# A MULTICRITERIA AWARE OPTIMAL ROUTING APPROACH FOR ENHANCING QUALITY OF SERVICE IN DEVICE TO DEVICE COMMUNICATION

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FACULTY OF ENGINEERING
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# A MULTICRITERIA AWARE OPTIMAL ROUTING APPROACH FOR ENHANCING QUALITY OF SERVICE IN DEVICE TO DEVICE COMMUNICATION

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# A MULTICRITERIA AWARE OPTIMAL ROUTING APPROACH FOR ENHANCING QUALITY OF SERVICE IN DEVICE TO DEVICE COMMUNICATION

## ABSTRACT

As the world is moving towards the digitalization era, increasing demands of higher data rates, energy efficiency, and seamless connectivity are skyrocketing. Device-to-Device (D2D) communication is one of the key technologies for future Fifth Generation (5G) network. D2D communication technology enhances network coverage, boosts spectral efficiency, has low latency, and enables the devices to communicate with each other, with partial or none involvement of network infrastructure. Therefore, factors of such nature make D2D communication a promising medium guarantying reliability to several telecommunications scenarios. D2D caters to all the needs of it's users, from the high demand of peer-to-peer users for data transmissions in Ultra-Dense Network (UDN) to building up a network that is resilient against natural disasters. In the orthodox cellular network, all the users are directly connected with a one-hop link to the network infrastructure. In contrast, for the D2D communication, a relay device is needed due to the multi-hop link between source and destination device for data transmission. For this, a routing approach plays a significant role in achieving efficient and reliable data transmission to the end-users. This study proposed three routing approaches in three main D2D communication scenarios. In the conventional D2D communication scenario, the network topology is highly dynamic and changes in an unpredictable manner due to the high displacement of devices in the network. This scenario affected the stability of the network and established routes which significantly degrades the network performance. Therefore, the Mobility, Residual energy, and Link quality Aware Multipath (MRLAM) routing approach is proposed to optimize the network and route stability for the conventional D2D communication scenario. Meanwhile, in the D2D communication

UDN scenario, traffic congestion occurs on a single mobile device when there is an excessive flow of packets, and it carries most of the network traffic. This scenario induces data packets transmission end-to-end delay in the network. Therefore, Multipath Battery, Mobility, and Queue length Aware (MBMQA) routing approach is proposed in order to balanced data traffic load among the mobile devices in the D2D communication UDN scenario. Whereas, in the D2D communication-based Disaster Management Scenario (DMS), the mobile devices are equipped with limited energy resources for their vital operation of data transmission. Thus, the connectivity of the devices suffers from packets drops as soon as the device's energy gets exhausted. Similarly, the mobile devices in the network, change their position frequently, which induces the chance of link failure in the established route. Therefore, Energy, Mobility, Backpressure, and Link quality Routing (EMBLR) approach is proposed in the D2D communication based on DMS to balance the energy consumption load among the devices and ensure reliable data transmission. Extensive simulations have been conducted that illustrate that proposed routing approaches significantly enhanced Quality of Service (QoS) network performance metrics for different D2D communication scenarios as compared with other well-known routing approaches. It is evident that the findings presented in the study are useful for designing the routing approach in future D2D communication.

**Index terms:** 5G network, D2D communication; Internet of Things; Routing; Multi-Criteria Decision Making.

**PENDEKATAN BERBILANG KRITERIA BAGI LALUAN OPTIMAL UNTUK MENINGKATKAN KUALITI PERKHIDMATAN DI DALAM KOMUNIKASI D2D**

## ABSTRAK

Sedang dunia bergerak ke arah era digitalisasi, peningkatan permintaan kadar data yang lebih tinggi, tenaga kecekapan, dan sambungan yang lancar semakin melonjak-lonjak. Komunikasi peranti ke peranti (D2D) adalah salah satu teknologi utama untuk rangkaian masa depan Generasi Kelima (5G). Teknologi komunikasi D2D dapat meningkatkan liputan rangkaian, meningkatkan kecekapan spektrum, mempunyai lengah yang rendah, dan membolehkan peranti berkomunikasi satu sama lain, dengan penglibatan sebahagian atau tiada rangkaian infrastruktur. Oleh itu, dengan wujudnya ciri-ciri ini, ia menjanjikan komunikasi D2D sebagai satu medium yang dijamin kepercayaannya kepada beberapa senario telekomunikasi. D2D memenuhi semua keperluan penggunanya, dari permintaan yang tinggi oleh pengguna akhir bagi penghantaran data dalam rangkaian pengguna yang sangat padat ("Ultra-Dense Network (UDN)") kepada membina rangkaian yang berdaya tahan terhadap bencana alam. Dalam rangkaian selular ortodoks, semua pengguna dihubungkan secara langsung dengan pautan satu hop ke infrastruktur rangkaian. Namun sebaliknya bagi komunikasi D2D, peranti geganti diperlukan bagi menjana sambungan pelbagai hop di antara peranti sumber dan peranti destinasi untuk penghantaran data. Untuk ini, suatu pendekatan laluan adalah memainkan peranan yang penting dalam mencapai penghantaran data yang cekap dan boleh dipercayai kepada pengguna akhir. Kajian ini mencadangkan tiga pendekatan laluan dalam tiga senario komunikasi D2D utama. Dalam senario komunikasi D2D konvensional, topologi rangkaian adalah sangat dinamik dan berubah dengan cara yang tidak dapat diramalkan kerana sesaran peranti yang tinggi didalam rangkaian. Senario ini menjejaskan kestabilan rangkaian dan pendekatan laluan yang ditubuhkan dan mengakibatkan penurunan prestasi rangkaian

secara signifikan. Dengan itu, pendekatan laluan "Mobility, Residual Energy, and Link quality Aware Multipath (MRLAM)" adalah dicadangkan untuk mengoptimumkan kestabilan rangkaian dan pendekatan laluan untuk senario komunikasi D2D konvensional. Sementara itu, di dalam senario UDN komunikasi D2D, kesesakan lalu lintas berlaku pada satu peranti mudah alih apabila terdapat aliran yang berlebihan dan ia membawa turutan kesesakan rangkaian yang paling banyak. Senario ini menginduksikan kelewatan penghantaran data kepada pengguna akhir di dalam rangkaian. Oleh dengan itu, pendekatan laluan "Multipath Battery, Mobility, dan Queue Longware (MBMQA)" adalah dicadangkan agar dapat menyeimbangkan bebanan data trafik di kalangan peranti mudah alih di dalam senario UDN komunikasi D2D. Manakala, di dalam Senario Pengurusan Bencana (DMS) yang berasaskan komunikasi D2D, peranti mudah alih adalah dilengkapi dengan sumber tenaga yang terhad bagi operasi penghantaran data yang penting. Oleh itu, kesambungan peranti mengalami kemerosotan dari "paket jatuh" sebaik sahaja tenaga peranti menjadi semakin lemah. Begitu juga, bagi peranti mudah alih di dalam rangkaian, yang menukar kedudukan mereka dengan kerap, mendorong kepada peluang kegagalan pautan dalam laluan yang telah ditetapkan (sedia ada). Oleh itu, pendekatan laluan "Energy, Mobility, Backpressure, and Link quality Routing (EMBLR)" adalah dicadangkan di dalam komunikasi D2D berdasarkan DMS untuk mengimbangi bebanan penggunaan tenaga di antara peranti dan memastikan penghantaran data yang boleh dipercayai. Simulasi dan mendalam telah dijalankan dan menggambarkan pendekatan laluan yang dicadangkan telah dapat meningkatkan metrik prestasi rangkaian dan Kualiti Perkhidmatan (QoS) dengan ketara untuk senario-senario komunikasi D2D yang berbeza jika dibandingkan dengan pendekatan laluan yang terkenal. Adalah jelas bahawa penemuan yang dibentangkan dalam kajian ini adalah berguna untuk mereka bentuk pendekatan laluan dalam bagi komunikasi D2D yang akan datang.

**Kata kunci:** Rangkaian 5G, Komunikasi D2D; Internet Pelbagai Perkara; Pendekatan Laluan; Pengambilan Keputusan Berbilang Kriteria.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| 5G | : | Fifth Generation |
| ACK | : | Acknowledgement |
| AEADMRA | : | Ant-based Energy Aware Disjoint Multipath Routing Algorithm |
| AHP | : | Attribute Hierarchy Process |
| AODV | : | Ad Hoc On-Demand Distance Vector |
| BIP | : | Biobjective Integer Programming |
| BP | : | Backpressure |
| CA-MANETs | : | Cloud Assisted-Mobile Ad Hoc Networks |
| CBR | : | Constant Bit Rate |
| CEI | : | Composite Eligibility Index |
| C-RAN | : | Cloud-Radio Access Network |
| D2D | : | Device-to-Device |
| DMP | : | Disjointed Multipoint |
| DMS | : | Disaster Management Scenario |
| DSDV | : | Destination Sequenced Distance Vector |
| DSR | : | Dynamic Source Routing |
| EAX | : | Expected Any-path Count |
| EECA | : | Energy Efficient Collision Aware |
| EECRM | : | Energy-Efficient Cloud-Assisted Routing Mechanism |
| EE-PDSR | : | Energy Efficient Preemptive Dynamic Source Routing |
| EHARA | : | Energy Harvesting Aware Routing Algorithm |
| EIMO-ESOLSR | : | Enhanced Intellects Masses Optimizer Energy Efficient and Secure Optimized Link State Routing |
| EMA-MPR | : | Energy and Mobility Aware Multipath Routing |

| | | |
|---|---|---|
| EMBLR | : | Energy, Mobility, Backpressure, and Link Quality aware Routing |
| EMRP | : | Energy aware Multipath Routing Protocol |
| ETX | : | Expectation Number of Transmission |
| FF-AOMDV | : | Fitness Function Ad-hoc On-Demand Multipath Distance Vector |
| HETX | : | High load Expected Number of Transmission |
| HOLSR | : | Heterogenous Optimized Link State Routing |
| IoT | : | Internet of Thing |
| LCMR | : | Least Common Multiple based Routing |
| LEAR | : | Link-stability and Energy Aware Routing |
| LIA-MPOLSR | : | Link-disjoint Interference-Aware Multi-Path Optimized Link State Routing |
| LOADng-IoT-Mob | : | Lightweight On-demand Ad hoc Distance-vector Routing Protocol for mobile IoT networks |
| MAC | : | Medium Access Control |
| MADM | : | Multi Attribute Decision Making |
| MANET | : | Mobile Ad Hoc Network |
| MAR | : | Mobility Aware Routing |
| MARS | : | Multiple-Attributes Route Selection |
| MBMA | : | Multipath Battery and Mobility-Aware |
| MBMQA | : | Multipath Residual Battery, Mobility and Queue length Aware |
| MBP | : | Modified Backpressure |
| MCDM | : | Multi Criteria Decision Making |
| M-CML | : | Multipath-ChaMeLeon |
| MEQSA-OLSRv2 | : | Multipath Energy and Quality of Service aware Optimized Link State Routing version 2 |
| mmWave | : | Millimeters Wave |

| | | |
|---|---|---|
| MP-OLSR | : | Multipath Optimized Link State Routing |
| MP-OLSRv2 | : | Multipath Optimized Link State Routing version 2 |
| MPR | : | Multi Point Relay |
| MRLAM | : | Mobility, Residual energy and Link quality Aware Multipath |
| NTDR | : | Near Term Digital Radio |
| NUM | : | Network Utility Maximization |
| OLSR | : | Optimized Link State Routing |
| OPHMR | : | Optimized Polymorphic Hybrid Multicast Routing |
| PDR | : | Packet Delivery Ratio |
| PHY | : | Physical Layer |
| PSR | : | Proactive Source Routing |
| QL | : | Queue Length |
| QOLSR | : | Quality based Optimized Link State Routing |
| QoS | : | Quality of Service |
| RAN | : | Radio Access Network |
| RB | : | Residual Battery |
| RWP | : | Random Waypoint Model |

# CHAPTER 1: INTRODUCTION

## 1.1 Overview

From the first invention of the internet in the twentieth century, there are billions of online connections that connect daily to boost economic activity. Internet of things, namely (IoT), is nowadays greatly influencing our daily routines. The IoT is revolutionizing human lifestyles and provides a new gateway for the digitalization era. From basic domestic electrical appliances, such as television that are nowadays controlled by smartphones, to smart cars that provide the efficient navigation, or smartwatches that record our daily activities, IoT provides a gigantic network that connects multiple devices. These devices gather and send the data about how they are being used and the environment in which they have been operated. IoT provides a platform for all these devices to communicate with each other and dump all the data. In the IoT platform, data from various devices are collected and analyzed; valuable information is extracted and shared with other devices for better user experience, automation and improving efficiency (G. A. Akpakwu, Silva, Hancke, & Abu-Mahfouz, 2018; J. Lin et al., 2017; Metzger, Hoßfeld, Bauer, Kounev, & Heegaard, 2019; Mouradian et al., 2018; Novo, 2018). Throughout the world, every second, there are numerous devices connected with each other, transmitting trillions of bytes of data. To caters to these massive data packets information exchange, better telecommunications platforms are needed; 5G network is on such a possible platform. (Godfrey Anuga Akpakwu, Silva, Hancke, & Abu-Mahfouz, 2017; G. A. Akpakwu et al., 2018; S. Li, Da Xu, & Zhao, 2018; Shafi et al., 2017).

The 5G network is a far more superior telecommunications network that is expected to provides higher data rate, low latency and dense connections (Agiwal, Roy, & Saxena, 2016; Parvez, Rahmati, Guvenc, Sarwat, & Dai, 2018; Y. Wang et al., 2014). The 5G network is using new radio technology with a much higher frequency that enables the 5G technology to carry massive data and provide seamless communication. 5G supports higher data rates, spectral efficiency connection density, and computing resources that prevent low latency (Godfrey Anuga Akpakwu et al., 2017; Ferdouse, Ejaz, Raahemifar, Anpalagan, & Markandaier, 2017; Xiaohu Ge, Tu, Mao, Wang, & Han, 2016; Olwal, Djouani, & Kurien, 2016; Parvez et al., 2018; Yu et al., 2016). With IoT-5G combinations, all the significant data transfer can be instantaneous. The 5G is designed to increase the throughput and responsiveness of a wireless network. 5G can reduce an end-to-end delay in data transmission compared with 4G, which improves the latency issues (J. Lee et al., 2016; R. N. Mitra & Agrawal, 2015). All the technologies in the 5G core network are using backhaul technologies. Backhauling is a type of communication link between the global/core network and end-users (Xiaohu Ge, Cheng, Guizani, & Han, 2014; Ning Wang, Hossain, & Bhargava, 2015).

Millimeters wave (mmWave) is one of the key technologies in the 5G network, which has a band of spectrum between 30 GHz and 300 GHz (Bogale & Le, 2016; Rappaport et al., 2017; Xiao et al., 2017). Due to the variety of bandwidth it offers, it has been used for highspeed wireless broadband communication and in a broad range of products and services such as highspeed point-to-point local area and broadband access. However, the mmWave has a short range of communication, which is up to a maximum of 1 kilometer (Andrews et al., 2017; Hong, Baek, & Ko, 2017; Xiao et al., 2017). The mmWave travel by line of sight and is affected directly by high atmospheric attenuation, as the gas absorbs them in the atmosphere, the strength is reduced as well as the range of the wave increases (Ai et al., 2017; Kumbhar, Saxena, & Roy, 2017; P. Liu, Renzo, & Springer, 2016; Moltchanov et al., 2019). Based on these situations, many infrastructures need to be set up within close range to maintain network performance, which is not cost-effective. As a solution, the researchers have come up with an effective solution by using D2D communication in the 5G network (Doppler, Rinne, Wijting, Ribeiro, & Hugl, 2009; Jameel, Hamid, Jabeen, Zeadally, & Javed, 2018; Kar & Sanyal, 2018; L. Liang, Li, &

Xu, 2017; L. Wang, Tang, Wu, & Stüber, 2017; Y. Wu, Chen, Qian, Huang, & Shen, 2017; H. Zhang, Liao, & Song, 2017).

The D2D communication also known as peer-to-peer communication is a radio technology that allows the device to communicate directly with each other, without or partially going through the network infrastructure (Ahmad et al., 2017; A. Ali, Shah, Farooq, & Ghani, 2017; Gandotra & Jha, 2017; Gandotra, Jha, & Jain, 2017). Generally, the D2D communication provides the connection between the two wireless devices either directly when the both of the users are in the line of sight or by hopping when there is a blockage between the users (non-line of sight). When the device is communicating with each other, data offloading is shared among the devices in the network; thus it tremendously mitigates the traffic on overall core network (Cheng, Huang, & Pan, 2018; Cheon & Kim, 2019; Pescosolido, Conti, & Passarella, 2019; Sharafeddine & Farhat, 2018). Hence, due to its dynamic nature and reliability, the D2D is a promising technology that can be used in building a network system that is resistant to a natural or human-made disaster. In the state of emergency, where the network infrastructure is down, the devices can still communicate with each other (Masaracchia, Nguyen, Duong, & Nguyen, 2019; Moghaddam, Usman, & Granelli, 2018). A general scenario of a D2D 5G communication network is shown in Figure 1.1.

Generally, wireless network routing is crucial to ensure the data is efficiently sent to the destination device (end-user). Routing mitigates the data packet's loss in a network by adjusting the path or route in the response of dynamic network topology (H. Rong, Wang, Jiang, Xiao, & Zeng, 2019). The governing of the data from source to destination device to a complicated network is not an easy task; hence routing mechanism is needed. Routing can be exemplified in a situation when trying to reach a destination from one place (source) to another place (destination). In the scenario when the roads are full of traffics, applications such as google maps and Waze are being used to look up to the fastest route.

Based on the traffic situations and road conditions, the optimum path would be chosen to reach the desired destinations. Similarly, in the network traffic, the movement of data packets is adjusted or routed based on the state of network and data traffic logical situations to make the most efficient routing decisions. The main purpose of routing is to find the most efficient path where the data packets can be transferred reliably from the source to the destination device with respect to user preferences. Utilization of a sophisticated efficient routing protocol, the data packets can be directed on a specific path from source to the final desired destination by assessing the current state of the dynamic network (H. Huang et al., 2018; H. Liu, Su, & Chou, 2017; Pradittasnee, Camtepe, & Tian, 2017; Sharma & Bhondekar, 2018; J. Wang, Yue, Hai, & Fang, 2017; X. Wang, Wu, & Zhang, 2017). Routing can be either direct or using a multi-hop path to the destination's device, depending on the current network topological information.

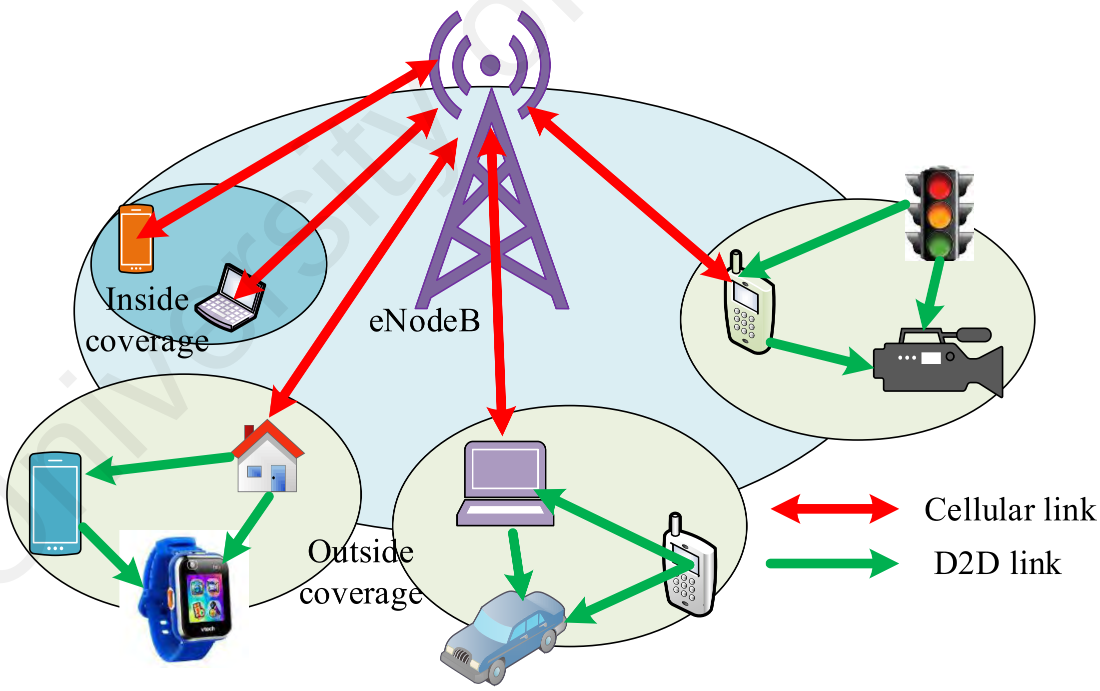


**Figure 1.1: A general scenario of D2D communication 5G network**

In the orthodox cellular network, all the users are directly connected with a one-hop link to the network infrastructure. In contrast, for D2D communication, a relay device is needed due to the multi-hop link between source and destination device for data transmission (Al-Turjman, Deebak, & Mostarda, 2019; Chen, Tang, & Coon, 2018; Shaikh & Wismüller, 2018). For this, a routing approach plays a significant role in efficient and reliable data transmission to the end-users. Incorrect routing decision in the D2D communication, lead to worse QoS performance than the orthodox cellular network. Due to the dynamic nature of the devices in the D2D communication, routing is pertinent to ensure standard QoS network performance is delivered (Bello, Zeadally, & Badra, 2017; Xuan Liu, Li, Yang, & Dong, 2017; Wenbin, Yin, Ming, & Dongbin, 2017; Y. Xu, Liu, Shen, Jiang, & Shiratori, 2017). Performance metrics such as link quality, energy constraints, network stability, and data packets traffic congestion will be updated based on the time stats and network connectivity. These factors do not need to be considered in the orthodox cellular network. Based on the current state of network information, new routes can be decided on each time stats (Kazeminia, Mehrjoo, & Tomasin, 2019; Kolios, Papadaki, & Friderikos, 2016).

Moreover, in D2D communication, the energy constraints of the device are a big hurdle that should be addressed properly. It can be depicted in a situation where one of the devices has an energy drain, the established route lifetime will be shortened, and a new path needs to be inaugurated (Masaracchia et al., 2019; X. Zhang, Huang, Guo, & Fang, 2019). The dynamic movement of the devices in the D2D communication is causing the instability of the network. Once a device is moving out of range, a new network path needs to be re-established. This chain of events during which the device is keep on exiting and adding to the network results in network instability and deterioration of QoS performance of the network (de Mello, Borges, Pinto, & Cardoso, 2016; Singh & Ghosh, 2019). In the D2D communication technologies, where the device is the key player, the queue length size of data at a particular device will lead to traffic congestion. The queue length waiting time at a specific device will result in data transmission delay and increased data traffic congestion in the network (Lei, Shen, Dohler, Lin, & Zhong, 2014; Sanyal &

Zhang, 2018; C. Xu, Feng, Zhou, Wu, & Perera, 2019; H. Zhang, Song, & Zhang, 2018). Whereas, link failure in D2D communication occurred when the intermediate device is changing their positions. Based on the updated network topology, the source device needs to reselect and reestablish a new route to send the data packets.

## 1.2 Problem of Statement

The selection of optimal route from the source to destination devices in a different D2D communication network scenario is limited due to the network instability, data packets traffic congestion, energy resource constraints, and link quality of the devices. These challenges are significantly degrading the overall QoS network performance in D2D communication scenarios. These challenges are discussed as follows:

The network topology in the conventional D2D communication scenario is highly dynamic and changes in an unpredictable manner due to high displacement with random addition or subtraction of devices in the network. The fluctuation in the number of devices and changing network topology causes intermittent interconnectivity and instability of the established route that leads to significant degradation of the network performance. Maintaining network and route stability is the major challenge when designing the routing protocol in the conventional D2D communication scenario.

Meanwhile, one of the limitations of the D2D communication UDN scenario is the traffic congestion that occurs when there is an excessive flow of packets injected on a single mobile device and carries most of the network traffic. Due to this, routing approaches suffer from load balancing among the intermediate devices of the network, which can further significantly degrade the overall network performance.

In addition, in the D2D communication based DMS, energy resource and link quality of the device play a significant role in providing a seamless connection with the end-users. In this scenario, mobile devices are equipped with limited energy resources for their vital operation of data transmission. Thus, the connectivity of the devices suffers from packets drops as soon as the device's energy gets exhausted. Limited energy resources and processing power of mobile devices are the significant sources of constraints to design an optimal route, which incurs severe impacts on network lifetime. Similarly, the mobile devices in the network, change their position in an unpredictable manner, which induces the chance of link failure in the established route between source and destination devices. Due to the link failure in the established route, the data packet needs to be retransmitted with a new link, and this acquires more bandwidth in the network. Therefore, combining link quality and residual energy of the device into the routing metric for the D2D communication based DMS will ensure data transmission reliability and balance energy consumption load among the devices.

In summary, the main problems can be stated as:

1. Network and route instability become a major hurdle in the conventional D2D communication scenario.
2. Data packets traffic congestion becomes the main issue in the D2D communication UDN scenario.
3. Energy resource shortage and link failure are the main challenges in the D2D communication based DMS.

Therefore, there is a need for optimal route selection in the different D2D communication scenarios, which considers the above challenges to improve the overall network performance.

## 1.3 Research Objectives

The main objective of the study to enhance QoS performance by designing the optimal routing approaches for the different D2D communication scenarios incorporating multicriteria device parameters such as mobility, queue length size, energy resources, and link quality of the devices. To integrate the best routing approaches for the three main scenarios, such as the conventional D2D communication, D2D communication in UDN, and D2D communication DMSs, these specific objectives need to be fulfilled as follows:

1. To optimize the network and route stability in the conventional D2D communication scenario.
2. To solve the packet traffic congestion issue in the D2D communication UDN scenario.
3. To improve energy efficiency and data transmission reliability in the D2D communication based DMS.

## 1.4 Scope of the Study

This study aims to design the optimal routing approaches for the different D2D communication scenarios by integrating device multicriteria parameters such as mobility, queue length size, energy resources, and link quality of the devices. The conventional D2D communication scenario is focused on the optimization of the network and route stability to improve overall network performance. Meanwhile, the D2D communication UDN scenario is focused on the data packets traffic congestion issue in the network in order to balance the data traffic load among the mobile devices. In addition, the D2D communication based DMS is focused on device energy consumption load balance and improve reliable data transmission between the source and destination devices. The outcome of the proposed routing approaches for the different D2D communication scenarios will be presented in QoS network performance metrics.

## 1.5 Thesis Outline

The thesis is comprised of five chapters. **Chapter 1** presents the background of D2D communication, the problem of statement, objectives, and thesis scope of work.

**Chapter 2** presents a concise literature review concerning the routing protocols in the D2D communication. Moreover, recent research is critically reviewed and discussed to provide a brief knowledge regarding the importance of routing protocols, advantages, and challenges that occur during route selection for the three different D2D communication scenarios.

**Chapter 3** comprehensively describes the methodologies of the proposed three routing approaches with the different D2D communication scenarios, such as conventional D2D communication scenario, the D2D UDN communication scenario, and the D2D communication DMSs.

**Chapter 4** critically analyzes the results of QoS performance metrics of the routing approaches in terms of throughput, end-to-end delay, packet delivery ratio, packets drop, energy consumption, energy cost, and convergence time with the variant device speed in the different D2D communication scenarios.

**Chapter 5** presents the overall conclusion of the research work and the possibility of the research impact on future technology. Finally, this chapter mentions the current limitation of the proposed work and gives direction for further improvement in the future.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Introduction

This chapter describes the importance of routing in the D2D communication 5G network. Moreover, the types of routing schemes in the wireless networks are briefly described to provide reliable data transmission to end-users. Finally, this chapter illustrates the challenges that occur during route selection in the three different scenarios, such as conventional D2D communication, D2D communication UDN, and D2D communication in DMS.

D2D communication technology is one of the essential components of the future IoT 5G mobile network. The D2D communication supports high-speed peer-to-peer data transmission; unlike traditional cellular communication, the D2D technologies work partially with or without the existence of the base station's infrastructure (Kılıç & Girici, 2019; C.-S. Lin & Sou, 2019; Shi, Cao, Zhang, Li, & Xu, 2016). Due to the flexibility of network deployment, spectrum utilization, and extend the network coverage, D2D technology is one of the promising methods to accomplish the vision of IoT and future 5G network. In times of calamitous events, such as an earthquake, orthodox cellular communication infrastructures may become dysfunctional or degraded, in such a situation, the D2D communication based IoT 5G network paradigm becomes the most convenient way to provide rapid deployment and self-manage wireless connectivity with the end-users. These functionalities and features of the D2D communication-based IoT 5G network has offered a broader possibility for extensive research in building the future 5G wireless network community (Agiwal et al., 2016; Al-Turjman et al., 2019; Y. Li, Liang, Liu, & Wang, 2018). The features of D2D communication technology is shown in Figure 2.1.

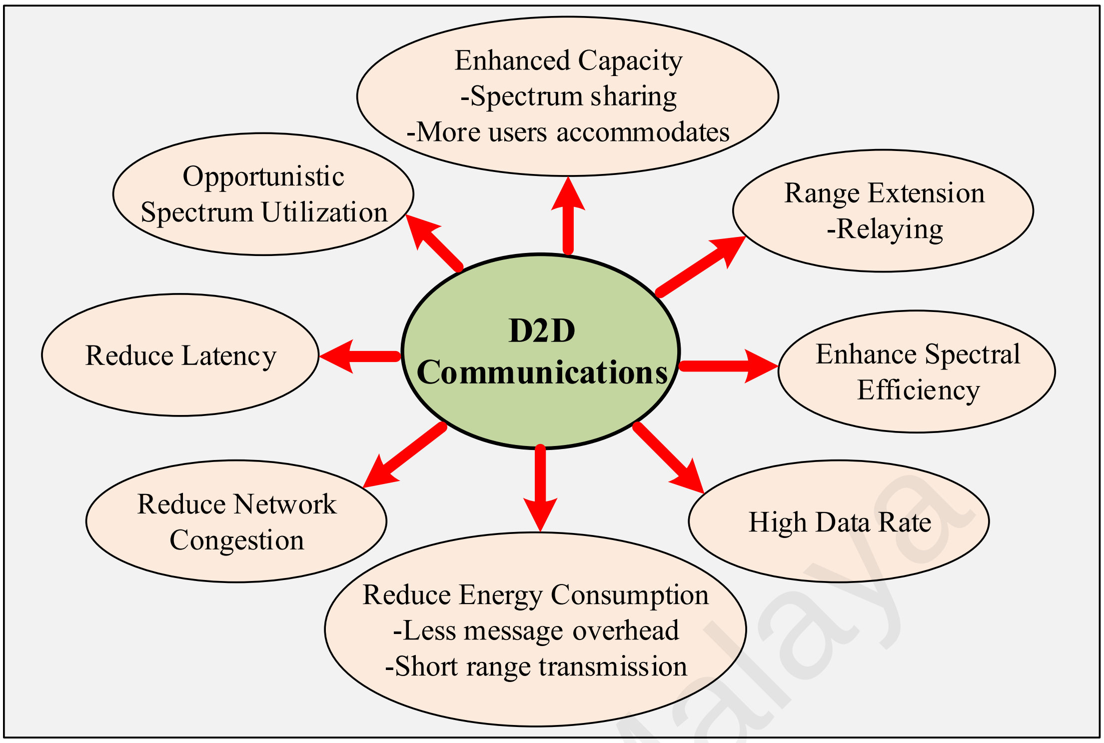


**Figure 2.1: Features of D2D communication technology**

## 2.2 The Importance of Routing in D2D Communication

To implement D2D communication in the 5G network, resource allocation and relay selection need to be considered for providing better QoS performances (Esmat, Elmesalawy, & Ibrahim, 2018; Gong, Li, & Li, 2018; Zhijian Lin, Huang, Zhao, Du, & Guizani, 2017; Z.-Y. Yang & Kuo, 2017). The mobile devices in the D2D communication have the ability to established connectivity among themselves without or partiality involve in the cellular network infrastructure, in which all mobile devices work as a host as well as a relay device for other devices to build network infrastructure. They can share some information among themselves in the form of data packets over the established channel links. In this scenario, if two devices do not share a direct link with each other, the source device utilizes the relay devices in the route for transmitting data packets towards the destination devices. One of the objectives in the relay selection problem is to minimize the average delay while keeping the packet loss under control that directly influenced by the selection of appropriate relay devices (M. Ali, Qaisar, Naeem, Mumtaz, & Rodrigues, 2017; Amodu, Othman, Noordin, & Ahmad, 2019; Bakhsh, Moghaddam, & Ardebilipour, 2019; Najeh, 2020).

