

Article

A Study of MANET Routing Protocols in Heterogeneous Networks: A Review and Performance Comparison

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Abstract: Mobile ad hoc networks (MANETs) are becoming a popular networking technology as they can easily be set up and provide communication support on the go. These networks can be used in application areas, such as battlefields and disaster relief operations, where infrastructure networks are not available. Like media access control protocols, MANET routing protocols can also play an important role in determining network capacity and system performance. Research on the impact of heterogeneous nodes in terms of MANET performance is required for proper deployment of such systems. While MANET routing protocols have been studied and reported extensively in the networking literature, the performance of heterogeneous nodes/devices in terms of system performance has not been fully explored yet. The main objective of this paper is to review and compare the performance of four selected MANET routing protocols (AODV, OLSR, BATMAN and DYMO) in a heterogeneous MANET setting. We consider three different types of nodes in the MANET routing performance study, namely PDAs (fixed nodes with no mobility), laptops (low-mobility nodes) and mobile phones (high-mobility nodes). We measure the QoS metrics, such as the end-to-end delays, throughput, and packet delivery ratios, using the OMNeT++-network simulator. The findings reported in this paper provide some insights into MANET routing performance issues and challenges that can help network researchers and engineers to contribute further toward developing next-generation wireless networks capable of operating under heterogeneous networking constraints.

Keywords: heterogeneous; MANET; AODV; OLSR; BATMAN; DYMO; heterogeneous networks



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1. Introduction

Mobile ad hoc networks (MANETs) are becoming very popular because these networks can be set up easily and be operated on the go. These features allow MANETs to be used in wide applications in areas such as battlefields, disaster relief operations, and even in hotel lobbies, airports, and cafes [1]. Another feature of MANETs is that the mobile nodes can configure themselves without any centralized control. However, it is a challenge to maintain a high level of performance on the part of the MANETs due to the node mobility, battery-powered nodes, and multi-hop routing structure [2–4].

Wired networks are faster and provide more security and reliability [5–7]. Faults are generally less common in wired networks. The difficulties with wired networks show mainly in the installation and overall costs to repair, maintain, and manage these setups. Unlike wired networks, wireless networks help to provide flexibility, as they allow users

within the network to work from anywhere within the boundaries of the network itself [2,8]. However, wireless networks are less reliable regarding the connections and security [9].

Infrastructure-based networks are where many wireless devices are connected to the network infrastructure via an access point or router [10]. The access point allows users to connect to external networks like the Internet. Infrastructure-less or ad-hoc networks can start with a peer-to-peer connection between two wireless devices. As more ad hoc wireless devices enter this network by sharing the same SSID (service set identifier), this becomes a multi-node system of connections where many users can exchange data and communicate with one another [7]. Between the two categories, ad hoc networks are simpler and easier to implement, because no pre-existing setups and hardware are needed to establish a connection. And because of this, the overall costs to implement such a network are low.

Ad hoc networks are categorized into wireless sensor networks (WSNs), wireless mesh networks (WMNs) and MANETs. A MANET is a network where the mobile nodes are in communication with one another without administration assistance [11,12]. Instead of having an access point, a wireless device connected to the network can act as a centralized router with access point software. In these networks, routing is needed to find a suitable path from a source node to its destination with the help of routing protocols.

1.1. Heterogeneous MANET Environment

A heterogeneous MANET (HMANET) is like a regular MANET, except that all the devices/nodes are connected to the network with varying capabilities, including the mobility, data transmission rates, distance coverage, battery life, and power consumption [13–16]. The heterogeneity of the nodes can be complex if multiple heterogeneous devices are connected to the network for communications. Using the OMNeT++ simulation tool, a heterogeneous MANET model is developed to study the impact of heterogeneous nodes on the performance of various MANET routing protocols.

1.2. Research Challenges

In this study, we address the following three research questions/challenges.

Research Question 1: How do the routing ad hoc on-demand distance vector (AODV), optimized link state routing (OLSR), better approach to mobile ad hoc networking (BATMAN), and dynamic MANET on-demand (DYMO) protocols affect the MANET performance in a heterogeneous environment?

MANETs are increasingly popular due to their ability to be set up easily and provide communication support in areas lacking infrastructure. However, maintaining a high level of performance in MANETs is challenging due to factors such as the node mobility, battery limitations, and multi-hop routing structures. While extensive research has been conducted on MANET routing protocols [1], the performance implications of heterogeneous nodes—devices with varying capabilities—remain underexplored. This study aims to review and compare the performance of four selected MANET routing protocols in a heterogeneous setting, considering different types of nodes, including PDAs (fixed nodes), laptops (low mobility), and mobile phones (high mobility).

Research Question 2: What impacts do heterogeneous nodes have on the quality of service (QoS) parameters in MANET routing protocols?

The heterogeneity of the nodes in MANETs introduces complexity into communications, potentially affecting the QoS metrics. Understanding how different types of nodes impact these metrics is crucial to optimizing the performance of MANETs. This research utilizes the OMNeT++ network simulator to measure and analyze the QoS metrics across the four selected routing protocols, providing insights into the performance variations based on the node capabilities and mobility. In fact, we stress the multimedia QoS perfor-

mance metrics such as the packet delay and throughput that we measure by simulation and compare the performance among the four selected MANET routing protocols. This multimedia QoS aligns with the focus of the special issue.

Research Question 3: How can the findings from the performance comparison of MANET routing protocols in heterogeneous environments inform the development of next-generation wireless networks?

The insights gained from studying the performance of AODV, OLSR, BATMAN, and DYMO in a heterogeneous MANET can guide future network researchers and engineers in developing robust wireless networks. Identifying the strengths and weaknesses of each protocol under varying conditions will be essential for creating systems capable of efficiently managing heterogeneous nodes and enhancing the overall network performance.

