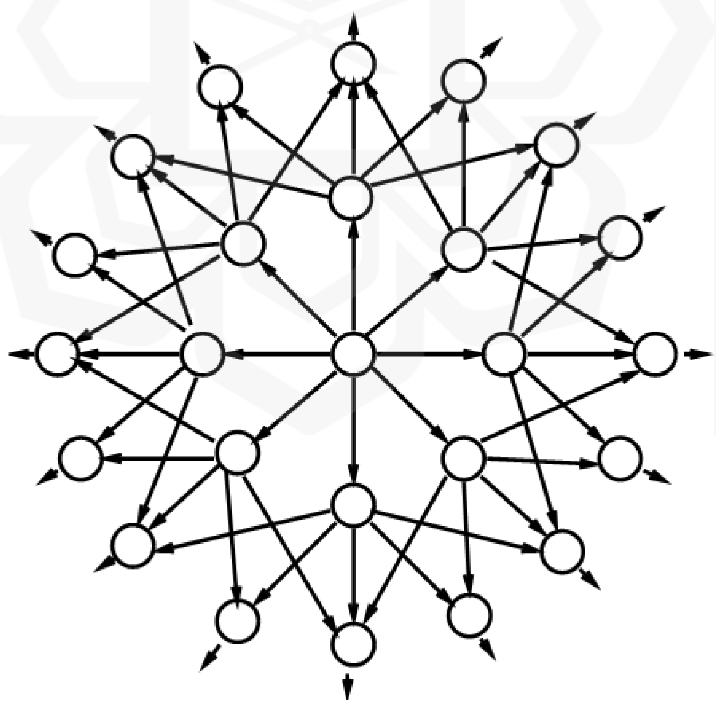


Figure 3.5 Flooding a packet in a wireless multihop network. The arrows show the way information is passed, not all transmissions

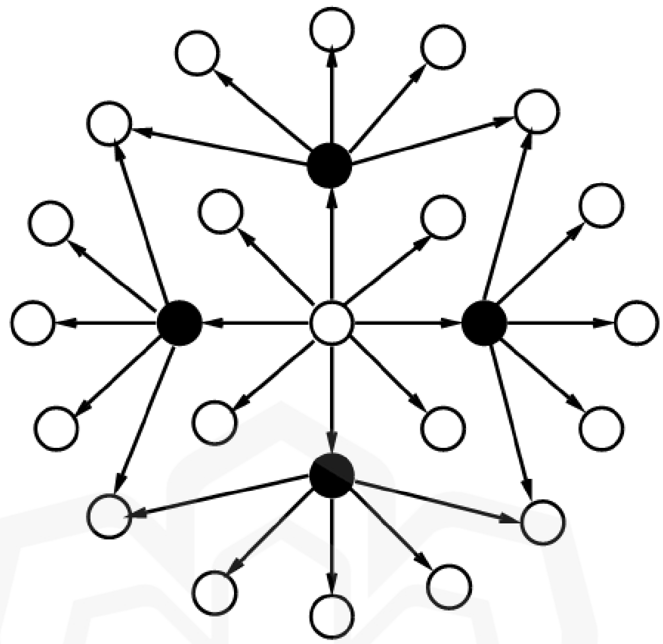


Figure 3.6 Flooding a packet in a wireless multihop network from the centre node using MPRs (black). The arrows show the way information is passed, not all transmissions

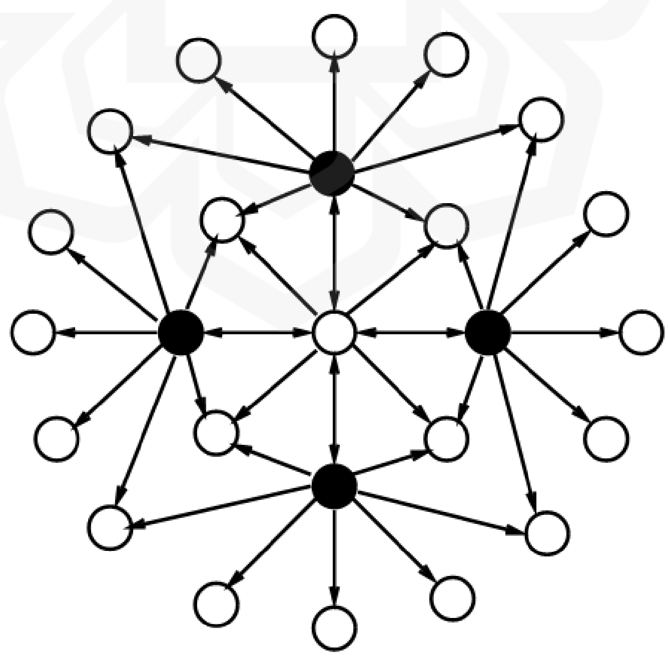


Figure 3.7 Flooding a packet in a wireless multi-hop network from the center node using MPRs (black). The arrows show all transmissions

- **The duplicate set**

  A cache of lately processed and forwarded messages is kept in order to determine whether a message has actually been retransmitted. The information that has been stored is the minimum required for message identification. This indicates that the content of the actual message is not recorded, but instead just the originator address, the message type, and the sequence number are kept (Addanki & Kumar, 2022). This data is stored in a cache for a certain amount of time known as DUP_HOLD_TIME, which the RFC recommends to be 30 seconds. The processed local node registers each message it receives in the set of duplicate. If the message is forwarded, the duplicate entry that represents this message is modified appropriately, and the recording on which interfaces the message is forwarded. When a node queries the duplicate set, it is then able to keep track of messages that it has been already processed and messages which have already forwarded on a per interface basis (Nabou et al., 2021).

- **Forward jitter**

  A jitter is inserted into the message forwarding in order to prevent radio collisions from occurring as a result of synchronized forwarding (Addanki & Kumar, 2022). This is a completely arbitrary and short interval in which the message is to be stored in the node's cache before being forwarded. Due to the possibility of receiving several messages inside the buffer interval while utilizing forward-jitter, piggybacking of messages is occurred. As a result, messages are packed inside the same OLSR packet (Nabou et al., 2021).

3.4.4.3 Link set optimization

Only nodes that have been selected as MPRs by one or more of their neighbours are required to declare their link state because of the nature in which the MPR selection operates. In actuality, it is sufficient for these nodes for declaring the MPR selectors inside the link-state messages (Addanki & Kumar, 2022). Once this data is flooded to all of the nodes in the MANET, all of the nodes can have sufficient data to compute the shortest path routes to all of the hosts. The default configuration of the OLSR specifies that a node can only flood link-state messages if it has been selected to act as the MPR through at least one neighbour, and it only notifies its MPR selectors within those messages. Only the nodes that have been chosen as MPRs (the grey nodes) through one or many neighbours can be able to transmit link-state messages in a topology as shown in Figure 3.8. It is straightforward to recognize that this data, in concert with a neighbour-sensing method, can be enough to construct a complete understanding of the topology (Nabou et al., 2021).

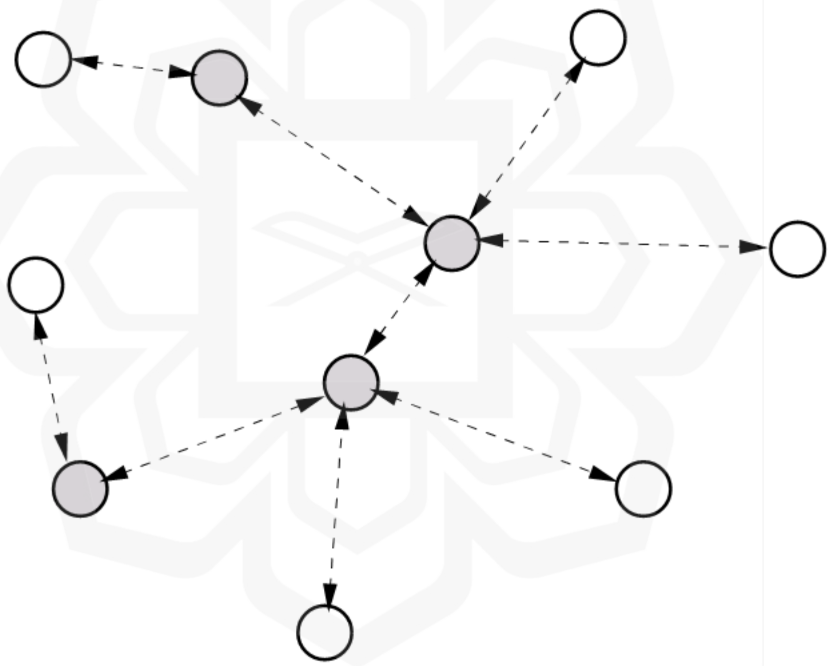


Figure 3.8 An OLSR routed network. The grey nodes are chosen as MPRs by one or more neighbour

3.4.5 Using multiple interfaces

It is possible for nodes that are participating of an OLSR routing domain to have multiple home networks. This indicates that they are able to conduct OLSR on numerous communication interfaces utilizing different identifiers (Nabou et al., 2021). Information regarding multi-homed nodes are transmitted via the use of Multiple Interface Declaration (MID) messages. A MID message is basically simply a list of addresses that are utilized by interfaces where a node executes OLSR. Figure 3.9 provides an illustration of the format of a MID message. Figure 3.9 provides an illustration of the structure that the MID message should adhere to. As shown in Figure 3.2, the information is transmitted as the message portion of an OLSR message that is included inside an OLSR packet.

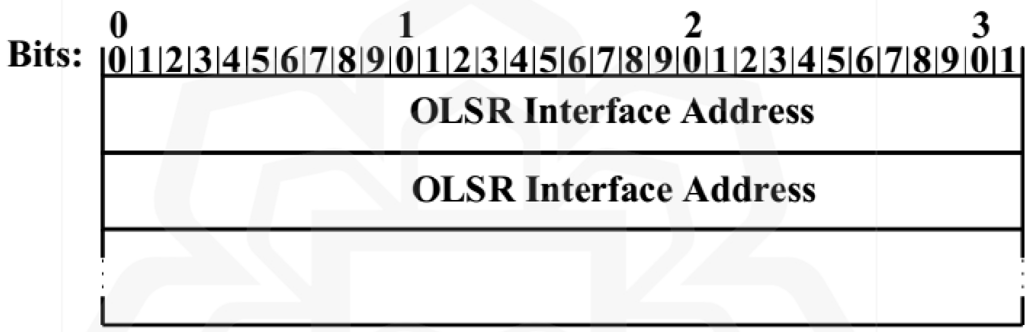


Figure 3.9 The OLSR MID message

In response to the data included in a MID message, a node makes modifications to its Multiple Interface Association Information Base. The primary address of the originator is recorded for all OLSR interfaces indicated in the MID message. The OLSR message header has a field labeled "originator", which contains the primary address. While a route is added to a node, OLSR adds routes to all addresses of the other interfaces where the remote node executes OLSR when utilizing the same path (Nabou et al., 2021).

MID messages are generated on a regular MID by all nodes executing OLSR on multiple interfaces. The default forwarding algorithm can be used to distribute MID messages across the network.

3.4.6 Neighbor discovery

In order for OLSR to work, it must be able to identify its neighbors and the state of their communication lines. As a result, the Hello message is broadcast on a regular interval. Figure 3.10 depicts a simpler version of a neighbor discovery process that makes use of Hello messages. The node A initially transmits an empty Hello message. The message from node A is received by node B and it register node A as an asymmetric neighbor, due to the reason that the node B unable to locate its own address inside the Hello message. After that, B can transmit a Hello to A, where it can declare that A is an asymmetric neighbor. As soon as A gets this message, it locates its own address inside it and, as a result, puts B as a symmetric neighbor. In this time, the node A contains the node B inside the Hello message that it transmits, and upon receiving the Hello message, the node B registers the node A to act as a symmetric neighbor (Chandan et al., 2018).

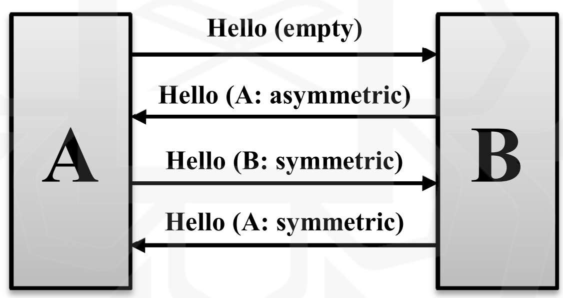


Figure 3.10 A typical neighborhood discovery for OLSR routing protocol

Nodes are responsible for transmitting information in Hello messages regarding all known links and neighbors. In addition to that, the types of the neighbors are indicated. This involves making a declaration about the MPRs that the node has chosen. To reduce byte consumption, registered links and neighbors are organized by link and neighbor type. On the other hand, it is crucial to keep in mind that the Hello messages are created on a per interface basis. This is due to the fact that Hello messages are utilized for link sensing, a process that needs the utilization of probable non-main addresses (Chandan et al., 2018).

Figure 3.11 provides an illustration of the format of the Hello message. As can be seen in Figure 3.2, this message is included into an OLSR packet as the "body" component of an OLSR message. The information regarding the neighbor link and the neighbor type is included in the link-code, which is eight bytes long. The state of the link is described by the link type, while the state of the neighbor is described by the neighbor type, together with relevant MPR information. It is important to keep in mind that if there are many links to the neighbor, a link may be configured as asymmetric even if the neighbor continues to be set as symmetric (Chandan et al., 2018). Figure 3.12 shows how the 8-bit link code data is arranged.

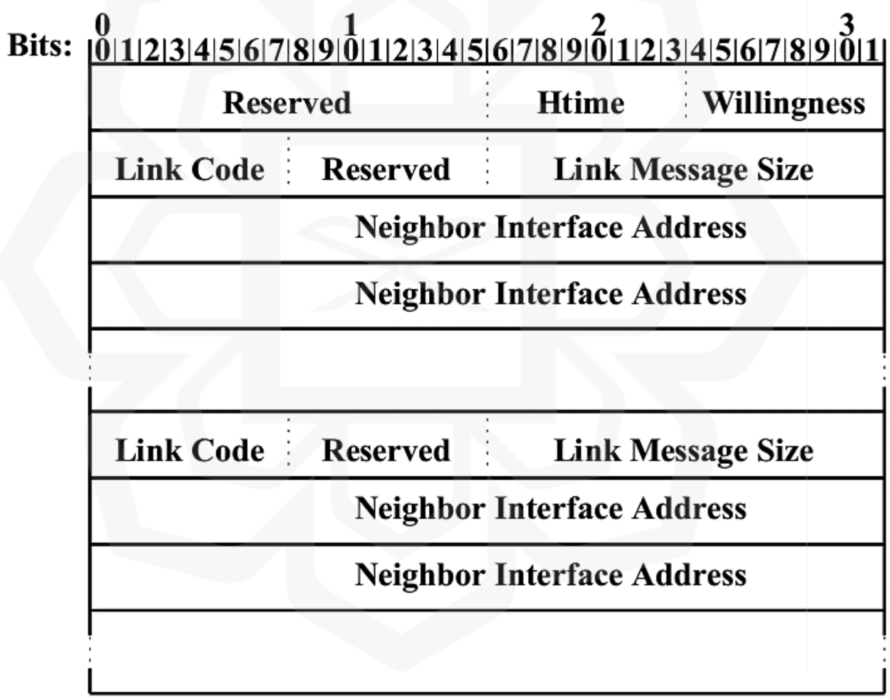


Figure 3.11 The OLSR Hello message

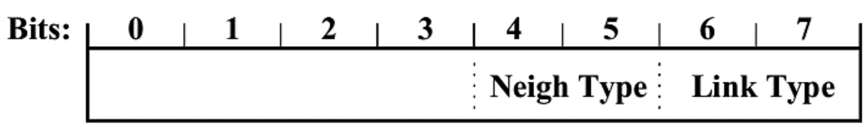


Figure 3.12 The 8 bit Link Code field

3.4.7 Link state declaration

The protocols used for link state routing are built on the idea that nodes can flood the network with data regarding their local links. Host-based smooth routing in OLSR means that the link state emitted defines links to neighboring nodes (Nabou et al., 2021). TC messages are used in order to do this. Figure 3.13 demonstrates the format that must be followed for a TC message to be valid.