All mobile devices in the D2D communication based IoT 5G network collaborate with each other and act as a relay device for one another, thereby providing a robust and effective operation throughout the whole network. The mobile devices are incorporated with routing functionality, and each device can join and/or leave the network at will depending on the capacity of its energy resources and nature of its network topology (T. Liu, Lui, Ma, & Jiang, 2018; D.-L. Wang, Sun, Li, & Liu, 2019). IoT based D2D communication is characterized by an event such as a constant change in network topology, which often leads to frequent link failure, degraded data transmission quality, and reduced network throughput (Abolhasan et al., 2018; Y. Cao & Sun, 2013; Chen et al., 2018; Shaikh & Wismüller, 2018). The D2D communication network concept is explored by researchers around the world due to the flexibility of network deployment and supports peer-to-peer high-speed data transmission without fixed infrastructure. Since the governing body in the D2D communication 5G network is unavailable, and the devices are in random movement, this scenario is already a challenging task for further network deployment. This constant random movement of the device becomes a challenge since it does not allow the re-use of previously calculated routes. Conventional routing approaches implemented in networks' infrastructure are not suitable for D2D communication due to the massive route’s calculations, and the constant changes in the network topology. Therefore, various routing protocols have been developed by the research community to address the challenges that arise from the mobility of the devices in the networks (Hamdi & Zaied, 2019; C. Huang, Zhai, Tang, & Wang, 2019; Pawar & Trivedi, 2019; Razzaq & Shin, 2019; Sharafeddine & Farhat, 2018).

Most of the previous works on routing protocols solely considered a single path to route the data traffic, which limits the devices' ability to efficiently utilize all the links towards the destination (Al-Baghdadi, Lian, & Cheng, 2020; Macit, Gungor, & Tuna, 2014; Sahin, Gungor, Kocak, & Tuna, 2014; Simha & Narahari, 1992; Vallet, Brun, & Prabhu, 2016). In order to improve the performance of the network, multi-paths have been considered by researchers in recent years and have turn out to be the optimum solution for D2D communication based IoT 5G network and its derivatives. Multiple links can significantly enhance the performance and efficiency of the network, as devices will be able to balance the traffic load between different paths leading to the same destination (Kim, Kim, Paek, & Bahk, 2017; Selvi & Manikandan, 2017).

## 2.3 Types of Routing Protocols

Routing protocols in wireless networks are classified into three categories, namely; proactive, reactive, and hybrid routing protocols, depending on the nature of underlying routing information and update mechanism they employ (Z. Cao, Jiang, Zhang, & Guo, 2017; Ferronato & Trentin, 2017; Pan, Popa, & Borcea, 2017; Pradittasnee et al., 2017; Shukla, Bhardwaj, Abouzeid, Salonidis, & He, 2018; Siraj et al., 2018). The proactive routing protocols are also known as table-driven routing protocols because of their tendency to store updated routing information in the form of tables. Notable examples of proactive routing protocols include destination-sequenced distance-vector (DSDV) (H. Zhang, Wang, Memarmoshrefi, & Hogrefe, 2017) and optimized link-state routing protocol (OLSR) (Haque, 2015). Each device maintains and stores the network topology information in a tabular form in order to maintain a consistent network view as the network topology regularly updates periodically due to the very nature of the wireless network. From time to time, devices that run the proactive routing protocol need to exchange up-to-date routing table information among themselves. Whenever a device needs to transmit packets, it firstly extracts routing information from the maintained table with which it routs the packets. Thus, less time is required for a route discovery process, which leads to reduced end-to-end delay for data transmission between the source and destination devices. In contrast, this periodic exchange of routing information and route request packets in the route discovery process leads to high control packet overhead throughout the network (Angelelli, Morandi, & Speranza, 2018; R. Mitra & Sharma, 2018; Mohamed et al., 2018).

On the other hand, the reactive routing protocols are also known as on-demand routing protocols due to their on-demand manner for the route selection process. Some good examples of reactive routing protocols are dynamic source routing (DSR) (Taha, Alsaqour, Uddin, Abdelhaq, & Saba, 2017) and Ad hoc On-demand Distance vector (AODV) (Kuo & Chu, 2016). Devices running the reactive routing protocols do not need to maintain any prior routing information but exchange routing information of the network only when there is a need for communication. Thus, source device based on reactive routing protocols discovers routes in an on-demand manner to establish a connection to a destination device; hence, few control packets overhead are generated for the maintenance of network topology information. Conversely, during the route discovery initiation process in reactive protocols, all devices exchange topology information with each other, which typically involves the flooding of packets in the network. Then, the reactive protocol takes time to gather and analyze the network topology information. This process tends to prolong the end-to-end delay for data transmission between the source and destination devices (Al-Dhief, Sabri, Fouad, Latiff, & Albader, 2017; Bai, Sadagopan, Krishnamachari, & Helmy, 2004; Bello-Salau et al., 2019; Chithaluru, Tiwari, & Kumar, 2019; Muchtar, Abdullah, Hassan, Khader, & Zamli, 2019).

Hybrid routing protocols such as zone routing protocol (ZRP) (Hurley-Smith, Wetherall, & Adekunle, 2017) and Secure Link State routing (SLSP) (Rosati, Krużelecki, Heitz, Floreano, & Rimoldi, 2016) handle routing activity by dividing the network into zones while combining the best features of reactive and proactive routing protocols to make a timely and informed routing decision. For instance, in the event that a device wants to transmit packets to a destination device within a specific geographical zone of its immediate neighboring network, it will choose the proactive approach to handle this task. On the other hand, if the destination device is outside the geographical zone of its immediate neighbor, it will instead use the reactive routing protocols. However, this approach increases the complexity, computational cost, and energy consumption of mobile devices (Torrieri, Talarico, & Valenti, 2015) during the route selection process in the hybrid routing protocol. These approaches are degrading the network performance due to repeatedly changing network zones and constant switching between routing protocols (Al Mojamed & Kolberg, 2016; Boussoufa-Lahlah, Semchedine, & Bouallouche-Medjkoune, 2018; Govindasamy & Punniakody, 2018; Muchtar, Abdullah, Hassan, & Masud, 2018).

## 2.4 Routing challenges in D2D Communication

The concept of Ad-hoc networks was first introduced in Near Term Digital Radio (NTDR) in the early 1990s and soon evolved into vast clusters of networks comprising of several hundreds of devices connected with any relay or intermediate devices (Xiaolan Liu, Yang, Jiang, Ma, & Shen, 2020; Ma, Li, Yan, & Yang, 2020; Malik & Sahu, 2019; Ramanathan & Redi, 2002). Networks that support such devices are termed as D2D communication based IoT 5G network, which does not rely on previously deployed infrastructure and is capable of forming connections on their own with the aid of intermediate relays to provide connectivity to the devices. The positions of devices are not defined, while freedom is provided in terms of initial positions. The free movement of the devices is considered as a challenge for the designers in order to retain a record of every device position so that the communication can be alive while the devices are free to move. Routing protocols are responsible for providing feasible routes to the required destination devices at a given time with the aim that the performance is not compromised and expectations in terms of QoS are met (Zhiting Lin & Wang, 2019; Mei, Lu, & Peng, 2019; Y. Wang, Yu, Huang, & Choi, 2019; B. Yang, Wu, Shen, & Jiang, 2019). Throughout the years, scholars have executed various approaches in order to discover the appropriate routing protocol in terms of fault tolerance, scalability, performance, reliability, improved utilization of resources, feature-specific, better QoS, etc (H. Huang et al., 2018; Maccari & Cigno, 2018; Pradittasnee et al., 2017; Pu, 2018; Sharma & Bhondekar, 2018).

Another challenge faced by the D2D communication 5G network is that the mobile devices are equipped with a limited amount of battery power; therefore, the utilization of energy must be optimized in order to maintain the activity of the network. Various strategies were explored and adopted in order to save energy, including limiting the broadcast to a cluster to share the information of the required energy or remaining within the metric of the routing protocol (Hasan, Al-Rizzo, & Al-Turjman, 2017; Zhao, Xu, Hui, & Hu, 2018). Though, most of the suggestions to save energy is solely based on single-path routing protocols. However, selecting the same path every time to forward the traffic from the source to destination device impacts the routing protocol efficiency, as well as it affects the battery life of the intermediate devices. Thus, low efficiency is obtained as the same path to a destination is selected to forward the data traffic, which in turn reduces the battery life of the devices. To overcome these issues, it is imperative to design, develop and implement a new generation of routing protocols that support robust and efficient routing in the D2D communication based IoT 5G network.

Based on the number of paths between the source and destination devices, routing protocols can be classified into a single path and multipath protocols (Abusalah, Khokhar, & Guizani, 2008). A fundamental limitation of single path protocols, is prone to device failures, resulting chiefly from the quick depletion of the device's battery. Such limitation occurs due to some device highly congested and carries most of the network data traffic, while some device does not involve in the routing process. Therefore, the device which carries higher data traffic, the battery gets exhausted soon as compared with the other network devices. Once the device battery gets exhausted in the established route, the established route is broken and need to discover another route for data transmission. Therefore, a new route discovery process, induce data transmission delay in the network and degrade the overall network performance. One solution to overcome this issue is to route the message via multiple paths simultaneously (Boushaba, Benabbou, Benabbou, Zahi, & Oumsis, 2014). Thus, even though only a single path is available for routing, the destination device can be able to receive the desired message from the source device; hence the desired message can be received with better QoS and less delay.

Multipath routing protocols have been extensively researched in the last few decades, and several wireless networks paradigms that are said to possess the ability to provide reliable communication, ensure data traffic load balancing, and improve QoS have been designed by researchers (Geng, Shi, Wang, & Yin, 2018; Guirguis, Karmoose, Habak, El-Nainay, & Youssef, 2018; Gupta, Jain, & Vaszkun, 2016; Khalid et al., 2019; Khalid, Cao, Ahmad, Khalid, & Dhawankar, 2018; Pu, 2018; Valerio et al., 2019; Vinitha & Rukmini, 2019). Multipath routing is an additional heuristic dimension introduced into routing paradigms to improve end-to-end delay, reduce packet overhead, and maximize network lifetime. Multiple paths could further improve the performance of the network by allowing devices to balance the traffic load from source to a destination via multiple links. The number of recent findings is summarized in this subsection, which focuses on multipath routing protocols for ubiquitous networks. Routing in the D2D communication based IoT 5G network involves establishing a stable and reliable route between a source and destination devices. However, researchers around the globe work on energy resource optimization, network stability, traffic congestion, and link quality of the devices constraints to improve network performance (Abd-Elmagid, ElBatt, & Seddik, 2019; Xiuwen Fu, Haiqing Yao, & Yongsheng Yang, 2019; C. L. Lim, Goh, & Li, 2019;

Xiaoqing Liu, Wen, Liu, Zou, & Li, 2019). Challenges occur during route selection in the three different D2D communication scenarios, such as conventional D2D communication, D2D communication UDN, and D2D communication in DMSs are discussed as follows:

### 2.4.1 The Conventional D2D Communication Scenario

The mobile device in a conventional D2D communication network scenario changes its position unpredictably; thus, the topology of the network also changes accordingly. Maintaining the network and route stability is the major challenge when designing the routing protocol to enhance the throughput of the network (Sharma & Bhondekar, 2018; Song & Zheng, 2018; Tang, Yang, Wu, Cui, & Chen, 2018; Vu, Bennis, Debbah, & Latva-Aho, 2019). In order to maintain network and route stability in the conventional D2D communication scenario, several studies have been conducted by researchers are discussed as follow:

#### 2.4.1.1 Related Work on Network stability

In article (M. Li, Zhang, Li, Shan, & Ren, 2005), the authors proposed an Energy-centric Multipath Routing Protocol (EMRP), in which exploits the information from the physical and the Medium Access Control (MAC) layers to estimate the energy level of nodes and link bandwidth status that enables it to select the optimal route during route computation process. Thus, EMRP increases the network lifetime and maximizes the links channel capacity. However, the scalability issue is associated with the flat routing scheme. The authors in (Luis Villasenor-Gonzalez, Ge, & Lament, 2005) suggested a variant of OLSR called Heterogenous OLSR (H-OLSR) routing scheme to solve the scalability issues often associated with the flat routing strategy in wireless networks. The H-OLSR protocol enhances the OLSR protocol in a way that it significantly minimizes the network overhead caused by the frequent exchanges of the topological messages such as HELLO and Topology Control (TC) in the network. The H-OLSR also exploits the best available links of the network to deliver data packets to the destinations reliably. Moreover, the proposed protocol has the ability to perform the route discovery process locally that enables it to achieve a reduced computation cost of the routes between a node and its neighbors without affecting the other network performances; thus, it is an interface-free scheme. Moreover, the H-OLSR increases the numbers of successfully delivered packets and shortens the end-to-end queuing delays while minimizing the occurrences of packets lost. Thus, the H-OLSR scheme improves the network performance and routing scalability in heterogeneous wireless networks as well as offers multiple radio interfaces for smooth communication with improved coverage and capacity of the radio links. However, the proposed scheme does not perform well in high device mobility scenarios.

An Optimized Polymorphic Hybrid Multicast Routing (OPHMR) protocol based on three design dimensions that include hybridization, adaptability, and power awareness is introduced to proactively reduce the impact and frequency of network control overhead (Mnaouer, Chen, Foh, & Tantra, 2007). The OPHMR protocol is an adaptive scheme with proper power management, performs better in the mobility level, and multi-behavioral operations modes of mobile nodes. Moreover, the OPHMR protocol can equally exhibit both the reactive and proactive behaviors depending on the routing demand, resulting in an extended battery life of the nodes, minimized end-to-end delay, and improved packet delivery probability of the network. However, the selection of a single path is easily broken and needs to perform a route discovery process again due to the dynamic topology of networks. The authors in (Z.-Y. Wu & Song, 2008) introduced ant colony-based meta-heuristic and swarm intelligence to optimize the routing protocol for energy efficiency in wireless networks. This proposed protocol could self-configure itself in order to adapt the alterations in the network, including topological and geographical changes. As it is based on real ant behavior in which ants wander randomly in a small geographical region. Rather than sending its current residual battery status to other devices, it takes into account the required battery power to deliver a single packet along the path and decides the optimization routing protocol based on the computed information. Results indicated that the proposed mechanism performs excellently when the device's number is increased. Nonetheless, point-based mobility measurement and route selection approaches do not consider individual device mobility.

In the article (Yi, Adnane, David, & Parrein, 2011), another variant of OLSR called a Multipath OLSR routing protocol (MP-OLSR) is proposed, in which presented a platform that allows simultaneous estimation of multiple paths by using the multipath Dijkstra algorithm. This approach has been simplified so that it is easier to locate the multiple paths in both dense and sparse network scenarios with two cost functions, such as node-disjoint and link-disjoint paths. Moreover, the MP-OLSR changed the proactive behavior of the OLSR to reactive or on-demand routing in order to minimize the cost of route discovery and route computation process. Besides, the MP-OLSR utilizes route recovery and loop detection functions to improve the packet delivery ratio and reduce the chance of link failure due to frequent change of network topology. Thus, the MP-OLSR is able to achieve an excellent network performance in terms of network-load-balancing in high mobility nodes scenarios. However, it is not guaranteed that the same path will always route to the same destination; therefore, route entries are held in reserve for a short duration of time, then they expire due to changes in the network's configurations. A parallel Disjointed Multipoint routing algorithm-based OLSR called DMP-EOLSR is proposed in (M. Huang, Liang, & Xi, 2012), which is a hybrid routing protocol that involves both reactive and proactive routing protocols. The DMP-EOLSR considers the living time of the device as well as the living time of links between devices based on the energy consumption and moving state of the mobile devices during route computation.

The living time of devices depends on the residual energy of the devices, whereas the living time of links between devices depends on the speed and direction movement of the devices. Meanwhile, an iterative algorithm is exploited to discover different node-disjointed or link-disjointed routes according to the multipath Dijkstra's algorithm. The DMP-EOLSR effectively mitigates the number of the interrupted network devices, improves the stability of the selected route links, and enhances the parallel transmission capacity of the routes. Nevertheless, it does not consider the adaptability of the established path to change the motion of devices.

The authors proposed a point-based mobility factor computing technique for route selection in (Sarkar & Datta, 2017), which provides better routing performance for frequent topology changing scenarios in wireless networks. The point-based mobility factor value is estimated based on the pause time, speed, and moving direction of the mobile devices for the static and dynamic scenario. Moreover, the Mobility Aware Routing (MAR) technique based on the mobility factor is used for the route selection process. It provides better QoS performance metrics for the static and highly dynamic network. However, when the network becomes dynamic, these mobility metrics have no advantage, and they take a high complexity for mobility estimation as compared with the simple methods. In the article (Chen et al., 2018), the authors proposed an optimal routing approach based on the trusted connectivity probability (T-CP) to select the optimal route for multi-hop social-based D2D communication with decode-and-forward relaying in the 5G IoT. The authors introduced a rank-based trust model to measure the trust probability between two D2D devices. The results showed that the designing of the optimal route in multi-hop D2D communication for 5G IoT applications is mainly based on the location of the base stations. For example, in a random location of the base station, the connectivity probability-based metric selects the optimal path between the source and destination devices. Nonetheless, the higher delay is induced in the network for data transmission due to the selection of an untrustworthy intermediate device in the path.

In the article (Sharafeddine & Farhat, 2018), the authors proposed a proactive approach and cluster formation mechanism with the utilization of the decision-making process in wireless networks with D2D cooperation to optimize network reliability. A heuristic approach combines with linear optimization problem formulation to provide high efficiency for high-density device networks such as IoT and wireless sensor networks. The proposed approach improves network reliability and prolongs the network lifetime. However, the scheme does not consider the scalability and behavior of device mobility. In the article (Sobral, Rodrigues, Rabêlo, Saleem, & Kozlov, 2019), the authors introduced a Lightweight On-demand Ad hoc Distance-vector Routing Protocol for mobile IoT networks (LOADng-IoT-Mob). The LOADng-IoT-Mob routing scheme allows the network device to track the position and manage the availability of the neighbor's device through the harnessing of periodically control messages. Therefore, the source devices select the best path and avoid the sending of data packets toward the broken path based on the received signal strength that enhances network stability and QoS. The LOADng-IoT-Mob approach has achieved a higher data rate, minimized the delay, and improved energy efficiency in the mobile IoT network. Nevertheless, the proposed scheme does not mention the scalability of the routing protocol. Table 2.1 illustrates the related work summary on network stability as discussed in this section.

**Table 2.1: Recent studies summary of network stability**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (M. Li et al., 2005) | An energy-centric multipath routing protocol | Energy level and link bandwidth status of the devices in the selection of route | Increases the network lifetime and maximize the links channel capacity | Scalability associated with the flat routing scheme |
| (Luis Villasenor-Gonzalez et al., 2005) | Heterogenous OLSR | Select the best available link and local route discovery | Increased packet delivery ratio, reduced route computation cost and minimized delay in the network | The scheme does not perform in high mobility device scenarios |
| (Mnaouer et al., 2007) | An Optimized Polymorphic Hybrid Multicast Routing | Adaptive scheme with proper power management and performs better in the mobility level and multi-behavioral operations modes of mobile nodes | The extended battery life of the devices minimized end-to-end delay, and reduce overhead control message in the network | The single route is easily broken and needs to perform a route discovery process again due to the dynamic topology of the network |
| (Z.-Y. Wu & Song, 2008) | Ant-based Energy-Aware Disjoint Multipath Routing Algorithm | Adapt ant behavior with random alterations in the network for topological and geographical changes | Mobility aware disjoint routing paths provide network robustness | Point-based mobility measurement and route selection approaches excluded in the individual device mobility |

**Table 2.1 Continued**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (Yi et al., 2011) | A Multipath OLSR routing protocol | -Apply multipath Dijkstra algorithm to simultaneous estimate multiple paths<br>-Utilize node-disjoint and link-disjoint paths metric<br>- Exploits route recovery and loop detection functions | -Changed the proactive behavior to reactive in order to minimize the cost of route discovery and route computation process.<br>- Reduce the chance of link failure due to frequent change of network topology | It is not guaranteed that the same path will always route to the same destination; therefore, route entries are held in reserve for a short duration of time, then they expire due to changes in the network's configurations |
| (M. Huang et al., 2012) | A parallel Disjointed Multipoint routing algorithm based OLSR | Considers living time of device and links between devices based on the energy consumption and moving state of mobile devices during route computation | Improve the stability of the selected links and enhance the parallel transmission capacity of the routes | Does not consider the adaptability of the established path to change the motion of devices |
| (Sarkar & Datta, 2017) | A point-based mobility factor computing technique | Mobility factor value is estimated based on the pause time, speed and moving direction of the mobile devices | Provides better QoS performance for the static and highly dynamic network | When the network becomes dynamic, these mobility metrics have no advantage, and they take a high complexity for mobility estimation as compared with the simple methods |

**Table 2.1 Continued**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
| --- | --- | --- | --- | --- |
| (Chen et al., 2018) | Optimal routing approach based on the trusted connectivity probability | A rank-based trust model is employed to measure the trust probability between two D2D devices | Random location of the base station, the connectivity probability-based metric provides the optimal path | Higher delay is induced in the network for data transmission due to the selection of untrustworthy intermediate device in the path |
| (Sharafeddine & Farhat, 2018) | A proactive approach and cluster formation mechanism | A heuristic approach combines with linear optimization problem formulation to provide high efficiency | Improves network reliability and prolongs the network lifetime | Exclude scalability and behavior of the device mobility |
| (Sobral et al., 2019) | A Lightweight On-demand Ad hoc Distance-vector Routing Protocol | Allows the network device to track the position and manage the availability of the neighbor's device through the harnessing of periodically control messages | Enhanced the network stability, improved energy efficiency, and QoS | Does not mention the scalability of the routing protocol |

### 2.4.2 The D2D Communication in Ultra-Dense Network Scenario

One of the limitations in the D2D communication base UDN is the traffic congestion on the network devices. When there is an excessive flow of packets injected and carries most of the network traffic on a single mobile device, it induces data transmission delay in the network. Due to this, routing approaches suffer from the load balancing among the intermediate devices of the network, which can further significantly degrade the overall network performance. These subsection summaries the studies of the data traffic congestion constraints and their performances on the D2D communication UDN scenario.

#### 2.4.2.1 Related Work on Traffic Congestion Constraints

The relationship between energy consumed by the network devices and data packets collision in the medium or channel is presented in (Zijian Wang, Bulut, & Szymanski, 2009). In this article, an energy-efficient and collision aware (EECA) node-disjoint multipath routing protocol for the wireless network have been proposed. The route discovery packets flooding is limited with the discovered route within the neighbor's device. Every device of the network sends route request messages and data packets with minimum power control component by using the device location information. Broadcast nature of wireless communication is utilized to avoid data packet collisions between two discovered routes without extra overhead packets. The EECA provides significant network performance, energy efficiency, and reliable data transmission in the network. However, traffic along multiple paths will interfere with each other in this scheme. While the authors in (Badis & Al Agha) proposed a Quality-OLSR (Q-OLSR) multipath routing in wireless networks based on multiple metrics such as bandwidth and delay metrics for path selection criteria. Their method has offered data traffic load balancing and minimizes end-to-end delay, which will be ideal for the wireless networks routing approach. Nevertheless, the scheme does not characterize scalability with different communication capabilities and multiple radio interfaces. Due to the scalability problem of flat routing schemes in wireless networks, in (L. Villasenor-Gonzalez, Ying, & Lament, 2005), the authors presented the Heterogenous OLSR routing (HOLSR) scheme, which is more suitable for large-scale heterogeneous networks. The hierarchical network architecture exploits numerous interfaces formed at distinct logical levels in the network topology. The HOLSR scheme utilizes multiple interfaces and reduces control message overhead in the network to improve the performance of the routing mechanism. Nonetheless, the scheme induces network instability, which degrades network performance.

The paper in (Yi et al., 2011) proposed a Multipath-OLSR (MP-OLSR) routing for mobile wireless networks. The proposed routing scheme able to manage the scalability, security, network privacy, lifetime, wireless transmission instability with their adaptation to wireless network applications. In this paper, the MP-OLSR is established from the modification of the Dijkstra algorithm and auxiliary functions. This paper offers route recovery and loop detection mechanisms, which are employed to boost the network performance and the QoS. The proposed approach improves network reliability and prolongs the network lifetime. However, the proposed scheme is limited to stationary wireless networks. In the article (Zehua Wang, Chen, & Li, 2014), the authors introduced a Proactive Source Routing protocol (PSR) to facilitate opportunistic data forwarding in wireless networks. Each device has full information about the network topology and periodically exchanges messages with neighbors' devices. The exchanged messages contain link cost information based on the number of devices along the path from source to destination. The PSR routing approach maintains more network topology information than distance vector routing, making it ideal for source routing since it incurs less routing overhead with improved data transmission capability. Nevertheless, the proposed scheme does not consider cross-layer overhead in the network. In addition to that, the authors in (Pham & Hwang, 2017) addressed a network utility maximization (NUM)-based congestion control paradigm for cross-layer designs for wireless networks. In this paper, the authors have considered the problem of cross-layer congestion control arises from the several dimensions, specifically, elastic or inelastic traffic, same or multi time scale, and single or multipath transmissions. Moreover, it gives comprehensive discussions on various mathematical techniques and solutions used for cross-layer congestion control problems. The Successive Convex Approximation (SCA) method is also discussed, which strongly depends on initial conditions and network scenarios. Overall, it concluded that the cross-layer congestion control in wireless networks could be solved by utilizing network generation such as Software-defined networking (SDN) and cloud- radio access network (C-RAN) with efficient central controller and network statistics. Nonetheless, the scheme does not perform well in a scenario with a dynamic network.

In the article (Jiazi Yi & Benoît Parrein, 2017), the authors proposed a Multipath OLSR Protocol version 2 (MP-OLSRv2) to discover multiple disjoint paths for wireless networks. The MP-OLSRv2 exploits multipath Dijkstra's shortest path algorithm to explore multiple disjoint routes from a source device to a destination device based on the network topological information. The proposed approach avoids the disjoint routes if the single link failure occurs and transmits the data packets in a parallel manner to aggregates network throughput. The MP-OLSRv2 approach enhances the overall network throughput and increases the data forwarding reliability in the dynamic and high-loaded network scenarios by avoiding device link failure in the optimal route. However, the proposed approach only considers the number of devices hop in the route selection. It does not consider the queuing delay due to the congestion at the intermediate devices. In (Bhattacharya & Sinha, 2017), a routing protocol called Least Common Multiple based Routing (LCMR) is proposed for wireless networks that balance the load among the different possible paths. The LCMR routing distributes packets and properly uses them for route computation along with the multiple paths to minimize the overall routing time. Nevertheless, the proposed scheme is restricted to the particular network and the flexibility is required for the heterogeneous network. The authors in (Nguyen, Khan, & Ngo, 2018a) proposed a protocol which they call Energy-harvesting-aware routing algorithm (EHARA) for heterogeneous IoT network, in combination with the "energy back-off" parameter. This method is able to tackle the challenges of the load balancing and energy consumption of the network devices. With their method, the device's lifetime and network QoS parameters have been increased. Nonetheless, control overhead needs to be significantly reduced in the proposed scheme before it can be implemented in practical networks scenario.

In (Debroy, Samanta, Bashir, & Chatterjee, 2019), the authors proposed a Spectrum aware Energy-Efficient multi-hop multi-channel routing scheme for D2D communication in IoT mesh network (SpEED-IoT). The authors have utilized radio environment maps (REM) in the multi-hop routing protocol to find the optimal route, better channel among the devices, and optimal power transmission for each hop. The proposed scheme utilized a selective flooding technique to minimize the flooding of route discovery packets in the network that lead to mitigation of the energy consumption of the network devices. The SpEED-IoT scheme maximized overall network data rate optimization performance and ensured fairness, unlike spectrum agnostic or greedy based route assignment. However, in the proposed approach, a collision occurs in the MAC layer when the data packets transmitted simultaneously through multiple routes. Table 2.2 illustrates the related work summary on data packets traffic congestion, as discussed in this section.

**Table 2.2: Recent studies summary of data packets traffic congestion**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (Zijian Wang et al., 2009) | An energy-efficient and collision aware node-disjoint multipath routing protocol | Broadcast nature of wireless communication is utilized to avoid collisions between two discovered routes without extra overhead | Provides significant network performance, energy efficiency and transferred data efficiently | Traffic along multiple paths will interfere with each other |

**Table 2.2 Continued**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (Badis & Al Agha) | A Quality-OLSR multipath routing | Route selection based on multiple metrics such as bandwidth and delay metrics | Offered data traffic load balancing and minimize end-to-end delay | Does not characterized with different communications capabilities and multiple radio interfaces |
| (L. Villasenor-Gonzalez et al., 2005) | Heterogenous OLSR routing | The hierarchical network architecture utilizes multiple interfaces formed at distinct logical levels | Reduce control overhead and optimize routing computations | Induces network instability which degrades the network performance |
| (Yi et al., 2011) | Multipath-OLSR | - Employ the Dijkstra algorithm and auxiliary functions<br>- Exploits route recovery and loop detection mechanism | Manage the scalability, security, network privacy lifetime and wireless transmission instability | Limited to stationary wireless networks |
| (Z. Wang et al., 2014) | Proactive Source Routing protocol | Each device has network topology information through exchanged messages contain link cost information based on the number of devices along the path | Reduce routing overhead with improved data transmission capability | Does not consider cross-layer overhead in the network |
| (Pham & Hwang, 2017) | Network utility maximization-based congestion control paradigm | Successive convex approximation methods and solutions mechanism used for cross-layer congestion control problems | Cross-layer congestion control in wireless networks can be solved by utilizing network generation such as SDN and Cloud-RAN | Does not perform well in a scenario with dynamic network |

**Table 2.2 Continued**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (Jiazi Yi & Benoît Parrein, 2017) | Multipath OLSR version 2 | -Multipath Dijkstra's shortest path algorithm to explore multiple disjoint routes<br>- Avoided the disjoint routes if the single link failure occurred | Enhance the overall network throughput and increase the data forwarding reliability | It only considers the number of devices hop in the route selection. It does not consider the queuing delay due to congestion at the intermediate devices |
| (Bhattacharya & Sinha, 2017) | Least Common Multiple based Routing | Distributes packets and properly uses them for route computation along multiple paths | Minimize the overall routing time | Restricted to the particular network and the flexibility is required in the heterogeneous network |
| (Nguyen et al., 2018a) | An Energy-harvesting-aware routing algorithm | Energy-harvesting-aware routing with combination with the “energy back-off” parameter | Load balanced and reduce the energy consumption of the network devices | Control overhead needs to be significantly reduced before it can be implemented in practical networks |
| (Debroy et al., 2019) | Spectrum aware Energy-Efficient multi-hop multi-channel routing scheme | Radio environment map and selective flooding technique utilized for the selection of optimal route | Optimize network data rate performance, minimize flooding effect and reduce energy consumption | The collision occurs at the MAC layer when data packets are transmitted simultaneously through multiple routes |

### 2.4.3 The D2D Communication based Disaster Management Scenario

In the D2D communication based DMS, the mobile devices are equipped with limited energy resources for their vital operation of data transmission. The connectivity of the devices will suffer from the packets drops as soon as the device's energy gets exhausted. Limited energy resources and processing power of mobile devices are the significant sources of constraints in designing an optimal route, which incurs severe impacts on network lifetime. Various strategies have been adopted in order to save energy consumption of the devices, including limiting the broadcast messages in the network (Al-Turjman et al., 2019; Ghahfarokhi, Azadmanesh, & Khorasani, 2018; Huynh, Chen, Huynh, & Hai, 2019; J.-M. Liang, Chang, Chen, Huang, & Tseng, 2018; K.-W. Lim, Jung, & Ko, 2015; Mukherjee, Gupta, & Varsamopoulos, 2009; H. Rong et al., 2019; Swain & Murthy, 2020). Though most of the suggestions to save energy consumption is solely based on single-path routing protocols. However, selecting the same path every time to forward the data traffic from the source to destination device impacts the routing protocol efficiency, as well as it affects the battery life of the intermediate devices. Thus, low efficiency is obtained as the same path to a destination is selected to forward the data traffic, which in turn reduces the device battery lifetime.

Moreover, the mobile devices in the network, change their position in an unpredictable manner, which induces the chance of link failure in the established route between source and destination devices. Due to the link failure in the established route, the data packet needs to be retransmission with a new link, and this acquires more bandwidth in the network. The dynamic time-varying characteristics of the wireless network pose link failure and severely degrade network performance (Bao, Matyjas, Hu, & Kumar, 2018; X. Fu, H. Yao, & Y. Yang, 2019; Gazestani & Ghorashi, 2018; Thorat, Raza, Kim, & Choo, 2017; Yan et al., 2018). The link quality among the devices plays a significant role in the selection of the optimal route. Therefore, combining link quality and residual energy of the device into the routing metric for the D2D communication based DMS will ensure data transmission reliability and balance energy consumption load among the devices. The subsection below summarizes the recent studies of the energy resource and the link quality constraints on the D2D communication based DMS.