1.3. Research Scope and Contributions

The main contributions of this paper are summarized as follows.

- Comparative analysis of MANET routing protocols in heterogeneous environments: We thoroughly review and compare the performance of four selected MANET routing protocols (AODV, OLSR, BATMAN, and DYMO) in a heterogeneous MANET. To this end, we analyze the impact of various node types on the QoS parameters, such as the end-to-end delays, throughput, and packet delivery ratios. We provide insights into the performance of the routing protocols in heterogeneous networks.
- Evaluation of the node types impacting the QoS parameters: This study highlights the significance of the node heterogeneity in MANETs and its effect on the system performance. Using the simulator, we measure the QoS metrics for heterogeneous nodes, thereby informing future implementations of MANETs in real-world applications.
- Guidance for next-generation wireless networks: The findings of this research offer valuable insights that can assist network researchers and engineers in developing next-generation wireless networks capable of accommodating heterogeneous networking constraints. By understanding the performance issues associated with various MANET routing protocols, this paper contributes to the ongoing advancement of efficient and robust wireless communication systems.

1.4. Structure of the Paper

The rest of this paper is organized as follows. Section 2 presents related work on the routing protocols in MANETs and their performance in heterogeneous environments, focusing on the key literature addressing various protocols, like AODV, OLSR, BATMAN, and DYMO. Section 3 discusses the research methodology, detailing the experimental setup using the OMNeT++ simulation tool, as well as the design and performance metrics used to evaluate the selected routing protocols.

In Section 4, the system evaluation and test results are presented, analyzing the impact of heterogeneous nodes on the performance metrics, including the end-to-end delays, throughput, and packet delivery ratios. Section 5 presents the research findings. Finally, Section 6 concludes the paper by summarizing the main findings and suggesting potential areas for future research to enhance the routing performance in MANETs.

2. MANET Routing Protocols: Background and a Review of the Literature

2.1. MANET Classification

MANETs have been extensively studied due to their ability to operate in infrastructure-less environments, making them ideal for applications such as disaster recovery, military operations, and IoT deployments. However, the performance of MANETs in heterogeneous environments—where the nodes have varying capabilities in terms of the mobility,

transmission rates, and energy consumption—remains a critical challenge. This section reviews recent advancements in MANET routing protocols, focusing on their performance in heterogeneous networks and highlighting unresolved research gaps. MANETs have emerged as a vital networking technology, especially in scenarios where the traditional infrastructure is unavailable. Their flexibility and self-configuring capabilities allow for dynamic networking solutions in diverse environments, such as battlefields and disaster relief operations. As highlighted in [14], the performance of MANETs significantly hinges on the choice of routing protocols, which are crucial for establishing efficient communication paths among mobile nodes.

MANET routing protocols can be broadly classified into three categories: reactive (on-demand), proactive (table-driven), and hybrid protocols. Reactive protocols, such as AODV, establish routes only when needed, minimizing the overhead during periods of low network activity [17]. Proactive protocols, such as OLSR, maintain up-to-date routing information for all the nodes, enabling immediate route availability at the cost of increased control overhead [18]. Hybrid protocols, such as DYMO, combine the strengths of both reactive and proactive strategies, offering improved scalability and adaptability in dynamic environments [19].

Recent studies have explored enhancements to these protocols to address the challenges of heterogeneous networks. For instance, [17] proposed modifications to AODV, demonstrating improved performance in terms of the delay and throughput in heterogeneous MANETs. Similarly, [18] conducted a comparative analysis of OLSR and AODV, highlighting the trade-offs between the proactive and reactive approaches in dynamic environments. These studies underscore the importance of protocol design in optimizing the performance in heterogeneous networks.

The evaluation of routing protocols in heterogeneous environments remains a crucial area of research. Studies by [20] explored the performance of AODV and DYMO in varying conditions, emphasizing the importance of understanding how different node types influence network performance metrics such as the end-to-end delay and throughput. Furthermore, the BATMAN protocol has been introduced as an innovative approach to address some limitations associated with traditional routing protocols, focusing on maximizing the message delivery probabilities while minimizing the control overhead [21–23].

Our findings concerning AODV's throughput align with previous studies, such as [19], which also reported lower throughput in high-mobility scenarios. However, the inclusion of heterogeneous nodes in our study introduces additional complexity, leading to slightly lower throughput compared to homogeneous networks. These comparisons highlight the impact of node heterogeneity on protocol performance and underscore the need for adaptive routing strategies. The authors of [24] reviewed recent advancements in routing strategies aimed at minimizing energy consumption in MANETs. They highlighted that energy-efficient protocols are critical to prolonging the operational life of battery-powered devices, which are prevalent in mobile ad hoc networks. Their findings suggest that integrating energy awareness into routing protocols can substantially improve the sustainability of MANETs. The integration of MANETs with emerging technologies, such as 5G and the IoT, has opened up new avenues for research. The authors of [20] explored the integration of MANETs with delay-tolerant networks (DTNs), discussing the implications for 5G-enabled heterogeneous networks. Similarly, [21] investigated the challenges of integrating MANETs with IoT devices, focusing on queue-buffer optimization and its impact on routing performance.

Recent work has also shed light on the challenges faced by MANETs due to the diversity of node capabilities. The authors of [19] analyzed the performance of AODV alongside the OLSR protocol in mobile ad hoc networks. Their comparative study reveals

that while AODV excels in dynamic environments due to its reactive nature, OLSR’s proactive approach allows for faster route establishment under stable conditions. This analysis underscores the importance of context when selecting routing protocols, as the ideal choice can vary depending on the mobility patterns and network topology.