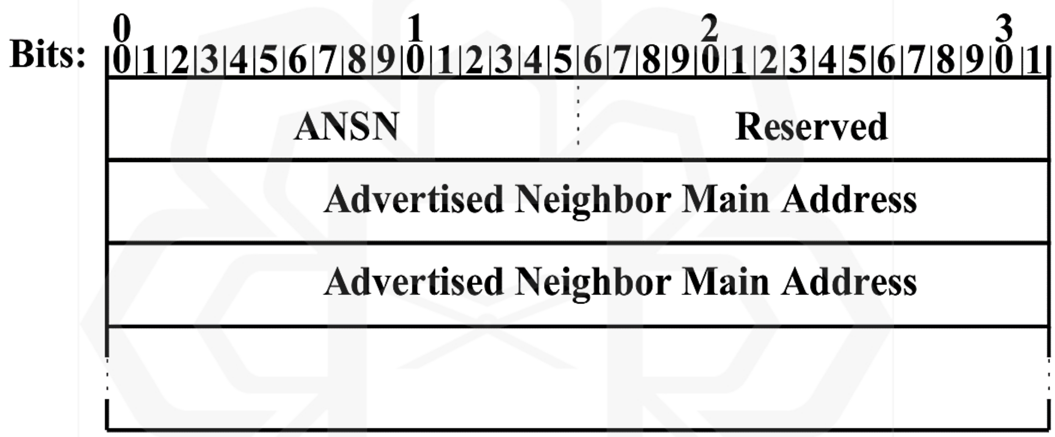


Figure 3.13 OLSR Topology Control message format

The MPR optimization floods the TC messages. This is carried at specified intervals, however TC messages are produced instantly if there is a detectable modification in the MPR selection set. The use of MPRs enables OLSR's flooding process to be optimized, and the MPR approach also enables two optimizations to be made to the link-state declaration process. It is also possible to tune OLSR nodes such that they broadcast more than just their MPR selection set. The fact that declaring more than MPR selection set may lead to more powerful routing (Nabou et al., 2021).

3.4.8 Route Calculation

A very easy implementation of the shortest-path method is proposed as the heuristic for use in route computation in RFC3626 (Benjbara et al., 2021). The following is a summary:

1. Add all symmetric neighbors with a hop count of 1 to the routing table.
2. For each one-hop neighbor, add all two-hop neighbors registered on that neighbor who have has:
    - not yet been added to the routing table.
    - A symmetrical connection to the next door.

A hop count of two and the current neighbor are used to add these entries.

3. for every new node N in the routing table with hop count n = 2 in the TC set, add all the entries from the TC set with the following formula:
    - the originator in the TC entry == N
    - the destination has not already been added to the routing table

   n+1 hops are added to each new entry, with the next-hop value being the next-hop registered on Ns' routing entry.
4. When there are no more items in the routing table with hop-count == n + 1 in the routing table, increase n by one and repeat step 3.
5. The MID set is queried for address aliases for all entries E in the routing table. Es hop-count and Es next-hop are added to the routing table for each alias address if they already exist there.

3.5 CHAPTER SUMMARY

This chapter presents the research methodology and methods, which are discussed in detail and illustrated in diagrams to determine this research approaches, outfit the research objectives, and promote a solution for answering the research questions. Then, the evaluation metrics that measures the performance of both the proposed routing protocol and OLSR are demonstrated. Finally, the core functionality of OLSR protocol, which is used in this research work.

CHAPTER FOUR

DESIGN OF THE PROPOSED (EX-OLSR) ROUTING PROTOCOL

4.1 INTRODUCTION

This chapter introduces an enhanced routing protocol for WCNs that meets the standards of efficiency in terms of stability and scalability. Section 4.2 represents the architecture of the EX-OLSR routing protocol. While, sections 4.3, 4.4, and 4.5 show the components of the proposed approaches according to multicasting expansion, MPR selection based on Analytical Hierarchical Process (AHP), and composite metric for optimal route selection respectively. In addition, EX-OLSR information repositories relations are represented in section 4.6.

4.2 CONCEPTUAL ARCHITECTURE OF THE PROPOSED ROUTING PROTOCOL

This research focuses on designing and implementing an enhanced routing protocol for WCNs based on OLSR protocol that meets the standards of efficiency in terms of stability and scalability. The proposed routing protocol is developed using C++ programming language for the purpose of simulation. The enhancements include multicasting expansion, MPR selection based on AHP, and a composite metric for optimal route selection. The proposed framework consists of four components as shown in Figure 4.1. A description of each component is given in the following sections.

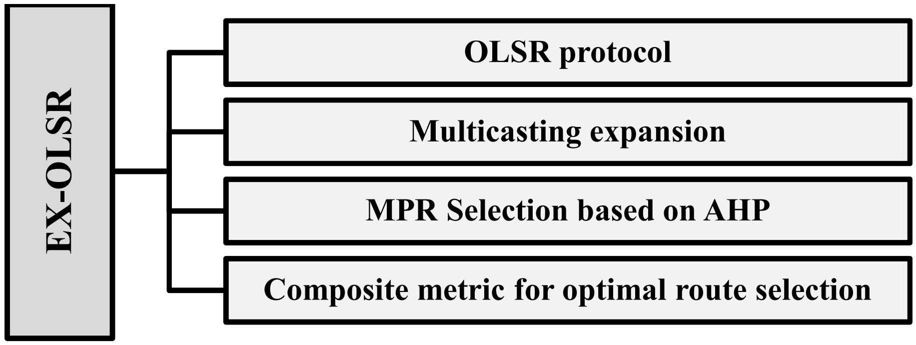


Figure 4.1 The proposed EX-OLSR

The code used to create EX-OLSR was inspired by OLSRd. Figure 4.2 depicts the architecture of the implemented solution. The EX_OLSR module is currently implemented as an application layer program in our environment for the sake of development and debugging. The EX_OLSR module should be integrated into the Linux kernel as a kernel module in the future for efficiency and practical use rather than in a testbed to avoid frequent context switches after the protocol test has been completed.

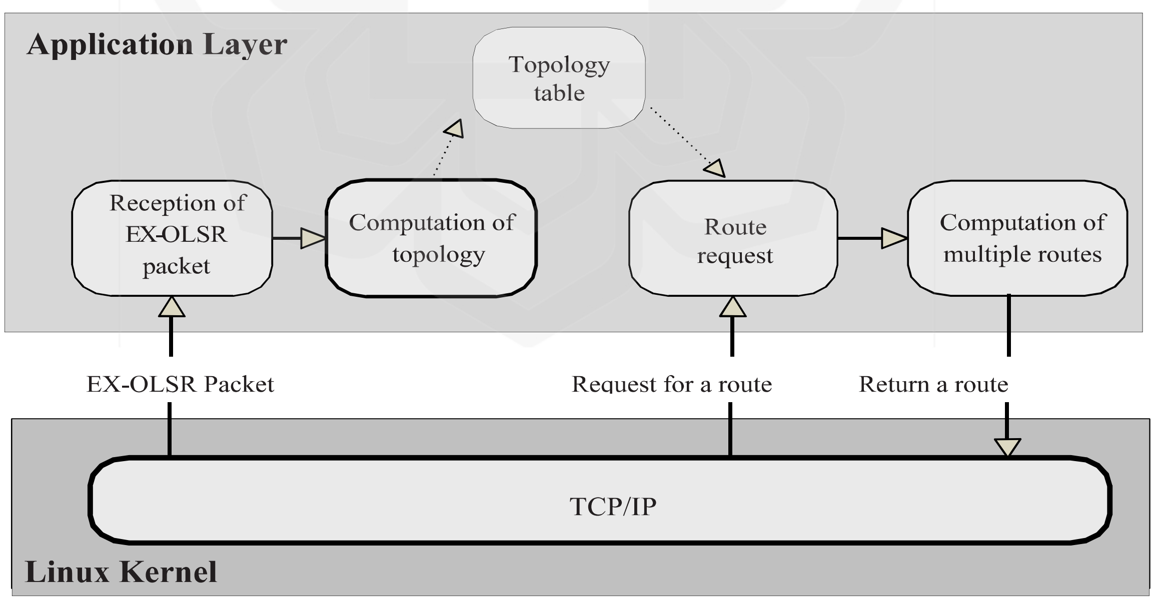


Figure 4.2 The architecture of the implemented EX-OLSR

4.3 MULTICASTING EXPANSION

In order to decrease the overhead caused by flooding as OLSR uses unicast traffic, multicast traffic is expanded to the OLSR routing protocol in WCNs. In order to communicate with the multicast group, the most recent sequence numbers are utilized. Unicast, multicast, and broadcast capabilities are all included in the multicast extended OLSR. A major benefit of using multicast expanded OLSR is that it prevents bandwidth waste by allowing each node inside the group to deliver multicast data packets instead of sending unicast data packets to a group of receivers. This loss of bandwidth is caused by sending unicast data packets to the group of receivers. The multicast operations are composed of two phases: the tree initialization phase and the tree maintenance phase as detailed in the following subsections.

4.3.1 Tree Initialization Phase

In a multicast group, the node that joins first becomes the group leader and is responsible for updating the group sequence number and broadcasting it periodically using the group hello message. When a group's members continue to be connected within a multicast tree, the multicast expanded OLSR are not required to do any tasks. However, when a node decides to join or leave a multicast group, it has a significant role. A unicast Route REQuest (RREQ) message is sent to the multicast group leader by a node that wishes to join the multicast group and has the address of the leader. The nodes that does not have the group leader's IP address broadcasts the group Hello message to the network. Route REPly (RREP) message is sent by the member of group. It is now possible to get to a multicast tree via the RREP message being unicasted back to the RREQ message. Recipient node distance from the group leader and recent group sequence number are included in this RREP. The receiver node receives many RREPs, from which it chooses the most recent and shortest path and then transmits the Multicast ACTivation (MACT) message. The routes are activated by the MACT message.

4.3.2 Tree Maintenance Phase

The nodes that are in the multicast group have a very high dynamic behavior. All multicast group members have the ability to join or leave freely at any moment. For the node to exit the tree, one of two things must happen: the node must either be a leaf node or it must be an intermediary tree with a preceding node that departs from the tree as well. In the event that a leaf node wishes to leave from the group, it can send a prune message to the nodes that are upstream from it, which can be sent higher in the tree. Next hop link status is monitored continuously by nodes in multicast tree. Therefore, if there is any link break, the nodes detect it and repair it through the RREQ, RREP, MACT messages. An example of multicast route discovery is shown in Figure 4.3.

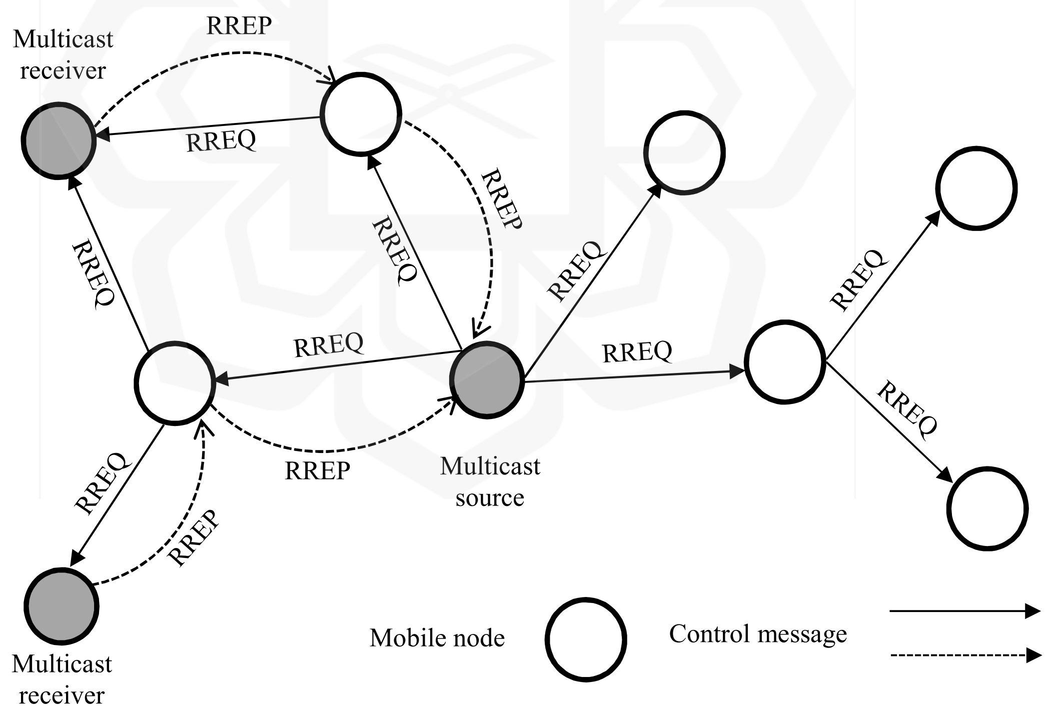


Figure 4.3 Multicast route discovery

4.4 MPR SELECTION BASED ON AHP

The MPR selection strategy is at the heart of OLSR's mechanism. The core benefit of the MPR algorithm is to reduce the TC messages which leads to minimizing the control overhead. Furthermore, the network topology is maintained through MPR selector set which can be used as an information. This means that each node in the network must select reliable and consistent MPR nodes in order to maintain a stable and robust topology. OLSR, on the other hand, only considers connectivity, or the number of two-hop neighbors, when making an MPR choice. No matter how many two-hop neighbors the selected MPR node covers, there is a possibility that the MPR selection set is no longer be valid because of the node's movement. As a result, the worst-case scenario is that the incorrect network topology can be kept until the TC message hold timer expires.

In this research, a modified strategy is proposed for the MPR selection algorithm of the OLSR routing protocol to maintain a stable topology using a Multi-Criteria Decision Making (MCDM). There are several sub-disciplines of operations research called MCDMs, which are devoted to finding the best possible outcomes in a wide range of difficult situations. Multiple criteria are taken into account simultaneously in the MCDM method to create a flexible decision making process. Multiple metrics can be weighted according to MCDM: AHP (Y. Liu, Eckert, & Earl, 2020). Each node establishes an MPR set based on a single cost determined with the given metrics. The detailed explanation of the AHP technique, metrics for MPR selection, and the modified MPR selection algorithm are presented in the coming subsections.

4.4.1 AHP Description

When it comes to making multi-criteria decision analysis, the AHP is a robust and adaptable method. AHP (Y. Liu et al., 2020) can be broken down into four steps, as indicated in Figure 4.4:

1. A hierarchical representation of a difficult decision problem.
2. Comparing the weight (importance or priority) of several items by comparing them to each other in pairs. Priority weights can be found here.
3. Pair-wise comparisons are used in order to assess the relative weight (importance) of distinct elements at various levels of the hierarchy. As a result, the score of each level inside each element can be calculated.
4. Incorporate the weights from step 2 and step 3 to generate a final score for decision alternatives. After that, the option with the highest total score will be chosen.

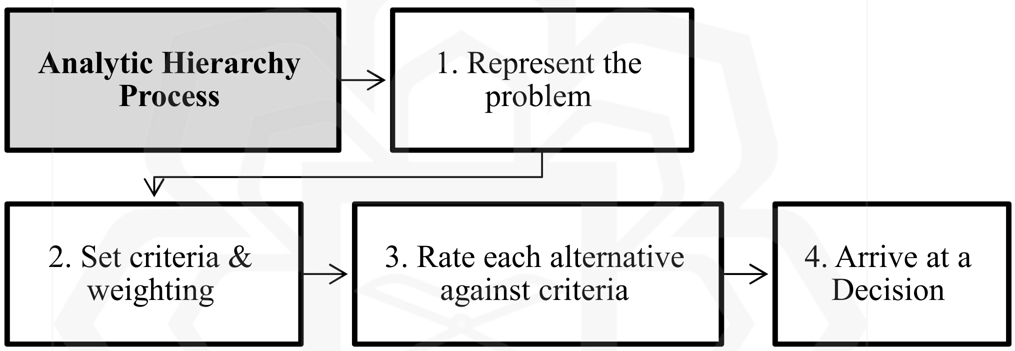


Figure 4.4 The main steps of AHP technique

4.4.2 Metrics for MPR Selection

In order to choose a stable MPR set in WCNs, the following two metrics can be used in the MPR selection algorithm:

1. **Link Change Rate (LCR)**

   The LCR is a measure of how much the neighbor table entry has been modified throughout the time interval t. As a result, the greater the value of LCR, the greater the connection loss owing to the movement of nearby nodes. It is possible to compute the LCR using the formula (Bianchi, Ciampolini, & De Munari, 2018):

$$LCR_i = \frac{Countnew_i + Countlost_i}{t} \tag{4.1}$$

Where the *Countnew*$_i$ denotes the number of new links of node *i* during time interval *t*. The *Countlost*$_i$ indicates the number of lost links of node *i* during time interval *t*. The *Countnew* and *Countlost* can be calculated by referencing the entry of the neighbor table. Generally, since the neighbor table is updated when each node receives the Hello message from neighboring node, hello interval is defined as t.

2. **Receive Signal Strength Indicator (RSSI)**

The RSSI is used as a link quality metric. There are many prediction models for estimating RSSI, and a free space propagation model is adopted. The free space propagation model is based on the assumption that there are no obstacles between transmitter and receiver, and they are in the line of sight. A simplified estimation model can be defined as (Bianchi et al., 2018):

$$RSSI_{i,j} = C_f \frac{P_t}{d^2} \quad (4.2)$$

Where *RSSIi, j* means the received signal strength between node *i* and *j*, C_f indicates the constant value depending on a transceiver, and P_t represents transmitting power. The *d* means distance between transceiver and receiver.