#### 2.4.3.1 Related Work on Energy Resource Constraints

The first version of the OLSR reactive routing protocol is introduced in (Clausen & Jacquet, 2003), in their paper some specific devices named as Multi-Point Relay (MPR) is selected during routing to minimize packets traffic overhead and copes with a message flooding problem in the network. These MPR devices are selected by two hops away from the neighbor device to be used for forwarding data packets to the destination device. Thus, excessive load is induced on MPR devices, which contributes to the rapid depletion of their battery and increases the chance of link failure. In another study, Energy-aware Multipath Routing Protocol (EMRP) is presented in (M. Li et al., 2005), where the battery's residual energy information of the devices is exchanged within a neighbor device along with the routing information. Hence, when the devices are selecting the best paths, they will consider the remaining energy of all the devices as well, which are present in the selected path(s). The EMRP protocol prolongs the network lifetime, minimize energy consumption, and increase packets delivery ratio. However, the single path is easily broken and needs to perform a route discovery process again due to the dynamic topology of networks, which induce packets flooding and data transmission delay in the network. Meanwhile, in (Z.-Y. Wu & Song, 2008), the authors proposed the swarm intelligence based Ant-based Energy-Aware Disjoint Multipath Routing Algorithm (AEADMRA), which considers the “devices energy consumption” as one of the device selection criteria in the route. The proposed algorithm is a subset of swarm intelligence, which utilizes the ability of ants to solve complex problems by cooperating among themselves. The AEADMRA discover multiple energy aware routing paths with a low routing overhead based on swarm intelligence especially on the ant colony based meta heuristic. The results show that the proposed scheme delivers better performance in terms of reducing routing complexity and improved route discovery process. However, the bandwidth constraint arises due to maintaining the up-to-date state of network information is a complex task.

The authors in (Kunz & Alhalimi, 2010) have proposed an energy-efficient proactive routing protocol in the wireless network which provides energy metrics accuracy. In their research, the authors have discussed a framework to reinforce energy-efficient routing by inaugurating the energy metrics. In this study, the authors have proved that their proposed two techniques, which are prediction and smart prediction have able to mitigate energy level inaccuracies and establish it under a variety of traffic rates compared with underlying OLSR protocol. Besides, with their proposed method, the accuracy has been elevated under all the traffic load. However, their work scope is limited to a monotonic decreasing level, such as energy level only. At the same time, the authors in (De Rango, Guerriero, & Fazio, 2010) introduced a Link-stAbility and Energy-aware Routing (LAER) protocol with minimum drain rate energy consumption in distributed wireless networks has been investigated. The LAER is based on a joint metric and a modified perimeter forwarding strategy for the recovery from the local maximum. They are working to increase the device selection performance with higher link duration. Nonetheless, their work is limited to optimization formulation thus excluded the protocol analysis, protocol management, and protocol performance.

In another work carried out in (Ramesh, Supriya, & Subbaiah, 2014), the authors presented an Energy Efficient Preemptive DSR (EE-PDSR), a header processing mechanism to reduce the overhead information attached to each packet. The proposed mechanism ensured that devices process the header more rapidly while consuming less energy in data processing, which consequently saves energy for the whole network to be utilized later. This technique will not only save energy and processing time but also reduces the load on the network links since there is fewer data to be carried and improved the capacity of the links. The obtained simulation data indicated a significant improvement in the packet delivery ratio. At the same time, the authors further justified that the proposed algorithm performs better when the network is highly dynamic, with frequent changes in the position of the devices. However, the work does not investigate scalability and quantitatively level accuracy of the QoS performance metrics. In (Taha et al., 2017), a Fitness Function Ad-hoc On-Demand Multipath Distance Vector (FF-AOMDV) routing protocol is proposed, which uses a technique known as a fitness function to discover the optimal and shortest path to forward data towards the destination node. The FF-AOMDV chooses the best forwarding path based on two metrics, such as the residual energy and the distance from the transmitting and receiving node. This enables it to reduce device energy consumption and thereby extends the network lifetime. However, route broken occurs when the device mobility is induced and most of device energy is consumed and waste for investigating the shortest route.

An energy-aware routing model named enhanced intellects masses optimizer energy-efficient and secure optimized link state routing (EIMO-ESOLSR) is proposed in (Kanagasundaram & Kathirvel, 2018) for energy-efficient and secure MPR selection in OLSR routing scheme. The MPR selection in the route discovery process is based on the willingness and Composite Eligibility Index (CEI) for each device in the network. The willingness value is estimated based on the available bandwidth, lifetime, and queue occupancy metrics of the network devices, whereas the CEI value is calculated based on the power factor, misbehaving probability, and forwarding behavior of the network devices. The results show that the proposed EIMO-ESOLSR routing scheme reduces the energy consumption, provides a secured MPR device selection, and minimized the packets flooding in the network. However, the EIMO-ESOLSR schemes assume a stable network, and it is not directly feasible for the dynamic topology of networks.

In (Nguyen et al., 2018a) authors introduced an effective energy-harvesting-aware routing algorithm (EHARA) in which energy harvesting mechanism is utilized to investigate the issue of energy efficiency, QoS, network lifetime, and heterogeneity of IoT devices. The proposed routing scheme exploited two cost metrics, such as harvested energy and the residual energy of the device, to select the optimal path for forwarding data packets from source to the destination devices. The EHARA scheme enhanced the device lifetime, the network QoS performance metrics, and energy efficiency with various traffic loads for distributed heterogeneous IoT networks. However, the proposed scheme does not consider the number of hops during the route computation process that induces data transmission delay in the network. In (Waheb A. Jabbar, Saad, & Ismail, 2018), the authors introduced hybrid multipath energy and QoS-aware OLSR protocol version 2 (MEQSA-OLSRv2) to provide a tradeoff between energy efficiency and QoS in IoT networks. For optimal path selection between source and destination devices, it utilized the device rank metrics according to the multiple criteria (energy and QoS) to evaluate link assessment function during multiple path computation. Flooding of the topological packets is reduced with the selection of the highly energy efficient MPR sets of the devices in the network. Overall, the MEQSA-OLSRv2 significantly enhance the network QoS in the heavy traffic load and high-mobility scenarios networks by transmitting data packets over multiple disjoint paths based on link quality assessment function. Nevertheless, the work does not investigate quantitatively level of accuracy of the QoS performance metrics.

In the article (Ladas, Deepak, Pavlatos, & Politis, 2018), the authors proposed a selective Multipath-ChaMeLeon (M-CML) routing protocol for ubiquitous networks. In their study, the M-CML is able to address the network instabilities due to the link failures caused by higher mobility and energy constraints of the network devices. Their technique offers many advantages such as mitigation of unessential information, sustain the quality of packets performance, reduce network routing load, minimize energy consumptions, offer flexibility, and independent in network infrastructure. Nevertheless, the scheme does not consider its behavior in high mobility scenarios. In (Riasudheen, Selvamani, Mukherjee, & Divyasree, 2020), the authors proposed an Energy-Efficient Cloud-Assisted Routing Mechanism (EECRM) for Cloud Assisted-Mobile Ad Hoc Networks (CA-MANETs). The Bellman-Ford algorithm is modified for a fast route recovery mechanism to obtain the alternate route when the link failure occurs among the devices. The authors introduced three new functions named service scheduling, information update and information notice for maintaining connections in the CA-MANETs. The EECRM scheme has minimized energy consumption, enhanced routing performance, and extended the lifetime of CA-MANETs. However, the scheme does not consider the QoS performance metric, such as delay and packets delivery ratio, for a better understanding of the routing protocol. Table 2.3 illustrates the related work summary on energy resource constraints, as discussed in this section.

**Table 2.3: Recent studies summary of energy resource constraints**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (Clausen & Jacquet, 2003) | OLSR reactive routing protocol | MPR devices are selected based on two hops away from the neighbor device for forwarding data packets | -Mitigate the packets flooding in the network particularly suitable for large and dense networks<br>-Provides optimal routes with the minimum number of hops | Excessive load induces on MPR devices contributes to the rapid depletion of battery life and increases the chance of link failure |

**Table 2.3 Continued**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (M. Li et al., 2005) | Energy-aware Multipath Routing Protocol | Battery's residual energy information is exchanged within neighbors' devices along with routing information | Prolong network lifetime, minimize energy consumption, and increase packets delivery ratio | The single path is easily broken and needs to perform a route discovery process again that lead to increase delay and control overhead packets due to the dynamic topology of networks |
| (Z.-Y. Wu & Song, 2008) | Swarm intelligence -based Ant-based Energy-Aware Disjoint Multipath Routing Algorithm | Discover multiple energy-aware routing paths with a low routing overhead based on swarm intelligence and ant colony metaheuristic. | Reduce route selection complexity and improve the route discovery process | Bandwidth constraints due to maintaining up-to-date state information of the network is a complex task |
| (Kunz & Alhalimi, 2010) | An energy-efficient proactive routing | Prediction and smart prediction employed to mitigate energy level inaccuracies | Energy level accuracy has been adjusted under all the traffic load. | The work scope is limited to monotonic decreasing level such as energy level only |
| (De Rango et al., 2010) | A link-stAbility and Energy-aware Routing protocol | Scalable routing protocol based on a joint metric such as link stability and energy drain rate for the recovery from the local maximum | Increase the device selection performance with higher link duration | The work is limited to optimization formulation thus excluded the protocol analysis, management, and performance |

**Table 2.3 Continued**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (Ramesh et al., 2014) | An Energy-Efficient Preemptive DSR | A header processing mechanism is utilized to reduce the overhead information attached to each packet | Minimize device energy consumption, data processing time, network load, and improve the channel capacity | The work does not investigate scalability and quantitatively level accuracy of the QoS metric |
| (Taha et al., 2017) | A Fitness Function Ad-hoc On-Demand Multipath Distance Vector routing protocol | Select the best forwarding path based on two metrics such as the residual energy and the distance of the devices | Optimize energy consumption of the devices and extends the network lifetime | The route is broken when the mobility of the device is induced. Most of the device energy consumed and waste for investigating of the shortest route |
| (Kanagasundaram & Kathirvel, 2018) | Enhanced intellects masses optimizer energy-efficient and secure OLSR | Energy-efficient and secure MPR selection with willingness and composite eligibility index | Reduces energy consumption, provides a secured selection of MPR devices and minimizes packets flooding in the network | The schemes assume stable network and it is not directly feasible for the dynamic topology of networks |
| (Nguyen et al., 2018a) | An effective energy-harvesting-aware routing algorithm | Exploits two metric such as harvested energy and the residual energy of the device to select the optimal path | Enhanced device lifetime, network QoS, and energy efficiency with various traffic loads | Does not consider the number of hops during the route computation process which induces a higher delay in the network |

**Table 2.3 Continued**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (Waheb A. Jabbar et al., 2018) | Hybrid multipath energy and QoS-aware OLSR protocol version 2 | Utilized the device rank metrics according to the multiple criteria (energy and QoS) to evaluate link cost assessment function during multiple route computation | Enhance the network QoS in the heavy traffic load and high-mobility scenarios | Does not investigate the level of accuracy of the QoS metric quantitatively |
| (Ladas et al., 2018) | A selective Multipath-ChaMeLeon routing protocol | Address the network instabilities due to link failures caused by the higher mobility and energy constraints of the network devices | Mitigation of unessential information, sustain the quality of packets performance, reduce network routing load, minimize energy consumptions | The scheme does not consider its behavior in high mobility scenarios |
| (Riasudheen et al., 2020) | An energy-Efficient Cloud-Assisted Routing Mechanism | -Three new functions named service scheduling, information update and information notice for maintaining connections in the network<br>-The Bellman-Ford algorithm is modified for fast route recovery mechanism to obtain the alternate route when the link failure occurs | Minimize energy consumption, enhance routing performance and extended the network lifetime | The scheme does not consider the QoS performance metric such as delay, packets delivery ratio, for better understanding of the routing protocol |

#### 2.4.3.2 Related Work on Link Quality Constraints

The authors in the article (Badis & Al Agha) introduced a multipath routing scheme called Quality OLSR routing (QOLSR), in which path selection criteria is based on the multiple QoS routing metrics such as bandwidth and delay. The paths are loop-free and multiple devices disjoint, computed by using the shortest–widest path algorithm. Moreover, a correlation factor is presented, which defines the number of links between every two disjoint paths that minimize the interferences between multiple paths to achieve better QoS with improved network resource utilization. However, the proposed scheme, focusing only on the optimization problem is formulated, whereas no analysis on the proposed protocol management and performance has been carried out. To realize reliability and stability in the wireless network, a scheme named as a Link-disjoint Interference-Aware Multi-Path routing protocol (LIA-MPOLSR) is proposed by authors in (Le & Pujolle). The performance of the named routing protocol is boosted with the integration of OLSR for a more accurate estimation of intermediate link quality status between source to the destination nodes before transmitting data, resulting in a higher packets delivery ratio in the network. The LIA-MPOLSR operates by calculating the link quality between a node and its neighbors to determine interference level and forward the packets towards destinations by using geographical distance instead of the number of hop counts. The proposed approach provides less routing overhead and normalized routing load in the network. Nevertheless, the proposed approach is suitable only for static network topology scenarios in which nodes do not change locations.

Another approach proposed an MP-OLSR routing protocol (Yi et al., 2011), where the multipath Dijkstra algorithm has been modified in order to find multiple routes for the sparse and dense network. It utilized two cost function to generate device disjoint and link disjoint paths. Results proved that the proposed algorithm is able to achieve high flexibility by using different link cost metrics and cost functions. In addition, two new concepts were introduced, namely; route recovery and loop detection in order to improve the packet delivery ratio and reduce the chance of link failure due to the frequent changing of network topology. The MP-OLSR routing improved overall network performance, especially in heavily loaded network scenarios. Nonetheless, the proposed scheme does not consider the device's mobility for either route computation nor MPRs selection mechanism. A scalable routing protocol named Link-stability and energy Aware Routing protocol (LAER) has been proposed in (De Rango, Guerriero, & Fazio, 2012), which is based on the joint metric of link stability and energy drain rate. A Biobjective Integer Programming (BIP) model is adopted to achieve an optimal solution in the route selection process. The BIP model selects next hop device among the neighbor devices, which has better link stability and less energy consumption rate. The LAER scheme prolongs the network lifetime and maintains the robustness of the network. However, the proposed approach does not adopt link state assessment factors of node energy and iterative factors to find multiple parallel disjoint routes.

In the meantime, the authors in (M. Huang et al., 2012) introduced a parallel Disjointed Multi-path Routing (DMP_EOLSR) algorithm based on OLSR in wireless networks. The method is considering the living time of the devices and the links based on the energy consumption and moving mode of devices, respectively. In their paper, the authors suggest that they have mitigated broken links to enhance network stability. However, their scheme has a limitation with the living time of links, which is always required for the current location of the neighbor's device that is not available all the time. In the article (Joshi & Rege, 2012), a modified version of OLSR named MOLSR routing protocol is proposed to solve the issue of end-to-end delay associated with the route discovery and route selection process in the OLSR routing, which utilizes the concept of multipath and source routing. The MOLSR chooses the neighbor node with a higher residual energy reserve and better link quality. Thus, the proposed scheme is capable of achieving a well-balanced, fairer traffic, and energy load distribution among the network nodes. Nevertheless, the proposed approach induces a higher delay in discovering a new route when the link failure occurs in the established route.

To enable opportunistic data transmission in wireless networks, the authors in (Z. Wang et al., 2014) designed a scheme called Proactive Source Routing (PSR) that allows every node to maintain a complete and up-to-date network topology information including the link cost of each network node by periodically exchanging topological information with neighbor nodes. The designed routing scheme performed better in terms of data transportation capability and minimized routing overhead in the network. Nonetheless, the proposed approach to device energy consumption is not considered in the packet forwarding process. In a dynamically changing network topology, link quality is severely impacted, resulting in frequent link failure in the network. To solve this, a Smooth Mobility and Link Reliability-based OLSR (SMLR-OLSR) routing scheme is proposed in (Z. Li & Wu, 2017). The Semi-Markov Smooth and Complexity Restricted mobility model (SMS-CR) is used to provide enough smoothness and low complexity for reliability enhanced MPR selection that facilitate longer MPR lifetime and less routing overhead in the network. However, the proposed scheme does not perform well in the scenario with the mobility of the devices. In the article (Yanjun Li, Chi, Chen, Wang, & Zhu, 2017), the authors studied the mobile user relay selection mechanism to achieve the optimal expected delivery ratio and expected a two-hop delay in the narrowband IoT systems with D2D communication. The dynamic programming-based technique is used to handle the optimization problems and obtain the optimal working schedule of the relays. The results proved that the proposed scheme enhanced the system performance compared with the other state-of-the-art algorithms. Nevertheless, the proposed scheme does not employ link failure detection and route recovery mechanism in the route selection process.

In the article (Jiazi Yi & Benoit Parrein, 2017), the authors proposed a multipath extension version of MP-OLSR stated as MP-OLSRv2, which belongs to the category of hybrid multipath routing protocol that involves proactive and reactive routing concepts for data transmission. The MP-OLSRv2 uses two incremental cost functions for the link cost between the devices to generate multiple node-disjoint and link disjoint paths. It discovers multiple disjointed paths instead of a single disjointed path for data transmission with the multipath Dijkstra algorithm in a frequently changing network topology. The MP-OLSRv2 mechanism is divided into two phases (topology sensing and route computation) to maintain the multiple routes from source to destination pairs. It delivers reliable communication and facilitates traffic load distribution into multiple paths, thereby ensuring load balancing among the devices of the network. Nonetheless, the proposed scheme does not investigate network QoS performance metrics. Multipath data transmission is a way of increasing network throughput while maintaining the link robustness with reliable transmission in the network. The Multipath Battery and Mobility Aware-OLSR (MBMA-OSLR) solution is then proposed in (Waheb A Jabbar, Ismail, & Nordin, 2017), which utilizes the battery and mobility information from devices and selects multiple paths by Energy and Mobility Aware Multipath Routing (EMA-MPR) procedure. The results indicated its superior performance as compared to MP-OLSRv2 in terms of the energy consumption and packet drop rate. However, the proposed scheme is limited to specific network scenario.

For link instabilities, energy resource constraints, and device mobility of frequently topology changing networks, in (Ladas et al., 2018) introduced a Multipath-ChaMeLeon (M-CML) routing protocols to stabilize and enhance the QoS and network performance. The Wilcoxon signed-rank test model and intelligent algorithm are employed to reduce the amount of generated duplicate packets in the network and help to minimize routing overhead and energy consumption of mobile devices. Nevertheless, the proposed scheme does not consider the uncertainty events in the networks. Besides, a Synchronized Fuzzy Ant system (SynFAnt) routing scheme for wireless networks is proposed by authors (Kacem, Sait, Mekhilef, & Sabeur, 2018) to find alternative routes with the best cost metric in the event of link or node failure. The proposed protocol uses fuzzy logic to discover the best route and employs the ant system to guarantee survivability and nominal traffic flow. A fuzzy synchronized Petri net transition is further applied in the routing decision mechanism for the detection of the unforeseen events in the wireless network. The proposed routing approach has also use the integration detection process to reduce propagation delay, control overhead, link failure, and mitigate interference, which exploits the intermediate nodes link status before transmitting the data. Nonetheless, this scheme increases the complexity of the route selection procedure. Table 2.4 illustrates the related work summary on link quality as discussed in this section

**Table 2.4: Recent studies summary of link quality**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (Badis & Al Agha) | Quality OLSR routing | -Route selection criteria are based on the multiple QoS routing metric such as bandwidth and delay<br>- A correlation factor is presented which defines the number of links between each two disjoint paths | Minimize the interferences between multiple paths to achieve better QoS with improved network resource utilization | Only the optimization problem was formulated, whereas no analysis on the protocol management and performance has been carried out |

**Table 2.4 Continued**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (Le & Pujolle) | Link-disjoint Interference-Aware Multi-Path routing protocol | -Estimate link quality between a device and its neighbors to determine interference level<br>-Forwards packets towards destination using geographical distance instead of the number of hop counts | It provides less routing overhead and normalized routing load. | Suitable for static network topology scenarios only in which nodes do not change locations |
| (Yi et al., 2011) | Multipath OLSR routing protocol | - Dijkstra algorithm has been modified in order to find multiple routes<br>- Two cost function to generate device disjoint and link disjoint paths<br>- Route recovery and loop detection mechanism employed | -Achieve great flexibility by using different link cost metrics and cost function<br>- Improve the packet delivery ratio and reduce the chance of optimal link failure | Does not consider the devices mobility for either route computation nor MPRs selection mechanism |
| (De Rango et al., 2012) | Link-stability and energy Aware Routing protocol | - A joint metric of link stability and energy drain rate<br>- BIP is employed for optimal route selection. | Prolongs the network lifetime and maintains the robustness of the network. | Does not adopts link-state assessment factors of node energy and iterative factors to find multiple parallel disjoint routes |

**Table 2.4 Continued**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (M. Huang et al., 2012) | A Parallel Disjointed Multi-path routing protocol | Consider the living time of the devices and the links based on the energy consumption and moving mode of devices in the route selection | Mitigated broken links to enhance the network stability | Living time of links always required the current location of the neighbor's device which is not available all time |
| (Joshi & Rege, 2012) | Modified OLSR routing protocol | Select the neighbor device with higher residual energy reserve and better link quality | Achieve traffic load balance and energy load distribution among the network nodes | Higher delay in discovering a new route when the link failure occurs. |
| (Z. Wang et al., 2014) | Proactive Source Routing | Allow every device to maintain a complete and up-to-date network topology information including the link cost | Enhanced data transportation capability and minimized routing overhead | Device energy consumption is not considered in the packet forwarding**.** |
| (Z. Li & Wu, 2017) | Semi-Markov Smooth and Complexity Restricted mobility model | Smoothness and low complexity for reliable MPR selection | Facilitates extended MPR lifetime and less routing overhead in the network | Does not perform well in the scenario with the mobility of the devices |
| (Yanjun Li et al., 2017) | Mobile user relay selection mechanism | The dynamic programming-based technique is used to handle the optimization problems and obtain the optimal working schedule of the relays | Enhanced the system performance in compared with the other state-of-the-art algorithms | Link failure detection and route recovery mechanism is not employed |

**Table 2.4 Continued**

| References | Models/ Scenarios | Methodologies | Advantages | Disadvantage /Limitation |
|---|---|---|---|---|
| (Jiazi Yi & Benoit Parrein, 2017) | Multipath extension OLSR version 2 | -Discovers multiple disjointed paths instead of a single disjointed path for data transmission with the multipath Dijkstra algorithm<br>- Employed topology sensing and route computation metric to maintain multiple routes | Provide reliable communication and facilitates traffic load balance distribution into multiple paths | The network QoS performance metric is not investigated. |
| (Waheb A Jabbar et al., 2017) | Multipath Battery and Mobility Aware routing scheme | Energy and mobility aware multipath routing employed for the selection of efficient MPRs | Reduce the number of packets dropped and higher energy efficiency | Limited to specific network scenario |
| (Ladas et al., 2018) | Multipath - ChaMeLeon routing protocols | Apply the Wilcoxon signed-rank test model and intelligent algorithm to reduce the amount of generated duplicate packets in the network | Stabilize and enhance the QoS network performance | Does not consider uncertainty events in the networks |
| (Kacem et al., 2018) | Synchronized Fuzzy Ant System routing scheme | -Utilize fuzzy logic to discover the best route and employs the ant system to guarantee survivability and nominal traffic flow<br>- A fuzzy synchronized petri net transition is applied in the routing decision | Reduce propagation delay, control overhead, link failure, and mitigate interferences | Increases complexity of the routing scheme |

## 2.5 Summary

Based on the previous discussion, it can be observed that network stability is a crucial obstacle in maintaining standard QoS performance in the conventional D2D communication scenario. While in the D2D communication UDN scenario, data traffic congestions are the primary cause of data packets transmission delay. Whereas in the D2D communication based DMS, the energy resource and link quality constraints are the key selection criteria that need to be critically considered when designing and implementing a routing protocol. Overall, the selection of highly qualified intermediate devices in the route selection process remains one of the most important and critical issues for efficient and reliable data transmission in the different D2D communication scenarios network.

# CHAPTER 3: METHODOLOGY

## 3.1 Introduction

This chapter proposes three routing approaches with their features, structures, models, and functionalities in three different D2D communication scenarios, such as conventional D2D communication scenario, D2D communication UDN scenario, and D2D communication based DMS. In the conventional D2D communication scenario, the proposed MRLAM routing approach is employed, which focused on optimizing the network stability in a highly dynamic and frequent topology changing networks. Meanwhile, in the D2D communication based UDN scenario, the proposed MBMQA routing approach is employed to focus on the traffic congestion of packets in the network in order to balance the data traffic load among the mobile devices. Furthermore, in the D2D communication DMS, the proposed EMBLR routing approach is employed to focus on the energy consumption load balance among the devices and reliable data transmission between the source and destination devices. Overall, the flowchart in Figure 3.1 shows the optimal route selection procedure of the proposed three routing approaches in the three different D2D communication scenarios. The flowchart gives a summary of the studied scenarios, namely: conventional D2D communication, D2D communication based UDN scenario, and D2D communication DMS. The following subsections comprehensively describe these three scenarios with the respective routing approaches:

## 3.2 The Conventional D2D Communication Scenario

In the conventional D2D communication scenario, the proposed MRLAM routing approach select a route between the source and destination devices with the active participation of intermediate devices that do not change their position frequently in the network, in order to optimize the network and route stability in a highly dynamic and

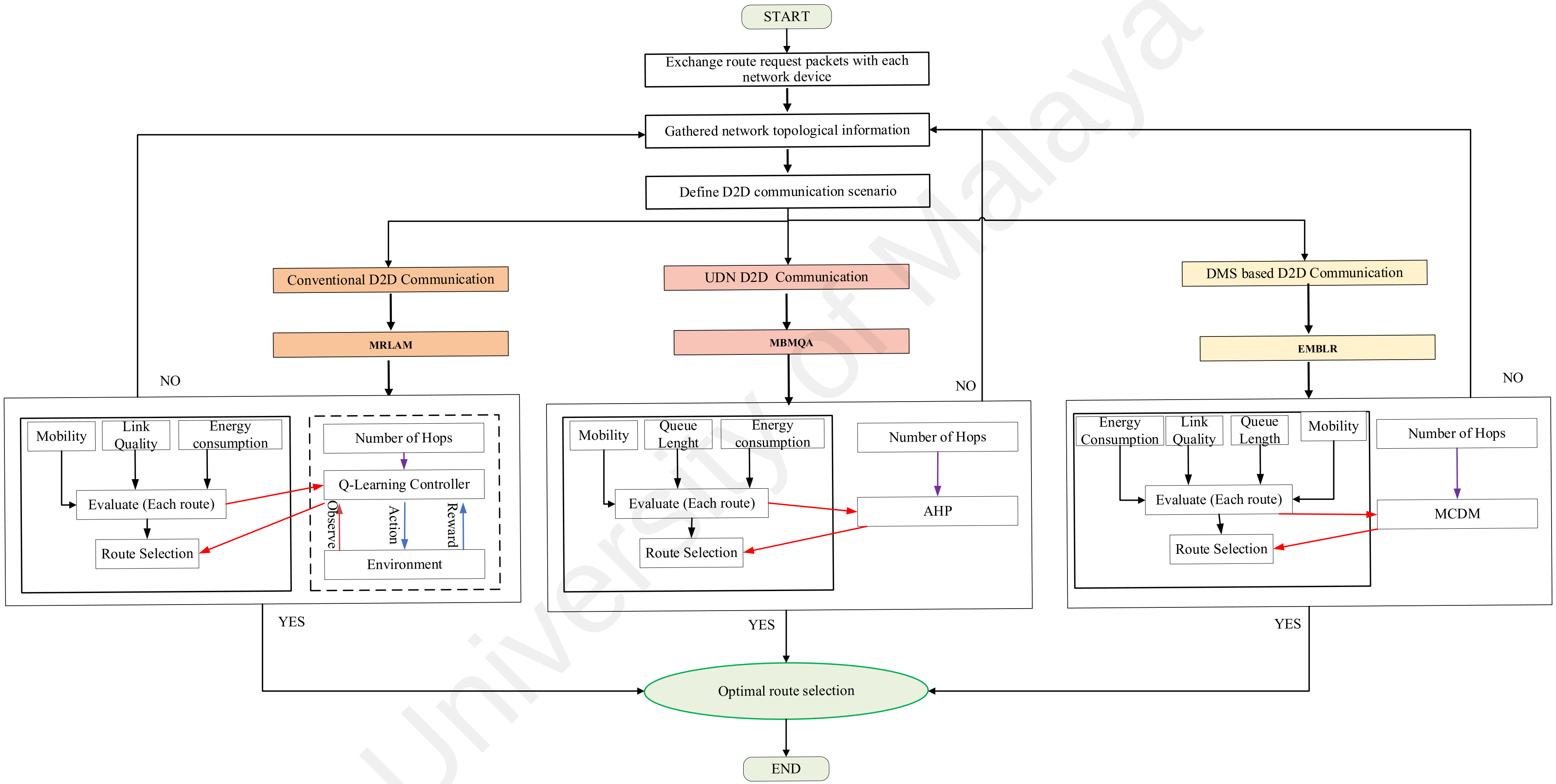




**Figure 3.1: The optimal route selection of the proposed three routing approaches in the three different D2D communication scenarios**

frequent topology changing network. Moreover, in the conventional D2D communication scenario, energy consumption and link quality of the devices also play a significant role in the route selection procedure to provide better QoS performance. Therefore, for robust and efficient route selection in the conventional D2D communication scenario, mobility of the devices with a sufficient amount of energy resources and better link quality of the device's estimation should be considered in the route selection procedure. The following subsection describes the system model of the proposed MRLAM routing approach for the conventional D2D communication scenario as follows:

### 3.2.1 System Model

The conventional D2D communication environment can be represented as a graph $G = (V,\ L)$ wherein $V$ is the set of devices and $L$ is the link between the devices. The link between the source device $s$ and the destination device $d$ is denoted by $(s,\ d)$ , i.e. $s,\ d \in V$ .Whenever the device $s$ is the neighbor of the device $d$, both of which can directly communicate with each other. In a centralized network, the network topology information is maintained by a network controller. In a decentralized network, network topology information is maintained by the information exchange between the device and its neighbors. The proposed routing approach is for a decentralized network, in which all mobile devices work as hosts as well as an intermediates device for other devices to build network infrastructure.

In the conventional D2D communication scenario, the route selection and data transmission are based on the collaboration among network devices for topological information exchange among each other. Due to the dynamic movement of devices, network topology continuously changes in an unpredictable manner. In this scenario, if two devices do not share a direct link with each other, they will utilize routing protocols to establish a connection by using intermediate devices between them to transfer the data.

The proposed routing approach utilizes mobility as a key factor with energy consumption and link quality of the intermediate devices in the route computation process to optimize the network stability and QoS of communicating devices as discussed below:

### 3.2.2 Device Mobility Estimation

Device mobility estimation governs the unpredictable movement of a device in a conventional D2D communication scenario, which helps to optimize route and network stability in advance. The random waypoint (RWP) is extensively used for estimation of the device's mobility and simulation analysis in the mobile wireless network due to its simplicity and better QoS performance (X. Ge, Ye, Yang, & Li, 2016). In the conventional D2D communication scenario, several parameters, such as speed, moving time, pause time, and separation distance of the mobile devices, are configured for the estimation of the device's mobility. The RWP model periodically estimates the mobility of devices and selects the random destination point ("waypoint") in the network based on the above parameters. Once the devices reach their selected waypoints, devices are pause for a defined duration of time (pause time), and this process is repeated. The waypoints are uniformly and randomly chosen in the network area. In the conventional D2D communication scenario, devices can move randomly in an area of operation and pause for an arbitrary period of time. The maximum and minimum velocity ($v_{\max}$ and $v_{\min}$) of each device is configured based on the RWP model along with its calculation of pause time duration to simulate real deployment scenarios. Network devices are uniformly distributed in the RWP model between the velocities range $[v_{\max} - v_{\min}]$, where $v_{\max}$ and $v_{\min}$ are the minimum and maximum velocities of the devices, respectively. The device speed distribution $f_{(s,d)}(v)$ in the dynamic network is described as below:

$$f_{(s,d)}(v) = p_{mov} \cdot \frac{1}{v \ \mathrm{In}(v_{\max} / v_{\min})} + p_{pause} . \delta(v) \tag{3.1}$$

where the velocity function $v$ is defined in the range of $v \in [v_{\max} - v_{\min}]$, $p_{pause}$ and $p_{mov} = (1 - p_{pause})$ are the probabilities of devices in the pause and moving states in the network, respectively. $\delta(v)$ defines the Dirac delta function, whose value updates according to the velocity of the device. The value of $\delta(v)$ varies from 0 to 1, when the velocity of a device is maximum, $\delta(v)$ is updated to 0, and when the velocity of the device is minimum, $\delta(v)$ become 1. The pause time of devices is considered to be $t_p \geq 0$, and the value of the probability of pause time $p_{pause}$ can be calculated as follows:

$$p_{pause} = \frac{t_p}{t_p + E[D]\dfrac{\text{In}(v_{\max} / v_{\min})}{(v_{\max} - v_{\min})}} \qquad (3.2)$$

where $E[D]$ denotes the expected value of distance cover due to device movement on the whole trip, and it is estimated with the RWP mobility model. If a device starts from the pause state $p_{pause}$, it pause time is set to be $t_p$. On the other hand, if the device starts from the moving state $p_{mov}$, it will select the device speed range $v \in [v_{\max} - v_{\min}]$. Recall that $p_{pause}$ is the probability of a mobile device in the pause state, while $t_p$ is the time spent by the device during pause state. The mobility of devices in a distributed dynamic network is calculated as follows:

$$\text{Mobility} = \min_{v \in [v_{\max} - v_{\min}]} \sum_{(s,d) \in N} f_{(s,d)}(v) \qquad (3.3)$$

The stability of an established path between the source and destination devices depends on the mobility of the intermediate devices which form the path. Therefore, a path will be unstable if the mobility of the constituent devices of the path is high. Based on the above mobility value of the devices in the conventional D2D communication scenario, the proposed routing approach prioritizes devices with less mobility resulting in the route's stability and network's lifetime improvement.