The authors of [22] offered a broader perspective by surveying various routing protocols used in MANETs, outlining key issues and challenges, such as security vulnerabilities, scalability, and energy efficiency. Their work points to a growing need for innovative solutions that address these challenges while maintaining reliable communication. In another study, [23] compared hybrid routing protocols under different mobility models, concluding that hybrid approaches can effectively balance the trade-offs between proactive and reactive strategies. This adaptability is essential in environments with varying mobility levels, as it allows for dynamic adjustments to routing behavior based on real-time conditions. A trust-based routing protocol tailored to heterogeneous nodes, emphasizing the need for reliable communication is discussed in MANETs [24]. Their approach highlights the significance of incorporating trust metrics into routing decisions, which can enhance the security and network performance in the face of varying node capabilities.

The authors of [25,26] have highlighted the importance of heterogeneity in MANETs, particularly in scenarios where the nodes possess varying mobility, energy consumption, and processing power. The impact of dynamic topology on routing efficiency suffering from excessive overhead in high-mobility is discussed in [19]. Additionally, [25] investigated energy-aware routing mechanisms, emphasizing the trade-off between route stability and power conservation in heterogeneous MANETs. Our study builds upon these works by evaluating four key routing protocols (AODV, OLSR, BATMAN, and DYMO) under varying heterogeneous conditions using OMNeT++ simulations.

The MANET routing protocols can be classified into three main categories, namely reactive (on-demand), proactive (table-driven) and hybrid, as shown in Figure 1. These routing protocols are briefly described below.

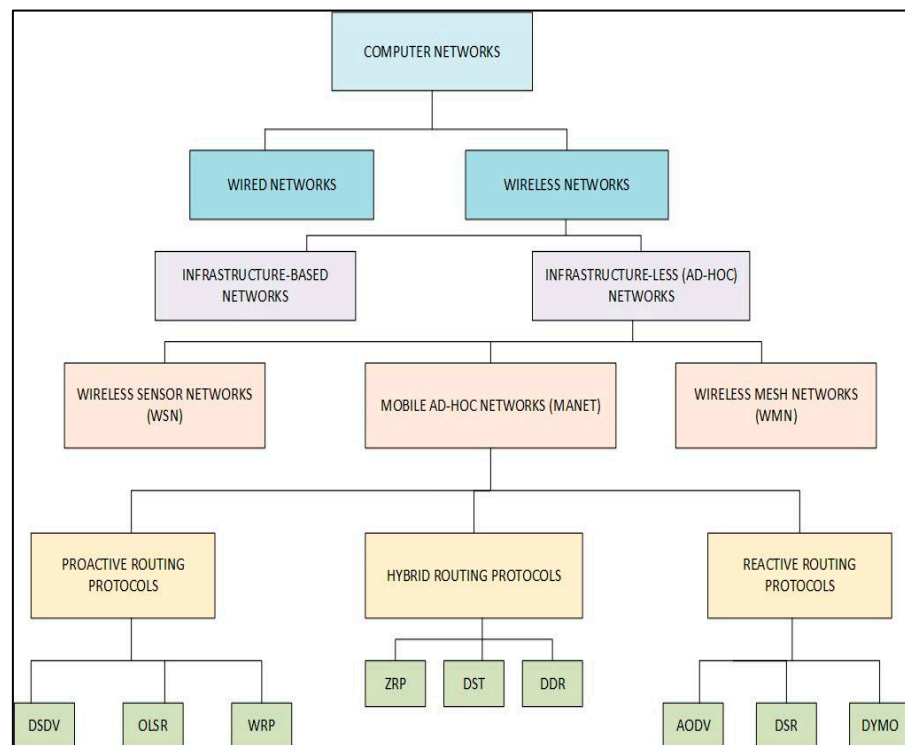


Figure 1. Classification of MANET routing protocols.

- **Reactive (on-demand) routing protocol:** Reactive protocols look to set up routes that are available on-demand. Suppose nodes want to establish a communication channel with a node with no path. In that case, these routing protocols will try to develop a route connecting two nodes to engage in communication [16]. Every node in a reactive routing protocol obtains a route to a destination in an on-demand fashion, which means that a source node demands a path to the destination when it is needed. Reactive protocols do not maintain up-to-date routes to any destination in the network and do not generally exchange periodic control messages. Reactive protocols were designed to reduce the overheads in proactive protocols by maintaining information for active routes only. The performance of the AODV protocol has been a focal point of MANET research, particularly regarding its application in heterogeneous environments. The authors of [27] enhanced the AODV protocol specifically for heterogeneous MANETs, demonstrating that modifications to routing mechanisms can significantly improve network performance. Their findings suggest that adopting AODV to consider node capabilities, such as the transmission rates and mobility patterns, can lead to reduced end-to-end delay and increased throughput.
- **Proactive (table-driven) routing protocol:** Every node in the network has one or more routes to any possible destination in its routing table at any given time. Each node maintains routing information concerning every other node (or nodes located in a specific part) in the network. The emphasis behind proactive protocols is that control messages are exchanged between nodes periodically [28,29]. Messages can be sent to inform and enable nodes to know their local network, exchanging knowledge of the network topology amongst all the nodes within a network. The authors of [30] conducted a comprehensive survey of the routing protocols in MANETs, highlighting the inherent challenges and solutions associated with different protocols. Their study outlines how the dynamic nature of MANETs, characterized by node mobility and varying transmission capabilities, complicates routing decisions. They emphasize that a robust understanding of the operational environment and the characteristics of the nodes is critical to optimizing the protocol performance. The advantage of proactive protocols is that the required routes are immediately available. Still, the downside of this is that the bandwidth suffers due to the flooding of control messages and periodic updates of the network topology amongst the nodes locally.
- **Hybrid routing protocols:** Hybrid routing protocols are a combination of both distance-vector routing and link-state routing. Hybrid protocols aim to work out the kinks that both distance-vector and link-state protocols have by having the ability to choose which protocol is most suitable for use [31,32]. Every node acts reactively in the region close to its proximity and proactively outside that region or zone. Hybrid protocols are a new generation of protocols that are both proactive and reactive in nature. This protocol is designed to increase the scalability by allowing the nodes near each other work together to form a backbone to reduce the route discovery overheads.