4.4.3 MPR Selection Strategy Using AHP

This subsection discusses how to apply the AHP to design an MPR selection strategy. The AHP module takes multi criteria as input values and returns the final score as shown in Figure 4.5. The final score is the weighted sum of all of the individual metrics, and it is this number that is utilized to determine which option is the most suitable.

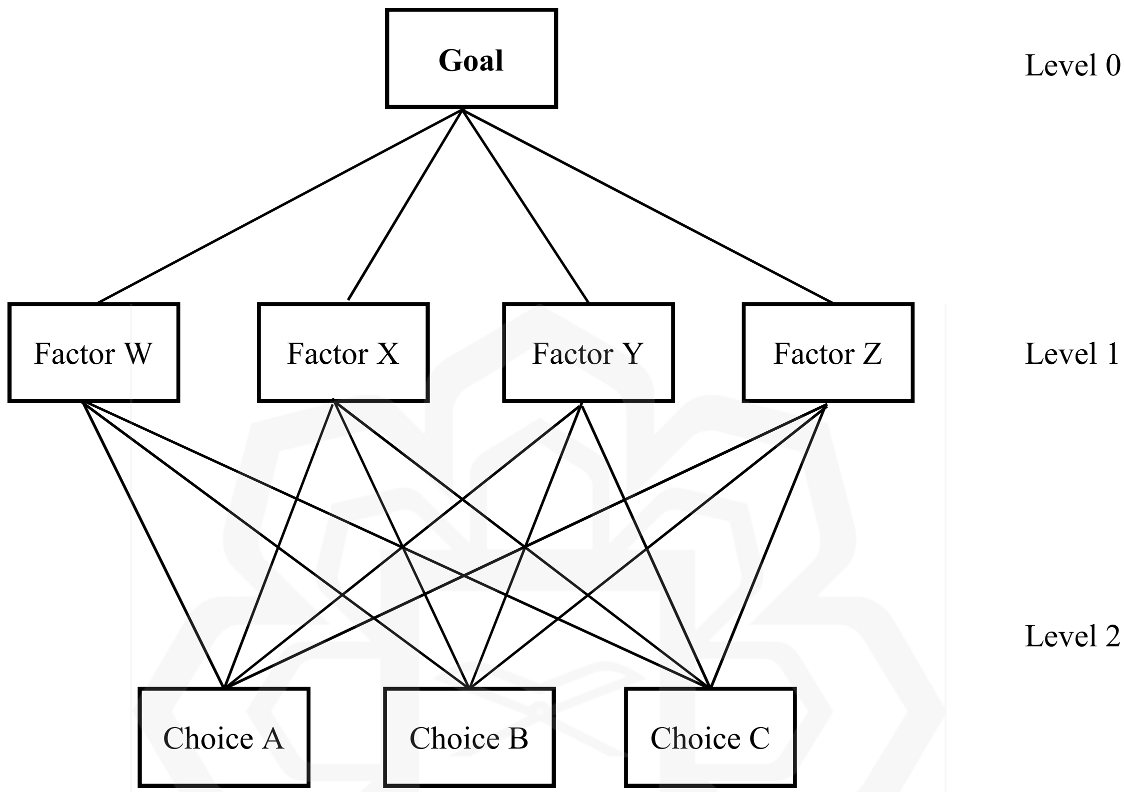


Figure 4.5 AHP hierarchy process

Two new fields are added to the header of the Hello packet. Until it has covered all of its two-hop neighbors, each node keeps track of two metrics for its one-hop neighbors and uses the one-hop neighbor with the highest final score as an MPR. Keep in mind that the RSSI refers to the average RSSI value with one-hop neighbors. You can see how the MPR selection algorithm has been changed in Algorithm 4.1. This research does not take into account a node's willingness; instead, two metrics are weighted equally. The final score is used to choose one of the nodes with the same degree who can be an MPR.

Algorithm 4.1: The proposed MPR selection algorithm

Input: t, n, TwoHopSet, MprCandidate, and degree_i

Where t is the total number of two-hop neighbors, n represents the number of one-hop neighbors, TwoHopSet refers to a two-hop neighbor set which can only be accessed through one-hop neighbor, MprCandidate refers to a candidate which has the potential to be chosen as an MPR amongst one-hop neighbors, and degree_i is a number of two-hop neighbors that connect to the one-hop neighbor of node_i.

Output: FinalScore

Where FinalScore is a weighted sum of every one of the metrics used to choose MPRs.

```
while t > 0 do
    for i = 1 to N do
        if node_i = MPR then
            continue
        end if
        FinalScore = AHP_MODULE (LCRi, RSSIi)
        if degree_i > MaxDegree then
            MprCandidate = node_i
            MaxDegree = degree_i
        else if degree_i = MaxDegree and FinalScore > MaxScore then
            MprCandidate = node_i
            MaxScore = FinalScore
        end if
    end for
    SelectMPR (MprCandidate)
    UpdateMBRSet (TwoHopSet, t)
end while
```

4.5 COMPOSITE METRIC FOR OPTIMAL ROUTE SELECTION

The dynamic topology of WCNs makes finding the best routes extremely difficult. In addition, because of the dynamic link characteristics of wireless networks, the hop count metric used in the OLSR protocol is not suitable. In this research, a composite metric is proposed using multiple parameters in order to ensure good knowledge of the status of links that can guarantee picking the most stable links in the network. The flowchart of route selection mechanism using a proposed composite metric is shown in Figure 4.6. It is calculated as a cost function of three parameters as stated below:

1) **Residual Energy:**

   In the proposed approach, the link cost function incorporates the nodes' remaining battery energy during the route computation.

2) **Age of Information (AoI):**

   AoI refers to the amount of time that has passed since the creation of the most recent message containing correctly received update information.

$$\Delta(t) = t - U(t) \qquad (4.3)$$

   t: current time

   U(t): the time instant when the most recently received update message was generated.

3) **Node Degree:**

   The number of connections that it has to other nodes in the network. The less number of connected nodes the better the cost of the link.

   Finally, the link cost function is:

$$LinkCost_{ij} = (k*RE_{ij}) + (l*AoI_{ij}) + (m*ND_{ij}) \qquad (4.4)$$

RE_{ij} refers to the ratio of remaining amount of battery energy at nodes i and j

AoI_{ij} is the ratio of Age of information for both nodes i and j

ND_{ij} is the ratio of node degree for both nodes i and j

K, **l**, and **m** are weight factors.

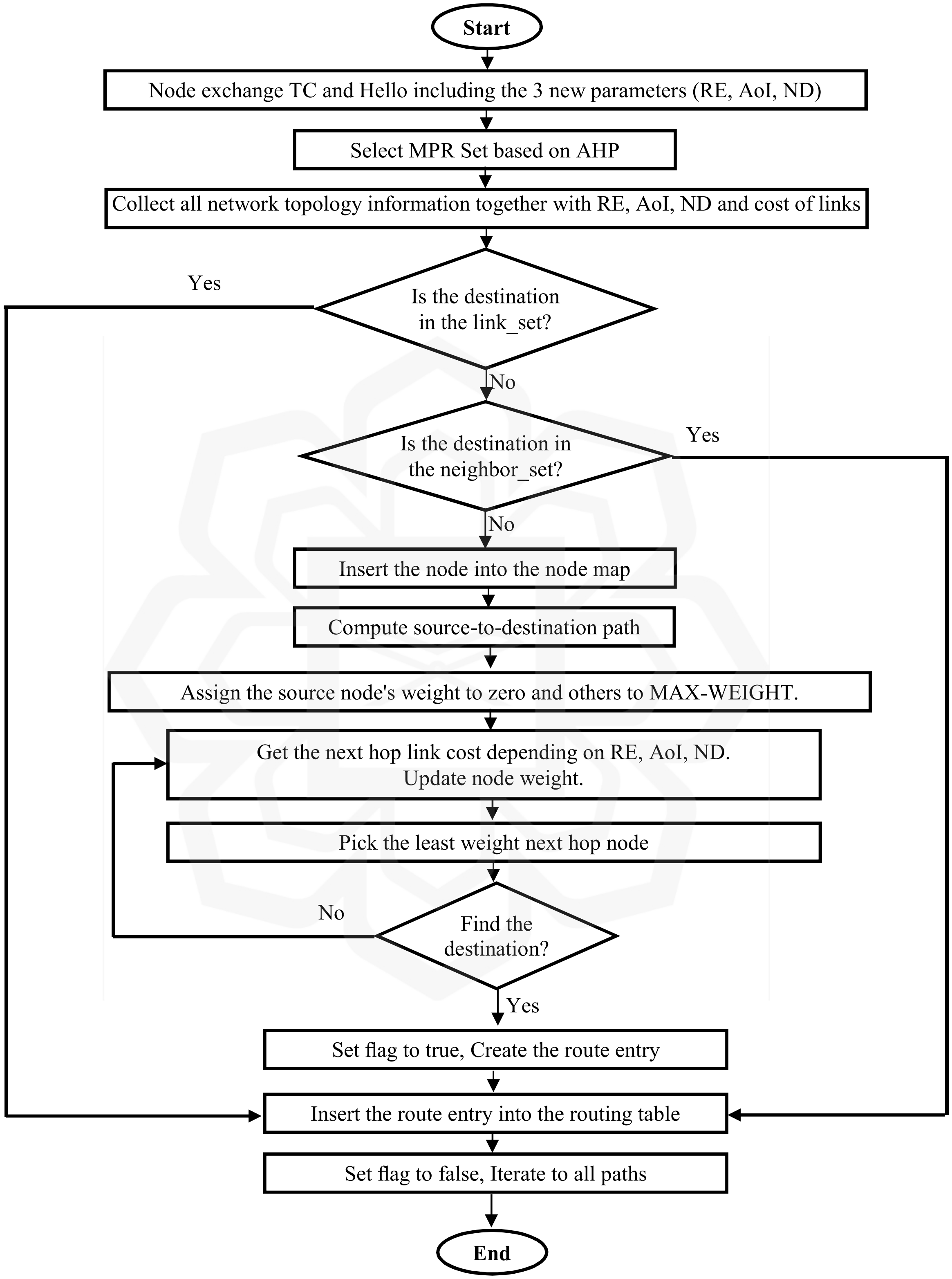


Figure 4.6 Flowchart of route selection mechanism using a proposed composite metric

4.6 EX-OLSR INFORMATION REPOSITORIES RELATIONS

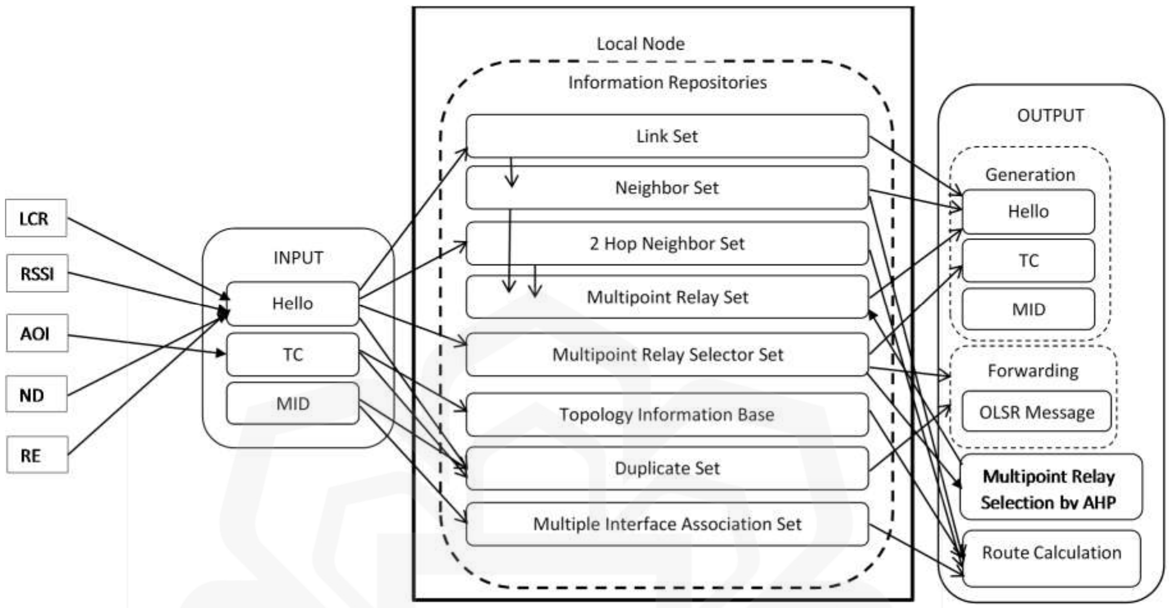


Figure 4.7 high level representation of the operations of EX-OLSR

Figure 4.7 provides a high-level perspective of the information repositories that are included inside EX-OLSR, as well as their relationships to the operations of MPR selection based on AHP, and route computation. The Hello messages that are received cause changes to be made to the link set, which in turn causes updates to be made to the neighbor set, which in turn causes a recalculation of the MPR set. After receiving a Hello message, the two hop neighbor set has been modified, causing the MPR set to be recalculated again. Lastly, the information that is found in the Hello messages is used to modify the MPR selection set. Modifications to the topological set are triggered when TC messages are received, whereas modifications to the MID set are triggered when MID messages are received. In addition, all messages that have been received are added to the duplicate set if they have not previously been included.

4.7 CHAPTER SUMMARY

In this chapter, an enhanced routing protocol are proposed for WCNs that meets the standards of efficiency in terms of stability and scalability. In addition, the components of the proposed approaches are shown according to multicasting expansion, MPR selection based on AHP, and composite metric for optimal route selection respectively.

CHAPTER FIVE

PERFORMANCE EVALUATION OF THE PROPOSED (EX-OLSR)

5.1 INTRODUCTION

This chapter highlights and explains the primary findings of this research work. It proceeds as follows: in order to guarantee that all simulation scenarios are compared fairly, the simulation environment is initially defined in Section 5.2, which presents simulation parameters and simulation environment details. Section 5.3 conducts the simulation scenarios and critical analysis of results in order to explore the reliability and efficiency of the proposed routing protocol in comparison with the standard OLSR protocol. Section 5.4 contains a summary of the contents of this chapter.

5.2 SIMULATION ENVIRONMENT

In order to evaluate the efficiency of the proposed routing protocol, NS-2 simulator has been used for simulation and analysis. Moreover, OLSR is used as a benchmark in the simulation scenarios. Primarily because our enhanced routing protocol is proposed to act as an improvement of OLSR. In addition, OLSR remains one of the most common routing protocols employed for WCNs and is widely used as the reference WCNs' routing protocol by the research community. Therefore, the performance of the proposed routing protocol in WCNs is compared with OLSR routing protocol through NS-2. In this chapter, our goal is to examine the effects of multicast expansion, MPR selection using AHP, and the use of composite metric for route selection.

In this simulation, a random topology is considered, with 1000 m x 1000 m area with 51 nodes. Only one of them is configured to act as a base station and is positioned in the middle of the network. A screen capture of the network topology is demonstrated in Figure 5.1.