### 3.2.3 Energy Consumption Estimation with Device Mobility

The energy consumption of the device greatly depends upon the movement of the device in the network. Therefore, the energy consumption of devices collaborates with device mobility plays a significant role in the selection of robust and qualified intermediate devices in the optimal route to improve the overall conventional D2D communication network performance. The mobile devices in conventional D2D communication are battery-operated, and their energy is limited due to the absence of direct power supply. Therefore, the battery life of the devices should be taken into account while selecting a set of intermediate devices for route establishment to a destination in the network. Moreover, the mobile devices operate in four states, which are; transmission, receiving, idle, and sleep states. The energy consumption in idle and sleep states is low; hence, the transmission and receiving states of devices are considered in the design of the routing algorithm of the proposed approach.

In the conventional D2D communication, the energy of each device is linearly discharged as a function of the current load based on the Coulomb counting technique (P. Rong & Pedram, 2006), which accumulates the dissipated Coulombs from the beginning of the discharge cycle. It estimates the residual energy based on the difference between the accumulated value and prerecorded full charge value of the battery capacity. The proposed approach utilizes a generic radio energy model (Nguyen, Khan, & Ngo, 2018b) to estimate the consumed energy for each state of the device, such as [$E^{c}_{Initial}(t)$, $E^{c}_{Residual}(t)$, $E^{c}_{Consumption}(t)$ and $E^{c}_{operation}(t)$]. Energy consumption in different states of devices and duration of time in each state of devices affect the performance of the proposed routing approach. The initial energy level of the intermediate device $c$ at the time $t$ is denoted by $E^{c}_{Initial}(t)$ and the residual energy $E^{c}_{Residual}(t+\tau)$ of intermediate devices $c$ at the period of time $\tau$ is calculated as follows:

$$E^{c}_{Residual}(t+\tau) = E^{c}_{Initial}(t) - E^{c}_{Consumption}(t+\tau) \tag{3.4}$$

where $E^{c}_{Consumption}(t+\tau)$ refers to the energy consumption of device $c$ for a period of $\tau$, which is the energy consumed during transmission, receiving, exchanging routing information control packets, and during the internal operation time of devices. In the proposed routing approach for the conventional D2D communication scenario, energy consumption is estimated based on the circuitry power consumption, the number of packets exchanged, and the time spent in each state. Thus, the energy consumption in a transmission state of the intermediate device $c$ for transmitting $n$ number packets can be calculated as follows:

$$E^{c}_{Transmission}(t+\tau) = n \times P^{c}_{Transmission}(t+\tau) \tag{3.5}$$

whereas $P^{c}_{Transmission}(t+\tau)$ denotes the amount of power consumed during transmission of $n$ the number of data packets and exchanging routing information control packets with neighbor's devices at the period of $\tau$ time, the unit is in Watts per second. Similarly, the energy consumed by the intermediate device $c$ during the receiving state for transmitting $m$ numbers of packets and including control packets at the period $\tau$ is calculated as follows:

$$E^{c}_{Recieve}(t+\tau) = m \times P^{c}_{Recieve}(t+\tau) \tag{3.6}$$

where $P^{c}_{Recieve}(t+\tau)$ represents power consumed by the device $c$ during exchange control messages and receiving $m$ number of packets at a time $\tau$. Moreover, all the devices consume energy when they perform an internal operation such as connecting, managing, catching, and updating the database at the time of $\tau$ period, which is denoted by $E^{c}_{operation}(t+\tau)$. Therefore, the total energy consumption of the intermediate device $c$ at the time period $\tau$ in all transmission, reception and operation states can be calculated as follows:

$$E^{c}_{Consumption}(t+\tau) = E^{c}_{Transmission}(t+\tau) + E^{c}_{Recieve}(t+\tau) + E^{c}_{operation}(t+\tau) \quad (3.7)$$

Finally, the residual energy of the device $c$ updated at the time $\tau$ is denoted as follows:

$$E^{c}_{Residual}(t+\tau) = E^{c}_{Initial}(t) - \{E^{c}_{Transmission}(t+\tau) + E^{c}_{Recieve}(t+\tau) + E^{c}_{operation}(t+\tau)\} \quad (3.8)$$

The above expression provides information on the amount of remaining energy and the amount of energy that will be consumed by intermediates device $c$ at a time $t+\tau$. Based on this, the proposed routing approach in the conventional D2D communication scenario gives higher priority to devices that have higher available residual energy and less energy consumption rate with device mobility while establishing a connection between end-users.

### 3.2.4 Link Quality Estimation with Device Mobility

Links among the devices in the conventional D2D communication scenarios are typically unreliable, as they often experience fluctuations in quality and weak connectivity due to the movement of the network devices. The efficiency of the route selection mechanism of the proposed routing approach depends on the accuracy of the link quality value to increase the routing approach reliability. Therefore, the link quality of the channel with device mobility is one of the key factors in the selection of the reliable route in the conventional D2D communication scenario, which is estimated based on the Expected Number of Transmission (ETX) and Expected Any-path Count (EAX) parameters (W. Xu, Jiang, Tang, & Yang, 2017). The ETX is the expected number of transmissions required before a packet is successfully delivered to the next hop, which also determines link quality and packet loss on both directions of a link. The device $c$ is the intermediate device whose probabilities of receiving and forwarding data packets are $\lambda_c$ and $\mu_c$, respectively. These values are measured through the probe message that is transmitted using a dedicated link before actual data transmission. Each device broadcasts a probe message to all of its neighbor devices and maintains records of transmitted probe messages for a designated period of $\tau$ seconds. Accordingly, the packet delivery ratio probability from a source device to neighbor devices is calculated as follows:

$$\lambda_c = \frac{n_w}{w / \tau} \tag{3.9}$$

whereas $n_w$ denotes the number of probe messages delivered in a period of $w$ seconds satisfying the condition $w > \tau$. The probability that a neighbor's device $c$ receives a packet from at least one forward device is $p_{for} = 1 - \prod_{c>s} (1 - \mu_s \lambda_c)$, and the probability that the device $c$ successfully delivers a packet to at least one backward device is $p_{back} = 1 - \prod_{d>c} (1 - \mu_c \lambda_d)$. Here $\lambda_c$ and $\mu_c$ define as probabilities of receiving and forwarding data packets to the device $c$. Consequently, the expected number of transmissions that the device $c$ needs to take can be calculated as:

$$ETX = \frac{1}{p_{for} \times p_{back}} = \frac{1}{\left(1 - \prod_{s>c} (1 - \mu_s \lambda_c)\right)\left(1 - \prod_{d>c} (1 - \mu_c \lambda_d)\right)} \tag{3.10}$$

The ETX calculates the expected number of transmissions needed to successfully deliver a packet from source to destination through the forward device set $c$. The ETX metric selects all forwarded candidates and prioritizes them based on the equation (3.10). However, the ETX metric also includes forwarded sets that increase packet overhead in the network. To address this issue, the EAX metric is employed to select only the optimal forwarded sets and prioritize them based on opportunistic routing. This decreases interference with neighbor's device and minimized packets overhead, and the number of transmissions to some extent. The hop-count parameter is useful for optimized routing performance with minimum hop-count value. In addition to that, EAX minimizes the number of intermediate devices and the number of transmissions required for reliable packet delivery on the optimal route without contrarily affecting the performance of the network. $C^{s,d}$ defines the forwarded set of candidates from the device $s$ to $d$ and $C_c^{s,d}$

defines the device $c$ forwarded set prioritizing range from 0 to 1. Therefore, the delivery probability between source and $C_c^{s,d}$ is $p_{for}$ and vice versa (considering both the forward data and backward acknowledgment (ACK) transmissions). Then, the EAX value from source to destination through a forwarded set can be calculated as follows:

$$EAX(s,\ d) = \frac{1+\sum_c EAX(C_c^{s,d}, d)\left(1-\prod_{s>c}(1-\mu_s\lambda_c)\right)\prod_{j-1}^{c-1}\left(1-\prod_{d>c}(1-\mu_s\lambda_j)\right)}{\left(1-\prod_{s>c}(1-\mu_s\lambda_c)\right)} \quad (3.11)$$

In the above expression, the EAX metric selects and enables the potential candidate pairs of intermediate devices based on the packet's delivery probability. The selection of potential candidates in the optimal route from source to destination devices is performed as follows. Firstly, the ETX metric potential candidate $C_{potential}^{s,d}$ is determined based on the best path, such that if $ETX(s,d) > ETX(j,d)$, device $j$ will be added to the potential candidates in the route. Secondly, the subset of potential devices $C_{potential}^{s,d}$ is selected as the actual candidates set $C^{s,d}$ having the smallest ETX value to the destination. Also, a potential device is added to the forwarded set $C^{s,d}$ when it decreases the value of $EAX(s,\ d)$ by a factor $\delta$, which is defined as a configurable parameter. This step iterates until the new potential device is added in the network.

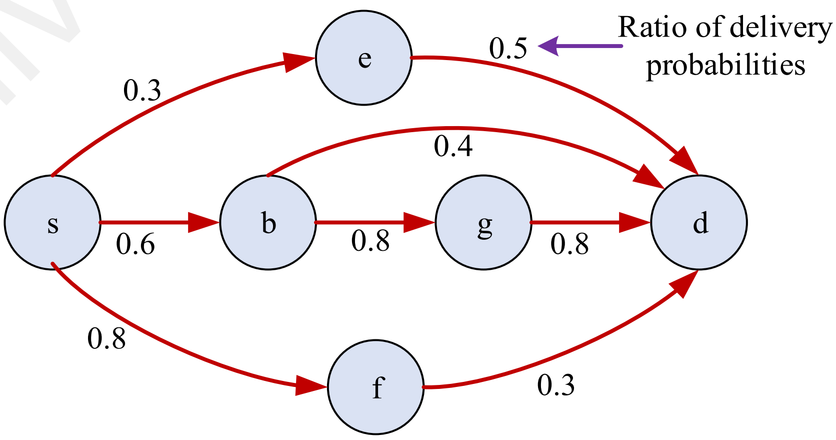


**Figure 3.2: The selection of intermediate potential candidate devices with ETX and EAX metrics**

The selection of intermediate potential candidate devices with ETX and EAX metrics is shown in Figure 3.2. It can be observed that source device $s$, destination device $d$, and next-hop neighbor devices $b$, $e$, and $f$ of device $g$ possess a different ratio of delivery probabilities. The ETX metric selects all three neighbor devices such as $b$, $e$, and $f$ because paths from these devices to $d$ have smaller ETX values than that from $s$ to $d$. These three neighbor's devices are sorted in ascending order based on the ETX value obtained by using equation (3.10). On the other hand, the EAX selects only two devices, such as $b$ and $e$, because with these two candidates, the EAX from $s$ to $d$ is less than the EAX from $f$ to $d$, adding $f$ to the candidate set does not decrease EAX between $s$ and $d$. Furthermore, EAX prioritizes device $b$ over the device $e$ as it possesses a smaller value of EAX based on equation (3.11). Next-hop selection comparison between ETX and EAX potential intermediate candidate's selection and prioritization from source to destination devices by ETX and EAX is illustrated in Table 3.1. Based on this, the proposed routing approach in the conventional D2D communication scenario gives higher priority to devices which have less EAX value with mobility of the devices while establishing a connection between end-users.

**Table 3.1: Selection of potential intermediate devices in the optimal route based on the ETX and EAX metrics**

| Methods | (Source, Destination) | Hop count | Devices in route | Priority |
|---|---|---|---|---|
| ETX | **(s, d)** | 3 | *b, e, f* | *e > b > f* |
| EAX | *(s, d)* | 2 | *b, e* | *b > e* |

### 3.2.5 Device Selection in Optimal Route based on Q-Learning Algorithms:

Q-Learning is a prevalent paradigm of reinforcement learning algorithms applied in a wireless multipath network for decision making policy to improve network performance. Some salient attributes of Q-Learning that make it the most widely adopted algorithm are its simplicity and model-free nature. Moreover, Q-Learning generates an optimal reward value within environments' state-action pairs that are described by Markov decision processes (Kiran, Venkatesh, & Murthy, 2007). Q-learning observes agent behavior through trial-and-error interactions with a dynamic environment through a tuple $(S, A, R)$ such as states, actions, and rewards, as shown in Figure 3.3.

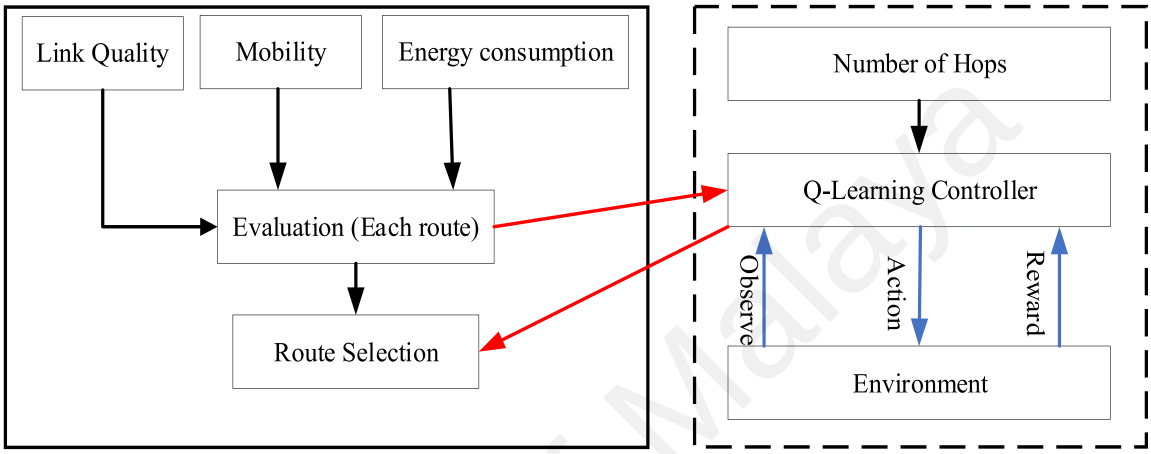


**Figure 3.3: Q-learning approach for route selection**

The objective of the agent is to maximize its long term rewards of the selection procedure which are obtained from immediate and discounted rewards for the estimation of the Q-value $Q_t^c(s_t^c, a_t^c)$, $(s \in S, a \in A)$ by taking a given action $a_t^c$ at the given state $s_t^c$. The Q-Learning algorithm training step to interact with the dynamic environment and adopts the best policy to solve the routing problems in a distributed manner by utilizing the Q-value equation is as shown below.

$$Q_{t+1}^c(s_t^c, a_t^c) \leftarrow (1-\alpha) \times Q_t^c(s_t^c, a_t^c) + \alpha \left\lfloor r^c(s_{t+1}^c) + \gamma \times \max_{a \in A} Q_t^c(s_{t+1}^c, a_{t+1}^c) \right\rfloor \tag{3.12}$$

where $\alpha$ is defined as the learning rate and ranges between $0 \leq \alpha \leq 1$, it depends upon the variation of Q-value that changes with the dynamic topology of the network. If Q-value changes very fast, the learning rate value goes to 1, and the agent takes only a new reward value such as $r^c$. The parameter $\gamma \in [0,1]$ is a discount factor, which determines the importance of future rewards. Low value, i.e. $\gamma = 0$, indicates the system is myopic and merely takes the results of the current action into account. By contrast, as $\gamma$ close to 1, future rewards play an important role in determining optimal actions. Besides, $\max_{a\in A} Q_t^c(s_{t+1}^c, a_{t+1}^c)$ is the model of maximum expected future reward, which selects possible action $a^i$ in the next state $s_{t+1}^i$. Based on different decision factors, i.e., link quality, mobility, and energy consumption of devices, as described above, a new reward function for device $c$ updated at each instant $t+1$ is formulated and is as follows:

$$R_{t+1}^c = w_1 \times EAX(s,d) + w_2 \times \text{Mobility} + w_3 \times \text{Residual Energy} \tag{3.13}$$

where $\mathrm{w}_1$, $\mathrm{w}_2$, and $\mathrm{w}_3$ are the corresponding weight assigned to each criterion based on the availability status of devices (i.e., mobility, link quality, and residual energy), which range from 0 to 1, and their sum equals to 1. The above criteria's value and weights facilities the sensitivity of decision factors for future reward value such as $R_{t+1}^c$. Therefore, Q-value of the device $c$ is updated with a previously stored value and the new reward $R_{t+1}^c$ which is calculated using the following equation as below:

$$Q_{t+1}^c(s_t^c, a_t^c) \leftarrow (1-\alpha)\times Q_t^c(s_t^c, a_t^c) + \alpha \left\lfloor R_{t+1}^c(s_{t+1}^c) + \gamma \times \max_{a_{t+1}^c \in A} Q_t^c(s_{t+1}^c, a_{t+1}^c) \right\rfloor \tag{3.14}$$

Lastly, based on the expression, the next-hop device which has a higher Q-value is selected for the optimal route. All the network nodes update the routing table information with each other through periodic exchange of topological information. In the case of when the new node joins or existing node leaves the network, the Q-value is initially computed with a previously stored value and the new reward value accordingly. The flowchart of the MRLAM routing approach in the conventional D2D communication scenario shown in Figure 3.4 describes the process of selection of optimal route from source to destination based on Q-learning algorithms. The proposed routing approach in the conventional D2D communication scenario selects the optimal route applying decision policy-based Q-learning algorithms, which can effectively reduce the redundant information in the network topology and enhance overall network performance. The route selection based on mobility, residual energy, and link quality with the Q-Learning algorithm is described as follow:

**Q-Learning Algorithms for route selection**

1. At every edge and device between source and destination device
2. **Initialize** $Q_i(s_t^c, a_t^c) \;\; \forall (s \in S, a \in A)$
3. Choose action $a_t^c$ from the state $s_t^c$ using best policy derived $Q_{t+1}^c$
4. **Q-value** at time as:

   $$Q_{t+1}^c(s_t^c, a_t^c) \leftarrow (1-\alpha) \times Q_t^c(s_t^c, a_t^c) + \alpha \left\lfloor r_{t+1}^c(s_{t+1}^c) + \gamma \times \max_{a \in A} Q_t^c(s_{t+1}^c, a_{t+1}^c) \right\rfloor$$

5. Based on mobility, residual energy and link quality new reward function

   $$R_{t+1}^c = w_1 \times Mobility + w_2 \times RB + w_3 \times Link\ Quality$$

6. **Update Q-value** with new reward function as:

   $$Q_{t+1}^c(s_t^c, a_t^c) \leftarrow (1-\alpha) \times Q_t^c(s_t^c, a_t^c) + \alpha \left\lfloor R_{t+1}^c(s_{t+1}^c) + \gamma \times \max_{a_{t+1}^c \in A} Q_t^c(s_{t+1}^c, a_{t+1}^c) \right\rfloor$$

7. Select the optimal route with update Q-value

### 3.2.6 Simulation Setup

Extensive simulations have been conducted with MATLAB 2018a simulator to evaluate the performance of the proposed MRLAM routing approach, which is compared with MP-OLSR and its extended version MP-OLSRv2 routing approaches, using the different speed of device scenario. Random topologies with a maximum of 49 devices are generated over a rectangular field in the area of 1000 meters × 1000 meters. The devices are placed in the middle of the simulation area, and seven data sources are randomly chosen for the scenarios, and all sources are transmitting their data to the destination device. The Constant Bit Rate (CBR) generates traffic into networks having a size of the CBR 512 bps from sources, and the simulation runs in total for 200 times. 802.11a standard and modules of the wireless physical layer are utilized in the simulation in order to provide a high level of accuracy.

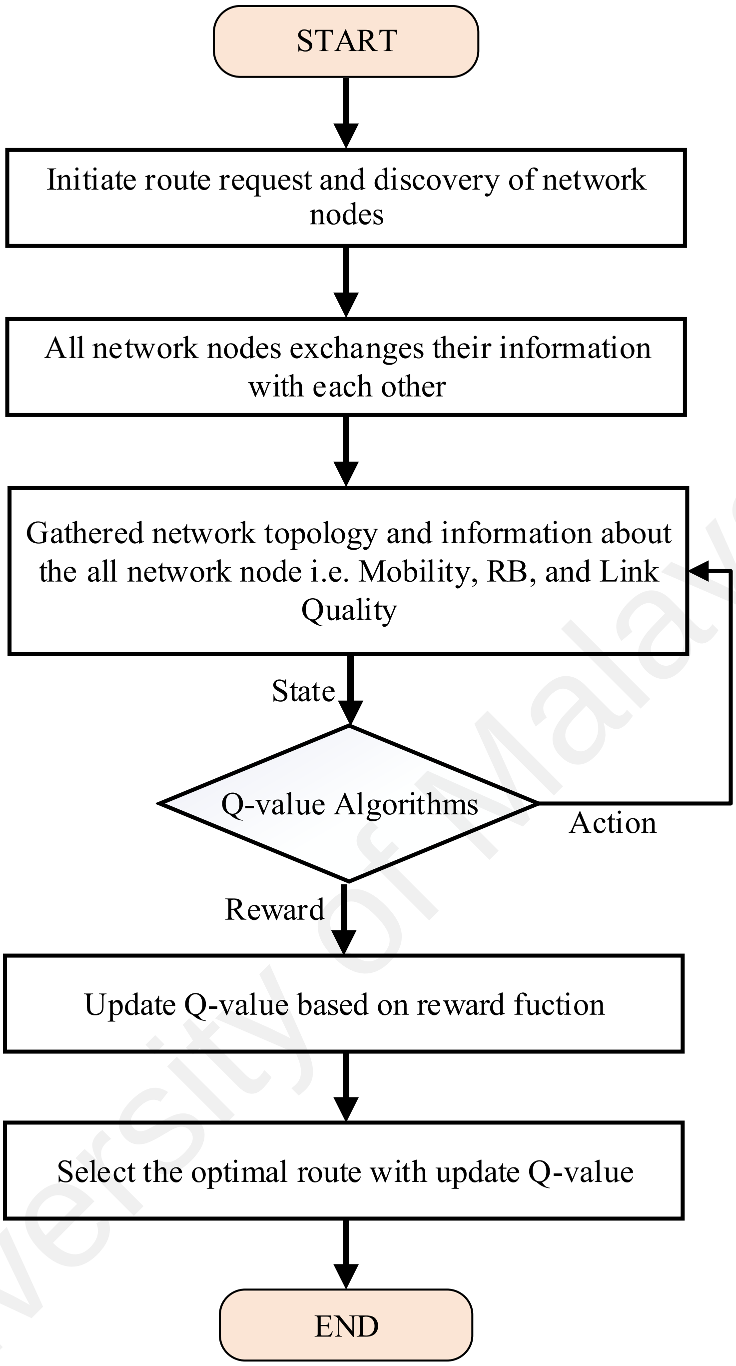


**Figure 3.4: Route selection procedure of the MRLAM routing approach**

The User Datagram Protocol (UDP) has been used as the transport layer protocol, which, in contrast to Transmission Control Protocol (TCP), provides a simple transmission model. The RWP mobility model is used as the mobility standard that enables device speed variation from 10 m/s to 60 m/s. The other performance evolution scenarios are presented in Table 3.2 as follows:

**Table 3.2: The conventional D2D communication scenarios simulation parameters**

| Simulation parameters | Value |
|---|---|
| Routing protocols | MRLAM, MP-OLSR, MP-OLSRv2 |
| Simulation time | 200 Seconds |
| Traffic type | CBR, 20 Packets/sec |
| Battery capacity | 3600 mAh |
| Propagation model | Two ray ground |
| Generic energy model | $P_{Transmission} = 1300\ mW$ and $P_{\mathrm{Re}cieve} = 900\ mW$ |
| Signal transmission power | 31.623 mW |
| RWP mobility model | Minimum velocity $v_{\min}$ = 10 m/s, Maximum velocity $v_{\max}$ = 60 m/s |
| Learning rate | [0, 1] based on Q-value |
| Discount rate | 0, current reward value 1, future reward value |
| Dirac delta function | 0, when $v_{\max}$ or 1 when $v_{\min}$ |
| Pause time | 10 Second |
| Battery model | Linear battery model |
| Transmission range | 270 Meters |
| MAC layer protocol | IEEE 802.11 |
| Physical layer model | PHY 802.11b |

## 3.3 The D2D Communication based Ultra-Dense Network Scenario

The D2D communication based UDN scenario, the proposed MBMQA routing approach, selects a route between source and destination devices to evaluate the packet traffic congestion in the network to balance the data traffic load among the mobile devices. Moreover, in the D2D communication UDN scenario, mobility, battery, and queue length of the devices also play a significant role in providing better QoS performance in the route selection procedure. Therefore, for robust and reliable route selection in the D2D communication UDN scenario, the MBP algorithm with the lower energy consumption, better link quality, and smaller queue length size of the device's estimation should be considered in the route selection procedure. The following subsection describes the system model of the proposed MBMQA routing approach for the D2D communication based UDN scenario as follows:

### 3.3.1 System Model

The D2D communication UDN scenario has been modeled and described by a graph $G(V,L)$, where $V$ is the set of devices and $L$ refers to the links between these devices. The packets are injected from the source device $s$, $s \in V$ and flow on the multiple paths in order to reach their destination. Every device $s$ can specifically interact with its neighboring devices within its range. If the destination is not on the neighbor list, it will utilize the routing protocol to transmit the packet to the destination. A direct link from the device $s$ to $d$ is denoted by $(s, d)$, while the transmission data rate matrix link is $\mu_{(s,d)}(t)$ in slotted time $t \in \{t_1, t_2 ...\}$. The routing variable data rate of a packet destined for device flow on the link $(s, d)$ is denoted by $\mu_{(s,d)}^{f_c}(t)$. In this study, the flow, $f_c \in V$, has been denoted by its destination $f_c$ for clarity. Due to the changes in the device's position, the device's selection to build an optimum path will be dynamically modified as well. In order to attain optimal throughput and performance enhancement, the Modified-Backpressure (MBP) strategy has been considered for the D2D communication UDN scenario, which has been discussed extensively in the next section.

### 3.3.2 Modified Backpressure Algorithm

The MBP algorithm is extensively explored in all the possible routes between source and destination devices to evaluate the packet traffic congestion in the network in order to balance the data traffic load among the mobile devices. The MBP algorithm provides efficient performance and optimal throughput in the D2D communication UDN scenario (N. Wang, Zhao, & Hai, 2019). The MBP forward the data packets towards the lower queue length device to avoid data traffic in the network. The MBP does not perform route discovery of intermediate devices from the source to destination; instead, each packet independently develops its own routing decision by solving the maximum weight process at each time slot. There are two different levels to deliver data, the selection of the flow problem at the device level, and the scheduling of links at the network level, which have been discussed below.

#### 3.3.2.1 Flow Selection

At the initial stage, the aim is to decide a weight for each intermediate device link on $(s,d) \in L$, so that the traffic packet flow to the next forwarding operation in the optimum path. The $Q_s^{f_c}(t)$ is described as the number of packets for flow $f_c \in V$ at the beginning of time $t$, that is backlogged at the device $s \in V$. Let $Q_{(s,d)}^{f_c}(t)$ denote the backlog of flow $f_c$ on the link $(s,d)$. In fact, $Q_{f_c}^{f_c}(t) = 0$ for all $f_c \in V$, since no device forwards the packets for itself. Each device $s \in V$ computes weight, for each outgoing link, as a function of a local flow queue $Q_s^{f_c}(t)$. For a given flow $f_c$ on a link $(s,d)$, when the link is activated, packets from flow $f_c$ will be scheduled if flow $f_c$ achieves the maximal weight of the link $(s,d)$. The max weight has been denoted by $W_{(s,\,d),}^{f_c}(t)$, also referred to as MBP, such that

$$W_{(s,\,d),}^{f_c}(t) = Q_s^{f_c}(t) - Q_d^{f_c}(t) \tag{3.15}$$

where $W_{(s,d)}^{f_c}(t)$ is the maximum MBP weight on the link $(s,d)$ at slot $t$, i.e.,

$$W_{(s,d)}(t) = \ max_{f_c \in N} W_{(s,d)}^{f_c}(t) \tag{3.16}$$

#### 3.3.2.2 Link Scheduling

In the second stage, a set of links have been selected to be activated simultaneously among the list of all non-conflicting links in the network. For each TTI (Transmission Time Interval), the transmission rates allocated to the maximal weight of link $(s,d)$ will be set, while the optimal commodity (data stored in a backlog queue of $s$ device that is destined for $d$ device) for any link will be solely transmitted. As a result, the MBP max weight schedule could be described as follows:

$$\mu_{(s,d)}^{f_c}(t) = \max \sum_{s\in N} \sum_{d\in N} \mu_{(s,d)}(t) \times W_{(s,d)}(t) \tag{3.17}$$

For each link $(s,d) \in L$, a transmission rate $\mu_{(s,d)}^{f_c}(t)$ is given to the corresponding flow $f_c$, while the flow is referred to as the flow selected for the maximal weight of the link $(s,d)$ during the transmission.

### 3.3.3 Residual Battery Estimation with Modified Backpressure Algorithm

At the time when the data traffic load exceeds the available channel capacity of the device, congestion and packets buffer overflow occur that lead to increase the energy consumption of the network devices and the established path will be prematurely disconnected due to insufficient energy of the device (Muchtar, Abdullah, Al-Adhaileh, & Zamli, 2019). Therefore, the residual energy of the device should be considered with MBP to maximize network throughput with an acceptable end-to-end packet delay and minimal energy consumption of devices. The residual battery of a device refers to the amount of charge remaining on the battery attached to the device at an instant of time, which is calculated with utilizing the Linear Battery Model (Sheng, Saber, & Khandelwal, 2016). It is a power consumption aware metric and is embedded with the MBP algorithm to enhance the performance of the proposed approach in the D2D communication UDN scenario by selecting the intermediate devices, which possess higher energy levels during the transmission, while intermediate devices with lower energy level are avoided. The $DS_{RB}(s,d)$ metric enhances the packet power consumption ratio in the D2D communication UDN scenario, which is calculated based on the devices' residual energy with MBP as follow:

$$DS_{RB(s,d)}(t) = \max_{fc \neq s,d} \{Q_s^{fc}(t) - \frac{RB_c(t)}{RB_c^{\max}(t)} \times DR_c(t) \times Q_c^{fc}(t)\} \tag{3.18}$$

where $RB_c(t)$ is the residual battery of the intermediate device $c$, $RB_c^{\max}(t)$ denotes the maximum battery level of the device $c$ in mAh, which is configured from the battery energy model, and $DR_c(t)$ denote the drain rate of device $c$ in mAh an instant of time $t$, which is calculated as follow:

$$DR_c(t) = \frac{Q \times E_{total}}{V_g \times T} \tag{3.19}$$

where $T$ is the simulation time in a second, $E_{total}$ denotes the total energy consumption by devices in mWh, $Q$ is coulombs charge of devices in Ah, and $V_g$ is the voltage supply in Volts.

### 3.3.4 Mobility Estimation with Modified Backpressure Algorithm

By considering the mobility of devices with MBP, it helps to prevent a high-speed device from participating in the route selection procedure. This leads to the selection of a highly stable route and reduces the routing overhead in the network. The RWP mobility model has been utilized for calculating the speed of the devices (X. Ge et al., 2016). Here, we consider a factor called a mobility factor $M_{(s,d)}$ of a device $d$ with respect to the device $s$ in the D2D communication UDN scenario. The mobility factor is employed to categorize the devices based on their mobility, which is measured based on the pause time $p$, speed $v$, and direction of the mobile devices $\theta$. The mobility of devices is based on the mobility aware route selection introduced in (Sarkar & Datta, 2017), where if the value of mobility factor is high, it indicates high pause time, suitable direction, and less speed. The minimum value of the mobility factor for selecting devices in an optimum route is known as the threshold value, with the range from 0 to 1. In cases where the value of the mobility factor of devices is greater or equal to the threshold value, those devices will be selected as an intermediate device between the source and destination, otherwise, the device is avoided. This device selection based on mobility of devices, i.e., $DS_{mob(s,d)}(t)$ metric improves the network stability for the unpredictable motion of devices in the D2D communication UDN scenario. $DS_{mob(s,d)}(t)$ is calculated based on the mobility of devices with maximum weight MBP as follow:

$$DS_{mob(s,d)}(t) = \max_{fc \neq s,d} \{Q_s^{fc}(t) - [\frac{1}{2} \times \frac{1}{m}\sum_{n=1}^{m} v_c^n(t) + \theta_c^n(t) + \frac{1}{p}\sum_{l=1}^{p} t_c^l] \times Q_c^{fc}(t)\} \tag{3.20}$$

here, $t^l \left(1 \leq l \leq p\right)$ is the $l^{th}$ time interval of pause state of devices and $t^m$ is the *n*th $\left(1 \leq n \leq \mathrm{m}\right)$ time interval motion of devices.