2.2. MANET Routing Protocols Considered

In this section, we provide an overview of the four selected MANET routing protocols, including AODV, OLSR, BATMAN, and DYMO.

- **AODV routing protocol:** AODV is a reactive routing protocol that combines with the DSR (dynamic source routing) protocol and is a descendant of the proactive routing protocol DSDV (destination sequence distance vector) [16]. With this protocol, when an active node desires a route to a node that is not active, it broadcasts a route request (RREQ) packet across the network. This is known as the route discovery process—the source node creates a RREQ packet that contains the (i) source and destination IP

addresses; (ii) source and destination sequence numbers; and (iii) broadcast ID number (is initiated each time a source node uses a route request packet). These broadcasts flow across the network through flooding, sending control packets to every node connected except for the source node. This allows for the discovery of available routes. Once one node receives the RREQ packet, an intermediate node (that is not the destination node) may send a route reply (RREP) packet. This packet notifies the source node that they are not the destination node and that it has a route to the destination with the corresponding sequence number. The sequence number may be greater or equal to that contained in the RREQ packet. Once the source receives RREP packets, it forwards the data packets to their original destination. If any node moves, whether the destination node or the intermediate nodes, link failures may result in route error (RERR) messages being sent to other nodes. If a source node moves, then the route discovery process starts again, and we must send new RREQ packets. RERR messages are sent to all the nodes connected within the network and mark the destination route as an invalid route—the distance to destination then becomes infinity in the routing table. If the source node still needs to connect to the route, the route discovery process is re-initiated.

- OLSR protocol: OLSR is a proactive routing protocol, and it reduces the overhead by using multipoint relay (MPRs) nodes that the protocol uses to retransmit the control message and is one of the main features of the OLSR routing protocol [14]. Due to its protective nature, one of the significant advantages of the OLSR protocol is that routes are immediately available when needed. This protocol can be split into three main modules: (i) neighbor/link sensing; (ii) optimized flooding/forwarding (multipoint relaying); and (iii) link-state messaging and route calculation. Using the pure link state protocol causes full flooding of the control packets among the nodes. All the nodes receive the HELLO message and flood it with all their neighbors, and this will lead to an increase in the overhead of the network. Packets are forwarded by hop-by-hop routing—meaning that each node can use the most recent information to route packets. Only nodes selected as MPRs can forward control traffic, thus reducing the size of the original control message [17,18]. Topology control (TC) messages are used along with the forwarding of multipoint relays to disseminate neighbor information throughout the network.
- Link-state routing often requires the topology database to be correctly synchronized across the network, whereas OLSR does not bother with reliability. Instead, it floods the topology data enough to ensure that the topology database does not go unsynchronized for long periods. The primary importance of the OLSR routing protocol is to reduce this flooding of the control packets in the network by application of the MPR technique.
- DYMO routing protocol: The DYMO routing protocol has most recently been developed and is the successor to the AODV routing protocol. It was implemented as an application layer module in the INET framework. The protocol shares and inherits many of AODV's features, such as route discovery, sequence numbers for loop freedom and route error (RERR) messages [7,16]. The protocol aims to have a much simpler design that helps to lower the system requirements from the nodes and simplify its implementation. Path accumulation is another feature that this routing protocol has inherited from the DSR (dynamic source routing) protocol. These accumulated paths provide information that the nodes are processing route discovery packets. From there, these routes that have been discovered are learned and used to route packets. The major difference between DYMO and its predecessor, AODV, is that the latter can only generate route table entries for the destination node and next hop node. DYMO,

on the other hand, stores routes newly discovered for each intermediate hop. What this means, essentially, is that instead of skipping intermediate nodes as AODV does, DYMO learns the routes to discover new paths to the destination nodes.

- **BATMAN protocol:** Due to the shortcomings of OLSR, the BATMAN protocol was introduced [17,18]. The weaknesses included routes regularly going up and down due to routing tables being unnecessarily flushed due to loops. In BATMAN, all the nodes connected broadcast HELLO packets, also known as originator messages, at periodic stages to their neighbors. These messages consist of their unique address and sequence number, and each neighbor changes the sending address to its address and re-broadcasts messages from there. On receiving the message, the originator makes a bidirectional link to confirm that the link detected can be used in both directions [31]. The currency of the message is then checked against the sequence number. This protocol does not maintain the full route to its destination. Instead, each node along the route only maintains information about the next link, which can be used to find the best route. BATMAN's objective is to maximize the probability of delivering a message and it does not attempt to check the quality of each detected link, it just checks to ensure that the link is there. The links are then compared in terms of the total of the originator messages that were received within the current window.

2.3. Related Work

A summary of the related work on heterogeneous MANETs and their routing performance is shown in Table 1.