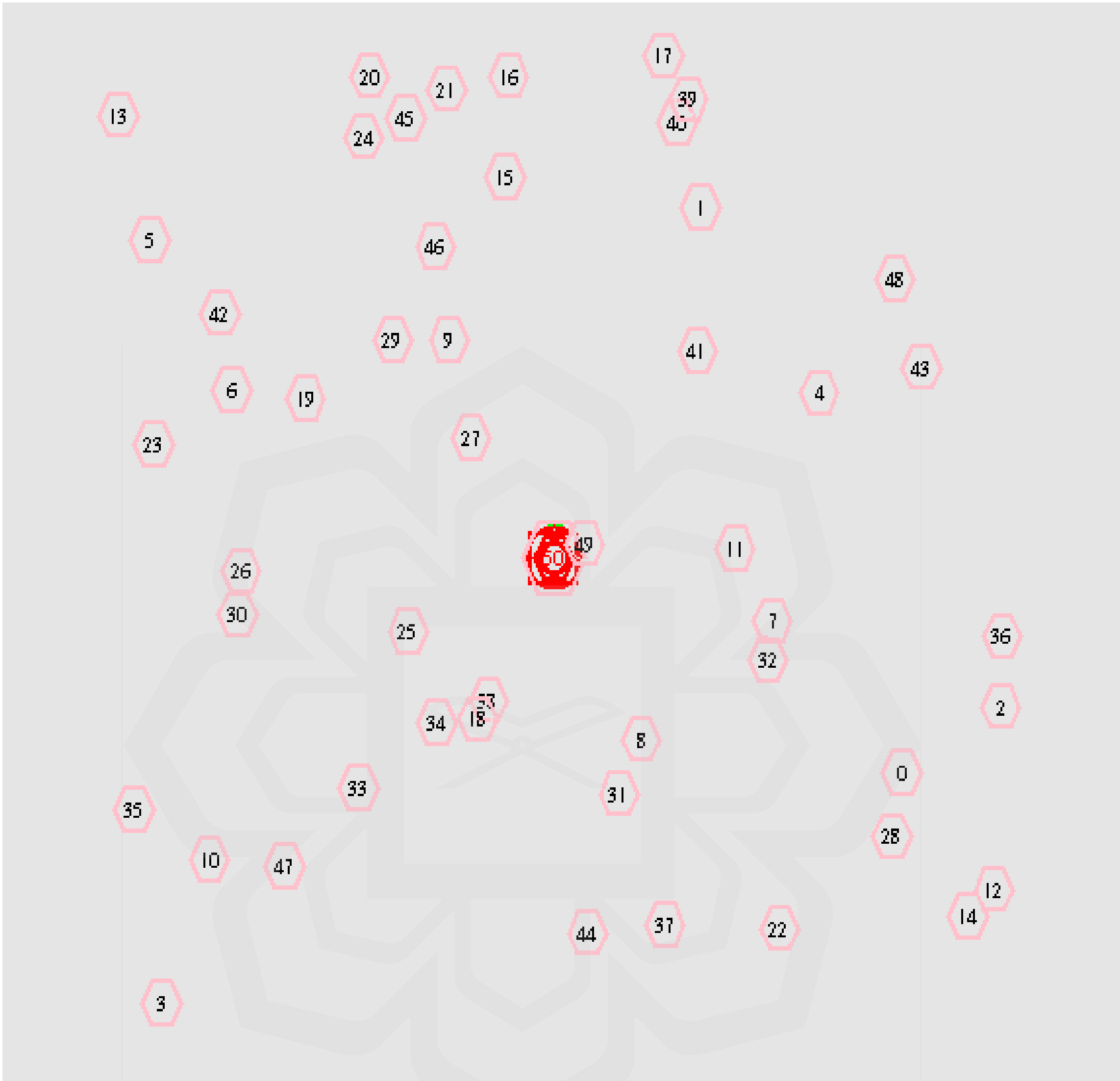


Figure 5.1 The topology of the network as represented in NS-2

The PHY802.11b model and the 802.11 MAC protocol are both used by every node. In addition, a CBR traffic source that uses data packets of 512 bytes is taken into consideration. We are going to assume that the bandwidth of the link is 2 Mbps, and the sending rate of CBR traffic is 4 packets per second. The InterFace Queue (IFQ) of all protocols is 50 packets. The IFQ is a First-In-First-Out (FIFO) priority queue. In this queue, routing packets are given a priority that is higher than data packets. Trace files record all the MAC layer and the network layer procedures on wireless network interfaces. Each trace file is parsed using parsing language to calculate the average end-to-end delay, energy consumption, network control overhead, and packet delivery ratio after the simulation is complete. Table 5.1 summarizes the simulation's parameters.

Table 5.1 Network simulation parameters

Parameters	**Values**
Simulator	NS-2.35
Size	1000 m X 1000 m
Time of Simulation	600 seconds
Total Number of Nodes	51
Node Placement	Random topology
Node Density	5,10,15,20,25,30,35,40,45,50
Speed	0, 5, 10, 15, 20
Traffic load	5, 10, 15, 20
Propagation Model	Two-ray ground
Wireless Standard	802.11b
Routing Protocols	OLSR, Extended OLSR
Size of Queue	50 packets
Transport Layer	UDP
Traffic Type	CBR
Packet Size	512 Byte

All simulated scenarios are performed on a computer system that has an Intel (R) Core (TM) i7-3612QM CPU running at 2.10 GHz, an 8 GB of memory, a 512 MB of Radeon graphics card, a 1 TB hard disk drive, and ubuntu-14.04 (32 bit) operating system. In order to execute the complete simulation scenarios, the prerequisites for the system configuration are summarized in Table 5.2.

Table 5.2 The system setup configurations

Computer System Configurations		
Hardware	Computer processor (CPU) Clock rate Memory size Capacity of graphics card Storage of hard disk drive	Intel (R) Core (TM) i7-3612QM CPU 2.10 GHz 8 GB 512 MB 1 TB
Software	Operating system IDEs	ubuntu-14.04 (32 bit os) NS-2.35 and xgraph-12.2

5.3 RESULT ANALYSIS

There are two simulation scenarios for evaluating the proposed routing protocol. In the first scenario, the number of nodes in the network is the main input parameter in this evaluation. The movement of each node in the network is completely random and the network size is increased from 5 till 50 nodes. The number of mobile nodes is raised by 5 after each run. A random number is assigned to each node in order to facilitate mobility. At random intervals, each node moves in random direction and subsequently change its direction randomly. In the second scenario, the node mobility speed, in conjunction with the traffic load, are the primary input parameters. From 0 m/s to 20 m/s, the mobility speed is increased by 5. The simulation is run with four different traffic loads (5, 10, 15, and 20) connections for every speed value. In this scenario the network size is fixed by 50 nodes. In both scenarios, every node has an initial energy level that is decreased as the network runs. Continuously using energy can lead to the full failure of nodes in a case when all of their energy has been consumed. Both OLSR and the proposed routing protocol are examined in these scenarios. Afterwards, data is gathered in order to compare the proposed routing protocol with OLSR. Simulation scenarios and their results are detailed in next subsections. The outline of simulation scenarios is represented in Figure 5.2.

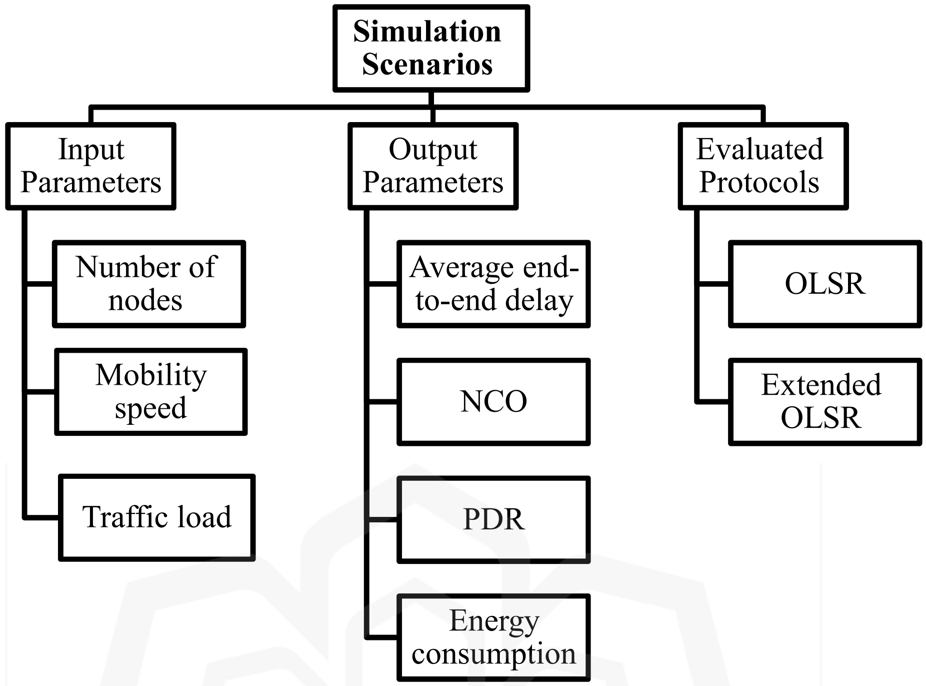


Figure 5.2 Outline of the simulation experiment

As previously stated, NS-2 network simulator is used in this research work to evaluate the proposed routing protocol. The simulation scenarios are executed for evaluating the effectiveness of the proposed routing protocol compared to the standard OLSR. Four performance measurement metrics have been used to evaluate this approach, which are:

- Average end-to-end delay: - It quantifies the time required for a packet to go from one network to another.
- NCO: - It is the additional load created by the broadcasting of routing packets, which helps to keep up-to-date routing information about the network.
- PDR: - It measures how many packets are successfully delivered vs how many packets are sent out.
- Energy consumption: - It is how much power is utilized in one unit of time.

5.3.1 Average End-to-End Delay

Figure 5.3 shows the comparison between the proposed routing protocol and OLSR by using the average end-to-end delay as a function of node density. The number of nodes is shown in X coordinates, while the average end-to-end delay is shown in Y coordinates in percentage. It is obvious that delay goes on slight increase for both OLSR and the extended OLSR. This is because the computation done by every node becomes more complex as the network size increases. Moreover, the extended OLSR minimizes the end-to-end delay as compared to standard OLSR at small and large network size. This leads to the fact that the proposed routing protocol is able to select durable and stable routes which as a result reduces path break frequency which results in delay reduction. From Table 5.3, it can be found that the proposed routing protocol achieves high improvement percentage compared to OLSR regardless of network size. The results show that the proposed routing protocol outperforms the OLSR routing protocol by 6% as an average in terms of average end-to-end delay.

Table 5.3 Average end-to-end delay vs. network size

Network density	5	10	15	20	25	30	35	40	45	50
OLSR	36%	36%	36%	37%	37%	37%	38%	38%	38%	39%
Extended OLSR	30%	30%	30%	31%	31%	31%	32%	32%	32%	33%
Improvement (%)	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%

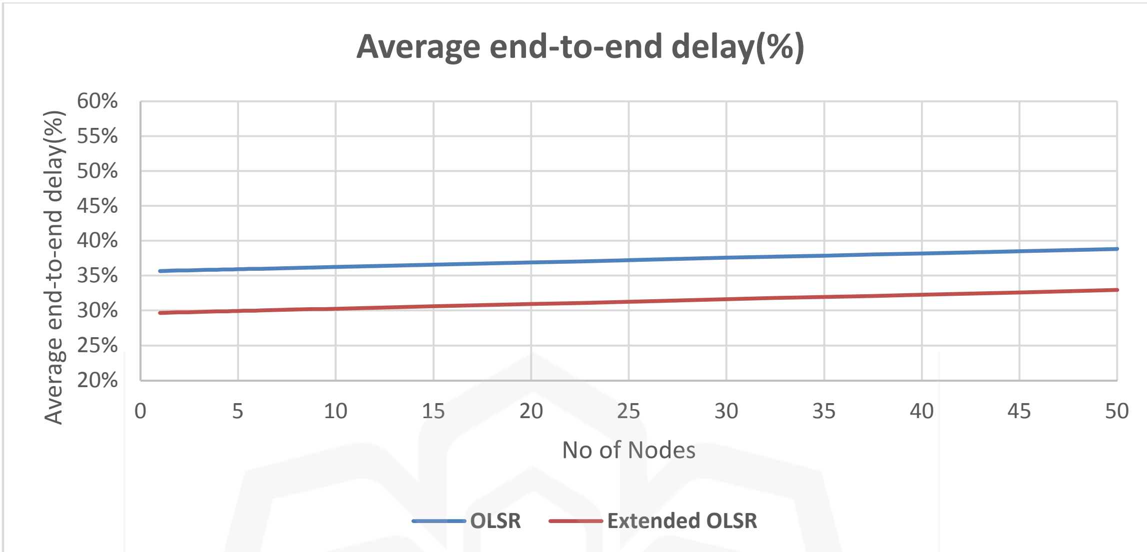


Figure 5.3 Average end-to-end delay vs. network size

The figures 5.4 to 5.8 show the comparison between the proposed routing protocol and the OLSR by using the average end-to-end delay as a function of traffic load with varying mobility speeds (0, 5, 10, 15, 20) respectively. In each figure the number of connections is shown in X coordinates, while the average end-to-end delay is shown in Y coordinates in percentage. It can be shown that the percentage of delay does not increase significantly as the traffic load increases. Moreover, the extended OLSR minimizes the end-to-end delay as compared to standard OLSR at low and high traffic load. This leads to the fact that the proposed routing protocol is able to select durable and stable routes even in high network load which as a result reduces path break frequency which results in delay reduction. Furthermore, as the mobility speed increases from no mobility to 20 m/s mobility the performance of the proposed routing protocol has not been affected. This indicates that the MPRs has been selected perfectly.