### 3.3.5 Queue Length Size Estimation with Modified Backpressure Algorithm

The queue length size describes a number of backlog packets at the device buffer and reflects the data traffic load of the mobile devices. Therefore, the MBP algorithm exploits the queue length size of the device to minimize traffic congestion in the network. Since devices are mobile and free to move in any direction, the value of queue length frequently changes in a small duration of time. The queue length of devices could be obtained from the queue length model in bytes. The devices which have lower queue length are assumed to have higher priority for selecting the optimal path. Overall, this device selection $DS_{QL(s,d)}(t)$ metric has been implemented for traffic congestion control based on queue length in the D2D communication UDN scenario by using MBP, calculated as follows:

$$DS_{QL(s,d)}(t) = \max_{fc \neq s,d} \{Q_s^{fc}(t) - [1 - \frac{QL_c(t)}{QL_c^{\max}(t)}] \times Q_c^{fc}(t)\} \tag{3.21}$$

where $QL_c(t)$ denotes the number of bytes in device $c$, and $QL_c^{\max}(t)$ is the maximum number of queue length size in devices.

### 3.3.6 Multiple Attributes Route Selection Metric

The proposed Multiple Attributes Route Selection (MARS) metric estimates the device selection criteria's values $DS_{RB(s,d)}(t)$, $DS_{mob(s,d)}(t)$ and $DS_{QL(s,d)}(t)$ continuously and independently, where the selecting of the optimal route requires a minimum threshold value of devices lifetime. The MARS combines all the device's selection criteria values collectively and constructs one function, shown in Equation (3.22). The weight of MARS will be calculated utilizing the Attribute Hierarchy Process (AHP) technique (Scripcariu & Vornicu-Albu, 2015) according to the user's preferences. The AHP is a well-known technique utilized to calculate the optimal weight as a multi-attribute decision-making technique, which aids in setting priorities and execute the optimal decision. The MARS decision is set as follows:

$$MARS = \{W_{RB} \times DS_{RB(s,d)}(t) + W_{mob} \times DS_{mob(s,d)}(t) + W_{QL} \times DS_{QL(s,d)}(t)\} \tag{3.22}$$

where $W$ is the weight obtained by AHP among the device's selection criteria according to the user's preferences. The devices which have higher MARS metric value are shortlisted for the selection of an optimal path for source-destination pairs. The computation steps of the proposed routing approach for the D2D communication UDN scenario has been illustrated in Algorithm 1. In order to arrange the destination, the multipath Dijkstra algorithm has been utilized for the route discovery process and computing the multipath between source and destination pair (Yin & Wang, 2010). The proposed routing approach for the D2D communication UDN scenario described with the flow chart has been presented in Figure 3.5.

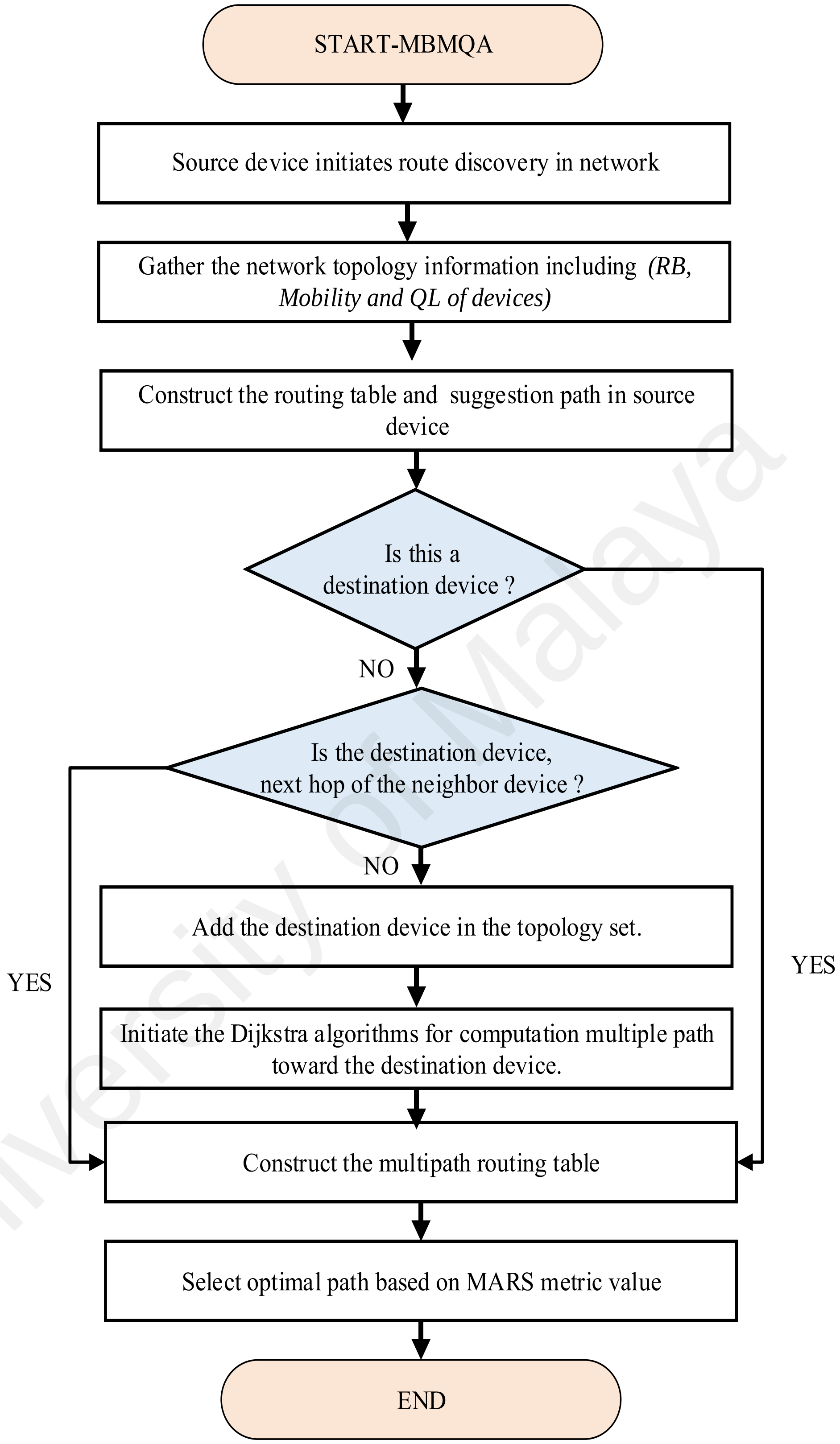


**Figure 3.5: Flowchart of the computations route in the MBMQA routing approach For the D2D communication UDN scenario.**

**Algorithms 1** Route computation MBMQA algorithm

```
Source device to s, Destination device to d
for all entries do                                  //source-destination pairs
    Source device start route discovery
    Set number of the path to L
    Exchange HELLO and Topology Control messages
    Gather all topology information, include devices (RB, Mobility, and QL)
    Construct the network graph
    if c is the destination device, then
        Add the entry to the multipath routing table
    else
        Set the device c in the topology
    end if
    Add the device c to the device's map
    for k equal to 0 to k equal to L-1 do                          //all paths
    Initiate the Multipath Dijkstra Algorithm    // To compute the multiple paths
    Set the max-weight to device c
    for all devices in the device map do
        Get the link_cost(c, f_c) to the next-hop devices
        Renew the weights of devices based on the link_cost( c, f_c)
        Select the next hop device f_c with minimum weight
    if the address of f_c = the address of j then
        Construct the routing entry
        Add the entry to the multipath routing table
        Select the optimal path based on MARS metric value
    else
        There is no route found
    end if
        Recalculate the cost of the link function
    end for
end for
```

### 3.3.7 Implementation and Validation of Proposed Routing Approach for the D2D Communication Ultra-Dense Network Scenario

The validation stage of the proposed routing approach for the D2D communication UDN scenario is completed by comparing the mathematical formulas and computation of the desired settings against parameter values received. In addition, route calculation functionality of the proposed routing approach for the D2D communication UDN scenario is performed based on device resources [residual battery (RB), mobility, and queue length (QL)]. The decision of the routing metric was compared with conventional MP-OLSRv2 and MEQSA-OLSRv2 approaches. For the purpose of analysis, all the devices were implemented as mobile with variable speed. In order to demonstrate the effectiveness of the proposed approach and avoiding the devices which have fewer resources in the optimal path, eight devices with different resources were randomly distributed, as shown in Figure 3.6. Devices 1 and 8 represent the source-destination pair and 2, 3, 4, 5, 6, and 7 are the intermediate devices with different attributes, respectively. The proposed approach selects devices 6 and 7, which appears to have sufficient resources for route selection, e.g., higher residual battery, comparatively lower mobility, and supplementary free queue slots. Through the comparison of available devices, the proposed approach selected route 1 → 6 → 7 → 8 as an optimal route among available ones. In addition, the shortest path, 1 → 2 → 3 → 8, is not selected for the optimal path due to the value of the low resources. Besides, these device resources value like RB, mobility, and QL were monitored during the simulation running time. It shows that the proposed routing approach for the D2D communication UDN scenario is strict energy, mobility, and queue length-aware routing approach.

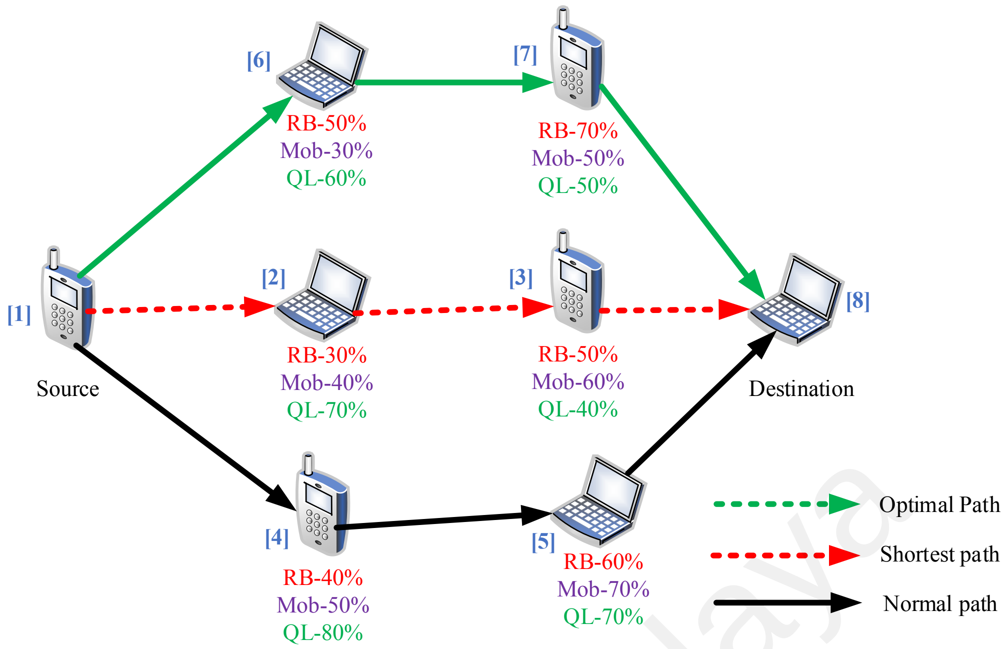


**Figure 3.6: The D2D communication UDN scenario of the proposed routing approach**

### 3.3.8 Simulation Setup

The developed MBMQA routing protocol is implemented using MATLAB. Comprehensive simulations are conducted to evaluate the performance of MBMQA along with the well-known MEQSA-OLSRv2 and MP-OLSRv2 routing approaches in the D2D communication UDN scenario. A simulation environment is established to investigate the performance of the proposed MBMQA approach and obtain the multipath routing conditions. The simulations are performed by using network topology with 49 devices deployed over a network area of 1000m x 1000m. Therefore, in the proposed network topology, there are a number of multi-hop and neighbor's devices with different resources. To simulate the linear battery model, the monitoring interval of the battery energy level is set to one second, and all the devices possessed an equal initial battery energy level of 3600 mAh. During conveying data packets, the devices exhausted their battery and eventually shut off due to a critically low battery level. A special eight source-destination joints are carefully selected, which included mid-devices on each side of the four corner devices so that multiple paths could be achieved through a satisfactory number of intermediate devices. The CBR is set to 30 packets/second with 512 bytes packet size. The data transfer started after 15 seconds of the simulation time, and enough time is spent to exchange routing messages (Yi et al., 2011). IEEE 802.11b wireless radio has been utilized in the simulation with a 15 Mbps data rate, and 270 meters radio transmission range. The simulation run time is assigned to 200 seconds with different initial topologies, and each simulation cycle is repeated 200 times to get the value of the average results. The simulation parameters employed in the simulation have been summarized in Table 3.3.

**Table 3.3: The D2D communication UDN scenario simulation parameters**

| Parameters | Values |
|---|---|
| Routing approaches | MBMQA, MEQSA-OLSRv2, and MP-OLSRv2 |
| Simulation run time | 200 Second |
| Number of devices | 49 |
| Traffic Type | CBR, 30 Packets/sec |
| Packet size | 512 Bytes |
| Generic Energy model | $P_{transmission}$ = 1400 mW, $P_{rececption}$ = 1000 mW, $P_{Idle}$ = 0 mW, $P_{Sleep}$ = 0 mW |
| Transmitted Signal Power | $P_{t =}$ 31.623 mW |
| Mobility of devices | RWP, Minimum speed 10 m/s, Maximum speed 60 m/s |
| Full battery capacity | 3600 mAh |
| Physical layer model | IEEE 802.11b |

## 3.4 The D2D Communication based Disaster Management Scenario

In the D2D communication based DMS, communication disconnection occurs due to the limited battery power of the network devices. Device battery power recovery is a critical issue for the emergency recovery scenario due to the absence of a direct battery power supply. Similarly, the link failure occurs among the devices due to the movement of the devices that lead to packets drop in the network. Therefore, in the D2D communication based DMS, the energy consumption and link quality level of the intermediate devices play a crucial role in efficient route selection in order to balance the energy consumption load among the network devices and route reliability during data transmission. The link quality and energy consumption of the devices is depending upon the movement of the device and data packets on the devices, respectively, which affects the routing and QoS performance. Therefore, the proposed EMLER routing approach in the D2D communication based DMS, consider the energy consumption and link quality with the mobility and queue length size of the intermediate devices in the optimal route selection to improve the overall network QoS performances. The conceptual structure, framework, implementation features, and methodology adopted for the proposed routing approach in the D2D communication based DMS is depicted in Figure 3.7.

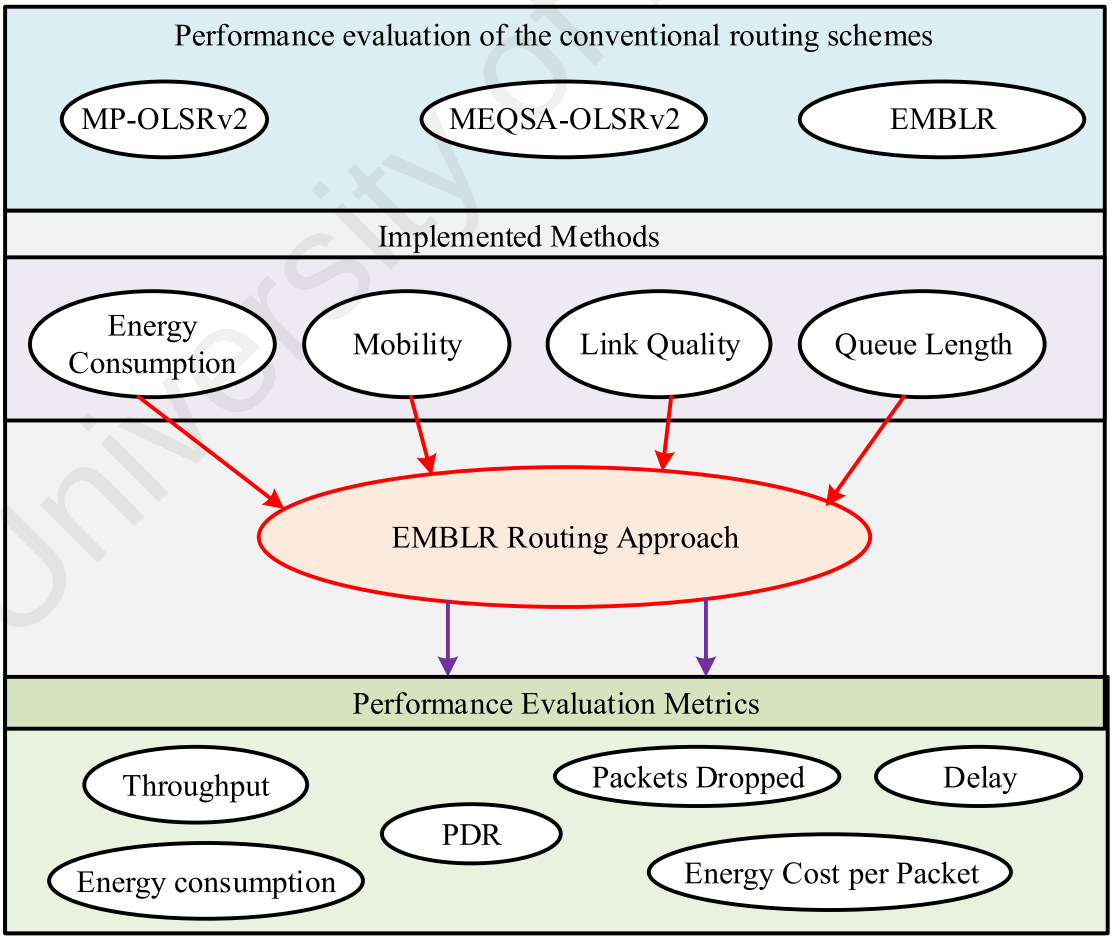


**Figure 3.7: Basic structure and framework of the proposed EMBLR routing approach in the D2D communication-based DMS**

Moreover, the framework elaborates on the structural elements of the proposed approach and their incorporation to accomplish the research objective. The EMBLR approach utilized the functionalities of the well-known routing approaches for the route selection procedure. The proposed approach is modified with the combination of device parameter metrics, i.e., mobility, energy consumption, link quality, and queue length size of the devices. Besides, the Multicriteria Decision Making (MCDM) metric is employed for the selection of the best route from the multiple routes. The following subsection describes the system model of the proposed EMBLR routing approach for the D2D communication based DMS as follows:

### 3.4.1 System Model

A directed graph $G(V, L)$ can model the D2D communication-based DMS, where $V$ is the set of devices that are randomly placed in the network and $L$ represented all feasible connection sets of the directed point-to-point wireless links. Here, $l(s,d) \in L$ is defined as the available connection link between two devices $s \in V$ and $d \in V$. Data packets transmission is scheduled when the two devices in the communication link with each other. In contrast, when the devices are not in the communication range with each other, the source device utilizes the relay/intermediate devices in the route for transmitting data packets towards the destination devices. The selection of the relay devices in the optimal path is based on the value of their estimated parameters, such as energy consumption, link quality, mobility, and queue length size. Therefore, the proposed routing approach in the D2D communication based DMS, utilize relay devices estimated parameter values for finding the optimal path to enhance the network performance. These parameters such as energy consumption, link quality, mobility, and queue length size of the intermediate device estimation, are discussed as follows:

### 3.4.2 Energy Consumption Estimation

The limited battery lifetime is the only source of energy for the devices to operate in the D2D communication based DMS for data transmission. The device performs a vital operation such as receiving data packets from neighbor's device and forwarding data packets toward the destination devices which utilized an excessive amount of energy that lead to energy depletion problem; thereby affect the routing and network performance. Hence, the energy consumption of the intermediate device in the D2D communication based DMS plays a significant role in the selection of an optimal route between source and destination devices. The device energy consumption is estimated with the utilization of the energy consumption model of wireless communication (Hu, Wang, & Chen, 2018). Device energy consumption mainly occurred during the transmission and receiving states of data packets transmission. The free space model ($\lambda^2$ power loss) and multipath fading model ($\lambda^4$ power loss) are exploits to calculate the signal transmission distance between the transmitter $(Tx)$ and receiver $(Rx)$ devices. Here $\lambda$ define the distance between the $Tx$ and $Rx$. Therefore, the free space model is utilized when the distance between $Tx$ and $Rx$ is lower than the threshold value ($d_0$). In contrast, the multipath fading model is utilized when the distance between $Tx$ and $Rx$ is higher than $d_0$. Furthermore, the transmission circuit and power amplification losses also consumed energy during the operation time of the circuit. Therefore, when the $k$ number of data packets transmitted in the network, the energy consumption of the devices can be calculated as follows:

$$E_{Tx}(k,\lambda)=\begin{cases} kE_{Tx-elec}+k\varepsilon_{f_s}\lambda^2 & \lambda<d_0 \\ kE_{Tx-elec}+k\varepsilon_{amp}\lambda^4 & \lambda>d_0 \end{cases} \tag{3.23}$$

$$E_{Rx}(k)=kE_{Rx-elec}, \tag{3.24}$$

Here $E_{Tx-elec}$ and $E_{Rx-elec}$ defines as the energy consumed per bit by $Tx$ and $Rx$ circuits. Also, $\varepsilon_{f_s}$ and $\varepsilon_{amp}$ are the power amplification factor of the free space and multipath radio models, respectively. Whereas, the threshold value $d_0$ is estimated via $d_0 = \sqrt{\varepsilon_{f_s} / \varepsilon_{amp}}$. The above equation (3.23) and (3.24) calculates the energy consumption of the device for $k$ number of data packets transmission. The proposed routing approach also utilized the intermediate device maximum energy ( $RE_{\max}$ ) and residual energy $(RE)$ for the selection of the optimal path. The $RE_{\max}$ and $RE$ value is estimated by exploiting the linear battery model (Tremblay, Dessaint, & Dekkiche, 2007). Thus, the rank of intermediate devices $c$ based on drain rate $DR^{c}_{(s,d)}$ in the optimal route between the source and destination devices can be calculated as follow:

$$DR^{c}_{(s,d)} = \frac{RE_c(k)}{RE_{\max}(k) \times \{E^{c}_{Tx}(k,\lambda) + E^{c}_{Rx}(k)\}} \tag{3.25}$$

### 3.4.3 Link Quality Estimation

Links failure is the most common issue in the limited battery life of the devices, and it affects the data packet losses and network stability. In order to maintain reliable high data delivery and network stability optimization, it is essential to detect the link failures rapidly and accurately in the network. Therefore, the link quality of the intermediate device plays a significant role in the selection of the optimal path, which minimizes the packet's losses in the network. Consequently, this subsection exploits the concept of expected transmission count (ETX) of the link, which is the number of transmissions and retransmission required for successful data transmission to the destination device over the link (De Couto, Aguayo, Bicket, & Morris, 2005). Probe message is sent to the link before data transmission, which does not include the data information. Therefore, the ETX value of the link is computed according to the forward delivery ratio $p_f$ and reverse delivery ratio $p_r$ of the probe message, such as: $1/(p_f \times p_r)$. The link quality estimated with ETX provides better performance in the light traffic network. However, when the network condition is highly loaded, the ETX induce flooding of route request (RREQ) packets in the network for finding the optimal route. Consequently, to mitigate the flooding effect of RREQ packets in the network, this study presents the concept of high load-ETX (HETX) (Tran, Mai, & Kim, 2015). The HETX is the extended version of the ETX metric that minimizes RREQ packets overhead incurred in the network. The HETX utilizes the current and previous time window rather than the current time window (ETX). The time window employed in this study is ten times of the probe packets. The window time is scaled into the discrete window time scale, having an equal size of $[t_{i-1}, t_i]$. The HETX value of the link is computed as below:

$$HETX = \frac{D_{(s,d)}}{p_f(t_i) \times p_r(t_i)} \frac{S_p}{R}, \quad t \in [t_i, t_{i+1}] \tag{3.26}$$

where $D_{(s,d)}$ is denoted as the distance from the source to destination devices. $S_p$ and $R$ defined as the packets size and rate of packets transmission, respectively. All network devices periodically broadcast probe packets for a window $w_i$ at an interval of $\tau$ second to evaluate the forward delivery ratio $p_f(t_i)$ and reverse delivery ratio $p_r(t_i)$. Every probe packet includes the number of probe packets and previous window information $w_{i-1}$, which is received from the neighbor's devices. Hence, the forward and reverse delivery ratios $r(t_i) = Num(t_{i-1}, t_i) / (w / \tau)$ are estimates with the use of the information contained in the probe packets. Here $Num(t_{i-1}, t_i)$ refers to the number of probe packets received at the current and previous time window. $w / \tau$ refers as the number of probe packets sent before the data transmission. The HETX metric estimates the link quality based on the probe packet transmission that avoids the high control traffic load generated and fewer data packets loss that indicates more accuracy link quality estimation. Therefore, the link quality calculates with the HETX metric reduced the flooding of RREQ packets in the network, minimize link failure, and improve overall the D2D communication based DMS network performance.

### 3.4.4 Mobility Estimation with Energy Consumption and Link Quality

The high movement of the device in the network severely affects the energy consumption and links quality of the devices, thereby significantly degrade the routing and network performance. Thus, the device mobility with energy consumption and link quality of the device should be considered for the selection of the optimal route to achieving the data reliability and energy efficiency tradeoff. For this, the well-known RWP mobility model is utilized to predict the mobility pattern of the devices (Rhee et al., 2011). In the D2D communication based DMS, the directional angle and speed of the devices affect the communication between the end-user. Therefore, the RWP estimates the device mobility in the D2D communication based DMS based on the position, directional angel, and trace time of the devices. The mobility of the intermediate device $c$ can be calculated as below:

$$M_{(s,d)}^{c}(t)=\frac{\sum_{T}\sqrt{\{pos_{c}^{T}(t)-pos_{c}^{T}(t-t_{0})\}^{2}+\{\theta_{c}^{T}(t)-\theta_{c}^{T}(t-t_{0})\}^{2}}}{\sum_{c}n(T)} \tag{3.27}$$

here, $T$ refers to the total tracing time of the devices, $pos_{c}^{T}(t)$ and $pos_{c}^{T}(t-t_{0})$ are referred to as the current and initial positions of the devices $c$ in trace time $T$. Moreover, $\theta_{c}^{T}(t)$ and $\theta_{c}^{T}(t-t_{0})$ defined as the current and initial directional angle of the mobile device $c$ in trace time $T$, respectively. Furthermore, $n(T)$ refers to the number of time samples taken during the trace time $T$. Therefore, the mobility value estimated based on the RWP mobility model make the route more robust and maintains the stability of the established route.

### 3.4.5 Queue Length Estimation with Energy Consumption and Link Quality

The queue length size of the device is referred to as the number of data backlogged packets that are stored at the device. Larger queue length size on the intermediate device induce data transmission delay in the network. The number of data packets in the queue is a metric reflecting the data traffic load of the mobile devices. The queue length size severely affects the energy consumption and link quality of the devices. Therefore, during the route selection procedure, the proposed routing approach utilized queue length size with energy consumption and link quality of the device to increase the data transmission efficiency, minimize packets retransmissions, increase energy efficiency and improve overall network performance. The queue length of the devices is evaluated by using the Backpressure algorithms (Bui, Srikant, & Stolyar, 2009). The Backpressure is referred to as the throughput optimal scheduling algorithm in the highly dynamic network, which forwards the data packets based on the congestion information of the devices. In a queuing network, packets are removed from the queue of the devices once it delivered and added to the next device queue. Next, when the packets received at the destination, the packets will be removed from the queue of all devices. Let $Q_n^c(t)$ denotes the number of data packets flow from the device $c \in V$ are backlogged at the device $n \in V$ at the time $t$. Therefore, the backlog packets on an intermediate device $c$ of the link $(s,d)$ are defined as $Q_{(s,d)}^c(t) = Q_s^c(t) - Q_c^d(t)$. All the devices in the network maintained backlogged packets information locally through the information packets exchange with each other. A weight assigned to the link $(s,d)$ over flow $c$ at the time $t$ is estimated as below:

$$w_{(s,d)}^c(t) = \max[Q_{(s,d)}^c(t), 0] \tag{3.28}$$

The $w_{(s,d)}^c(t)$ denotes the Backpressure weight on the link $(s,d)$, which is the maximum weight assigned to the link $(s,d)$ at the time slot $t$, i.e. $W_{(s,d)}(t) = \max_{c \in V} w_{(s,d)}^c(t)$. The packets are scheduled for flow $c$ only when the device $c$

attains the maximum weight on the activated link (N. Wang et al., 2019). In this way, the maximum weight on the link $(s,d)$ can be defined as below:

$$\max \sum_{s \in V} \sum_{y \in V} \mu_{(s,d)}(t) W_{(s,d)}(t), \quad \text{s.t. } \mu_{(s,d)}(t) \in \Gamma_{S(t)}. \tag{3.29}$$

Where $\mu_{(s,d)}(t)$ defines the transmission data rate matrix on the link $(s,d)$ in slotted time $t \in \{t_1, t_2 ...\}$ and $\Gamma_{S(t)}$ defines the set of data rate transmission matrix. The equations given above illustrates the maximization of the weighted network throughput by choosing transmission rates. The links scheduling is based on the primacy of order, i.e., the highest prioritized link would be the first to be scheduled. Based on the stability theory, the linear optimization by equation (3.29) is made with the queueing network toward stability; thereby, achieved the maximum network throughput performance in the D2D communication-based DMS (N. Wang et al., 2019).

Moreover, the maximum network throughput is attained in a queuing network if all the traffic arrival rates and all individual queue of devices are strongly stable. As a result, the channel capacity of the stable network with memoryless channels achieved equivalent to the Shannon channel capacity (I. Lee & Jung, 2017). Therefore, the maximum throughput can be attained in the queuing network to maintain the network stability with maximum data packets arrival rates and derived as follows:

$$\lim_{T \to \infty} \sup \frac{1}{T} \sum_{t=0}^{T-1} E[Q(t)] < \infty \tag{3.30}$$

The $E[Q(t)]$ refers to the expected average queue length of the network at a time $t$. The network backlog update at each time slot $t$ is obtained by transmission rate matrix $\mu_{(s,d)}(t)$, and it denotes the rate offered for flow $c$ on the link $(s,d)$ during the slot $t$. Thus, the Backpressure schedule algorithm based on the system queuing process dynamics is satisfied.

$$Q_n^c(t+1) \le \max[Q_n^c(t) - \sum_b \mu_{(n,\,d)}^c(t), 0] + \alpha_n^c(t) + \sum_a \mu_{(s,\,n)}^c(t) \qquad (3.31)$$

The equation, as mentioned above, expresses inequality due to an actual number of packets from neighbors device arrives at source device $m$ during slot $t$ is less than $\mu_{(s,n)}^c(t)$ if the neighbor's device has few or no packet to transmit. The notation $\alpha_n^c(t)$ refers to the number of exogenous flow $c$ packets generated at the source device $n$. Therefore, the proposed routing approach aims to maximize throughput in the D2D communication-based DMS with minimizing the backlog queue length between $Q_n^c(t+1)$ and $Q_n^c(t)$.

### 3.4.6 Multiple Criteria Decision-Making Technique

The MCDM metric is applied to access the link cost function of all the multiple routes and choose the best route based on the estimated parameter value of the relay devices. The MCDM aggregates all the estimated parameter value, namely; energy consumption, mobility, queue length size, and link quality of the relay devices into the single metric and assigns a weight to the relay devices accordingly. The parameter's value estimated and monitored periodically during the route discovery and topology sensing stage, which comprises link sensing, neighbor, and topology discovery by broadcasting the HELLO and TC topological packets to the neighbor’s devices. The MCDM metrics value is estimated locally at every device and broadcasted to their neighbors’ devices into a single metric value to mitigates the control packets overhead in the network instead of the individual device sending multiple metrics. The MCDM metric of relay devices $c$ in the routes is calculated as follows:

$$MCDM = \{W_{RE} \times EC_{(s,d)}^c(t) + W_{mob} \times Mob_{(s,d)}^c(t) + W_{LQ} \times LQ_{(s,d)}^c(t) + W_{QL} \times QL_{(s,d)}^c(t)\} \qquad (3.32)$$

where $W_{RE}$, $W_{mob}$, $W_{LQ}$, and $W_{QL}$ are weight assigned according to the estimated parameter value (Residual energy, mobility, link quality, and queue length size of the relay devices) and ranging from “0” to “1”. The relay device, which has a high MCDM metric value, has a higher chance for selection in the optimal route. Whereas, for the relay device which has below threshold MCDM metric value is avoided in the route selection. Therefore, the MCDM used these parameters value to make a decision to establish an optimal path between the sources and the destination device. The flow chart of the optimal route selection mechanism of the proposed routing approach in the D2D communication based DMS is shown in Figure 3.8.