Table 1. Summary of the related work on MANETs' heterogenous routing protocols.

| Reference | Scope | Routing Algorithm Addressed | Proactive/ Reactive? | Heterogeneous Nodes? | Simulation? |
|-----------|--|-----------------------------|----------------------|----------------------|-------------|
| [15] | Routing protocols and their overheads | AODV, OLSR | Reactive | - | ✓ |
| [26] | On-demand routing | AODV | Reactive | - | ✓ |
| [29] | Periodic control message exchanges | OLSR | Proactive | - | ✓ |
| [28] | Proactive protocols | OLSR | Proactive | - | ✓ |
| [32] | Hybrid protocols | Hybrid | Both | - | ✓ |
| [31] | Scalability in hybrid protocols | Hybrid | Both | - | ✓ |
| [7] | DYMO routing and path accumulation | DYMO | Reactive | - | ✓ |
| [17] | BATMAN protocol and its message delivery | BATMAN | Reactive | - | ✓ |
| [18] | Challenges in OLSR and BATMAN | OLSR, BATMAN | Reactive | - | ✓ |
| [27] | AODV in heterogeneous MANETs | AODV | Reactive | - | ✓ |
| [19] | OLSR and AODV in mobile ad hoc networks | OLSR, AODV | Both | - | ✓ |
| [22] | Surveys MANET routing protocols | General | Both | - | ✓ |
| [24] | Reviews of energy-efficient routing MANETs | General | Both | - | ✓ |
| [23] | Hybrid routing protocols for MANETs | Hybrid | Both | - | ✓ |
| [30] | Routing protocols in MANETs | General | Both | - | ✓ |
| Our work | Performance comparison of AODV, OLSR, BATMAN and DYMO in heterogenous networks | | Both | ✓ | ✓ |

3. Simulation Environment and Settings

OMNeT++ simulation software was used for network modeling and simulation purposes. It is an extensible, modular, component-based C++ simulation library and framework for building network models for performance study [28]. It was chosen for this study due to its modular architecture, extensibility, and robust support for heterogeneous network modeling. Unlike NS-3 and QualNet, OMNeT++ provides a graphical runtime environment and the INET framework, which simplifies the visualization and simulation of complex MANET scenarios. These features make this simulator particularly suitable for evaluating the performance of routing protocols in heterogeneous networks, where nodes with varying capabilities and mobility patterns must be accurately represented. OMNeT++ provides a component architecture for its models. These components are written in the C++ programming language, where the modules' relationships and communication links are then stored as plain-text network description (NED) files. These models can be reused as often as you like since the software is open source for the community of users. Simulations of these network models can be run interactively with the graphical environment or with command-line applications. This application supports GUI extensively, and because of its architecture, the simulation models can be easily embedded into applications. In addition to variations in the mobility and transmission rates, we now incorporate energy consumption and hardware resource constraints into the heterogeneous node model. PDAs, laptops, and mobile phones are assigned different energy capacities, reflecting their real-world power limitations. Similarly, hardware constraints such as the CPU processing power and memory availability are considered to assess their impact on the routing efficiency. These refinements allow for a more realistic evaluation of how resource availability affects MANET routing performance, particularly in scenarios requiring prolonged network operation.

3.1. The INET Framework

The INET framework is an open-source model library for the OMNeT++ simulation environment. It helps to provide network models, various protocols and agents for researchers and students to configure and develop communication networks. The framework is useful for the design and validation of network protocols, as well as the exploration of new and rare networking scenarios. The simulator contains models for the Internet protocol stack (TCP, UDP, IPv4, IPv6, and OSPF), as well as link layer protocols (e.g., Ethernet). There is also support for mobility and MANET routing protocols and other protocols and components. Other simulation frameworks have extended the INET framework further whilst using it as a base to extend in specific directions, such as peer-to-peer networks and LTE (4G).

INET builds on the concept that network modules communicate through message passing (routing). Networks can be built using devices such as hosts (nodes), routers and switches and a network operating system. New networking devices can be developed, but the existing components help users to understand and make it easier to modify certain areas of components. It benefits from the infrastructure that the OMNeT++ simulator provides, and models can be developed, tested, and evaluated from the comfort of the simulation IDE. The command line can also provide the same functionalities as the simulation IDE.

INETMANET has been based on the INET framework, and to this day, it is continuously being developed, which is like the INET framework, except that INETMANET includes additional protocols and components that become useful when developing, testing, and evaluating wireless communication scenarios. OMNeT++ and the INET framework help to provide all the necessary components and models needed for simulating networks and protocols in general. And because of the architecture that OMNeT++ provides, it is

more than suitable for modeling, simulating and implementing sophisticated, complex network protocols.

3.2. Modeling the Network and Mobility Issues

We developed a MANET model with heterogeneous nodes (fixed node, mobile nodes with varying speed/mobility, and transmission ranges) using the OMNeT++ simulation software. Figure 2 shows the network model. Heterogeneous nodes comprise PDAs (fixed nodes), laptops serve as low-mobility nodes, and mobile phones serve as high-mobility nodes. In addition to the random waypoint mobility model, we also evaluated the performance of the routing protocols using the Gauss–Markov mobility model, which provides more realistic node movement patterns. The results obtained with the Gauss–Markov model were consistent with those from the random waypoint model, confirming the robustness of our findings.

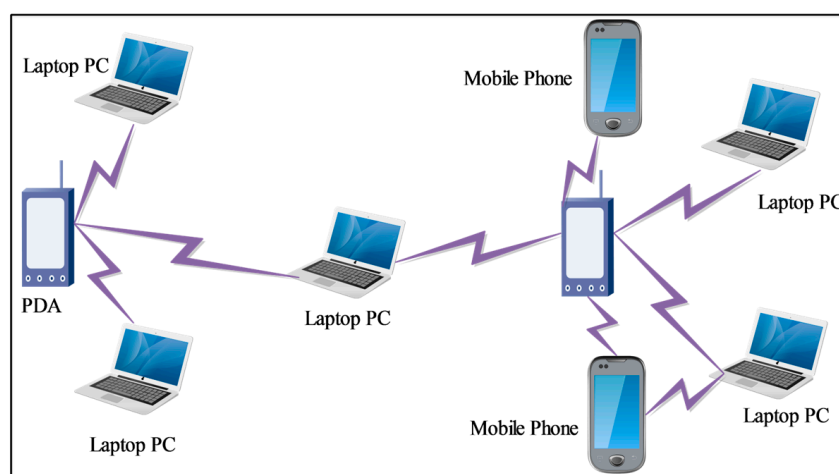


Figure 2. The network model comprises PDAs, laptops, and mobile phones.