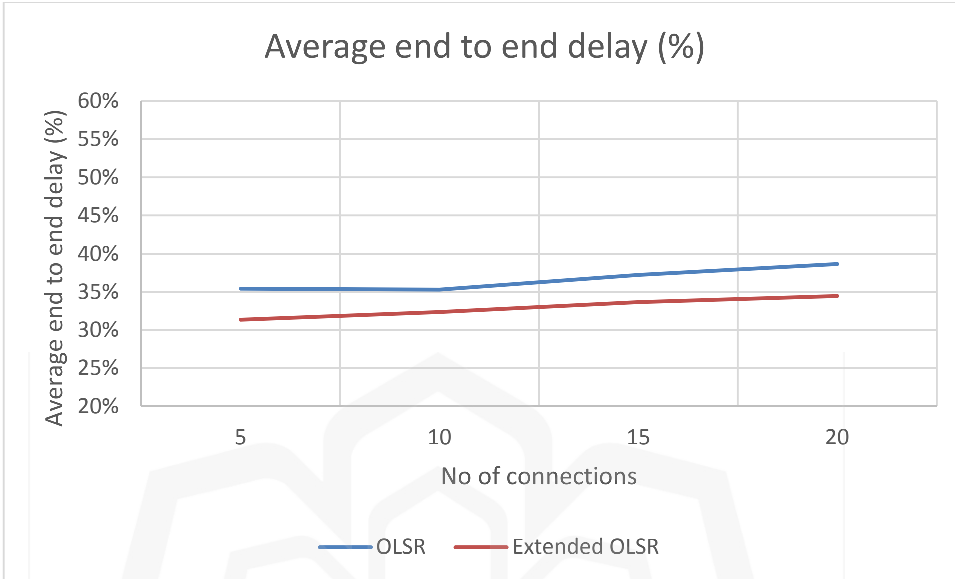


Figure 5.4 Average end-to-end delay vs. traffic load with 0 m/s mobility

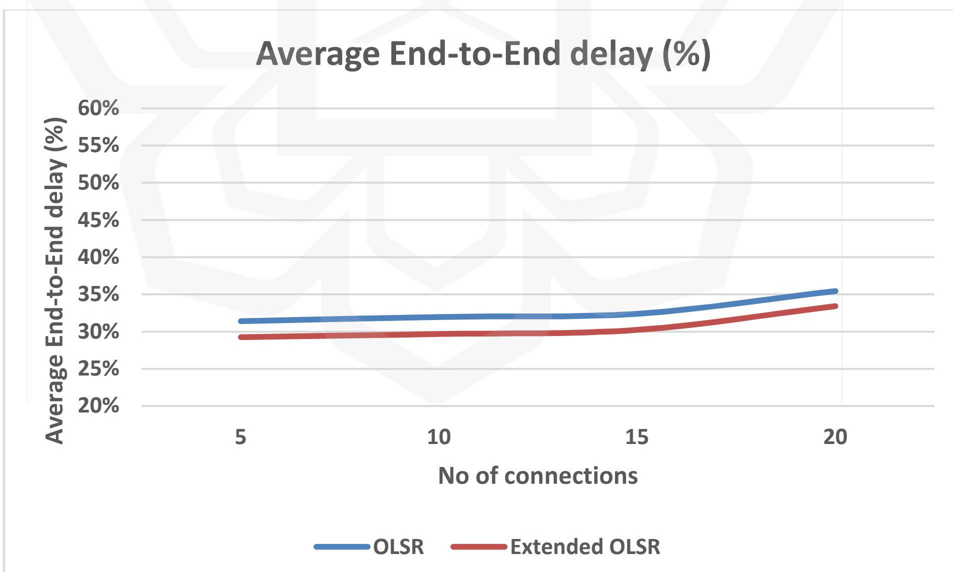


Figure 5.5 Average end-to-end delay vs. traffic load with 5 m/s mobility

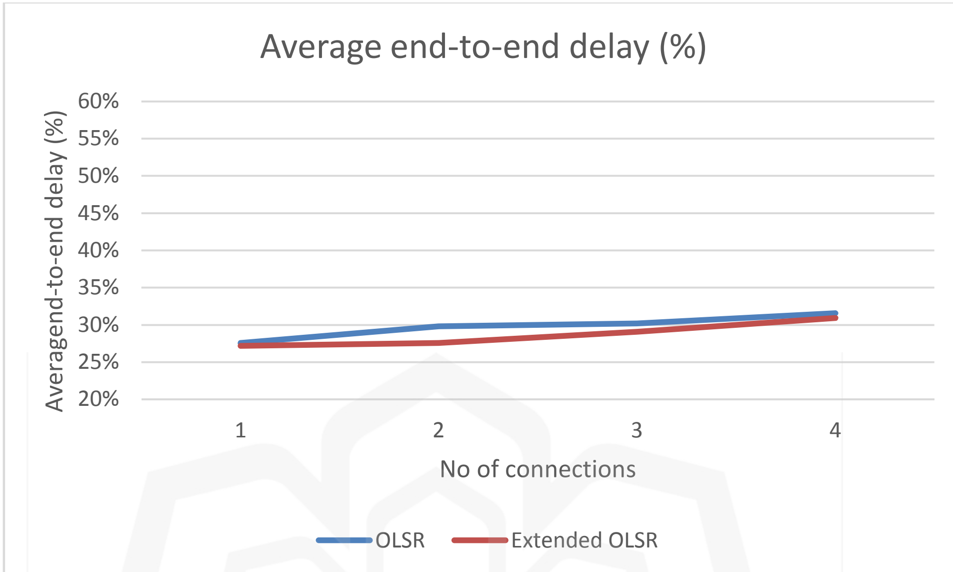


Figure 5.6 Average end-to-end delay vs. traffic load with 10 m/s mobility

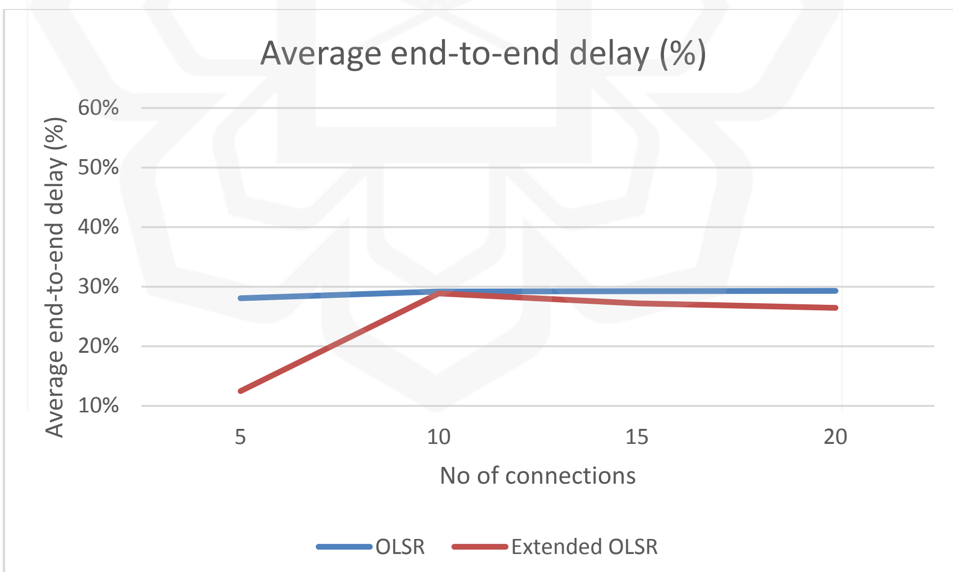


Figure 5.7 Average end-to-end delay vs. traffic load with 15 m/s mobility

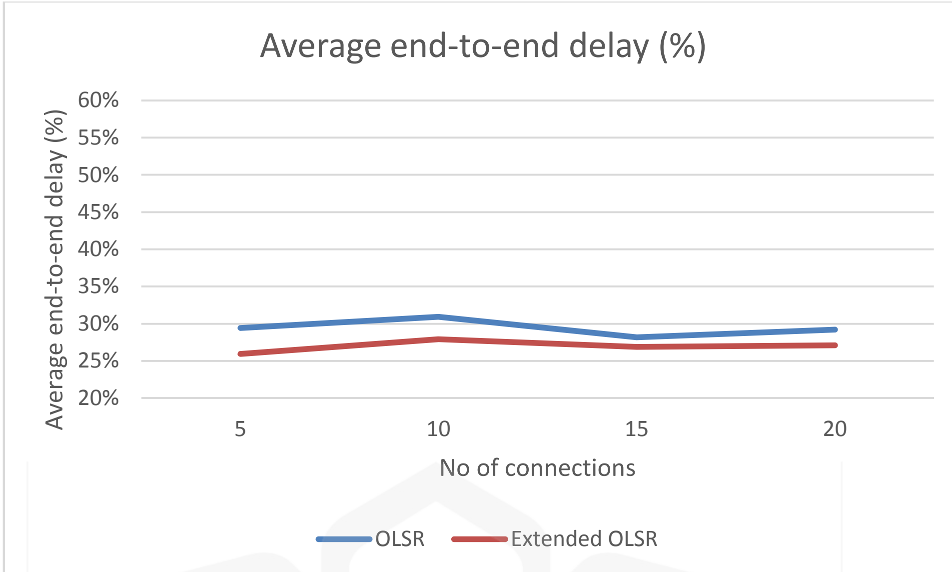


Figure 5.8 Average end-to-end delay vs. traffic load with 20 m/s mobility

Table 5.4 summarizes the performance evaluation results of the OLSR and the Extended OLSR in terms of Average end-to-end delay. The table shows the effect of changing mobility speed and traffic load on the delay. It can be found that with 0 m/s mobility the Extended OLSR outperforms OLSR by 4% on average. While Extended OLSR outperforms OLSR by 2 % on average at 5 m/s, 10 m/s, and 20 m/s mobility. It can be concluded that the proposed routing protocol achieves high improvement percentage compared to OLSR regardless of the increase of traffic load and mobility speed. The results show that the proposed routing protocol outperforms the OLSR routing protocol by 3% as an average in terms of average end-to-end delay.

Table 5.4 Average end-to-end delay vs. traffic load with varying mobility

Mobility speed	Evaluated protocols	No of traffic sources			
		5	10	15	20
0 m/s	OLSR	35%	35%	37%	39%
	Ex-OLSR	31%	32%	34%	34%
	Improvement (%)	4%	3%	3%	5%

5 m/s	OLSR	31%	32%	32%	35%
	Ex-OLSR	29%	30%	30%	33%
	Improvement (%)	2%	2%	2%	2%
10 m/s	OLSR	28%	30%	30%	32%
	Ex-OLSR	27%	28%	29%	31%
	Improvement (%)	1%	2%	1%	1%
15 m/s	OLSR	28%	29%	29%	29%
	Ex-OLSR	13%	29%	27%	26%
	Improvement (%)	15%	0%	2%	3%
20 m/s	OLSR	29%	31%	28%	29%
	Ex-OLSR	26%	28%	27%	27%
	Improvement (%)	3%	3%	1%	2%

5.3.2 Network Control Overhead

Figure 5.9 shows the comparison between the proposed routing protocol and OLSR by using the NCO as a function of node density. The number of nodes is shown in X coordinates, while the NCO is shown in Y coordinates in percentage. It is obvious that the larger the network size, the more the overhead of the network. Overhead goes on slight increase for both OLSR and the Extended OLSR as the network size increases. This is due to many factors:

- The exchange of control packets (e.g. routing packets, route requests, route replies) increases as the network size increases in order to update the routing tables.
- Furthermore, the exchange of control packets in order to update the MPR set.

The Extended OLSR minimizes the NCO as compared to standard OLSR at small and large network size. This is due to the extension of multicast that leads to decreasing the flooding of control packets as well as modifying the MPR algorithm that leads to guarantee of the stability of routes. From Table 5.5, it can be found that the proposed routing protocol achieves high improvement percentage compared to OLSR in both large network size and small network size. For network density of 5, 10, and 15 nodes, the proposed routing protocol improves the NCO by approximately 15%. While, for network density of 50 nodes, the proposed routing protocol improves the NCO by 9% compared to OLSR. This happens due to an increase in the total number of nodes. Results show that the proposed routing protocol outperforms the OLSR routing protocol by 14% as an average in terms of network control overhead.

Table 5.5 NCO vs. network size

Network density	5	10	15	20	25	30	35	40	45	50
OLSR	56%	60%	61%	63%	66%	68%	71%	74%	77%	79%
Extended OLSR	42%	45%	46%	47%	49%	54%	56%	61%	63%	70%
Improvement (%)	14%	15%	15%	16%	17%	14%	15%	14%	14%	9%

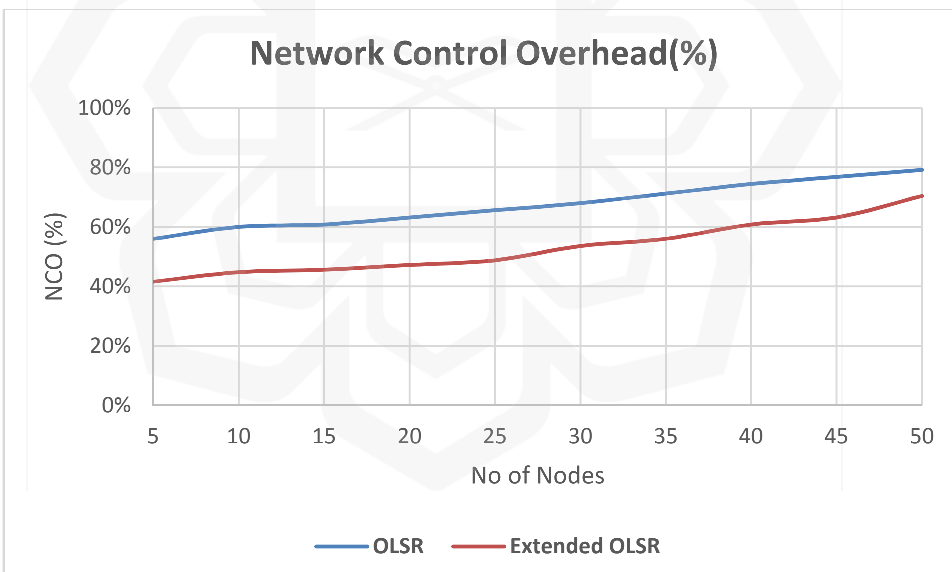


Figure 5.9 NCO vs. network size

The figures 5.10 to 5.14 show the performance comparison between the proposed routing protocol and OLSR in terms of the NCO as a function of traffic load with varying mobility speed (0, 5, 10, 15, 20) respectively. In each figure the number of connections is shown in X coordinates, while the NCO is shown in Y coordinates in percentage. It can be shown that overhead does not increase at the low traffic load. While it has slight increase for both evaluated routing protocols with medium traffic load. However, overhead has a significant increase at high traffic load. This is because the high increase of exchanging TC messages. On the other hand, the Extended OLSR minimizes the NCO as compared to standard OLSR at high traffic load and high mobility speed. This is because of fast response of the proposed routing protocol to the fast network changes. As the extension of multicast that leads to decreasing the flooding of control packets as well as modifying the MPR algorithm that leads to guarantee of the stability of routes.