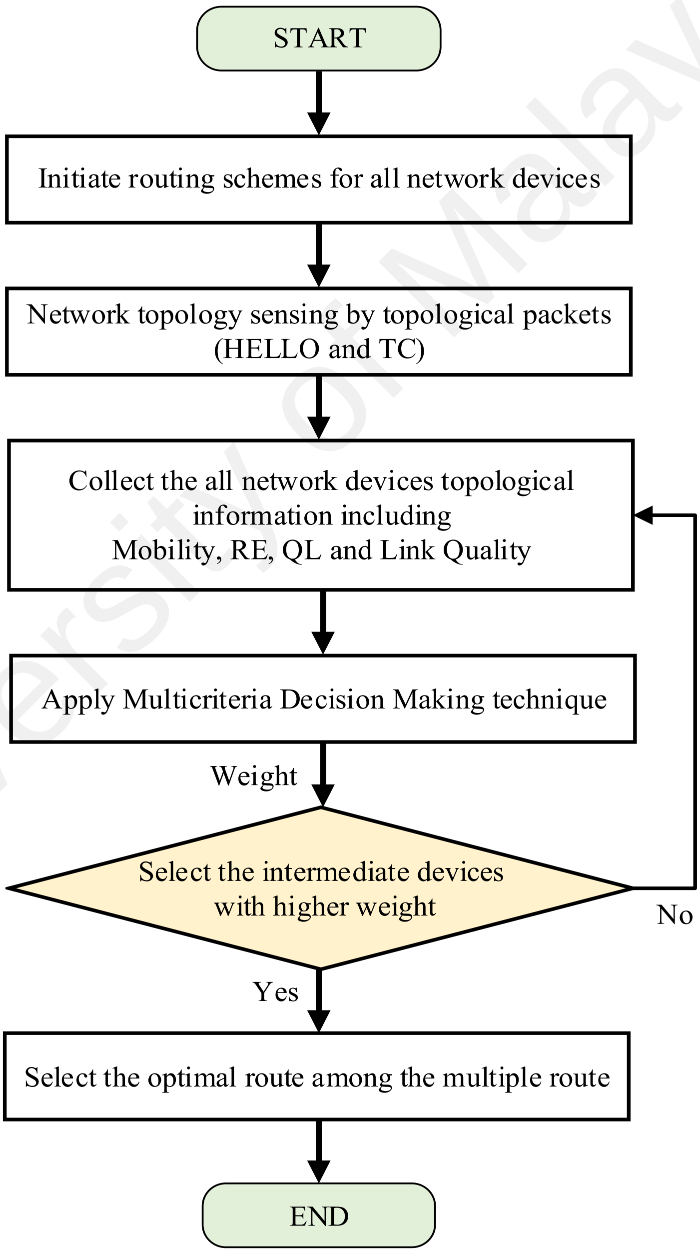


**Figure 3.8: Flow chart of optimal route selection for the D2D communication-based DMS**

### 3.4.7 Simulation Setup

MATLAB 2018a simulator is employed to execute extensive simulations that assess the performance of the routing approaches with the various speed of device scenario. In this simulation, the scenarios used 49 devices randomly distributed in an area of 1000 meters × 1000 meters. The mobile device moves in the network according to RWP mobility with speed from 10m/s to 60 m/s. CBR is set to 20 packets per second that correspond to each source and destination devices flow that generates universal datagram protocol packets 512 bytes size at the source device. The radio transmission distance is set at 270. The 802.11b radio data link layer and channel capacity is set to 11 Mbps. The simulation run time is assigned to 200 seconds, and each simulation cycle is repeated 200 times to get the average results value. The other parameters value is presented in Table 1 as follows:

**Table 3.4. The D2D communication based DMS simulation parameters**

| Simulation parameters | Value |
|---|---|
| Routing protocols | EMBLR, MEQSA-OLSRv2, and MP-OLSRv2 |
| Traffic type | CBR, 20 Packets/sec |
| Battery capacity | 3600 mAh |
| Generic energy model | $P_{Transmission}$ =1300 mW and $P_{Recieve}$ =900 mW |
| Battery model | Linear battery model |
| Transmission range | 270 Meters |
| Mobility model | RWP model with Min 10 m/s, Max 60 m/s |
| Simulation area | 1000m × 1000m |
| Application packet size | 512 Bytes |
| Transport protocol | Universal datagram protocol |
| Pathloss model | Two ray ground |

### 3.5 Performance Evaluation Parameters

In order to evaluate the performance of the routing approaches with different D2D communication application scenarios, the following performance evaluation metrics have been carried out through extensive simulation.

*(i) Throughput:* The total number of bytes that can be successfully received at destination on a specific duration of time. It can be calculated as follow:

$$Throughput = \frac{Total\ Number\ of\ Bytes\ \mathrm{Re}ceived \times 8}{(t - t_f)} \quad (3.33)$$

where $t_f$ refers the time of the first packet received, and $t$ denotes the time of the last packet received if the session is completed in seconds.

*(ii) Packet Delivery Ratio.* The ratio between a number of packets that were successfully delivered to a destination device and the number of packets that have been sent out by the source device.

$$PDR = \frac{N_{PR}}{N_{PS}} \times 100 \quad (3.34)$$

where $N_{PR}$ is the number of received packets at the destination device and $N_{PS}$ is the number of packets that were sent from the source device.

*(iii) End-to-End Delay.* It refers to the average time it takes to traverse the network. In other words, it is the time taken by a packet from source to destination device which is measured in seconds. Therefore, it includes all the delays in the network, such as queueing delay, retransmission delay, and buffering delay that is induced in routing time.

*(iv) Packet Drop.* It is the number of the packets which were received at the destination device.

$$N_{PD} = N_{PS} - N_{PR} \quad (3.35)$$

where $N_{PD}$ is the number of packets dropped during the simulation, $N_{PS}$ is the number of packets sent from the source device, and $N_{PR}$ is the number of packets received at the destination device.

*(v) Energy Consumption* ($E_{consume}$). It refers to the average energy consumption of all devices during simulation time in mAh. The energy consumption of device varies with respect to the state of the device such as transmission, reception, sleep and idle. The total average energy consumption ($E_{consume}$) of device $c$ is calculated as follow:

$$E_{consume} = \frac{1}{V}\sum_{c=1}^{n} E_{total}(c) \tag{3.36}$$

where $V$ is the total number of devices in the network.

*(vi) Energy Cost per Packet* ($E_{cost}$). It is defined as the ratio of average energy consumption to the total number of packets received successfully at the destination. The $E_{cost}$ is calculated as follows:

$$E_{cost} = \frac{Average\ Energy\ Consumption}{Total\ Packets\ \mathrm{Re}ceived} \tag{3.37}$$

*(vii) Convergence Time:* Convergence occurs in the network due to frequent network topology changes; meanwhile, the intermediate devices independently run routing algorithms and recalculate parameter values. The intermediate devices update routing information and build a new routing table based on the parameter's information. The convergence time is estimated based on the time required before all the intermediate devices can reach a consensus regarding the updated network topology.

### 3.6 Summary

In this chapter, three routing approaches have been presented with three different scenarios, that are conventional D2D communication scenario, D2D communication UDN scenario, and D2D communication based DMS. The detailed system model of the proposed MRLAM routing approach is studied in the conventional D2D communication scenario. Meanwhile, the detailed system model of the proposed MBMQA routing approach is studied in the D2D communication based UDN scenario. Finally, the detailed system model of the proposed EMBLR routing approach is studied in the D2D communication DMS. Overall, the optimal route selection procedure of the proposed three routing approaches in the three different D2D communication scenarios are presented in this chapter.

# CHAPTER 4: RESULT AND DISCUSSION

## 4.1 Introduction

This chapter has considered different parameters such as network topology, mobility pattern, energy model, number of relay devices, and users to cover the studied scenarios. The results acquired from the extensive simulation of the proposed routing approaches under various device speed for different D2D communication network scenarios are presented. The results of the proposed routing approaches are presented and comprehensively discussed with various network QoS performance parameter metrics, such as throughput, end-to-end delay, packet delivery ratio, packets drop, energy consumption, energy cost, and convergence time. Furthermore, critical analysis of the acquired results of the proposed routing approaches with different D2D communication network scenarios is also presented in the following section.

## 4.2 The Conventional D2D Communication Scenario

The comparisons have been done according to the well-known methods, which have been certified, verified, and well proposed for the different studied scenarios, as discussed in chapter 2. The extensive simulation results acquired from the simulation of MRLAM, MP-OLSR, and MP-OLSRv2 routing approach with respect to different device's speed for the conventional D2D communication scenario are studied. The MP-OLSR method has been studied for the conventional network state, whereas the MP-OLSRv2 method for the general network state. Therefore, the MRLAM routing approach is proposed for the conventional D2D communication scenario to enhance better QoS performance compared with both existing methods with various device speeds. The following subsection describes QoS network performance parameters results as follows:

### 4.2.1 Throughput Comparison

The throughput performance of the MRLAM, MP-OLSR, and MP-OLSRv2 routing approaches with increasing device speed, as shown in Figure 4.1, indicates that the proposed MRLAM routing approach consistently provides acceptable and better throughput performance than the MP-OLSR and MP-OLSRv2 routing approaches in all device speed scenarios. Higher throughput achieved through the MRLAM approach indicates that the mobility awareness factor is considered during the optimal route selection process. Whereas the other two routing approaches do not consider the mobility awareness factor in the route selection process, mainly when a link failure occurs due to a high device's mobility. The MP-OLSR routing approach employs route recovery and loop detection, while the MP-OLSRv2 routing approach employs the topology sensing and route computation mechanism for the selection of an intermediate device in the route. These mechanisms need to transmit extra packets in the network during the route establishment procedure, which reduced the number of packets received at the destination. The route selected by the MRLAM approach usually has lower mobility or more energy level than the other routes; therefore, the link is more stable and ultimately experiences fewer packets drop, which in turn maximizes the throughput. The link failure of devices in MRLAM routing is estimated by using EAX parameters. Based on the EAX parameter value, the proposed routing approach diverts the packet flow toward the intermediate devices, which have better link quality.

As the device speed increases, the number of links failure with the MRLAM routing approach remains lower than MP-OLSR and MP-OLSRv2 routing approaches, and accordingly, the throughput decreases constantly. Throughput decreases from 47.39 kbps to 39.87 kbps for MP-OLSR, from 49.17 kbps to 40.87 kbps for MP-OLSRv2, and from 50.86 kbps to 42.63 kbps for MRLAM when the device speed varies from 10 m/s to 60 m/s respectively. The proposed routing approach selects the route based on the link quality status metric, which reduces the number of transmissions and increases channel utilization efficiency depending upon which reliable link is selected. This, in turn, increases the throughput of the whole network. Compared with the other approaches, critical analysis of the simulation results demonstrates that the proposed MRLAM routing approach for the conventional D2D communication scenario performs better when it comes to selecting intermediate devices that are more qualified in terms of low mobility, energy level, and link quality. As a result, the route recovery process invokes less frequent link failure; therefore, improved overall network throughput is achieved.

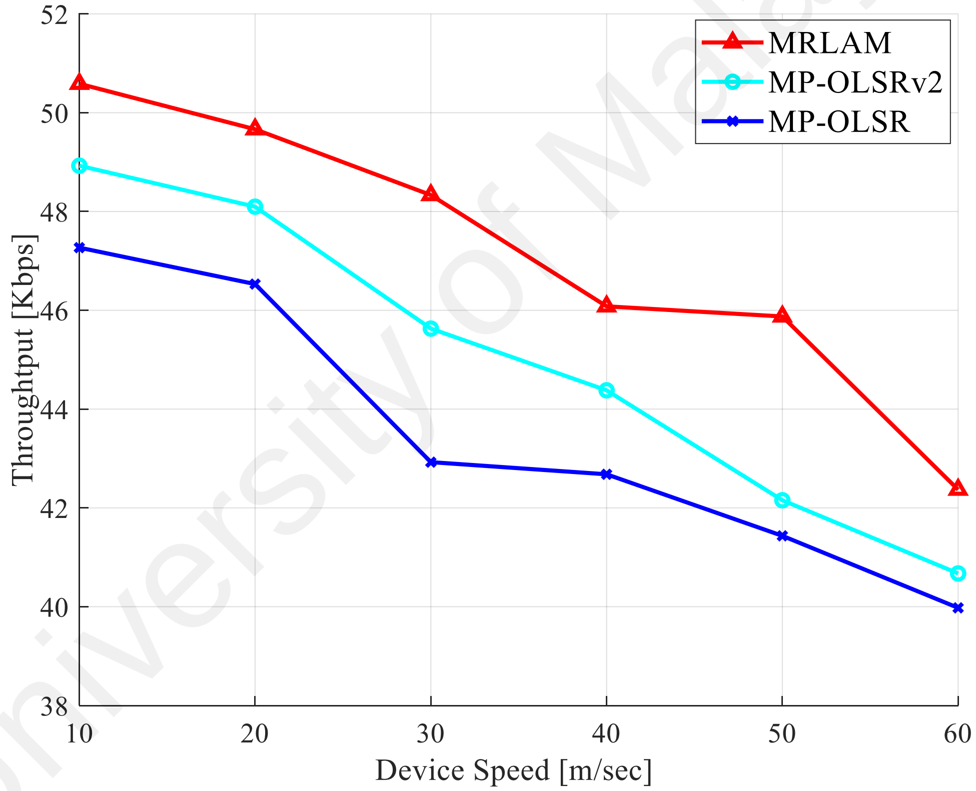


**Figure 4.1: Throughput with different speed of devices**

### 4.2.2 End-to-End Delay Comparison

Figure 4.2 illustrates the end-to-end delay comparison of the MRLAM, MP-OLSRv2, and MP-OLSR routing approaches with a variation of device speed between 10 m/s and 60 m/s for the conventional D2D communication scenarios. It can be seen from Figure 4.2 that all the routing approaches show almost similar results when the device speed is increased up to 30 m/s. As the device speed increases from 40 m/s, the end-to-end delay of the conventional MP-OLSR and MP-OLSRv2 routing approaches substantially increases. It is due to the fact that both routing approaches do not consider the mobility awareness factor of intermediate devices in the selection of an optimal route, which leads to increased delay at high-speed device scenarios. The MP-OLSR and MP-OLSRv2 routing approaches select the intermediate devices based on the multiple device-disjoint and link disjoint metric cost functions, respectively. Therefore, these routing approaches forward packets through a longer route from source to destination, which induces propagation and transmission delays in the network.

Moreover, the MRLAM approach maintains and controls end-to-end delay by exploiting the EAX metric that minimizes the number of intermediate devices and the number of retransmissions required for reliable packet delivery on the optimal route. Besides, the MRLAM utilizes pause time and moving time factor for the mobility estimation of devices from the RWP mobility model. Therefore, it stabilizes the dynamic D2D communication network to deliver the packet with less time effectively. Furthermore, by using the Q-learning algorithm, the MRLAM selects the intermediate devices which have low mobility and better link quality when determining the best path from available alternate paths for forwarding data packets toward the destination that leads to minimizing the end-to-end delay. Overall, it can be observed that the proposed MRLAM routing approach for the conventional D2D communication scenarios reduces the end-to-end delay by approximately 15% and 10% compared to MP-OLSR and MP-OLSRv2 routing approaches, respectively, at 60 m/s device speed.

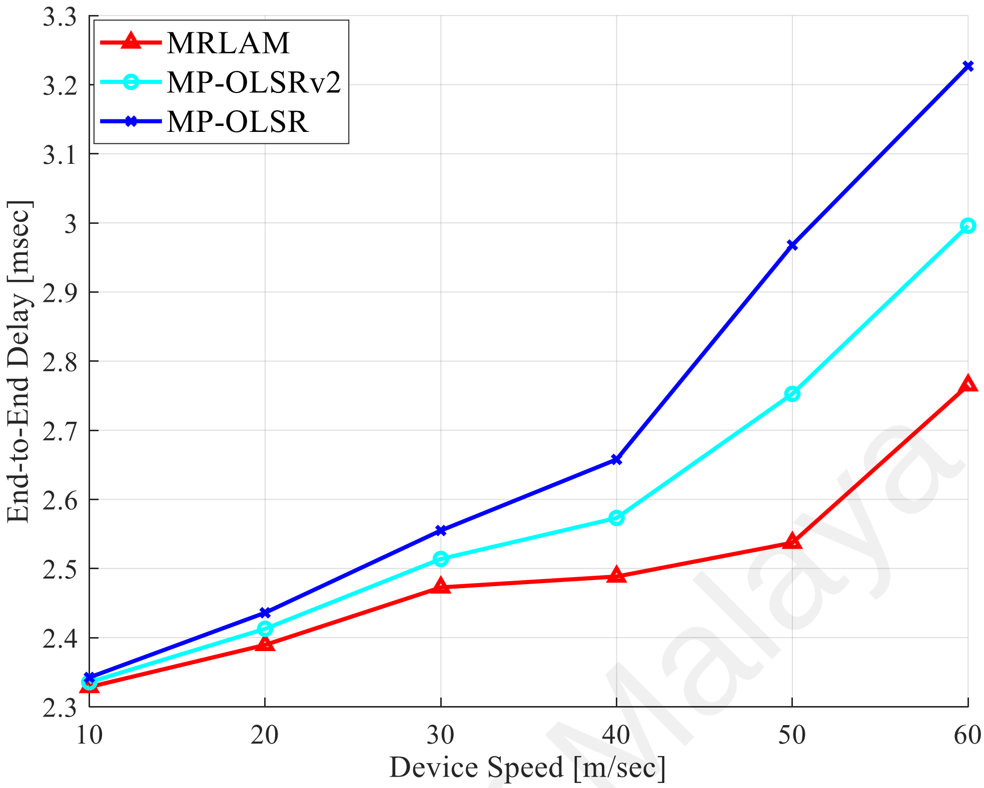


**Figure 4.2: End-to-end delay with different speed of devices.**

### 4.2.3 Packet Delivery Ratio Comparison

The MRLAM routing approach maintains the packet delivery ratio higher than 70% for all scenarios of device speed, which is a significant performance improvement for efficient data transmission in the conventional D2D communication scenario. These results are attributed to the effectiveness of the proposed routing approach for optimal route selection that synchronized with the Q-learning process for multiple parameters during the route establishment process. The Q-learning algorithm provides higher reward value to the intermediate device, which has better link quality with a neighbor device. This situation reduces the chances of frequent link failure and increases the successful delivery probability of data packets. Moreover, the MRLAM approach exploits the EAX metric that decreases the number of intermediate devices in the selection of an optimal route. This directly reduces the number of packets dropped during data transmission. In addition, the EAX decreases the number of trials for data retransmission and reduces link failure probability resulting from the conventional D2D communication scenario, thereby keeping a higher packet delivery ratio than other multipath routing approaches. In establishing a reliable route, the MRLAM routing approach avoids the devices which change their positions frequently and quickly exhaust their battery power. For high-speed device scenarios, it can be seen from Figure 4.3 that the proposed MRLAM routing approach for the conventional D2D communication scenario, achieves better performance compared to both of routing approaches, and the improvement percentages are approximately 18.36% and 14.28% compared to MP-OLSR and MP-OLSRv2, respectively.

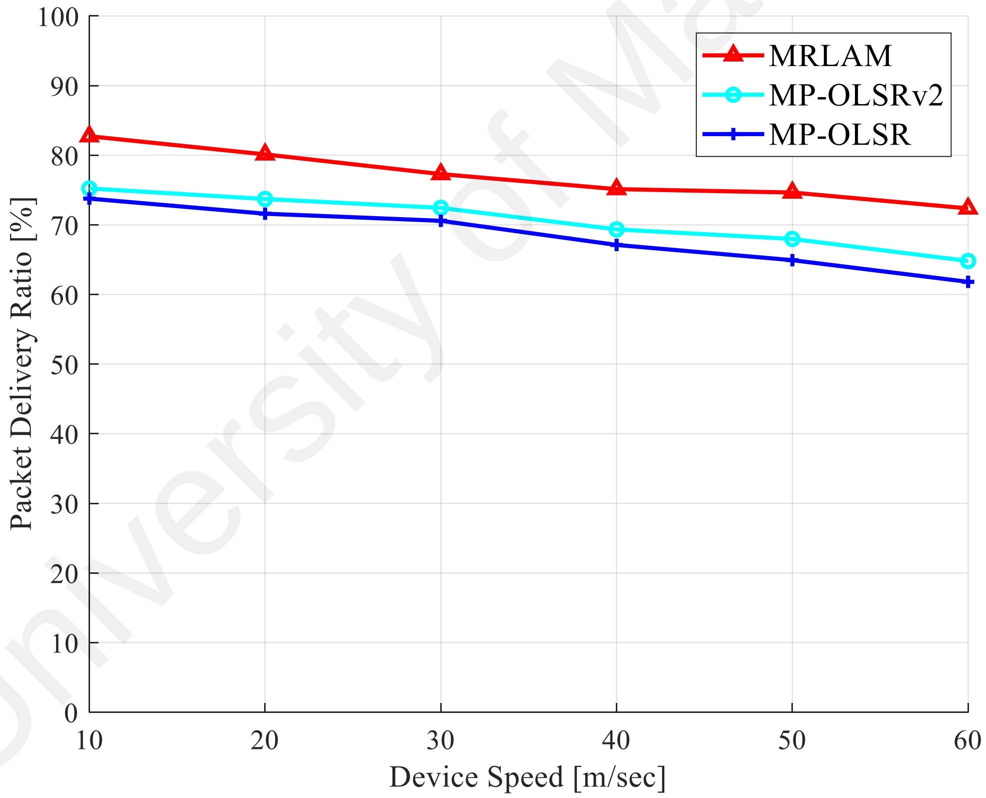


**Figure 4.3: Packet delivery ratio with different speed of devices**

### 4.2.4 Packets Drop Comparison

Figure 4.4 illustrates the packets drop comparison between MRLAM, MP-OLSRv2, and MP-OLSR routing approaches with various device speeds for the conventional D2D communication scenario. From this figure, it can be observed that the proposed MRLAM routing approach outperforms the other routing approaches. The MP-OLSR and MP-OLSRv2 routing approaches do not consider the channel condition among the devices for data transmission; due to this, there is a collision of the data packets at the MAC layer. Whereas, the MRLAM utilizes the EAX value before the data transmission to the link that minimizes the collision of the packets, as well as the packets drop in the network. When the device speed increases from 10 m/s to 60 m/s, the number of packets dropped in the network also increases. The MP-OLSR packets drop is 27.56%, and MP-OLSRv2 packets drop is 19.12%, which is higher than the MRLAM routing approach at the 60 m/s device speed.

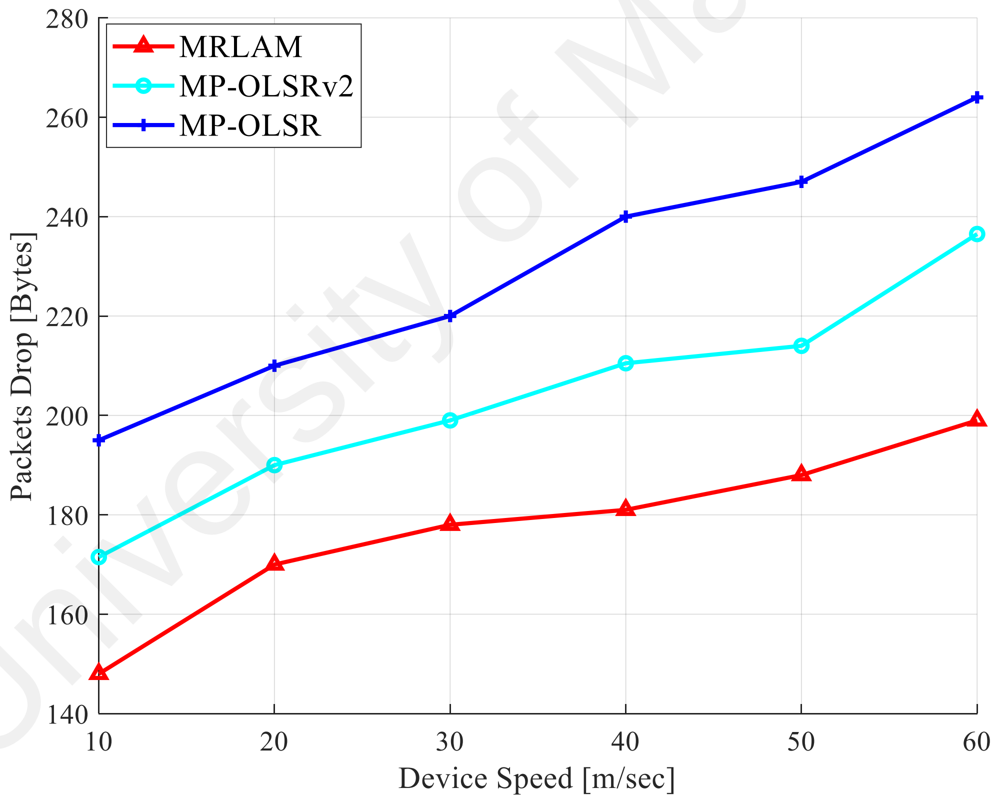


**Figure 4.4: Packet drop with different speed of devices**

### 4.2.5 Energy Consumption Comparison

A comparison of device energy consumption during the operation time of the conventional D2D communication scenario is shown in Figure 4.5. The result shows that MRLAM performs better than the other routing approaches in terms of energy consumption during path establishment and in exchanging routing topological information as it selects intermediate devices based on low EAX value for probe messages. Moreover, it has already been established that MRLAM selects the path with less chances of the link failure, resulting in lower energy consumption as it forwards data packets toward the destination device. The Q-learning technique provides high rewards value to the devices which have lower energy consumption, thereby enhancing energy utilization during data transmission. However, as the device speed increases, the energy consumption of devices increases. Energy consumption increases from 56.67 mAh to 57.26 mAh for MP-OLSR, from 56.43 mAh to 56.926 mAh for MP-OLSRv2, and from 56.15 mAh to 56.72 mAh for MRLAM approximately, when the device speed increases from 10 m/s to 60 m/s.

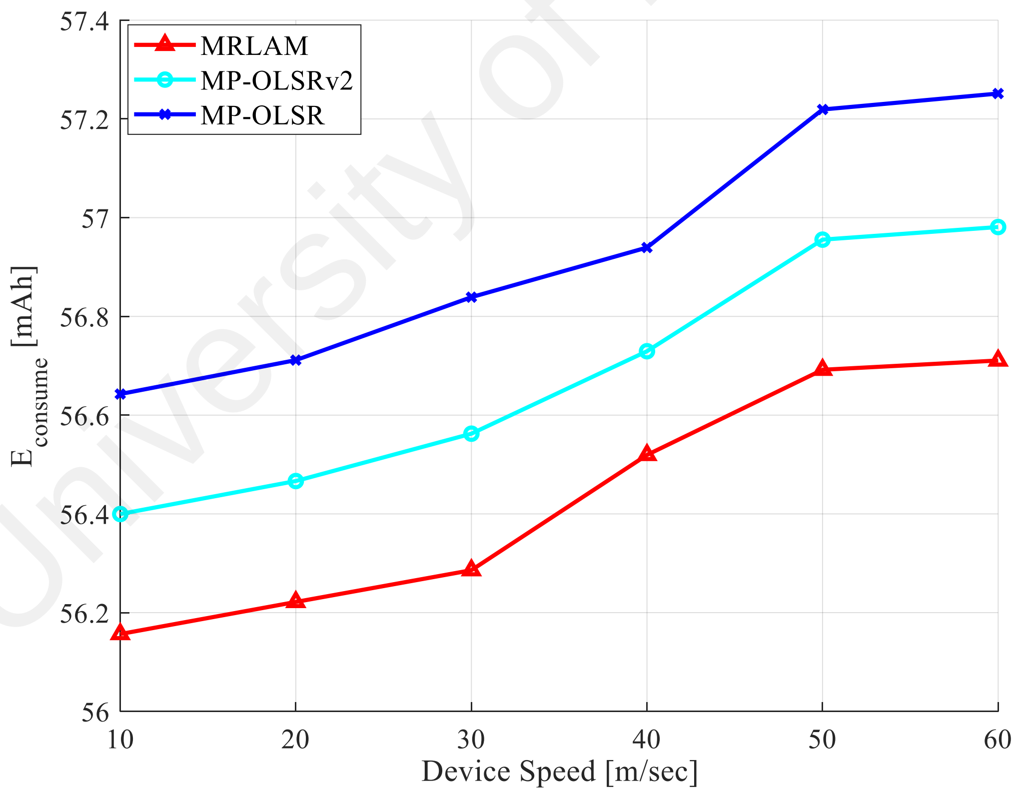


**Figure 4.5: Energy consumption with different speed of devices**

Overall, it can be observed that the proposed MRLAM routing approach for the conventional D2D communication scenarios has less energy consumption rating than MP-OLSR and MP-OLSRv2 approach because the source device forwards traffic flow towards intermediate devices which have the highest level of energy as opposed to its counterpart routing approaches.

#### 4.2.6 Energy Cost Comparison

Simulation results for energy cost per packet in the conventional D2D communication scenarios are shown in Figure 4.6; the proposed MRLAM routing approach attains lower energy cost due to the device selection mechanism it employs, which select only the devices with highest energy level. Displacement of intermediate devices in the path causes the variation of energy levels of devices while increasing mobility. The MRLAM approach also selects devices with better link quality and lower speed to decrease energy consumption and packets loss; this awareness is not used in the other routing protocols. The increase in a device's movement in the network increases the complexity of network topology for sensing and route computation process. However, the proposed MRLAM routing approach takes advantage of utilizing the Q-learning algorithm along with minimum device energy consumption for transmission packets that helps to reduce the energy cost as well as the complexity of the conventional D2D communication scenarios. The Q-learning algorithm periodically updates the state-action value with the learning rate based on the energy consumption of intermediate devices, as well as the number of packets transmitted and received. Moreover, there is reduced network packet flooding and energy cost per packets forwarded to the destination in the MRLAM approach compare with the other approaches. From the perspective of the overall device speeds, critical analysis of the simulation results shows that the proposed MRLAM routing approach for the conventional D2D communication scenarios a decrease in energy cost by 33% and 23% as compared to the MP-OLSR and MP-OLSRv2 routing approaches, respectively.

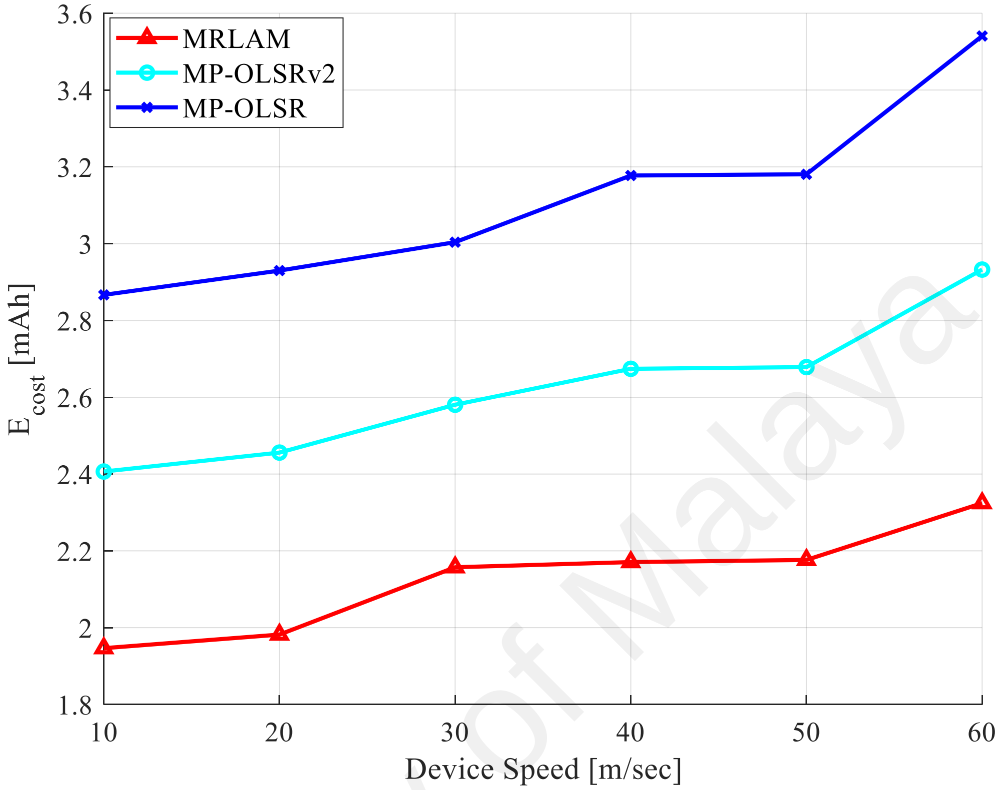


**Figure 4.6: Energy cost with different speed of devices**

### 4.2.7 Convergence Time Comparison

The convergence time for all routing approaches for the conventional D2D communication scenarios is depicted in Figure 4.7. It can be seen from Figure 4.7 that all the approaches show similar results when the device speed is up to 30 m/s. As the device speed increases to 40 m/s, the convergence time of the conventional MP-OLSR and MP-OLSRv2 routing approaches substantially increases. This because other routing approaches select the longer path from source to destination devices based on the link cost function and multiple disjoint metrics, while the MRLAM selects the shortest path with more stable devices and better links, which reduces data packet transmission delay. In addition, the MRLAM routing approach utilizes the mobility and link quality status of the mobile devices, which leads to minimizing the frequent change of network topology.