As MANET routing protocols must cope with a wide range of network topologies, evaluations are only often performed when there is random waypoint mobility. The issue with this is that worst-case scenarios are not covered for these networks. The random topology that we applied involves the nodes being placed at random in a simulation grid and indicates how protocols may perform in an average scenario run. The density of the network also has an impact on the routing performance, as shown in the results we produced. As the distance between communicating nodes grew, it was evident that there were such latencies in the network, especially with message forwarding.

Mobility significantly impacts simulation outcomes, and one key insight from our study is that the random waypoint mobility model, while widely used, can lead to inaccuracies in results due to its simplistic assumptions. Despite these limitations, we simulated various scenarios using different routing protocols to evaluate the performance of the developed network. The results from these simulations were then analyzed to compare the network performance and assess the impact of varying configurations and parameters.

3.3. Simulation Parameter Settings

The parameter settings for our simulations remain the same across all four routing protocols. This ensures that comparisons of these routing protocols can be made adequately and accurately. We set the simulation parameters up and configure the network appropriately. To study the impact of heterogeneity on system performance, we consider the mobility of various node types, data transmission speed, and transmission ranges of all the nodes in the network. The following nodes are considered in this study.

- Fixed PDAs (no mobility).
- Laptops (low mobility), speed ranging from 1 to 2 Mbps.
- Mobile phones (high mobility), speed from 10 to 15 Mbps
- Radio transmission ranges of all the nodes in the network (2 to 5 mW).

3.4. Performance Metrics

To study the performance of the four selected MANET routing protocols in heterogeneous networks, we considered the following three performance metrics, including the throughput, end-to-end delay, and packet delivery ratio, which were appropriate for our investigation. The simulation model we created can record several statistics, such as the number of packets being routed and delivered over a given period and the latencies in message forwarding. The throughput is measured in bits per second and is the total number of packets delivered to the receiver. The end-to-end delay (in sec) is the average time that a packet takes from a source node to the destination. The packet delivery ratio is a performance metric that measures the ratio of packets received to those generated by their sources.

3.5. Simulation Control and Setup

The simulation setup is the same, with all four selected routing protocols being tested, for comparison between each protocol, given various constraints and parameter conditions. These conditions include the mobility of nodes, fixed or mobile, and the radio transmission ranges. Because each network must be heterogeneous, each node must be configured differently in each scenario. By configuring the mobility speeds of each node and their transmission ranges, we could achieve the heterogeneity of the nodes. To ensure the reliability of the simulation results, a warm-up period of 100 s was included at the start of each simulation run. This allowed the random number generator to stabilize, ensuring that the results were not affected by transient initial conditions. To evaluate the impact of the node density on the protocol performance, we conducted additional simulations with varying numbers of nodes (ranging from 12 to 50). The initial placement of the nodes was determined by the simulator using a uniform random distribution within the simulation area. This approach ensured that the results were not biased by manual intervention and provided insights into the scalability of the routing protocols. Table 2 lists the parameters used in the simulation.

Table 2. Parameters used in the simulation.

| Parameter | Value |
|-----------------------|--|
| Number of nodes | 2 PDA (fixed node), 5 laptops, and 5 mobile phones |
| Node type | PDA (fixed); mobile hosts: 10 to 15 Mbps; laptops: 1 to 2 Mbps |
| Simulation time | 600 s |
| Simulation trajectory | 600 × 600 m |
| Routing protocols | AODV, OLSR, BATMAN, DYMO |
| MAC protocol | IEEE 802.11 g; 2.4 GHz |
| Mobility type | Random waypoint mobility |
| Mobility waiting time | 0.1 sec (default) |
| Communication port | UDP |
| Transmitter power | 2 to 5 mW (milliwatts) |
| Bitrate | 54 Mbps |

4. Results and Discussion

4.1. Delay Performance

These graphs illustrate the results that are gathered in part from the OMNeT++ simulation tool. Each simulation is recorded, along with the events that took place during the running of a simulation. We measure the end-to-end delays of the mobile nodes over the amount of latency in the sending/receiving packets.

The effect of various mobile node types on the end-to-end delays for the AODV routing protocol is shown in Figure 3. As the simulation progresses, the packet delays decrease, indicating improved route stability and efficiency. The performance variations among the heterogeneous nodes highlight the challenges in maintaining low latency in dynamic network conditions. AODV exhibits higher delays in high-mobility scenarios due to its reactive route discovery process. The blue line represents a mobile node that experiences significant delays until it moves within the transmission range of the gateway.