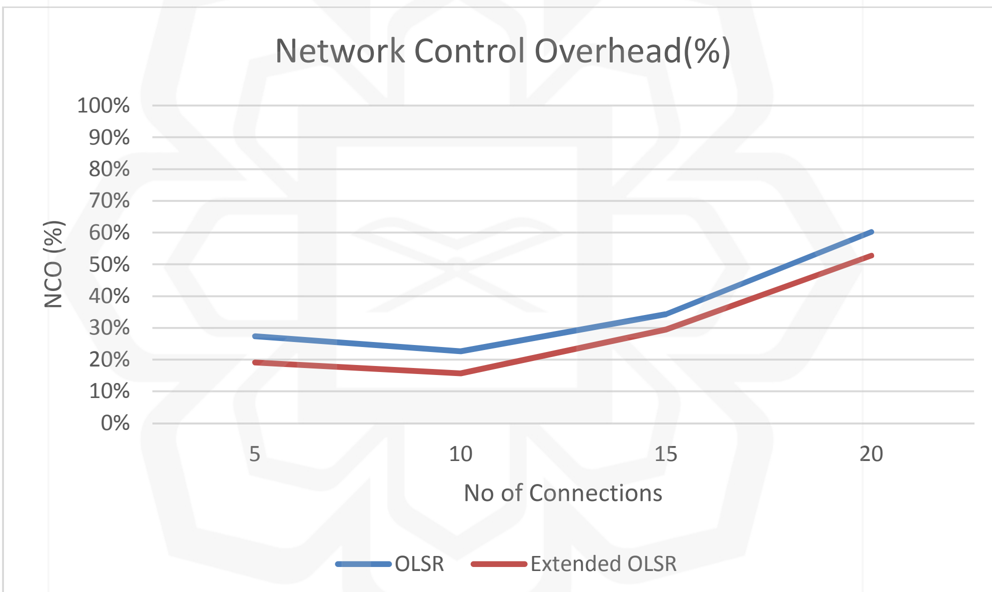


Figure 5.10 NCO vs. traffic load with 0 m/s mobility

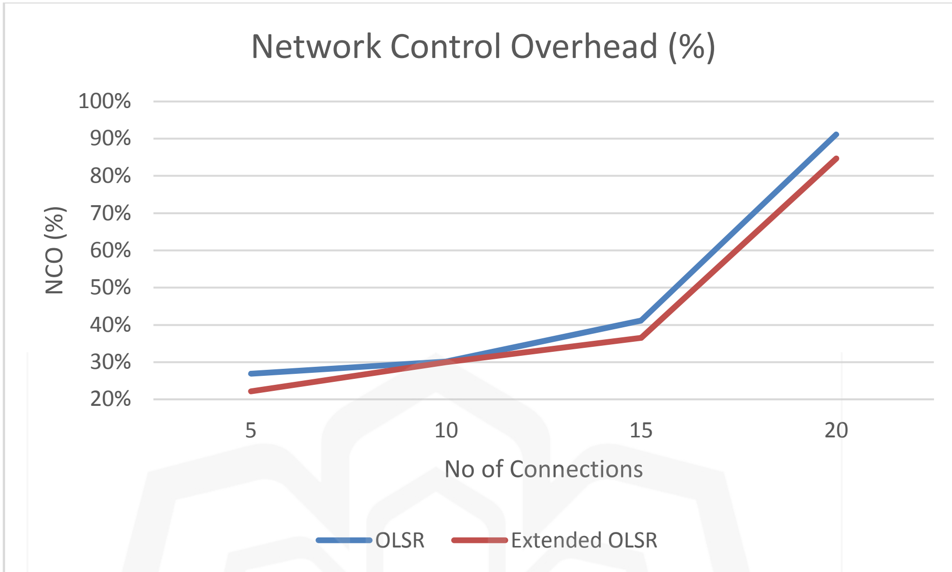


Figure 5.11 NCO vs. traffic load with 5 m/s mobility

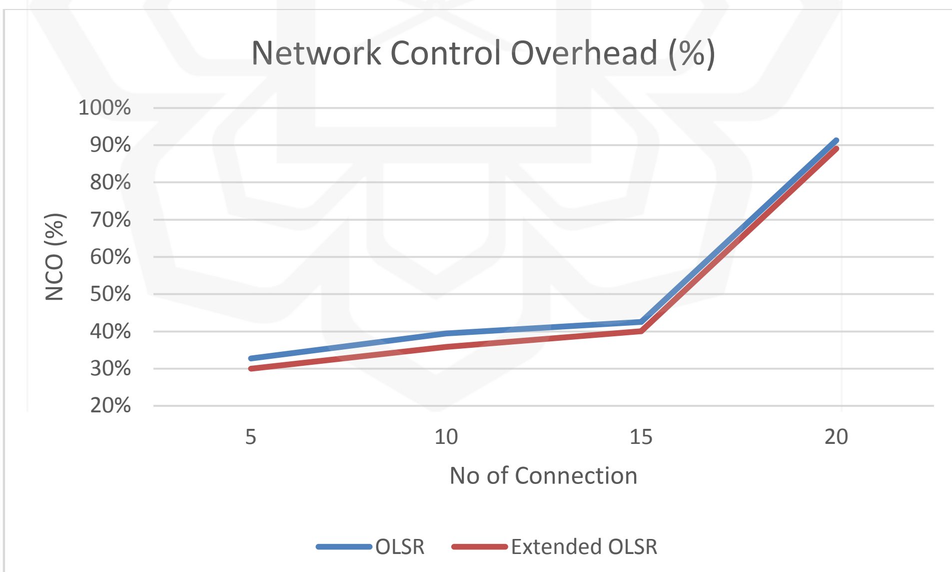


Figure 5.12 NCO vs. traffic load with 10 m/s mobility

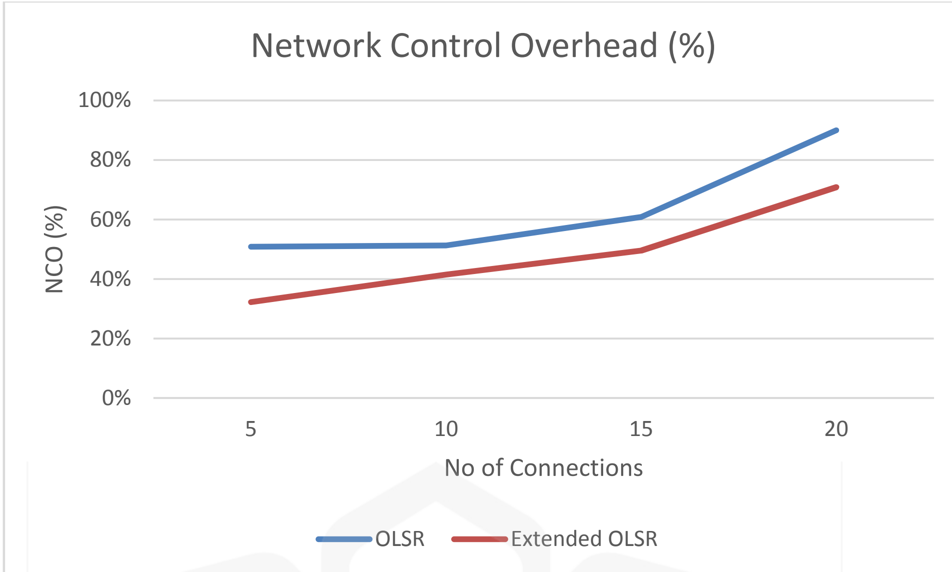


Figure 5.13 NCO vs. traffic load with 15 m/s mobility

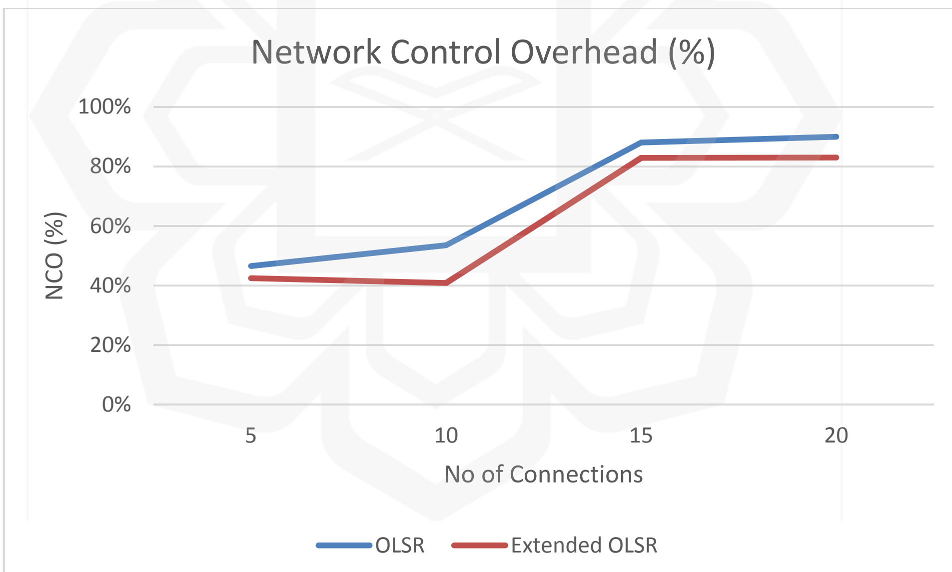


Figure 5.14 NCO vs. traffic load with 20 m/s mobility

From Table 5.6, summarizes the performance evaluation results of the OLSR and the Extended OLSR in terms of NCO. The table shows the effect of changing mobility speed and traffic load on the overhead. For mobility speed of 0 m/s, 5 m/s, and 10 m/s, the proposed routing protocol improves the NCO by approximately 7%, 4% and 3%

respectively. While, for mobility speed of 15 m/s and 20 m/s, the proposed routing protocol improves the NCO by 15% and 7% respectively compared to OLSR. This happens due to the ability of the proposed routing protocol to be more stable with the fast network changes. Results show that the proposed routing protocol outperforms the OLSR routing protocol by 7% as an average in terms of network control overhead.

Table 5.6 NCO vs. traffic load with varying speed mobility

Mobility speed	Evaluated protocols	No of traffic sources			
		5	10	15	20
0 m/s	OLSR	27%	23%	34%	60%
	Ex-OLSR	19%	16%	30%	53%
	Improvement (%)	8%	7%	4%	7%
5 m/s	OLSR	27%	30%	41%	91%
	Ex-OLSR	22%	30%	37%	85%
	Improvement (%)	5%	0%	4%	6%
10 m/s	OLSR	33%	39%	43%	91%
	Ex-OLSR	30%	36%	40%	89%
	Improvement (%)	3%	3%	3%	2%
15 m/s	OLSR	51%	51%	61%	90%
	Ex-OLSR	32%	41%	50%	71%
	Improvement (%)	19%	10%	11%	19%
20 m/s	OLSR	47%	54%	88%	90%
	Ex-OLSR	43%	41%	83%	83%
	Improvement (%)	4%	13%	5%	7%

5.3.3 Packet Delivery Ratio

Figure 5.15 shows the performance of the proposed routing protocol compared with OLSR in terms of PDR as a function of node density. The number of nodes is shown in X coordinates, while the PDR is shown in Y coordinates in percentage. It is obvious that the larger the network size, the more the PDR of the network. PDR goes on increase for the extended OLSR as the network size increases. This is due to the fact that with more nodes, it becomes easier to select a better MPR from neighboring nodes because the number of options grows. Moreover, from this figure it's obvious that the proposed routing protocol performs better than standard OLSR. This is due to the new modified MPR algorithm, which leads to the selection of MPR nodes that are more stable and robust. As a result, the proposed routing protocol decreases the frequency of link breaks when compared to existing techniques, and also decreases the frequency of queue overflow, which results in improving the PDR in the network. Table 5.7 shows that the proposed routing protocol slightly outperforms the OLSR routing protocol by 9% as an average in terms of PDR.

Table 5.7 Packet Delivery Ratio vs. network size

Network Density	5	10	15	20	25	30	35	40	45	50
OLSR	60%	58%	58%	57%	56%	56%	55%	54%	54%	53%
Extended OLSR	64%	64%	64%	64%	65%	65%	65%	66%	66%	66%
Improvement (%)	4%	6%	6%	7%	9%	9%	10%	12%	12%	13%

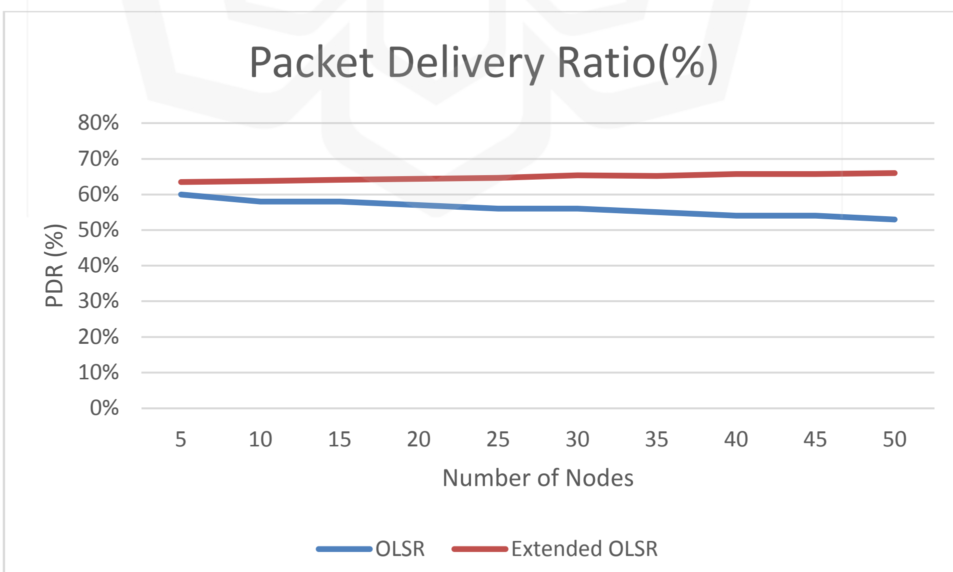


Figure 5.15 PDR vs. network size

The figures 5.16 to 5.20 show the performance of the proposed routing protocol compared with OLSR in terms of PDR as a function of traffic loads with varying mobility speeds (0, 5, 10, 15, 20) respectively. In each figure the number of traffic sources is shown in X coordinates, while the PDR is shown in Y coordinates in percentage. It can be noticed that with 0 m/s, 5 m/s, and 10 m/s mobility speed the PDR is stable and has not been affected by the node movement even in high traffic load. Moreover, the Extended OLSR outperforms the OLSR in terms of PDR at all mobility speeds as well as low and high traffic loads. This is because of the proposed route selection strategy that enables the Extended OLSR to keep the stability of the network in most of the conditions. In addition, the new modified MPR algorithm, which leads to the selection of MPR nodes that are more stable and robust. As a result, the proposed routing protocol decreases the frequency of link breaks when compared to existing techniques, and also decreases the frequency of queue overflow, which results in improving the PDR in the network. On the other hand, it can be noticed that with 15 m/s and 20 m/s mobility speed the PDR decreased for both OLSR and the Extended OLSR. This is due to the high mobility of the nodes that leads to fast repeated changes of the routing tables.

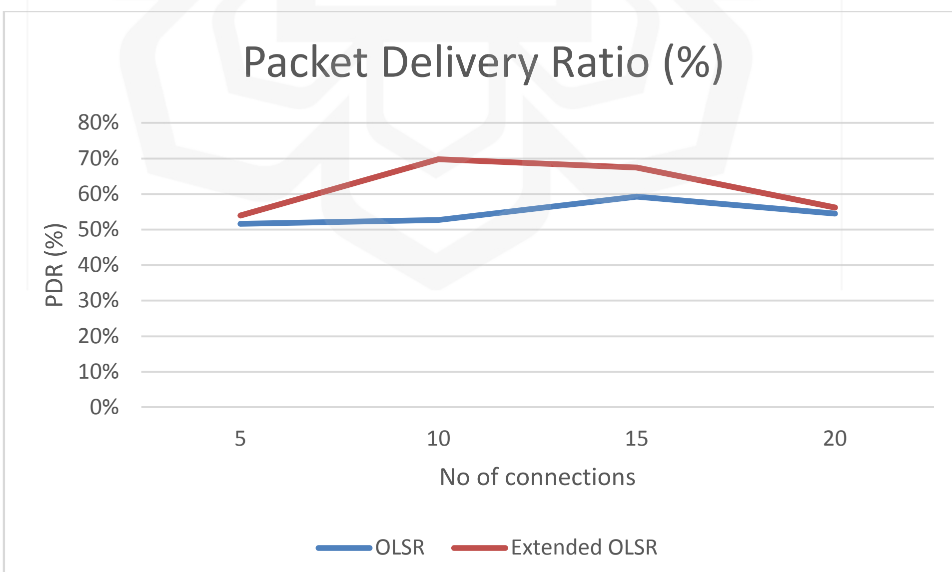


Figure 5.16 PDR vs. traffic load with 0 m/s mobility

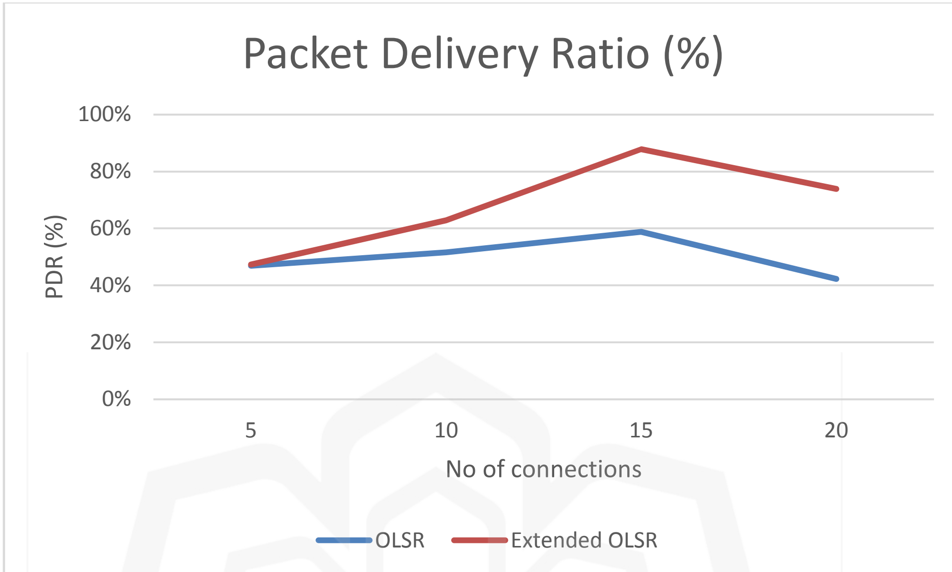


Figure 5.17 PDR vs. traffic load with 5 m/s mobility

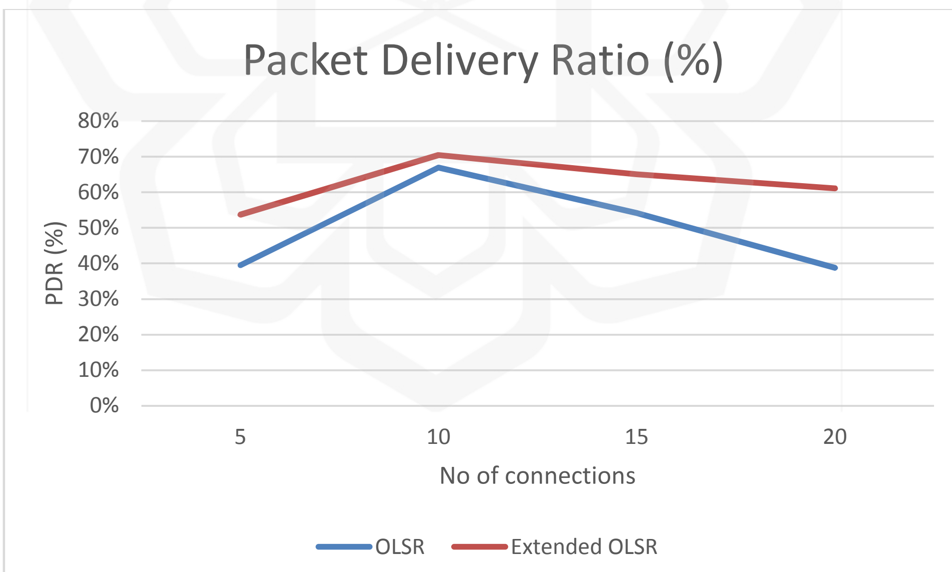


Figure 5.18 PDR vs. traffic load with 10 m/s mobility

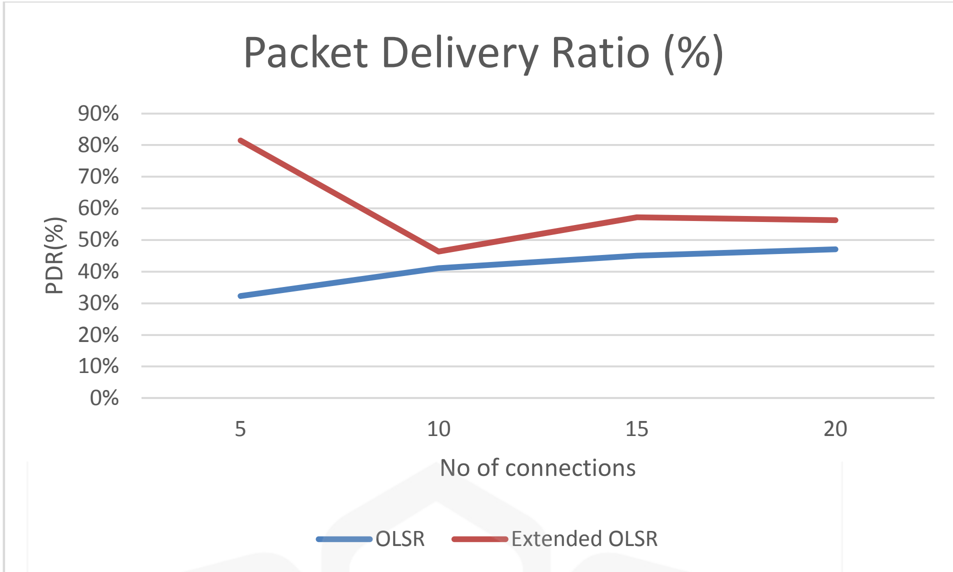


Figure 5.19 PDR vs. traffic load with 15 m/s mobility

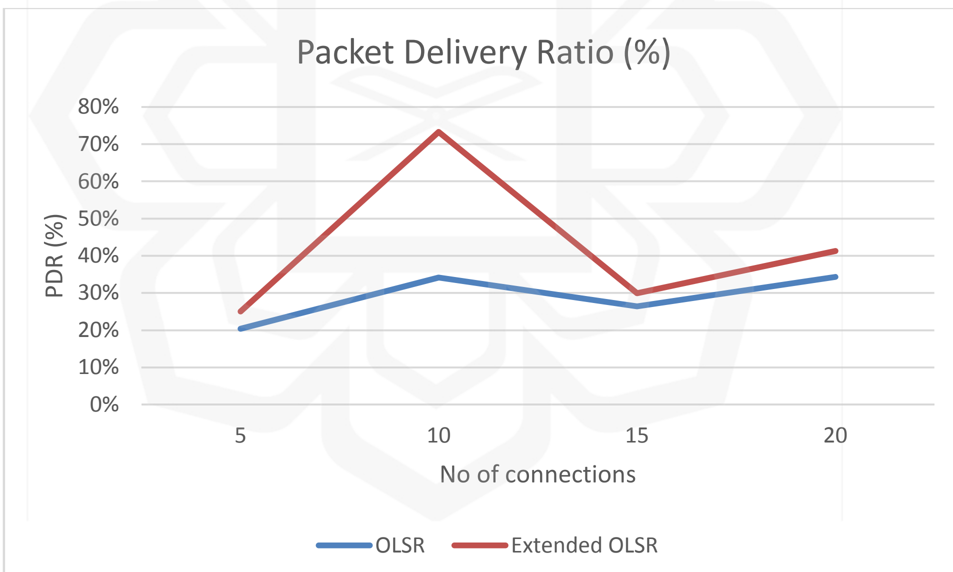


Figure 5.20 PDR vs. traffic load with 20 m/s mobility

From Table 5.8, summarizes the performance evaluation results of the OLSR and the Extended OLSR in terms of PDR. The table shows the effect of changing mobility speed and traffic load on the ratio of data delivery. It can be found that the Extended OLSR achieves a significant improvement over the OLSR in most of the network conditions. For mobility speed of 5 m/s, 15 m/s, and 20 m/s, the proposed routing protocol improves the PDR by approximately 18%, 21% and 14% respectively. While, for mobility speed of 0 m/s and 10 m/s, the proposed routing protocol improves the PDR by 7% and 15% respectively compared to OLSR. This happens due to the ability of the proposed routing protocol to be more stable with the fast network changes. Results show that the proposed routing protocol outperforms the OLSR routing protocol by 15% as an average in terms of packet delivery ratio.