Meanwhile, it uses the Q-learning algorithm, which quickly updates the routing information of the network with any changes occurring in the network, and this reduces the convergence time of the network. In the MRLAM routing approach, fewer intermediate devices need to converge; thus, the load on any given device or communication link is minimized. Therefore, it reduces the calculating costs of intermediate devices of the paths and improves communication efficiency. Overall, at the device speed of 60 m/s, the proposed MRLAM routing approach for the conventional D2D communication scenarios recorded the lowest convergence time of 16.49% and 11.34% in comparison to the MP-OLSR and the MP-OLSRv2 routing approaches, respectively.

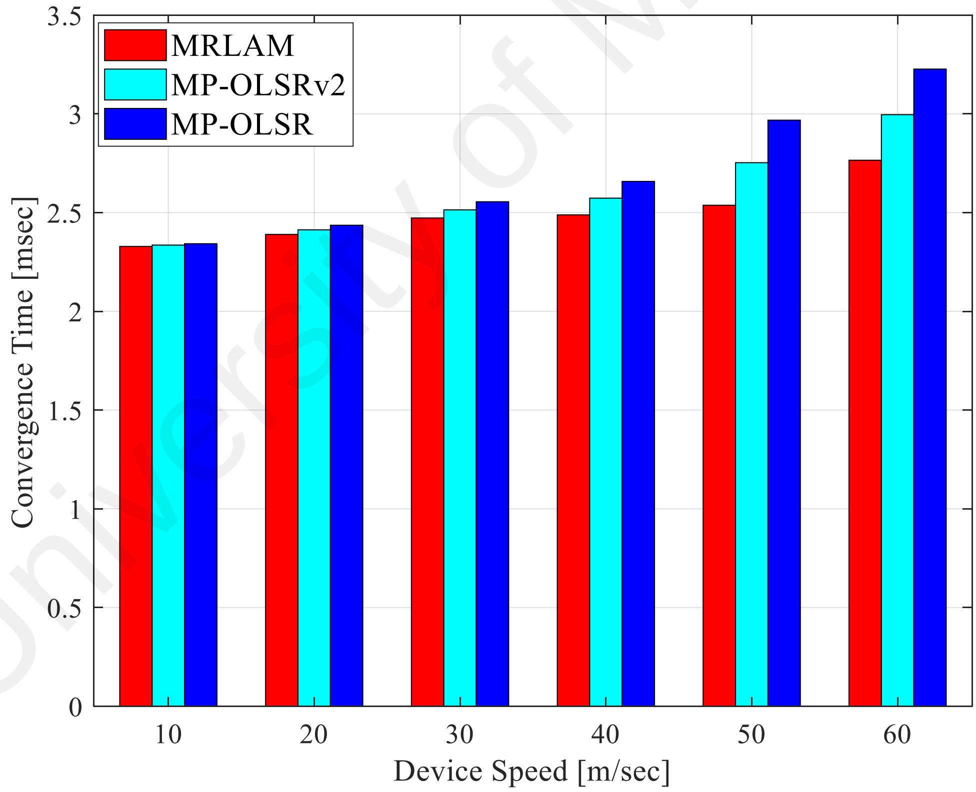


**Figure 4.7: Convergence time of routing approaches with different speed of devices**

### 4.2.8 Recapitulation of the Conventional D2D Communication Scenarios

This section represents an evaluation and comparative study of the proposed routing protocols in the conventional D2D communication scenarios, conducted under a series of simulations with varying device speed. A multipath routing approach called MRLAM is proposed in which the routing decision is made based on mobility, residual energy, and link quality status of the network devices. In addition, the MRLAM approach aggregates multiple parameters into a single metric by using the mechanism of the Q-learning process to make an optimal routing decision. The MRLAM routing protocol evaluates the status of devices during the route computation and topology sensing process to determine the optimal routes in a convergence network. Moreover, the proposed MRLAM approach has the ability to cope with link failure and sustains the network lifetime by avoiding devices with lower residual energy and higher mobility in selecting optimal and stable paths between all pairs of source and destination devices. The simulation results show that MRLAM has approximately 33% and 23% less energy cost per packet compared to MP-OLSR and MP-OLSRv2 routing approaches, respectively. Besides, the results have corroborated that MRLAM attains better throughput in all scenarios of device speed with successfully delivered data packets. In addition, the frequent change in the network topology increases the computational complexity of existing MP-OLSR and MP-OLSRv2 routing processes as the route computation process for the discovery of new routes becomes more intricate. In the proposed routing approach, the Q-learning aggregates multiple parameters related to mobility, energy, and link quality into a comprehensive metric. These dramatically reduce the complexity and avoid the control overhead caused by separate broadcasting multiple parameters. Furthermore, the results show that the MRLAM approach increases the packet delivery ratio up to 18.36% and 14.28%, approximately as compared to MP-OLSR and MP-OLSRv2 routing approaches, respectively. Overall, the proposed MRLAM routing approach for the conventional D2D communication scenario outperforms the well-known MP-OLSR and its extended version MP-OLSRv2 routing approaches in terms of throughput, end-to-end delay, packet delivery ratio, and energy consumption rate.

## 4.3 The D2D Communication in Ultra-Dense Network Scenario

The extensive simulation results have been compared with the well-known MEQSA-OLSRv2 and MP-OLSRv2 routing approaches. The effectiveness of the proposed MBMQA routing approach has been assessed with the MBP algorithm awareness evaluation study for the D2D communication UDN scenario. The simulation results of the proposed MBMQA routing approach has enhanced the overall network QoS performance at several device speed. The following subsection describes network performance parameter results as follows:

### 4.3.1 Throughput Comparison

Figure 4.8 illustrates the throughput of the proposed MBMQA routing approach concerning the speed of devices for the D2D communication UDN scenario. The obtained results indicated that the proposed approach has superior performance in comparison to other approaches. It can be observed from Figure 4.8 that the overall throughput with all the stated routing approaches slightly reduced through an increase in the speed of the devices. This is attributed to the increase in the difficulty of finding a stable route in cases where the device speed is high. The superiority of the proposed MBMQA approach as compared to both MP-OLSRv2 and MEQSA-OLSRv2 lies in the Backpressure algorithm employed, which does not solely rely on speed and battery levels of the devices when making the routing decision but caters to the queue length of packets (commodities) as well in order to be processed by each device. The incorrect selection of intermediate devices based on the speed and battery level will force the devices to be part of the route, which results in higher queue length, and devices will constantly discard the packets when the queue length is full. Avoiding devices that having higher queue length leads to a reduction in the network traffic, as the load is equally distributed among the devices and only devices with low queue length are selected to forward data. This distinction provides leverage to the proposed protocol and results in enhanced throughput in comparison to both MP-OLSRv2 and MEQSA-OLSRv2 routing approaches. The proposed MBMQA routing approach for the D2D communication UDN scenario demonstrated to be more stable than its counterparts due to its optimized approach in the selection of multiple relays and avoiding high mobility devices.

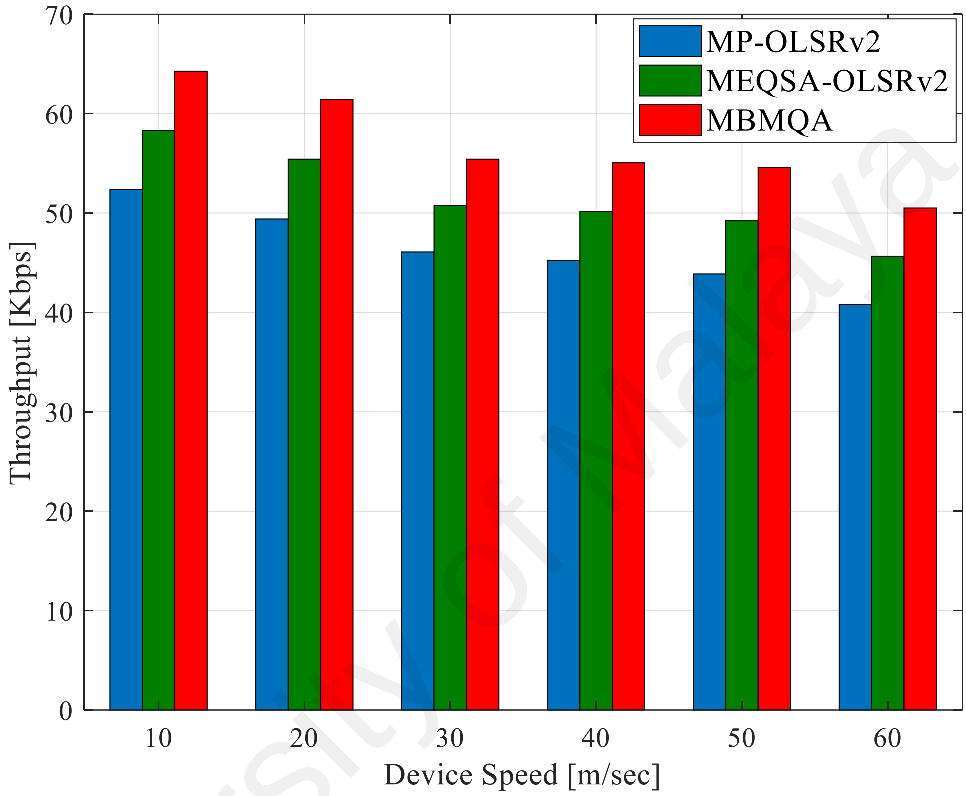


**Figure 4.8: Throughput for variant device's speed**

### 4.3.2 End-to-End Delay Comparison

Figure 4.9 illustrates that the proposed approach possesses consistent low delay values in comparison to other approaches, concerning the device's speed for the D2D communication in UDN. End-to-end delay is the time required for a packet to reach its destination comprising of several devices taking part in the route. Each packet is required to wait in a queue of the devices for a specific time until the device starts processing the packet and propagate towards the next device in the selected path. Queuing delay is a major part of the overall delay at situations where the congestion on the network is high and devices in the system which are operating at their full queue length capacity. In this condition, the selection of devices based on their queue length is more important than the mobility and battery level of the devices. Stated routing approaches (MP-OLSRv2 and MEQSA-OLSRv2) do not decide their forwarding decision on the queue length and relay, which leads to the generation of multiple paths towards the destination and does not positively affect the delay comparison, as some packets would be trapped in the network on devices with larger queue length. Until they are processed in the queue or the source device resents them, they tend to increase the amount of time to be delivered to the destination.

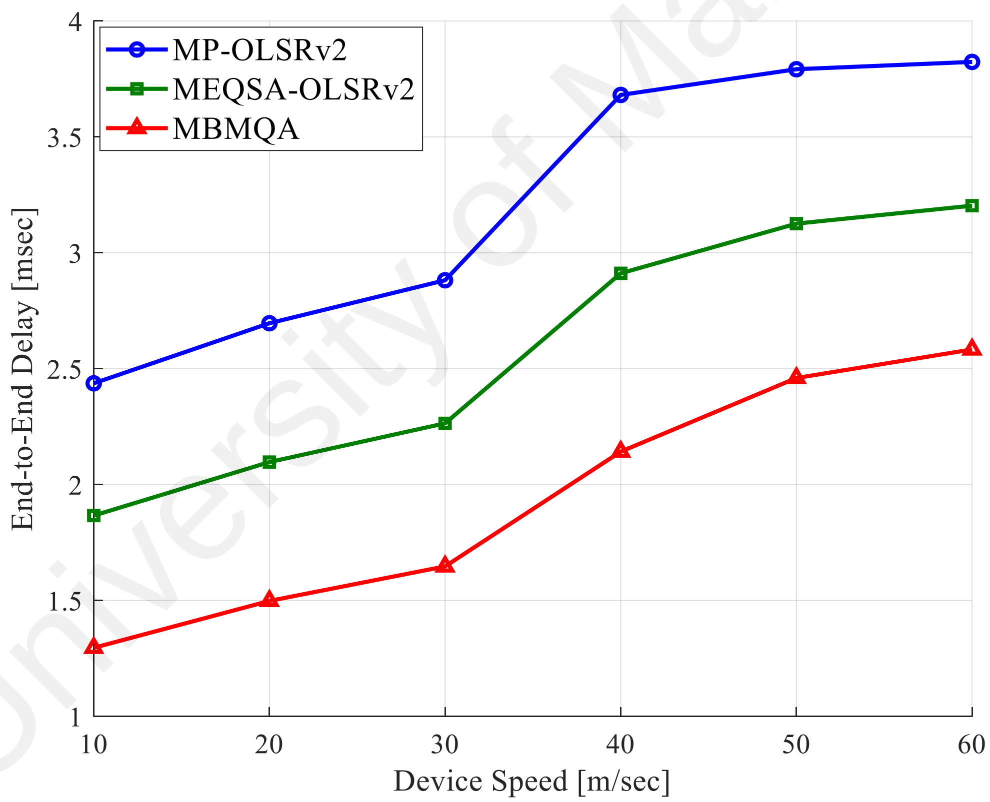


**Figure 4.9: End-to-end delay for variant device's speed**

The delay performance achieved by the MBMQA routing approach is 33.15% lower as compared to MP-OLSRv2 and 19.52% lower with MEQSA-OLSRv2, which is obtained at the maximum devices speed of 60 m/s. Moreover, the MEQSA-OLSRv2 exhibited better performance compared to MP-OLSRv2 as a result of analyzing the battery level of the devices and its effect on the forwarding path. Devices with a low amount of battery will eventually be exhausted and will lose the existing packets in the queue of the devices. These packets need to be re-transmitted by the source devices, which increases the overall time of the process.

### 4.3.3 Packet Delivery Ratio Comparison

It can be seen from Figure 4.10 that the proposed MBMQA routing approach ensures high packet delivery ratio value over both MP-OLSRv2 and MEQSA-OLSRv2 approach for the D2D communication UDN scenario. This is due to the fact that MBMQA takes advantage of the MARS metric to select devices with lower energy drain rates and an adequate amount of remaining energy levels. Consequently, the minimum number of retransmissions is required for transferring packets from the source to the destination device and avoids the selection of low resources devices. In addition, packet delivery is closely related to packets dropped by either low energy level of devices as well as packets dropped due to full queue of devices participating in multiple forwarding of packets. Therefore, the proposed approach demonstrates to provide better results in terms of delivering packets to the destination, since there is a limited number of packets dropped. Moreover, as the speed of devices increases, maintaining the connections with neighboring devices becomes difficult, which is the next hop for data forwarding. Furthermore, in order to forward packets to the next hop, the device needs to select another candidate for the successful transmission of the packet while fulfilling the requirements of the MARS metric. Based on the results obtained, the MBMQA approach for the D2D communication UDN scenario delivered approximately 28.47% more packets compared to MP-OLSRv2 and 15.26% more compared to MEQSA-OLSRv2.

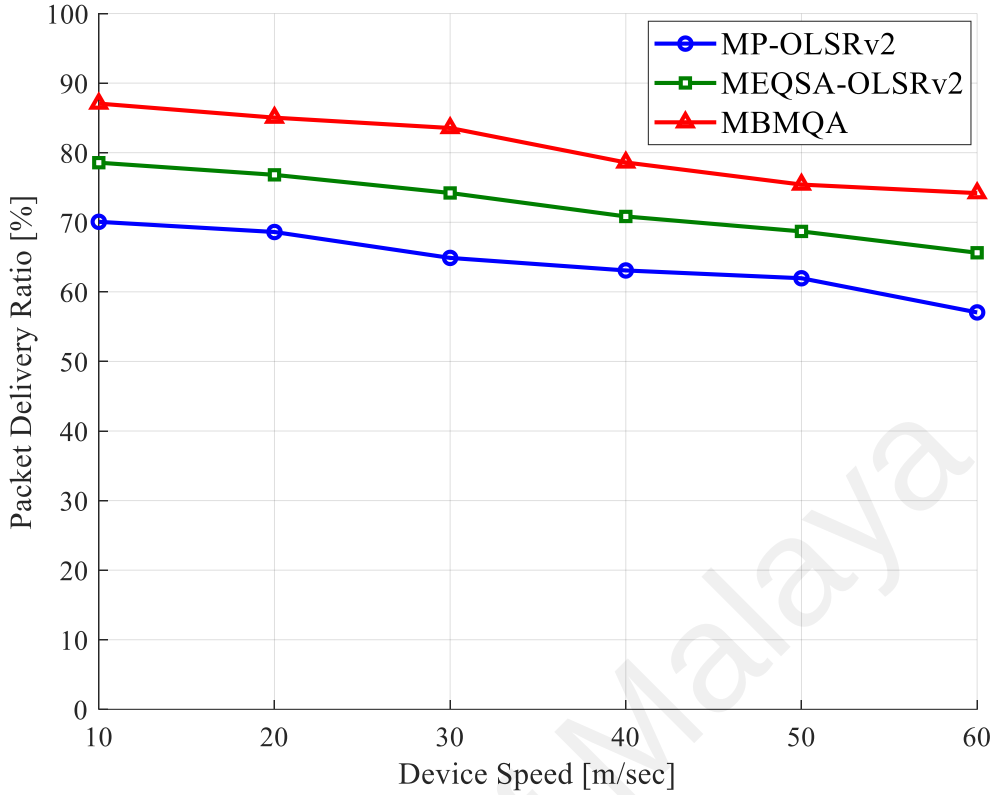


**Figure 4.10: Packet delivery ratio for variant device's speed**

### 4.3.4 Packets Drop Comparison

The results illustrated in Figure 4.11 indicated that the MBMQA possesses the lowest percentage of packet drop as compared to the approaches (i.e., 34.81 % lower as compared to MP-OLSRv2 and 24.67% lower as compared to MEQSA-OLSRv2), obtained at the 40 m/s speed of the device. The higher number of packets dropped in other routing approaches is due to the absence of the queue length size of intermediate devices awareness factor for selecting the best route, whereas the MBMQA routing approach for the D2D communication UDN scenario intelligently selects those devices which have a lower queue length in order to reduce the chance of traffic overhead and packet drop.

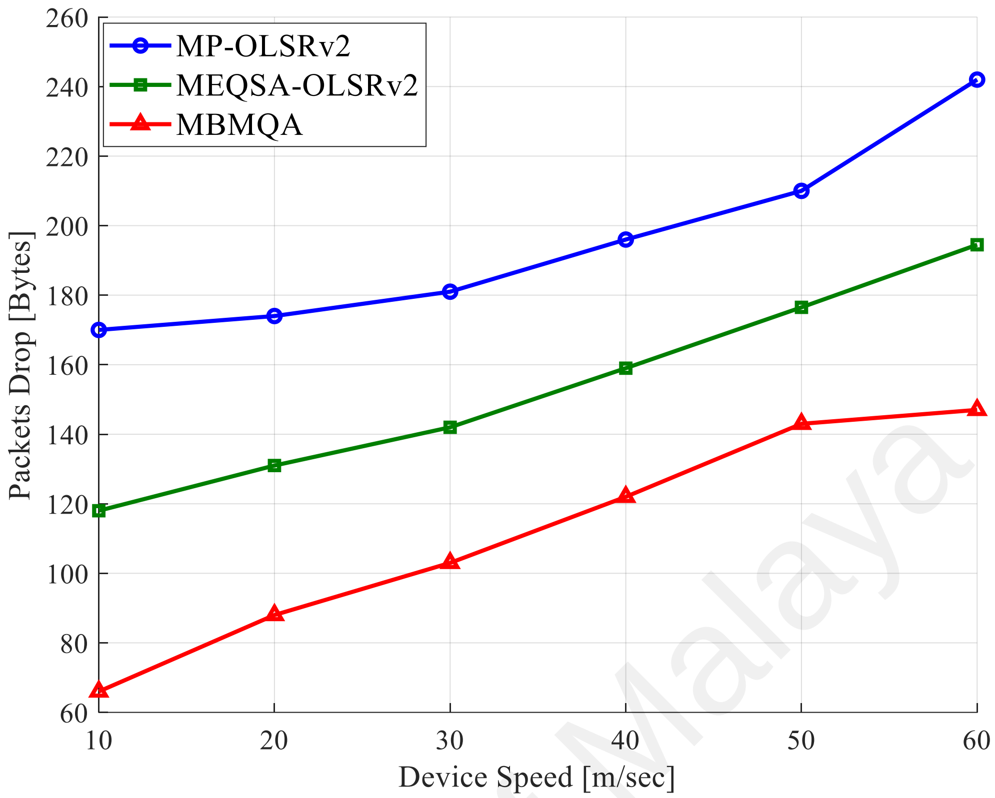


**Figure 4.11: Packets drop for variant device's speed**

### 4.3.5 Energy Cost Comparison

The results concerning the effect of altering the speed of devices with the energy cost per packet have been presented in Figure 4.12 for the D2D communication UDN scenario. It could be observed that the energy cost per packet of both MP-OLSRv2 and MEQSA-OLSRv2 increased as the device speed increased. It is approximately 22.53% and 12.72% higher in MP-OLSRv2 and MEQSA-OLSRv2, respectively, as compared to MBMQA with device speed up to 40 m/s. As defined previously, this is attributed to the fact that MBMQA selects the suitable path between source and destination devices, while taking into consideration the energy and the queue length of devices based on the MARS metric. This increases the packet delivery ratio and origins fewer packet drops. Since there are minimal packet drops and retransmission, extra energy is saved by transmitting most packets only once. Therefore, energy consumption during packet transmission is reduced.

The exploiting energy and QoS awareness techniques enable the proposed MBMQA routing approach to transmit more data packets with lower energy consumption, thus reducing the energy cost per packet for the D2D communication in the UDN scenario.

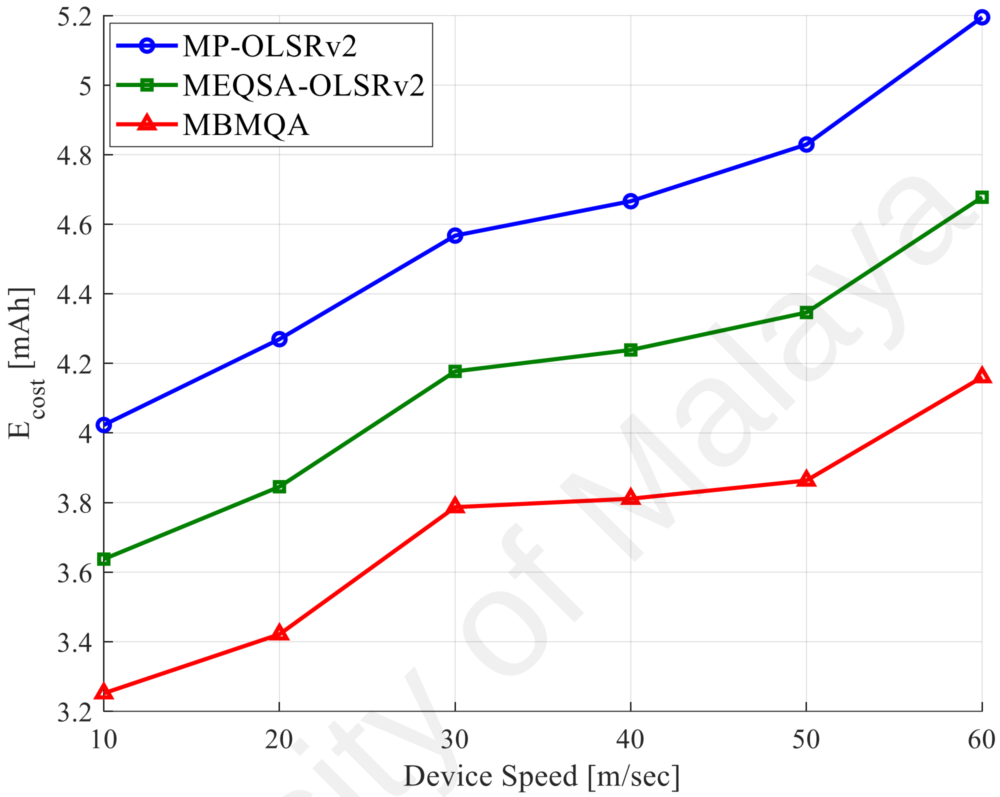


**Figure 4.12: Energy cost packet for variant device's speed.**

### 4.3.6 Energy Consumption Comparisons

Similarly, the overall power or energy consumed by the D2D communication in the UDN scenario is minimized as low power is required to transmit a single bit from source to destination, as depicted in Figure 4.13. Furthermore, the MBP reduced load congestion occurred in the path and further reduced the device drain rate. As the device speed increases, the energy consumption of devices increases. Energy consumption increases from 57.09 mAh to 57.48 mAh for MP-OLSRv2, from 56.91 mAh to 57.34 mAh for MEQSA-OLSRv2, and from 56.69 mAh to 57.18 mAh for the proposed MBMQA routing approaches approximately when the devices speed increases from 10 m/s to 60 m/s. As seen from the Figure 4.13, it can be observed that MBMQA for the D2D communication in UDN scenario, is able to consume lowest battery energy in comparison to MP-OLSRv2 and MEQSA-OLSRv2 in all device's speed because the source device forwards traffic flow towards intermediate devices which have the highest level of energy and lowest drain rate.

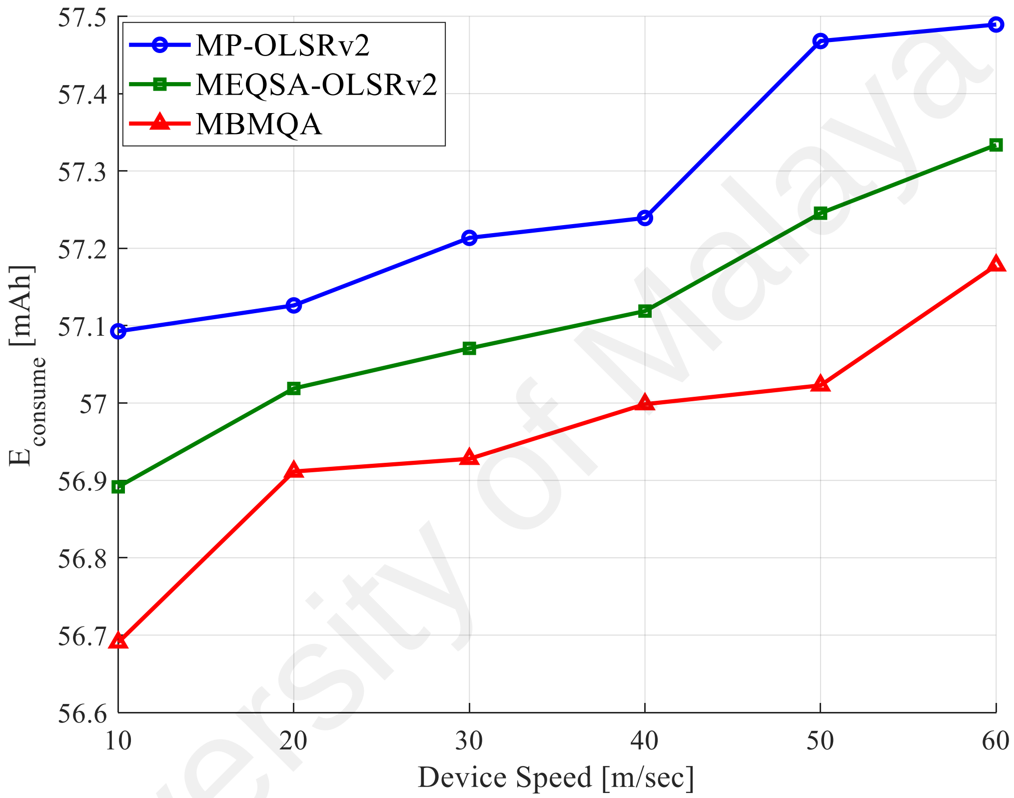


**Figure 4.13: Energy consumption for variant device's speed**



### 4.3.7 Convergence Time Comparison

The MBMQA routing approach has better convergence time performance as compared to the MP-OLSRv2 and MEQSA-OLSRv2 routing approaches, as shown in Figure 4.14. In the MP-OLSRv2 and MEQSA-OLSRv2 routing approaches, the packets are forwarded through the long and congested route, which induce a longer time for data packets transmission. The MBMQA exploits the MBP algorithms with the queue length size of the intermediate device. Consequently, it diverts the data packets flow from the high congested level device to the low congested level device that leads to load balance among the devices and minimizes convergence time of the network. Overall, at 30 m/s device speed, the results show that the proposed MBMQA routing approach reduces the convergence time by approximately 38.24% and 24.16% compared with the MP-OLSRv2 and MEQSA-OLSRv2 routing approaches, respectively.

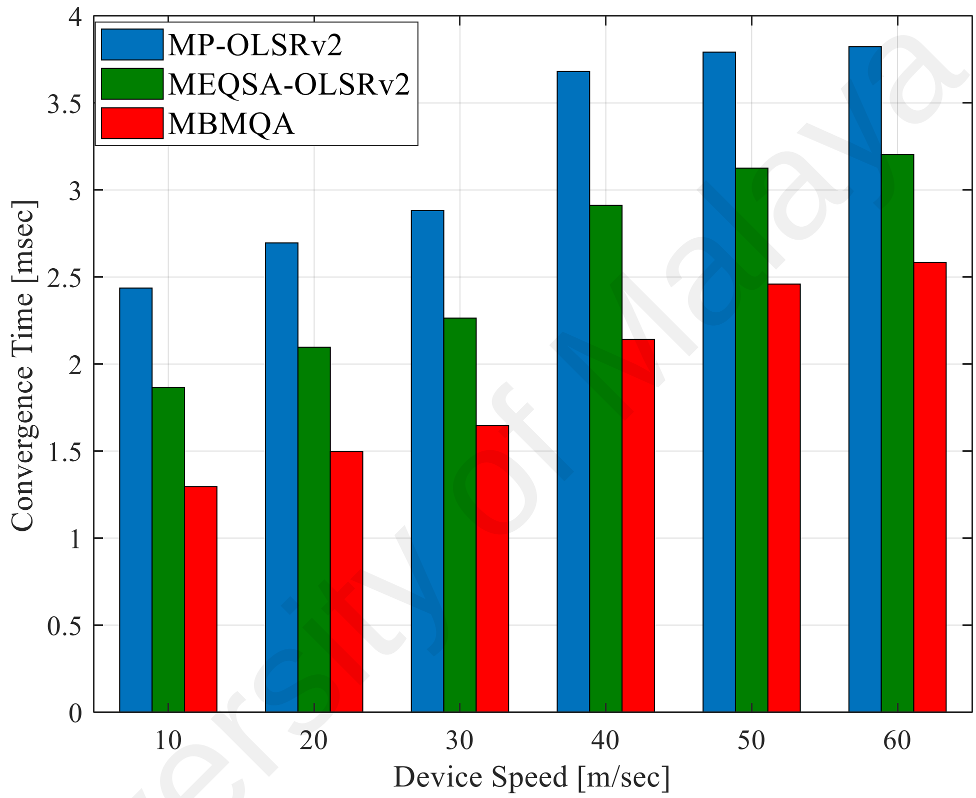


**Figure 4.14: Converngence time of routing approaches for variant device's speed**

### 4.3.8 Recapitulation of the D2D Communication in the Ultra-Dense Network scenario

This study presents a multipath hybrid MBMQA routing approach with the MBP algorithm strategy for D2D communication in the UDN scenario. The proposed MBMQA routing approach consists of multiple parameters, including energy consumption, queue length size, and mobility of the devices. In order to determine optimal paths that provide maximum network performance, the MBP forwards data packets toward the devices which have low queue backlogs, while maintaining network stability. The MBMQA ensures that multiple stable routes can be formed from source to destination without over-exhausting any single device's battery by enhancing the counterpart routing approaches. Moreover, the MARS decision metric is utilized to evaluate the device selection criterion in the optimal route based on the mobility, battery, and queue length size of the devices. It dramatically minimizes the complexity of multiple constrained considerations and avoids the control overhead caused by separate broadcasting multiple parameters. Simulation results indicated that MBMQA outperforms its MEQSA-OLSRv2 and MP-OLSRv2 counterpart in terms of packet delivery ratio, average end-to-end delay, throughput, packet drop, energy consumption, and energy cost, especially for the D2D communication in UDN scenario. In addition, the MBMQA approach mitigated the number of dropped packets and delivered a higher number of data packets at a lower energy cost per packet, which results in higher energy efficiency.