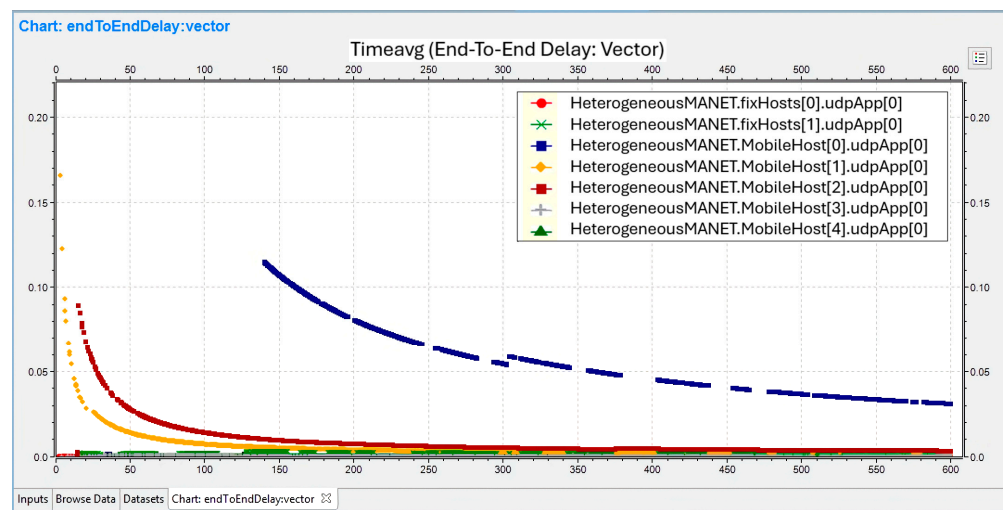


Figure 3. End-to-end delays for the AODV routing protocol.

The effect of various node types on the end-to-end delays for the BATMAN routing protocol is shown in Figure 4. Throughout the simulation, the delays tend to stabilize, reflecting the protocol’s proficiency in handling dynamic network conditions. The performance uniformity observed among the heterogeneous nodes highlights BATMAN’s ability to sustain low latency in diverse operational environments.

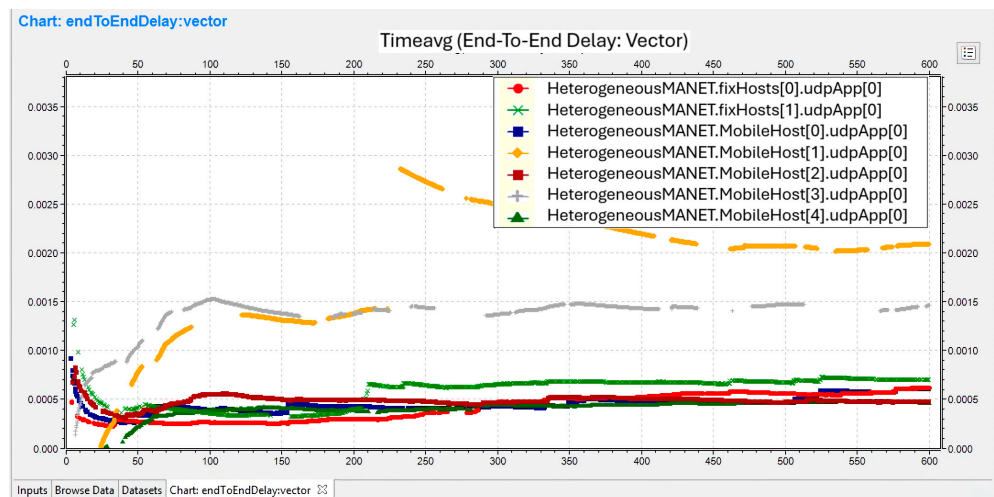


Figure 4. End-to-end delays for the BATMAN routing protocol.

The impact of the node types on the end-to-end delays for the DYMO routing protocol is shown in Figure 5. As the simulation advances, the packet delays experience a rapid decrease, indicating the protocol’s efficiency in establishing stable communication paths. The consistent performance across the heterogeneous nodes underscores DYMO’s effectiveness in maintaining minimal latency within dynamic networking scenarios.

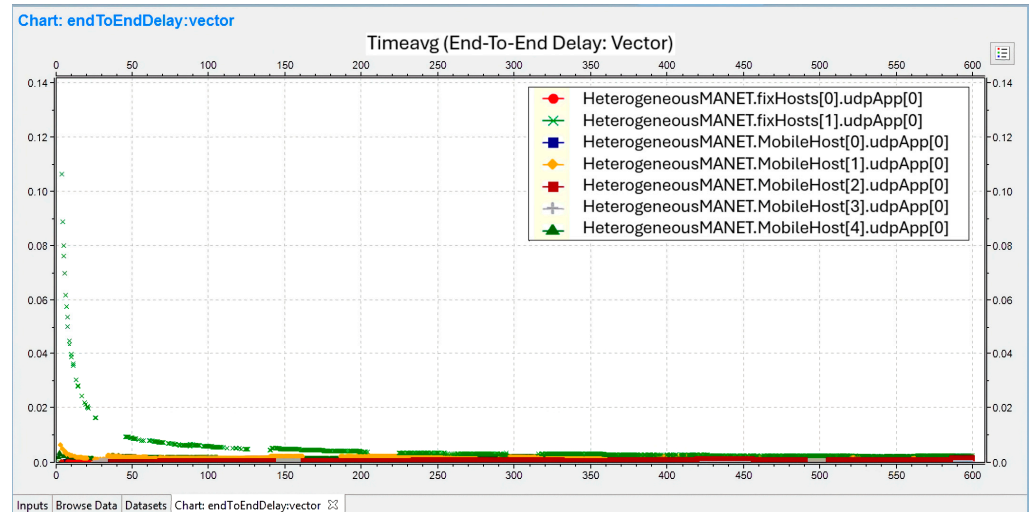


Figure 5. End-to-end delays for the DYMO routing protocol.

The effect of various node types on the end-to-end delays for the OLSR routing protocol is depicted in Figure 6. Throughout the simulation, the delays exhibit a gradual increase and eventual stabilization, illustrating the protocol’s ability to maintain consistent communication despite the mobility of the nodes. The performance differences among the heterogeneous nodes highlight OLSR’s strengths in managing routing efficiency in dynamic environments.