Table 5.8 PDR vs. traffic load with varying speed mobility

Mobility speed	Evaluated protocols	No of traffic sources			
		5	10	15	20
0 m/s	OLSR	52%	53%	59%	54%
	Ex-OLSR	54%	70%	67%	56%
	Improvement (%)	2%	17%	8%	2%
5 m/s	OLSR	47%	52%	59%	42%
	Ex-OLSR	47%	63%	88%	74%
	Improvement (%)	0%	11%	29%	32%
10 m/s	OLSR	40%	67%	54%	39%
	Ex-OLSR	54%	70%	65%	61%
	Improvement (%)	14%	13%	11%	22%
15 m/s	OLSR	32%	41%	45%	47%
	Ex-OLSR	81%	46%	57%	56%
	Improvement (%)	49%	15%	12%	9%
20 m/s	OLSR	20%	34%	26%	34%
	Ex-OLSR	25%	73%	30%	41%
	Improvement (%)	5%	39%	4%	7%

5.3.4 Energy Consumption

Figure 5.21 describes the energy consumption to act as a function of the number of nodes. The number of nodes is shown in X coordinates, while the energy consumption is shown in Y coordinates in percentage. One of the major concerns of routing protocols for WCNs is preserving the battery life of all nodes. Despite the fact that energy consumption is not the key issue in the design of the proposed routing protocol. However, it is not necessary for it to consume any more power. Figure 5.6 shows that energy consumption rises as the number of nodes grows in both extended OLSR and OLSR. This is due to the reason that the distance between nodes decreases when network density increases. As a result, this leads to a relative increment in the amount of power that is consumed by the nodes in order to transmit and receive data packets. Furthermore, from Table 5.9, it can be noticed that the proposed routing protocol and standard OLSR approximately gives the same power consuming. As the difference between the percentages of energy consumption for both is less than 0.5% for network size from 5 to 25 nodes, while for network size from 30 to 50 nodes is about 1%. This is due to these two facts. The proposed routing protocol utilizes the network resources more than standard OLSR. However, it considers the residual energy of the nodes during the route calculation process. According to the previous mentioned facts, we can conclude that the proposed routing protocol achieves a balancing in power consuming.

Table 5.9 Energy consumption vs. network size

Network density	5	10	15	20	25	30	35	40	45	50
OLSR	50.57	51.15	51.72	52.29	52.87	53.62	54.01	54.67	55.16	55.74
Extended OLSR	50.65	51.30	51.96	52.61	53.26	54.15	54.56	55.37	55.87	56.52
Improvement (%)	0%	0%	0%	0%	0%	-1%	-1%	-1%	-1%	-1%

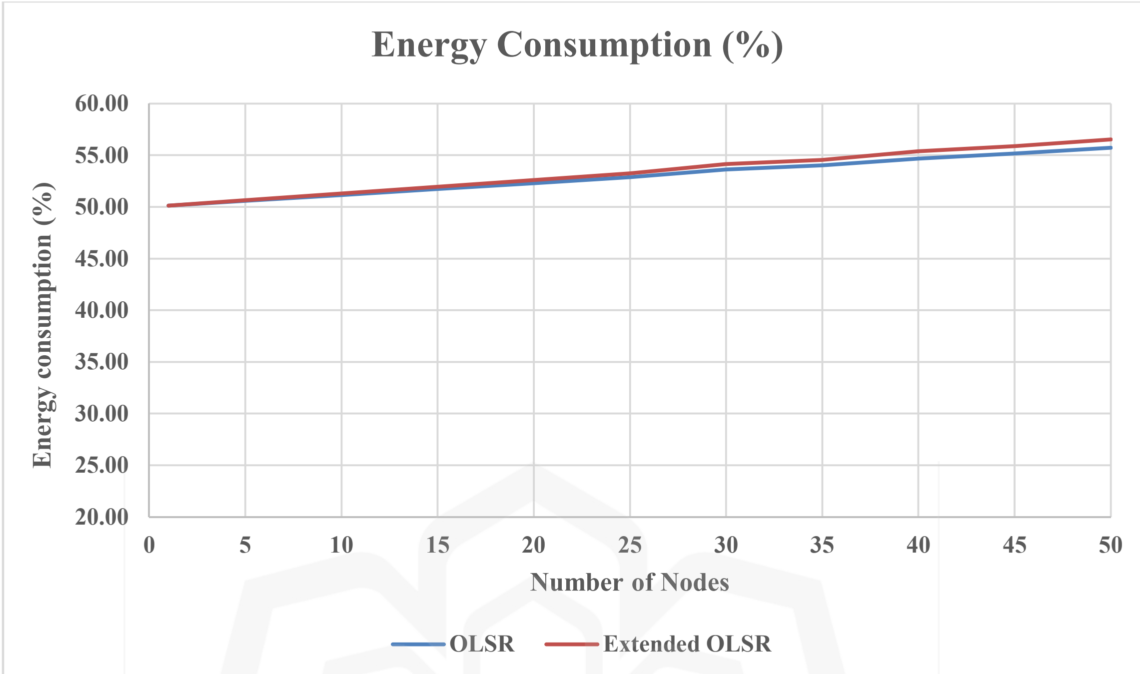


Figure 5.21 Energy consumption vs. network size

5.3.5 Discussion

The proposed routing protocol is able to select durable and stable routes which as a result reduces path break frequency which results in delay reduction. Therefore, the analysis of results shows that the proposed routing protocol outperforms OLSR routing protocol by 6% and 3% in terms of average end-to-end delay as a function of network density and traffic load with varying mobility speed respectively. However, the computation done by every node becomes more complex as the network size increases. Therefore, delay goes on slight increase for both OLSR and the extended OLSR.

The extension of multicast leads to decreasing the flooding of control packets as well as modifying the MPR algorithm that leads to guarantee of the stability of routes. Therefore, the proposed routing protocol minimizes the NCO as compared to standard OLSR at by 14% and 7% as a function of network density and traffic load with varying mobility speed respectively.

The new modified MPR algorithm leads to selecting more stable and durable MPR nodes. As a result, it reduces the chances of path break as compared to other approaches and also the chances of queue overflow are reduced in the proposed routing protocol, which results in improving the PDR in the network. Therefore, the proposed routing protocol outperforms the OLSR routing protocol in terms of PDR by 9% and 15% as a function of network density and traffic load with varying mobility speed respectively. Furthermore, with more nodes, it becomes easier to select a better MPR from neighboring nodes because the number of options grows. Therefore, PDR goes on increase for both OLSR and the extended OLSR at most of network conditions.

The proposed routing protocol utilizes the network resources more than standard OLSR. However, it considers the residual energy of the nodes during the route calculation process. Therefore, the proposed routing protocol and standard OLSR approximately gives the same power consuming. As the difference between the percentages of energy consumption for both is less than 0.5% for network size from 5 to 25 nodes while for network size from 30 to 50 nodes is about 1%.

5.4 CHAPTER SUMMARY

This chapter presents and discusses the actual performance evaluation of the proposed routing protocol in comparison with the standard OLSR protocol. Firstly, simulation parameters and simulation environment details are specified such that all simulation scenarios can be fairly compared. Lastly, the simulation scenarios and critical analysis of results are performed to explore the reliability and efficiency of the proposed routing protocol.

CHAPTER SIX

CONCLUSIONS AND FUTURE WORK RECOMMENDATIONS

6.1 SUMMARY

This section outlines the objectives of this research work and discusses how these objectives are fulfilled. Moreover, the closing remarks of this research work are also discussed in which it is concluded that the research work has achieved its objectives as described in Section 1.4 of this thesis according to the work presented throughout the chapters.

The first objective is to investigate the various routing protocols that used for WCNs and identify the main factors that affect the performance of these protocols. This objective is achieved by conducting a comparative study between four prominent MANET routing protocols over WCNs and highlighting the strengths and limitations of these protocols. The protocols are Babel, BMX6, OLSR, and OLSRv2. From investigation, it has been discovered that, these routing protocols suffer from stability and scalability issues when applied on WCNs due to the heterogeneous characteristics of these networks.

The second and third objectives are to design and implement an enhanced routing protocol for WCNs in terms of stability and scalability. To achieve this objective, an enhancement of the OLSR routing protocol is proposed for WCNs. Based on the investigations, OLSR routing protocol is selected to be enhanced for WCNs in order to meet the standards of efficiency in terms of stability and scalability. The proposed routing protocol include three enhancement components: multicasting expansion, MPR selection based on AHP, and a composite metric for optimal route selection.

Finally, the performance of the proposed routing protocol is evaluated and compared with the OLSR routing protocol using simulation, which is the last objective in this research. The performance of the proposed routing protocol is measured using four performance metrics: average end-to-end delay, NCO, PDR, and energy consumption in terms of network density and traffic load with varying mobility speeds. Results show that the proposed routing protocol outperforms the OLSR protocol in terms of average end-to-end delay, NCO, and PDR by 5%, 11%, and 12% respectively. While, the energy consumption for the proposed routing protocol is approximately similar to the standard OLSR protocol.

6.2 RESEARCH CONTRIBUTION

In the following, the main contributions of this research work are listed:

I. Multicast traffic is expanded to the OLSR routing protocol in WCNs in order to decrease the overhead caused by flooding as OLSR uses unicast traffic. The multicast operations are composed of two phases: the tree initialization phase and the tree maintenance phase.

II. A modified strategy is proposed for the MPR selection algorithm of the OLSR routing protocol to maintain a stable topology using a multi-criteria decision making (MCDM). There are several sub-disciplines of operations research called MCDMs, which are devoted to finding the best possible outcomes in a wide range of difficult situations. Multiple criteria are taken into account simultaneously in the MCDM method to create a flexible decision making process. Multiple metrics can be weighted according to MCDM: AHP. Each node establishes an MPR set based on a single cost determined with the given metrics.

III. A composite metric is proposed using multiple parameters in order to ensure good knowledge of the status of links that can guarantee picking the most stable links in the network. The aim of the new proposed metric is to make finding the best routes extremely easier with the dynamic topology of WCNs. In addition, it aims to avoid the use of hop count metric which is used in the OLSR protocol and is not suitable to the dynamic link characteristics of WCNs.

6.3 RECOMMENDATIONS AND FUTURE WORK

The proposed routing protocol shows promising outcomes with WCNs. On the other hand, there are still some directions that need to be investigated as future work. This section outlines the relevant interesting research challenges and future work directions that can be explored. Future related work can be conducted in the following directions:

I. Evaluating the performance of the proposed routing protocol in real environment using testbeds.
II. Increasing the number of base stations in the network and evaluating the scalability of the proposed routing protocol.
III. Studying how to improve the energy consumption all over the network.
IV. Increasing the input parameters that can be used to evaluate the proposed routing protocol such as speed.
V. Investigating the security issues related to the proposed routing protocol.