## 4.4 The D2D Communication based Disaster Management Scenario

The results obtained from the extensive simulation of the EMBLR, MEQSA-OLSRv2, and MP-OLSRv2 routing approaches with various device speed for the D2D communication-based DMS are presented in this section. The simulation results of the proposed EMBLR routing approach has enhanced the overall network QoS performance at several device speed. Overall, this section presents a critical analysis of the obtained simulation results:

### 4.4.1 Throughput Comparison

Figure 4.15 depicts the comparison of throughput of the EMBLR, MP-OLSRv2, and MEQSA-OLSRv2 routing approaches for the D2D communication-based DMS. It can be observed that the results achieved through the proposed approach is higher than the existing approaches in terms of network throughput. Both the MP-OLSRv2 and MEQSA-OLSRv2 routing approaches do not consider the link quality metric of the intermediate devices in the selection of the route. At the same time, the proposed EMBLR routing approach exploits the HETX value through the probe message before data transmission, which minimizes the chance of link failure and enhances the network throughput. Moreover, the EMBLR routing approach utilizes the Backpressure algorithms which forward the packets in the low congested device. Therefore, it balances the load among the devices that lead to the maximization of the network throughput. When the speed of devices increases from 10 m/s to 60 m/s, the network throughput decreases. The EMBLR decreases from 58.45 kbps to 49.64 kbps, the MEQSA-OLSRv2 decreases from 54.56 kbps to 46.22 kbps, and the MP-OLSRv2 also decreases from 53.12 kbps to 43.56 kbps. Overall, the proposed EMBLR routing protocol for the D2D communication-based DMS has a higher throughput performance than both MEQSA-OLSRv2 and MP-OLSRv2 in all different device speed.

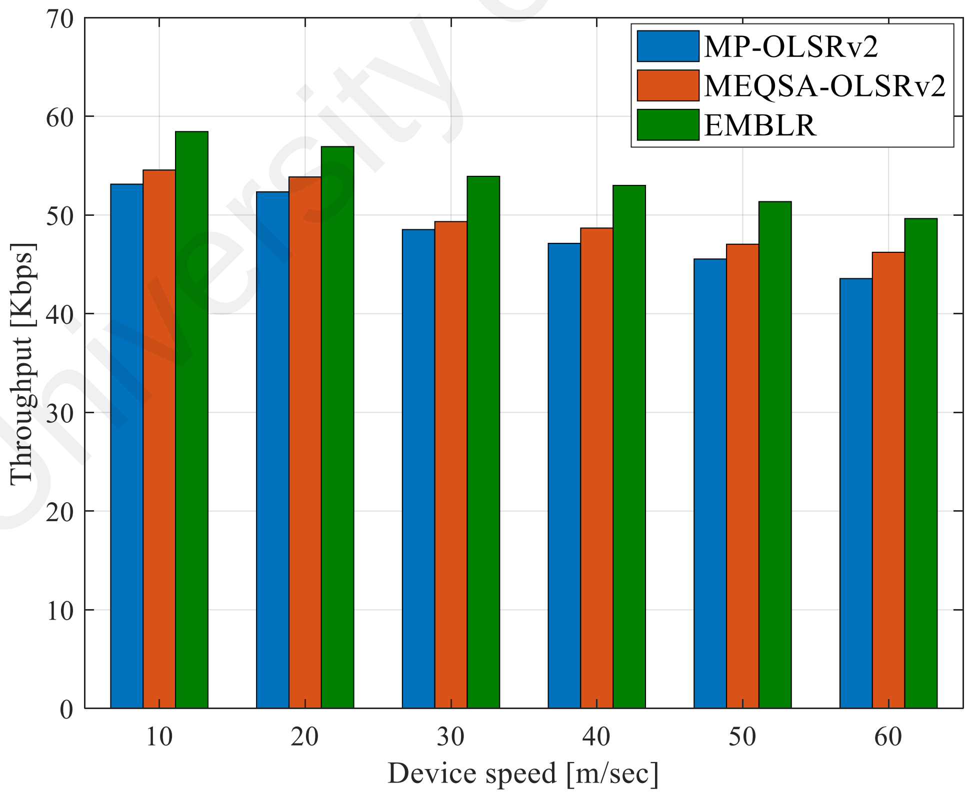


**Figure 4.15: Throughput vs. various devices speed**

### 4.4.2 End-to-End Delay Comparison

The proposed EMBLR routing approach performs much better end-to-end delay as compared with other routing approaches for the D2D communication based DMS, as shown in Figure 4.16. The end-to-end delay includes the propagation delay between the source and the destination device, together with queuing delay for every intermediate device. The other two routing approaches forward the data packets through the long and congested route, which induce more end-to-end delay. On the other hand, the EMBLR exploits the backpressure algorithms with the queue length size of the intermediate device. It diverts the data packets flow from high to a low congested device that leads to load balance, thereby, minimizes the data transmission time between source and destination devices. Furthermore, the EMBLR selects the high-reliable path, which keeps route stable and reduces the end-to-end delay for data transmission by exploiting the HETX metric.

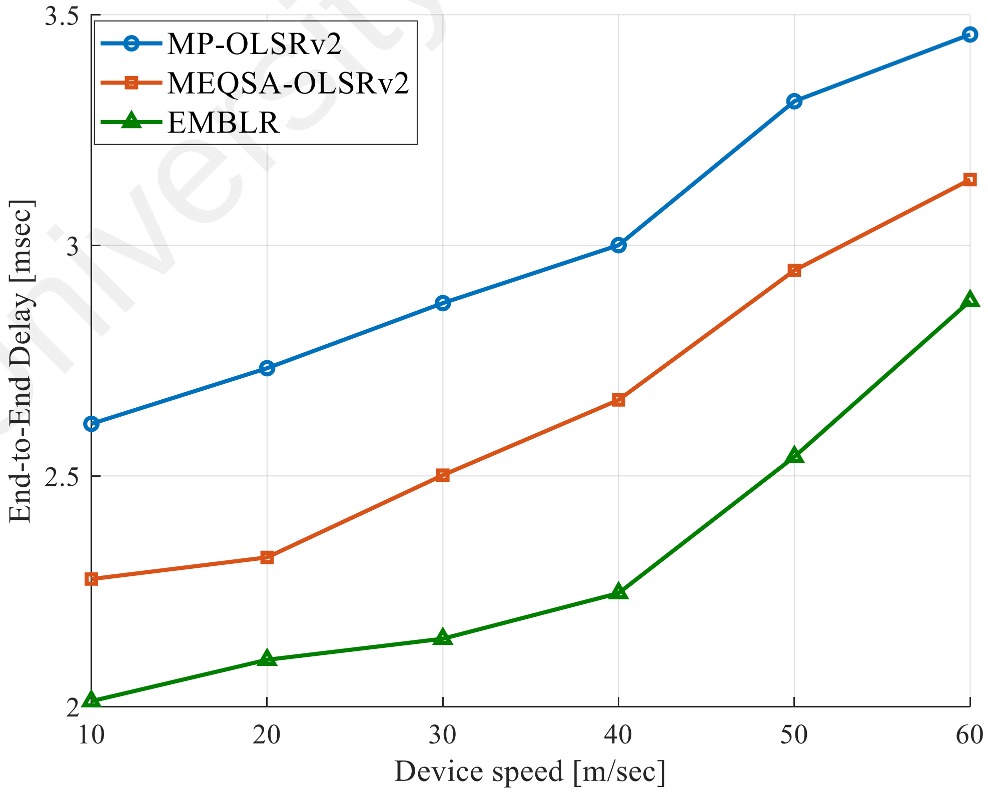


**Figure 4.16: End-to-end delay vs. various devices speed**

Overall, it can be seen that in the D2D communication-based DMS, the proposed EMBLR routing approach reduces the end-to-end delay by approximately 20.58% and 13.62% as compared with the MP-OLSRv2 and MEQSA-OLSRv2 routing approaches, respectively, at 60 m/s device speed.

### 4.4.3 Packet Delivery Ratio Comparison

The proposed EMBLR routing approach exploits HETX value that decreases the number of intermediate devices in the optimal path selection, which minimizes the number of dropped packets during data transmission. In addition, HETX decreases the number of trials for data retransmission and reduces link failure probability resulting from the dynamic nature of the D2D communication based DMS, thereby keeping a higher packet delivery ratio compared to the other multipath routing approaches.

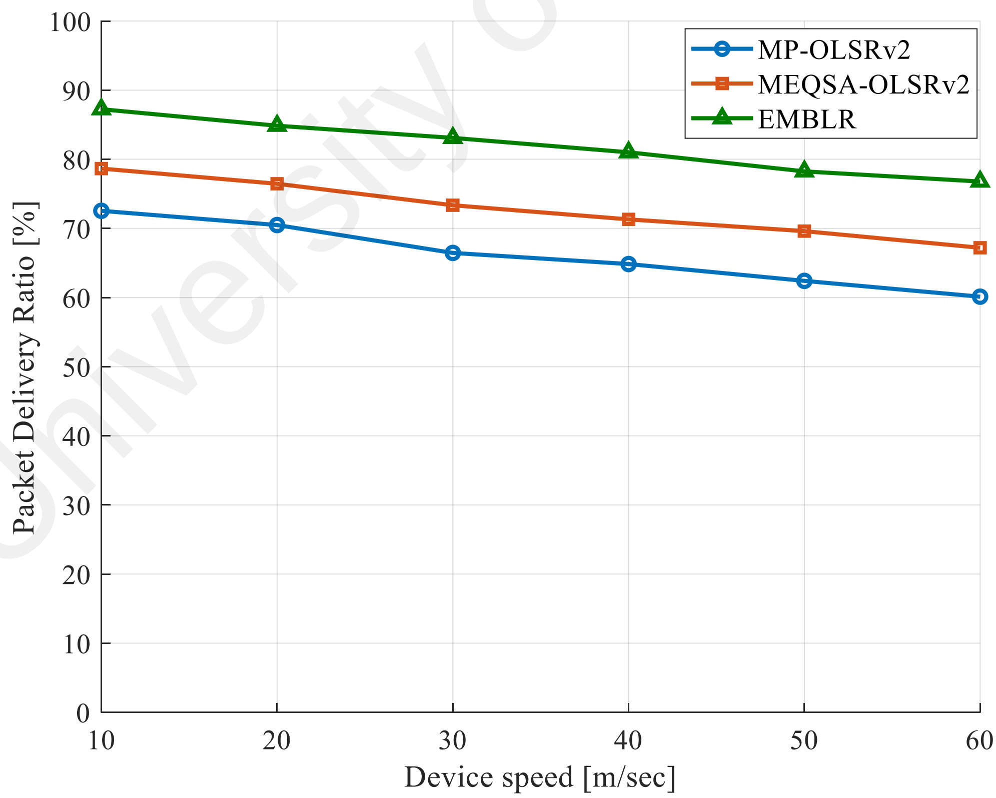


**Figure 4.17: Packet delivery ratio vs. various devices speed**

Besides, the EMBLR routing approach considers the rate of transmission and queue length of the intermediate devices during data transmission, which minimized the congestion level at the device. Therefore, it forwards the data packets towards the device with lower queue length, and a higher data rate transmission, which reduces the chance of packets dropped in the network. For high-speed device scenarios, it can be seen from Figure 4.17 that the proposed EMBLR approach attains better packet delivery ratio performance compared with the other routing approaches for the D2D communication based DMS. Consecutively, the EMBLR approach improved the average percentages of all device speed approximately 33.67% and 23.84% as compared with the MP-OLSRv2 and MEQSA-OLSRv2 routing approaches, respectively.

### 4.4.4 Packets Drop Comparison

Figure 4.18 illustrates the packets drop of the EMBLR, MP-OLSRV2, and MEQSA-OLSRv2 routing approaches with different speeds of network devices for the D2D communication-based DMS. It can be observed that the proposed EMBLR approach outperforms other routing approaches. The MP-OLSRv2 and MEQSA-OLSRv2 routing approaches exclude the channel condition for data transmission awareness; due to this, there is a collision of the data packets at the MAC layer. Whereas, the EMBLR utilizes the HETX value before the data transmission to the link that minimizes the collision of the data packets, as well as the dropped packets. As the device's speed elevates, the number of data packets dropped in the network also elevates. The MP-OLSRv2 packets drop (27.43%), and MEQSA-OLSRv2 packets drop (14.15%) is higher than the EMBLR routing approach for the D2D communication-based DMS at the highest 60 m/s device speed.

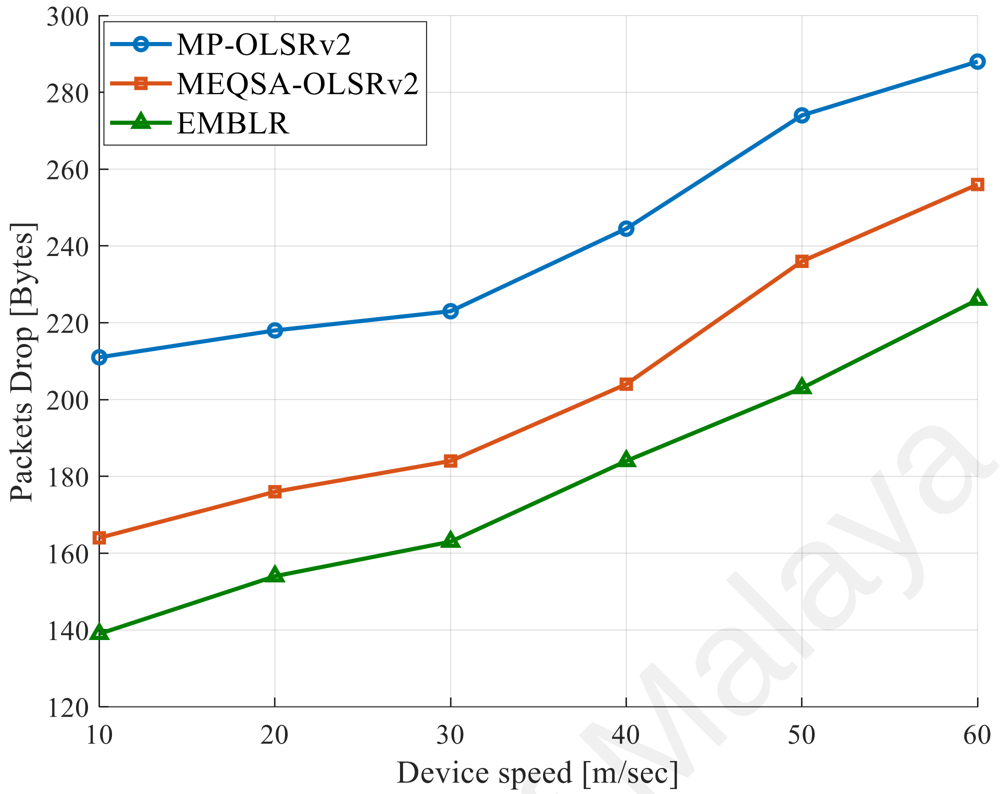


**Figure 4.18: Packet drop vs. various devices speed**

### 4.4.5 Energy Consumption Comparison

Figure 4.19 presents a comparison of device energy consumption of the routing approaches during network operation time in the D2D communication based DMS. The result shows that the proposed EMBLR routing approach superiority than the other routing approaches due to the simultaneous consideration of intermediate devices estimated parameters value during multiple route computation processes. The EMBLR routing approach selects intermediate devices based on low HETX value through probe messages before data transmission. In the EMBLR, the link quality among the devices is estimated by using the HETX metric that can mitigate the flooding impact of RREQ packets in the D2D communication based DMS. Therefore, HETX decreases the chance of frequent route failures that lead to the mitigation of the network load as well as device energy consumption in the route selection process. When the device speed increases from

(10, 20, 30, 40, 50, and 60), the device energy consumption also increases. The EMBLR increases from 53.354 mAh to 56.124 mAh, MEQSA-OLSRv2 increases from 54.541 mAh to 58.465 mAh, and MP-OLSRv2 increases from 56.145 mAh to 59.648 mAh. Overall, it can be observed that the proposed EMBLR routing approach has less energy consumption as compared to the MEQSA-OLSRv2 and MP-OLSRv2 routing approaches for the D2D communication-based DMS.

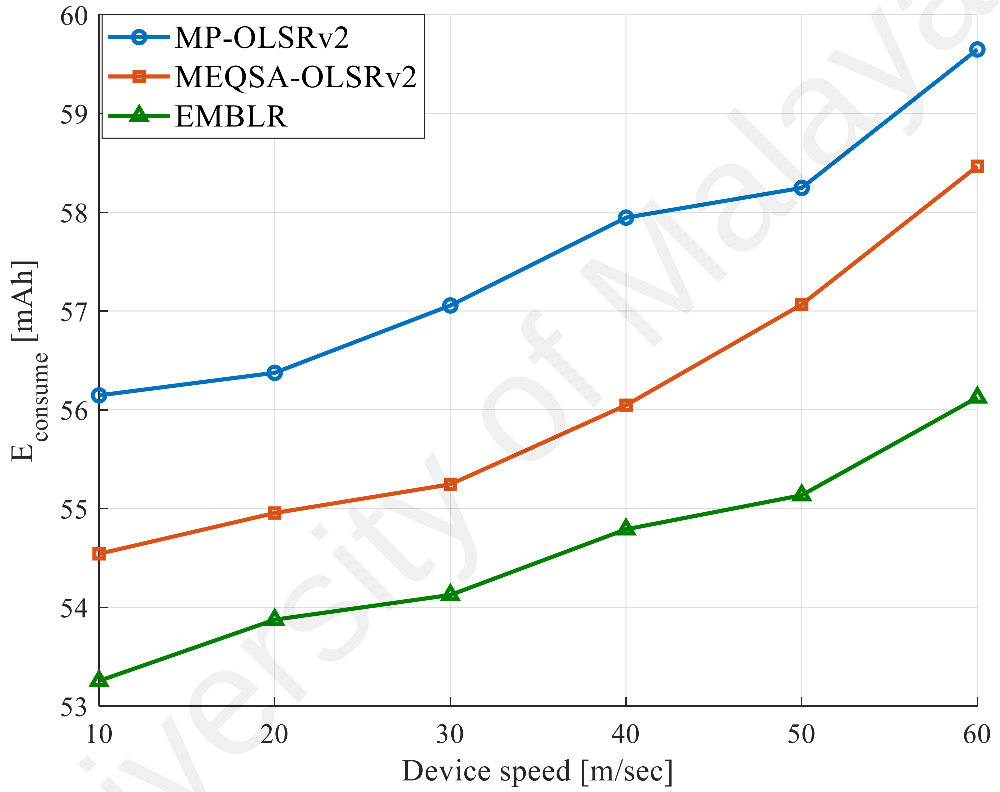


**Figure 4.19: Energy consumption vs. various devices speed**

### 4.4.6 Energy Cost Comparison

Figure 4.20 illustrates the result of energy cost per packet based on the routing approaches of various device speeds for the D2D communication based DMS. The proposed routing approach attains the lowest energy cost owing to exploitations of the HETX metric, which reduces packets flooding in the network. Therefore, the fewer number of RREQ packets induces in the network result in the minimization of the device energy cost. Frequent movement of intermediate devices in the network causes the variation of the device's energy levels while increasing mobility. The proposed EMBLR routing approach also selects devices with better link quality and lower speed to decrease energy consumption and packets loss; this awareness is not used in the other routing protocols. Overall, the proposed EMBLR routing approach recorded the lowest energy cost, followed by both MEQSA-OLSRv2 and MP-OLSRv2 in the D2D communication-based DMS. Energy cost attains by MP-OLSRv2 is 20.45 % and 19.22 %, while the MEQSA-OLSRv2 is 11.56% and 9.56% higher than the EMBLR when the device speed varies from 10 m/s to 60 m/s, respectively.

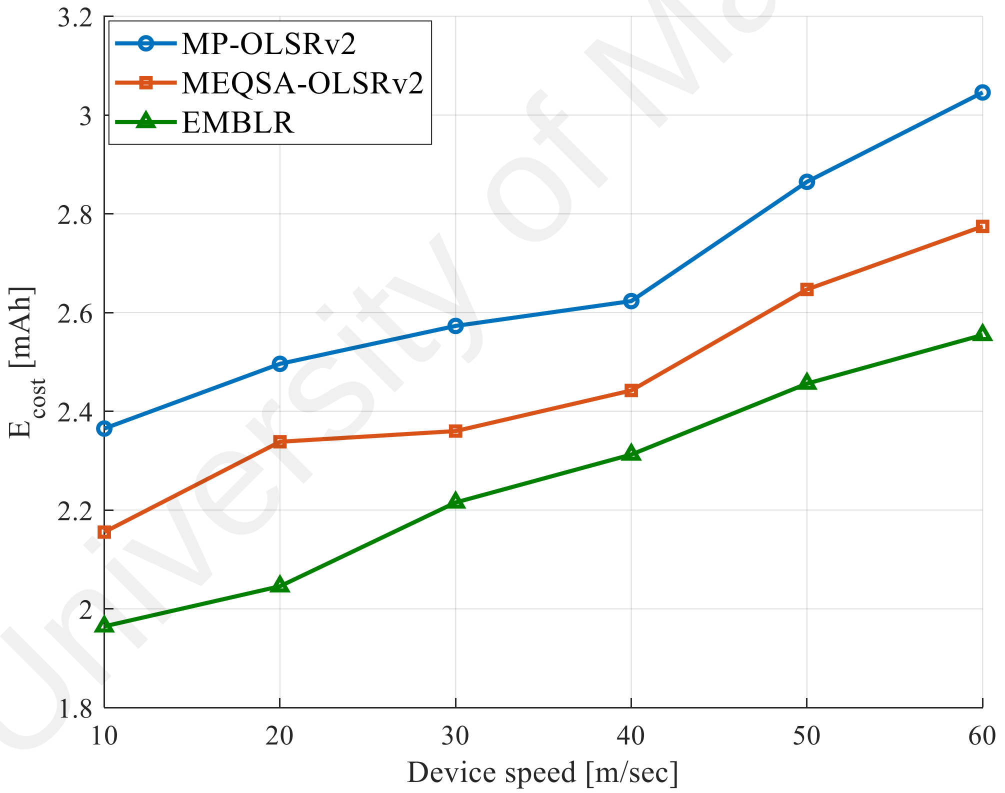


**Figure 4.20: Energy cost vs. various devices speed**

### 4.4.7 Convergence Time Comparison

Figure 4.21 shows that the proposed EMBLR routing approach provides a significantly lower convergence time in all scenarios of device speed as compared with the MP-OLSRv2 and MEQSA-OLSRv2 routing approaches. The reason behind the lower convergence time is that the EMBLR prohibits data flows in the congested and longer paths that minimize the data transmission time between the source and destination device. Moreover, the proposed EMBLR routing approach exploits the HETX metric value in order to reduce the chance of link failure among the device. Therefore, the EMBLR approach quickly updates the routing table information of the network with any changes occurring in the network that leads to minimizes the network convergence time. Overall, the Figure 4.21 shows that the proposed EMBLR approach achieves around 20.72 % and 12.43 % lower convergence time when compared with the MP-OLSRv2 and MEQSA-OLSRv2 routing approaches respectively, at device speed 30 m/s.

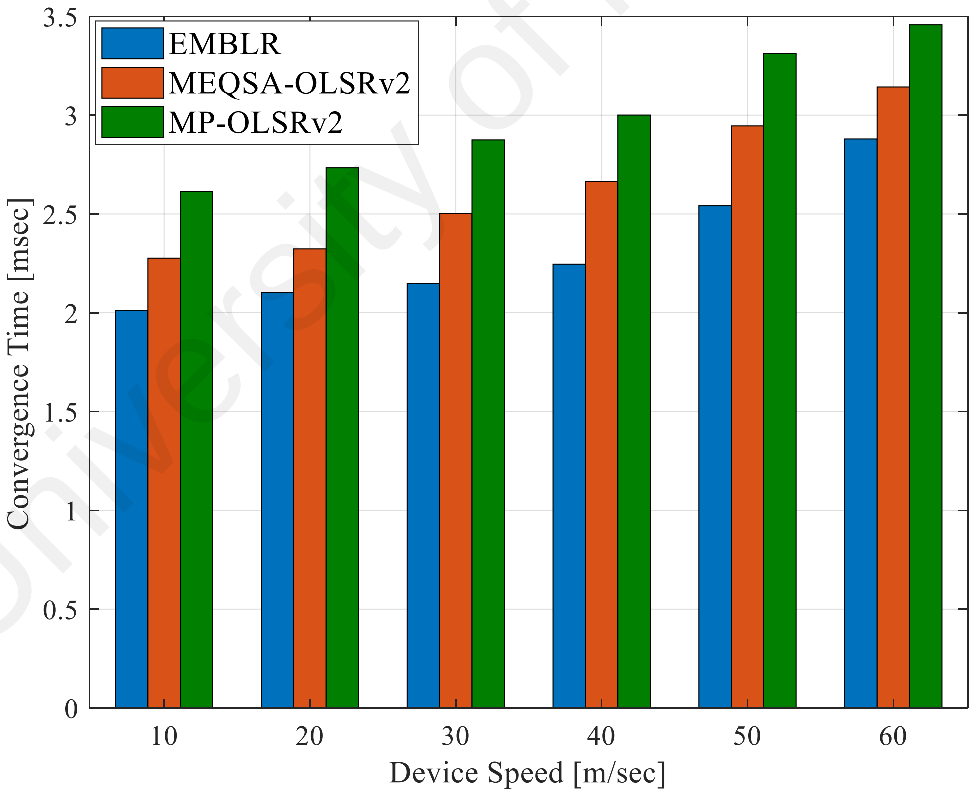


**Figure 4.21: Convergence time of routing approaches vs various devices speed**

### 4.4.8 Recapitulation of the D2D Communication based Disaster Management Scenario

This study presents an EMBLR routing approach by using device multicriteria selection in an optimal route between the source and destination devices for the D2D communication based DMS. In the EMBLR routing approach, energy consumption and link quality with mobility and queue length of the intermediate devices is estimated in the optimal route selection mechanism. Moreover, the MCDM multicriteria decision-making technique is employed to select the intermediate devices in the optimal path, which provides weight to the devices according to the estimated values. It significantly reduces the complexity of multiple constrained considerations and avoids the control overhead caused by separate broadcasting multiple parameters. Extensive simulation has been conducted with various device speeds, and the results have been illustrated in QoS network performance metrics. Based on the simulation results, it shows that the proposed EMBLR routing approach attains significant performance compared to the other well-known routing approaches for the D2D communication based DMS. Overall, the proposed EMBLR routing approach significantly improves end-to-end delay 20.58% and 13.62%, packet delivery ratio 33.67%, and 23.84%, and energy cost 20.45% and 11.56 % approximately as compare to the MP-OLSRv2 and MEQSA-OLSRv2 routing approaches, respectively.

## 4.5 Summary

Based on the discussed routing approaches, it can be concluded that in the conventional D2D communication scenario, the network topology is highly dynamic and changes in an unpredictable manner due to high displacement and random addition or subtraction of devices in the network. This scenario affected the stability of the network and established routes, which significantly degrades network QoS performance. Therefore, the MRLAM routing approach is proposed for the conventional D2D communication scenario to optimize the network and route stability in highly dynamic and frequent topology changing networks. Moreover, in the D2D communication UDN scenario, traffic congestion occurs when there is an excessive flow of packets injected and carries most of the network traffic on a single mobile device. This scenario induces data packets transmission end-to-end delay in the network. Thus, the MBMQA routing approach is proposed in order to balanced data traffic load among the mobile devices in the D2D communication UDN scenario.

Finally, in the D2D communication based DMS, the mobile devices are equipped with limited energy resources for their vital operation of data transmission. Hence, the connectivity of the devices suffers from packets drops as soon as the device's energy gets exhausted. Similarly, the mobile devices in the network, change their position in an unpredictable manner, which induces the chance of link failure in the established route between source and destination devices. Therefore, the proposed EMBLR routing approach in the D2D communication based DMS to balance the energy consumption load among the devices and ensure reliable data transmission between the source and destination devices.

# CHAPTER 5: CONCLUSIONS

## 5.1 Conclusion

This research proposed three routing approaches for three main network scenarios of D2D communication, that are conventional D2D communication scenario, the D2D communication UDN scenario, and the D2D communication based DMS. In the conventional D2D communication scenario, the network topology is highly dynamic and changes in an unpredictable manner due to high displacement and random addition or subtraction of devices in the network. This scenario is affecting the stability of the network and established routes, which significantly degrades network performance. Therefore, the MRLAM routing approach is proposed for the conventional D2D communication scenario to optimize the network and route stability in highly dynamic and frequent topology changing networks. The optimal route decision is made with Q-learning algorithms for mobility with residual energy, and link quality parameters of the devices. It can be concluded that for the conventional D2D communication scenario, the proposed MRLAM routing approach maximizes the packet delivery ratio up to 18.36% and 14.28% approximately as compared with conventional MP-OLSR and its extended version MP-OLSRv2 routing approaches, respectively.

Meanwhile, in the D2D communication UDN scenario, traffic congestion occurs when the single mobile device experiences an excessive flow of data packets since it carries most of the network data traffic, this scenario induces data packets transmission end-to-end delay in the network. Therefore, the MBMQA routing approach is proposed in order to balance the data traffic load among mobile devices in the D2D communication UDN scenario. The optimal route decision is made with the MARS multicriteria decision technique based on the three parameters such as mobility, residual battery, and queue length of the devices with the MBP algorithm. The MBP algorithm ensured that the device which has higher queue length is avoided in order to enhance the network performance and mitigate data transmission latency between source and destination devices. It can be concluded that in the D2D communication UDN scenario, the end-to-end delay performance achieved by the proposed MBMQA routing approach is 33.15% lower as compared to MP-OLSRv2 and 19.52% lower with MEQSA-OLSRv2 conventional routing approaches.

Furthermore, in the D2D communication based DMS, the mobile devices are equipped with limited energy resources for their vital operation of data transmission. Thus, the connectivity of the devices suffers from packets drops as soon as the device's energy gets exhausted. Similarly, the mobile devices in the network, change their position in an unpredictable manner, which induces the chance of link failure in the established route between source and destination devices. Therefore, the EMBLR routing approach is proposed in the D2D communication based DMS to balance the energy consumption among the devices and ensures reliable data transmission between the source and destination devices. The optimal route decision is made by exploiting the MCDM multicriteria decision technique based on energy consumption and link quality in combination with mobility and queue length parameters of the devices. It can be concluded that in the D2D communication-based DMS, the proposed EMBLR routing approach significantly improved the data packets drop to 27.43%, and 14.15%, and energy cost per packets 20.45% and 11.56% approximately lower as compare to the MP-OLSRv2 and MEQSA-OLSRv2 conventional routing approaches, respectively.

Overall, in the conventional D2D communication scenario, the network stability in highly dynamic and frequent changes in network topology is optimized by the proposed MRLAM routing approach. In the D2D communication UDN scenario, the data traffic load is balanced among the mobile devices by the proposed MBMQA routing approach. In addition, in the D2D communication based DMS, the energy consumption load is balanced among the devices and ensured the reliable data transmission between the source and destination devices by the proposed EMBLR routing approach.

## 5.2 Future Works

In order to fulfill the growing demand for peer-to-peer communication, the use of a D2D communication 5G network with efficient and reliable routing is one of the promising solutions that deliver better QoS network performance to the users. The integration of several device parameters into a single route computation metric in D2D communication technology promises several benefits. However, it also brings various technical challenges like substantial computation cost, modulation scheme selection for the mode of communication, and noise control, which need to be considered for optimal route and network performance. With the help of the proper resource allocation method, the higher system data rate can be achieved, yet, along with the security aspects, also need to be considered. D2D communication is one of the key technologies in the 5G network, and beyond the 5G network, further research in the heterogeneous network domain is imperative. Moreover, as the D2D link shares the same spectrum resources with cellular links and mobile devices, it causes interference among the spectrum-sharing links, thus decreasing the overall network performances.

Better spectrum utilization such as cognitive radio, coordinated multi-point joint transmissions can be used to the tradeoff of delay issues, QoS, network coverage probability, efficiency that can enhance network performance. Gauss-Markov Mobility Model could be applied in future aspects for device mobility estimation. In DMS, the Hata model can be used to estimate the radio propagation model with diffraction effect and deep shadowing effect; furthermore, channel fading impact on D2D communication performance can also be analyzed. In addition, faulty device injection in the network can be implemented in the simulation in order to test the robustness and practicability in the DMS. Overall, it is evident that proposed routing approaches can be served as the foundation and benchmark for routing approaches in the different D2D communication application scenarios.

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## LIST OF PUBLICATIONS AND PAPERS PRESENTED

1. **Tilwari, V**., Dimyati, K., Hindia, M. H. D., Fattouh, A., & Amiri, I. S. (2019). Mobility, Residual Energy, and Link Quality Aware Multipath Routing in MANETs with Q-learning Algorithm. *Applied Sciences*, 9(8), 1582.

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2. **Tilwari, V.,** Dimyati, K., Hindia, M. H. D., Izam T. F. T. M. N., & Amiri, I. S. (2020) EMBLR: A High-Performance Optimal Routing Approach for D2D Communication in Large-scale IoT 5G Network. *Symmetry*, 12 (3), 438.

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3. **Tilwari, V**, Hindia, MN, Dimyati, K, Qamar, K, & Abu, MST (2019). Contention Window and Residual Battery Aware Multipath Routing scheme in MANETs. *International Journal of Technology* 10 (7), 1376-1384.

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