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APPENDIX A: TCL SCENARIOS

```
set val(chan)    Channel/WirelessChannel
set val(prop)    Propagation/TwoRayGround
set val(ant)     Antenna/OmniAntenna
set val(ll)      LL
set val(ifq)     Queue/DropTail/PriQueue
set val(ifqlen)  50
set val(netif)   Phy/WirelessPhy
set val(mac)     Mac/802_11
set val(rp)      MOLSR
set val(nn)      51
set val(x)       1000
set val(y)       1000
set val(simtim)       172
set pckstr            0
set val(Speed)          20
set val(traffic)        UDP
set ns                [new Simulator]
Agent/MOLSR set use_mac_ true
Agent/MOLSR set debug_ false
Agent/MOLSR set willingness 3
Agent/MOLSR set hello_ival_ 2
Agent/MOLSR set tc_ival_ 5
set tracefd           [open MOLSR.tr w]
set namtrace          [open MOLSR.nam w]
$ns trace-all $tracefd
$ns namtrace-all-wireless $namtrace $val(x) $val(y)
set topo [new Topography]
$topo load_flatgrid $val(x) $val(y)
set god_ [create-god $val(nn) ]
        $ns node-config -adhocRouting $val(rp) \
                   -llType $val(ll) \
                   -macType $val(mac) \
                   -ifqType $val(ifq) \
                   -ifqLen $val(ifqlen) \
                   -antType $val(ant) \
                   -propType $val(prop) \
                   -phyType $val(netif) \
                   -channelType $val(chan) \
                   -topoInstance $topo \
              -wiredRouting OFF \
                   -agentTrace ON \
                   -routerTrace ON \
                   -macTrace OFF \
              -movementTrace OFF \
              -energyModel "EnergyModel" \
              -rxPower 1.0 \
              -txPower 2.0 \
```

```
                   -initialEnergy 10 \
              -sleepPower 0.5 \
              -transitionPower 0.2 \
              -transitionTime 0.001 \
              -idlePower 0.05
      $ns node-config  -energyModel EnergyModel \
                      -rxPower 1.0 \
                 -txPower 2.0 \
                 -initialEnergy 10 \
                 -sleepPower 0.5 \
                 -transitionPower 0.2 \
                 -transitionTime 0.001 \
                 -idlePower 0.05
       for {set i 0} {$i < $val(nn) } { incr i } {
             set node_($i) [$ns node]
       }
$node_(0) set Z_ 0.0
$node_(0) set Y_ 349
$node_(0) set X_ 686
$node_(1) set Z_ 0.0
$node_(1) set Y_ 339
$node_(1) set X_ 694
$node_(2) set Z_ 0.0
$node_(2) set Y_ 346
$node_(2) set X_ 734
$node_(3) set Z_ 0.0
$node_(3) set Y_ 431
$node_(3) set X_ 739
$node_(4) set Z_ 0.0
$node_(4) set Y_ 309
$node_(4) set X_ 741
$node_(5) set Z_ 0.0
$node_(5) set X_ 698
$node_(5) set Y_ 249
$node_(6) set Z_ 0.0
$node_(6) set X_ 660
$node_(6) set Y_ 193
$node_(7) set Z_ 0.0
$node_(7) set X_ 731
$node_(7) set Y_ 167
$node_(8) set Z_ 0.0
$node_(8) set X_ 732
$node_(8) set Y_ 221
$node_(9) set Z_ 0.0
$node_(9) set X_ 755
$node_(9) set Y_ 248
$node_(10) set Z_ 0.0
$node_(10) set X_ 730
$node_(10) set Y_ 94
$node_(11) set Z_ 0.0
$node_(11) set X_ 775
$node_(11) set Y_ 124
```

```
$node_(12) set Z_ 0.0
$node_(12) set X_ 766
$node_(12) set Y_ 122
$node_(13) set Z_ 0.0
$node_(13) set X_ 758
$node_(13) set Y_ 164
$node_(14) set Z_ 0.0
$node_(14) set X_ 843
$node_(14) set Y_ 135
$node_(15) set Z_ 0.0
$node_(15) set X_ 799
$node_(15) set Y_ 226
$node_(16) set Z_ 0.0
$node_(16) set X_ 843
$node_(16) set Y_ 212
$node_(17) set Z_ 0.0
$node_(17) set X_ 881
$node_(17) set Y_ 185
$node_(18) set Z_ 0.0
$node_(18) set X_ 858
$node_(18) set Y_ 256
$node_(19) set Z_ 0.0
$node_(19) set X_ 881
$node_(19) set Y_ 235
$node_(20) set Z_ 0.0
$node_(20) set X_ 278
$node_(20) set Y_ 488
$node_(21) set Z_ 0.0
$node_(21) set X_ 286
$node_(21) set Y_ 517
$node_(22) set Z_ 0.0
$node_(22) set X_ 322
$node_(22) set Y_ 473
$node_(23) set Z_ 0.0
$node_(23) set X_ 283
$node_(23) set Y_ 530
$node_(24) set Z_ 0.0
$node_(24) set X_ 332
$node_(24) set Y_ 525
$node_(25) set Z_ 0.0
$node_(25) set X_ 324
$node_(25) set Y_ 623
$node_(26) set Z_ 0.0
$node_(26) set X_ 344
$node_(26) set Y_ 641
$node_(27) set Z_ 0.0
$node_(27) set X_ 345
$node_(27) set Y_ 573
$node_(28) set Z_ 0.0
$node_(28) set X_ 397
$node_(28) set Y_ 566
$node_(29) set Z_ 0.0
```

```
$node_(29) set X_ 391
$node_(29) set Y_ 561
$node_(30) set Z_ 0.0
$node_(30) set X_ 40
$node_(30) set Y_ 579
$node_(31) set Z_ 0.0
$node_(31) set X_ 8
$node_(31) set Y_ 515
$node_(32) set Z_ 0.0
$node_(32) set X_ 48
$node_(32) set Y_ 518
$node_(33) set Z_ 0.0
$node_(33) set X_ 60
$node_(33) set Y_ 465
$node_(34) set Z_ 0.0
$node_(34) set X_ 90
$node_(34) set Y_ 548
$node_(35) set Z_ 0.0
$node_(35) set X_ 450
$node_(35) set Y_ 375
$node_(36) set Z_ 0.0
$node_(36) set X_ 157
$node_(36) set Y_ 271
$node_(37) set Z_ 0.0
$node_(37) set X_ 199
$node_(37) set Y_ 278
$node_(38) set Z_ 0.0
$node_(38) set X_ 193
$node_(38) set Y_ 248
$node_(39) set Z_ 0.0
$node_(39) set X_ 237
$node_(39) set Y_ 260
$node_(40) set Z_ 0.0
$node_(40) set X_ 99
$node_(40) set Y_ 456
$node_(41) set Z_ 0.0
$node_(41) set X_ 82
$node_(41) set Y_ 370
$node_(42) set Z_ 0.0
$node_(42) set X_ 53
$node_(42) set Y_ 429
$node_(43) set Z_ 0.0
$node_(43) set X_ 115
$node_(43) set Y_ 385
$node_(44) set Z_ 0.0
$node_(44) set X_ 73
$node_(44) set Y_ 365
$node_(45) set Z_ 0.0
$node_(45) set X_ 578
$node_(45) set Y_ 621
$node_(46) set Z_ 0.0
$node_(46) set X_ 610
```

```
$node_(46) set Y_ 594
$node_(47) set Z_ 0.0
$node_(47) set X_ 702
$node_(47) set Y_ 652
$node_(48) set Z_ 0.0
$node_(48) set X_ 657
$node_(48) set Y_ 662
$node_(49) set Z_ 0.0
$node_(49) set X_ 664
$node_(49) set Y_ 579
$node_(50) set Z_ 0.0
$node_(50) set X_ 500
$node_(50) set Y_ 500
      for {set i 0} {$i < $val(nn) } {incr i } {
            $node_($i) color black
            $ns at 0.0 "$node_($i) color odourless"
            $ns at 0.0 "$node_($i) add-mark m10 pink hexagon"
      }
    for {set i 0} {$i < $val(nn) } {incr i } {
      }
for {set i $val(nn)} {$i < $val(nn) } {incr i } {
$ns at 0.0 "[$node_($i) set ragent_] id"
}
for {set i 0} {$i < $val(nn)} { incr i } {
$ns initial_node_pos $node_($i) 30
}
for {set i 0} {$i < $val(nn) } { incr i } {
    $ns at $val(simtim) "$node_($i) reset";
}
$ns at 0.0000001 "destination"
$ns at 0.0000001 "$node_(50) label \" BS \""
$ns at 0.0000001 "$node_(50) color red"
$ns at 0.0000001 "$node_(50) add-mark m1 red circle"
$ns at 0.0000001 "$node_(50) add-mark m2 red square"
$ns at 0.0000001 "$node_(50) add-mark m3 red hexagon"
$ns at 0.0000001 "$ns trace-annotate \"      \""
$ns at 0.0000001 "$ns trace-annotate \" A Network , it consists
of 50 - Mobile Nodes and 1- Base Station.  \""
$ns at 0.0000001 "$ns trace-annotate \"      \""
$ns at 0.5 "$ns trace-annotate \" Calculate the energy for all
nodes.  \""
$ns at 0.5 "$ns trace-annotate \"          \""
$ns at 2.0 "$ns trace-annotate \" Select the source and
Destination nodes from the network  \""
$ns at 2.0 "$ns trace-annotate \"          \""
$ns at 3.5 "$ns trace-annotate \" Broadcast the hello packets
with Residual Energy,life time (AoI) and Node Degree and also
calculate the link cost/weight.  \""
$ns at 3.5 "$ns trace-annotate \"          \""
$ns at 5.0 "$ns trace-annotate \" Select the MPR (Multi-Point
Relays) set based on the Analytical Hierarchy Process (AHP)
algorithm process \""
```

```
$ns at 5.0 "$ns trace-annotate \"          \""
$ns at 6.5 "$ns trace-annotate \" Select the Efficient route
between the source and Destination nodes by using the MOLSR
routing protocol. \""
$ns at 6.5 "$ns trace-annotate \"          \""
$ns at 8.0 "$ns trace-annotate \" Perform the packet transmission
between the source and Destination nodes. \""
$ns at 8.0 "$ns trace-annotate \"          \""
$ns at 2.0 "$node_(0) label \" Source \""
$ns at 2.0 "$node_(0) color blue"
$ns at 2.0 "$node_(0) add-mark m1 blue hexagon"
$ns at 2.0 "$node_(0) add-mark m1 blue hexagon"
$ns at 2.0 "$node_(0) add-mark m1 blue hexagon"
$ns at 2.0 "$node_(1) label \" Destination \""
$ns at 2.0 "$node_(1) color blue"
$ns at 2.0 "$node_(1) add-mark m1 blue hexagon"
$ns at 2.0 "$node_(1) add-mark m1 blue hexagon"
$ns at 2.0 "$node_(1) add-mark m1 blue hexagon"
#$ns at 0.5 "destination1"
#exec awk -f Energy.awk MOLSR.tr > MOLSR_Energy.tr
#exec awk -f Delay.awk MOLSR.tr > MOLSR_Delay.tr
#exec awk -f PDR.awk MOLSR.tr > MOLSR_PDR.tr
source cbr20c
proc destination1 {} {
     source cbr
     set startval         1.3
     set startval1        3.5
     set startval2        0.5
     set startval3        3.5
     set startval4        5.0
     set startval5        6.5
     set startval6        8.0
     set stopval           2.5
     set stopval1           295
     cbrval $startval $stopval $startval1 $stopval1
     energycalc $startval2
     Broadcast $startval3
     relay $startval4
     routeSelection $startval5
     packetTrans $startval6
}
for {set i 0} {$i <  $val(nn) } { incr i } {
     set xx [expr {int(rand()*$val(x))}]
     set yy [expr {int(rand()*$val(y))}]
     $node_($i) set X_ $xx
     $node_($i) set Y_ $yy
     set nodeXpos($i) $xx
     set nodeYpos($i) $yy
     set nodeZpos($i) 0.0
}
proc do {body keyword expression} {
    if {$keyword eq "while"} {
```

```
       set expression "!($expression)"
    } elseif {$keyword ne "until"} {
       return -code error "unknown keyword \"$keyword\": must be
until or while"
    }
    set condition [list expr $expression]
    while 1 {
       uplevel 1 $body
       if {[uplevel 1 $condition]} {
          break
       }
    }
    return
}
set randnum 0
proc RandomInteger2 {max} {
    return [expr {int(rand()*$max)}]
}
for {set iter 0} {$iter < 10 } { incr iter } {
       set generatedrand($iter) -1
}
for {set iter 0} {$iter < 10 } { incr iter } {
do {
     set firsttime 1
     set randnum [RandomInteger2 29]
     for {set i 0 } {$i < [expr {$i && $firsttime}]} {incr i} {
                     if{$generatedrand($i) == $randnum} {
                         set firsttime 0
                     }
               }
   } while {!$firsttime}
set generatedrand($iter) $randnum
set Xpos($iter)  $nodeXpos($randnum)
set Ypos($iter)  $nodeYpos($randnum)
set Zpos($iter)  $nodeZpos($randnum)
}
for {set iter 0} {$iter <  $val(nn)} {incr iter} {
      set X_pos1 [expr $Xpos(0) - $nodeXpos($iter)]
      set Y_pos1 [expr $Ypos(0) - $nodeYpos($iter)]
      set distmean1($iter) [expr {abs($X_pos1)} + {abs($Y_pos1)}]
      set X_pos2 [expr $Xpos(1) - $nodeXpos($iter)]
      set Y_pos2 [expr $Ypos(1) - $nodeYpos($iter)]
      set distmean2($iter) [expr {abs($X_pos2)} + {abs($Y_pos2)}]
      set X_pos3 [expr $Xpos(2) - $nodeXpos($iter)]
      set Y_pos3 [expr $Ypos(2) - $nodeYpos($iter)]
      set distmean3($iter) [expr {abs($X_pos3)} + {abs($Y_pos3)}]
}
set listsize1 0
set listsize2 0
set listsize3 0
for {set iter 0} {$iter <  $val(nn)} {incr iter} {
```

```
if [expr {$distmean1($iter) < $distmean2($iter)} &&
{$distmean1($iter) < $distmean3($iter)}] {
                  set list1Xpos($listsize1) $nodeXpos($iter)
                  set list1Ypos($listsize1) $nodeYpos($iter)
            set nodes1($listsize1) $iter
            set listsize1 [incr listsize1]
} elseif [expr {$distmean2($iter) < $distmean1($iter)} &&
{$distmean2($iter) < $distmean3($iter)}] {
            set list2Xpos($listsize2) $nodeXpos($iter)
                  set list2Ypos($listsize2) $nodeYpos($iter)
            set nodes2($listsize2) $iter
            set listsize2 [incr listsize2]
} else {
                  set list3Xpos($listsize3) $nodeXpos($iter)
                  set list3Ypos($listsize3) $nodeYpos($iter)
            set nodes3($listsize3) $iter
            set listsize3 [incr listsize3]
}
}
set centroidXpos1 0
set centroidYpos1 0
for {set iter 0} {$iter < $listsize1} {incr iter} {
           set centroidXpos1 [expr $centroidXpos1 +
$list1Xpos($iter)]
           set centroidYpos1 [expr $centroidYpos1 +
$list1Ypos($iter)]
}
set centroidXpos1 [expr $centroidXpos1 /$listsize1]
set centroidYpos1 [expr $centroidYpos1 /$listsize1]
set centroidXpos2 0
set centroidYpos2 0
for {set iter 0} {$iter < $listsize2} {incr iter} {
           set centroidXpos2 [expr $centroidXpos1 +
$list2Xpos($iter)]
           set centroidYpos2 [expr $centroidYpos1 +
$list2Ypos($iter)]
}
set centroidXpos2 [expr $centroidXpos2 /$listsize1]
set centroidYpos2 [expr $centroidYpos2 /$listsize1]
set centroidXpos3 0
set centroidYpos3 0
for {set iter 0} {$iter < $listsize3} {incr iter} {
           set centroidXpos3 [expr $centroidXpos3 +
$list3Xpos($iter)]
           set centroidYpos3 [expr $centroidYpos3 +
$list3Ypos($iter)]
}
set centroidXpos3 [expr $centroidXpos3 /$listsize1]
set centroidYpos3 [expr $centroidYpos3 /$listsize1]
proc destination {} {
      global ns val node_
      set time 1.0
```

```
      set now [$ns now]
      for {set i 0} {$i< $val(nn)-1 } {incr i} {
            set xx [expr rand()*1000]
            set yy [expr rand()*1000]
           $ns at $now "$node_($i) setdest $xx $yy $val(Speed)"

      }
}
$ns at $val(simtim) "$ns nam-end-wireless $val(simtim)"
$ns at $val(simtim) "stop"
$ns at [expr $val(simtim) + 10.01] "puts \"end simulation\" ; $ns
halt"
proc stop {} {
    global ns tracefd namtrace
    $ns flush-trace
exec awk -f Energy.awk MOLSR.tr > MOLSR_Energy20.tr
exec awk -f Delay.awk MOLSR.tr > MOLSR_Delay20.tr
exec awk -f PDR.awk MOLSR.tr > MOLSR_PDR20.tr
    close $tracefd
    close $namtrace
exec nam MOLSR.nam &
exec ./xgraph MOLSR_Delay20.tr -t "Delay Graph" -x
"No.of.MobileNodes" -y "Delay" -bg gray &
#exec ./xgraph -bar -brw 0.5 MOLSR_PDR5.tr -t "PDR Graph" -x
"No.of.MobileNodes" -y "Mobile" -bg white &
exec ./xgraph MOLSR_Energy20.tr -t "Energy Graph" -x
"No.of.MobileNodes" -y "Energy" -bg pink &
}
$ns run
```

APPENDIX B: AWK SCRIPTS

```
#################################################################
###
#         AWK Script to calculate Average End-to-End Delay
#
#              Works with AODV, DSDV, DSR and OLSR             #
#################################################################

BEGIN {
        for (i in send) {
                send[i] = 0;
        }
        for (i in recv) {
                recv[i] = 0;
        }
        delay = avg_delay = 0
start_time = 0;
send_time = 0;
recv_time = 0;
fwd_time = 0;
}
{
        if ($2 != "-t") {
                 event = $1;
                 time = $2;
            printtime =$2;
                 if (event == "+" || event == "-") node_id = $3;
                 if (event == "r" || event == "d") node_id = $4;
                 flow_id = $8;
                 pkt_id = $6;
         }
        if ($2 == "-t") {
                event = $1;
                time = $3;
                node_id = $5;
                flow_id = $39;
                pkt_id = $41;
        }
        if ((event == "s")) {
                send[pkt_id] = time;
           send_time = time;
        }
        if (event == "r") {
                recv[pkt_id] = time;
           recv_time = time;
        }
        if (event == "f") {
                frwd[pkt_id] = time;
```

```
            fwd_time = time;
        }
if (printtime > 0) {
delay = (recv_time+fwd_time) - (send_time);
printf("%f\t%10g\n",printtime,delay);
}
}
END {
}

#################################################################
###
#         AWK Script to calculate Packet Delivery Ratio
#
#              Works with AODV, DSDV, DSR and OLSR            #
#################################################################

BEGIN {
        sendLine = 0;
        recvLine = 0;
        fowardLine = 0;
        if(mseq==0)
  mseq=10000;
 for(i=0;i<mseq;i++){
  rseq[i]=-1;
  sseq[i]=-1;
 }
}
$0 ~/^s.* AGT/ {
     sendLine ++ ;
}
$0 ~/^r.* AGT/{
     recvLine ++ ;
}
$0 ~/^f.* RTR/ {
        fowardLine ++ ;
}
END {
        printf "cbr s:%d r:%d, r/s Ratio:%.4f, f:%d \n",
sendLine, recvLine, (recvLine/sendLine),fowardLine;
}
```

```
#################################################################
###
#         AWK Script to calculate Normalized Routing Load
#
#              Works with AODV, DSDV, DSR and OLSR            #
#################################################################
###

BEGIN{
recvd = 0;#################### to calculate total number of data
packets received
rt_pkts = 0;################## to calculate total number of
routing packets received
}

{
##### Check if it is a data packet
if (( $1 == "r") && ( $35 == "cbr" || $35 =="tcp" ) && (
$19=="AGT" )) recvd++;

##### Check if it is a routing packet
if (($1 == "s" || $1 == "f") && $19 == "RTR" && ($35 =="AODV" ||
$35 =="message" || $35 =="DSR" || $35 =="OLSR")) rt_pkts++;
}

END{
printf("##########################################################
#########################\n");
printf("\n");
printf("                       Normalized Routing Load = %.3f\n",
rt_pkts/recvd);
printf("\n");
printf("##########################################################
#########################\n");
}
```

LIST OF PUBLICATIONS

1. Matter, S. S., Al Shaikhli, I. F., & Hashim, A. H. (2019). Theoretical review of routing protocols used for wireless community networks. *Journal of Computational and Theoretical Nanoscience*, Vol. *16, No.* 9, pp. 3656-3662, 2019. **[Scopus, Q4]** https://doi.org/10.1166/jctn.2019.8482
2. Matter, S. S., Al Shaikhli, I. F., Hashim, A. H., Ahmed, A. M., & Khattab, M. M. Enhanced MPR Selection Strategy for Multicast OLSR. *International Journal of Computer Science & Network Security,* Vol. *22, No. 10*, 2022 **[WOS]** https://doi.org/10.22937/IJCSNS.2022.22.10.18