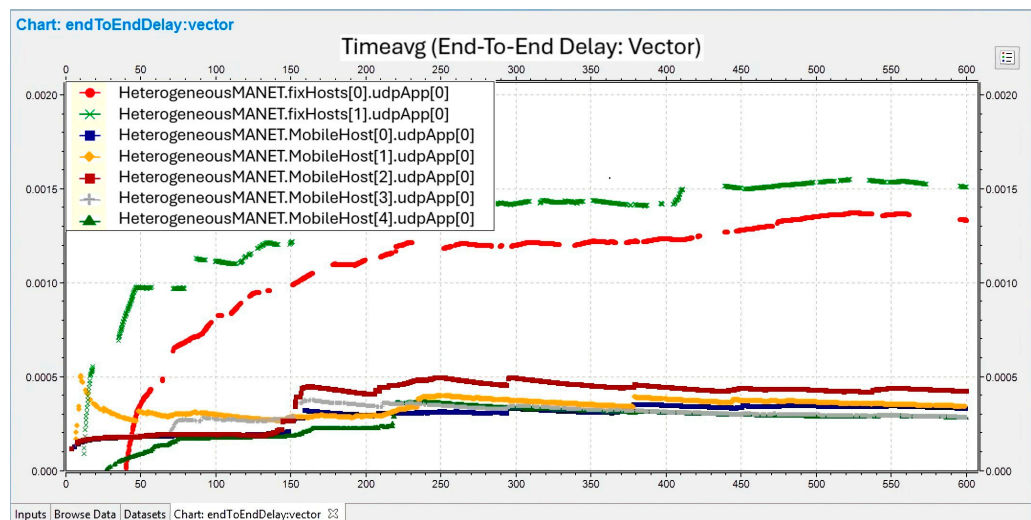


Figure 6. End-to-end delays for the OLSR routing protocol.

The superior performance of DYMO in terms of the end-to-end delay can be attributed to its hybrid approach, which combines the strengths of proactive and reactive routing. Unlike OLSR, which floods the network with periodic control messages, DYMO dynamically adapts to network conditions, reducing the route discovery time and minimizing the latency. Similarly, AODV’s reactive nature results in longer delays during route discovery, particu-

larly in high-mobility scenarios. BATMAN, while proactive, suffers from control overhead, leading to increased delays as the node mobility fluctuates. These insights highlight the importance of protocol design in addressing the challenges of heterogeneous networks.

4.2. Throughput Performance

In this section, we present the throughput results for all four MANET routing protocols that we considered in this study. The impact of various node types (PDAs, laptops, and mobile phones) on the system performance is also discussed and the results are presented.

4.2.1. Node Throughput for AODV Routing Protocol

To evaluate whether the observed differences in the protocol performance metrics are statistically significant, we conducted an ANOVA test at a 95% confidence interval. The results indicate that the protocol selection has a statistically significant impact on the throughput ($p < 0.05$), end-to-end delay ($p < 0.01$), and packet delivery ratio ($p < 0.05$). This analysis confirms that the performance variations observed in our simulations are not random fluctuations but meaningful differences attributable to the design and behavior of the routing protocols under study. By incorporating statistical testing, we ensure that our conclusions are robust and applicable to real-world MANET deployments. The throughput performance of the laptop nodes utilizing the AODV routing protocol is illustrated in Figure 7. Throughout the simulation, the throughput stabilizes at approximately 1000 kbps, demonstrating the protocol's capacity to efficiently manage data transmission across heterogeneous nodes. The consistent performance across different laptop hosts highlights AODV's effectiveness in maintaining robust communication in varied network conditions.

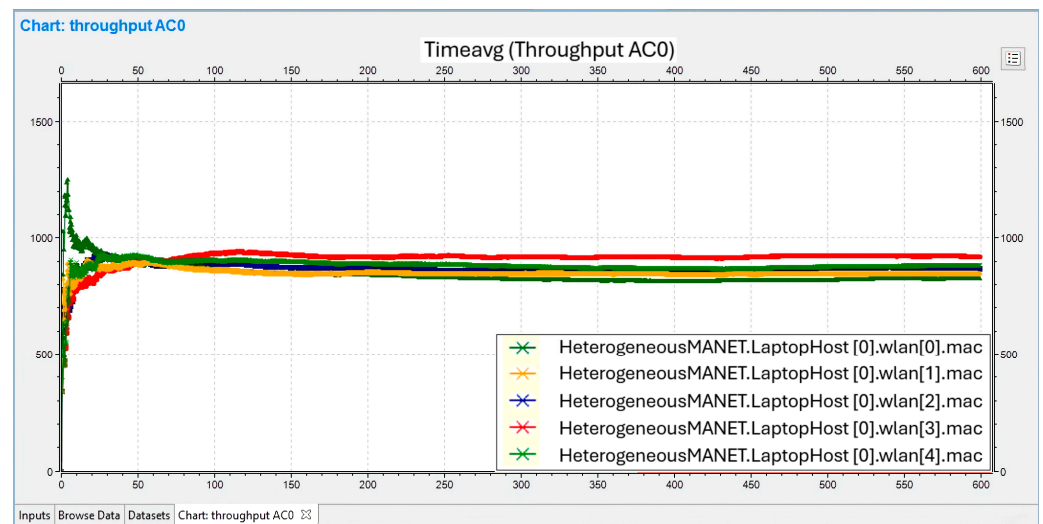


Figure 7. AODV's throughput for laptop nodes.

The throughput behavior of the mobile nodes for the AODV routing protocol is shown in Figure 8. The graph shows a gradual increase in throughput over time, eventually stabilizing between 30,000 and 40,000 kbps for most nodes. The variations in performance across the different nodes reflect the protocol's ability to manage varying mobility patterns and network dynamics, demonstrating its effectiveness in maintaining high throughput under heterogeneous conditions.

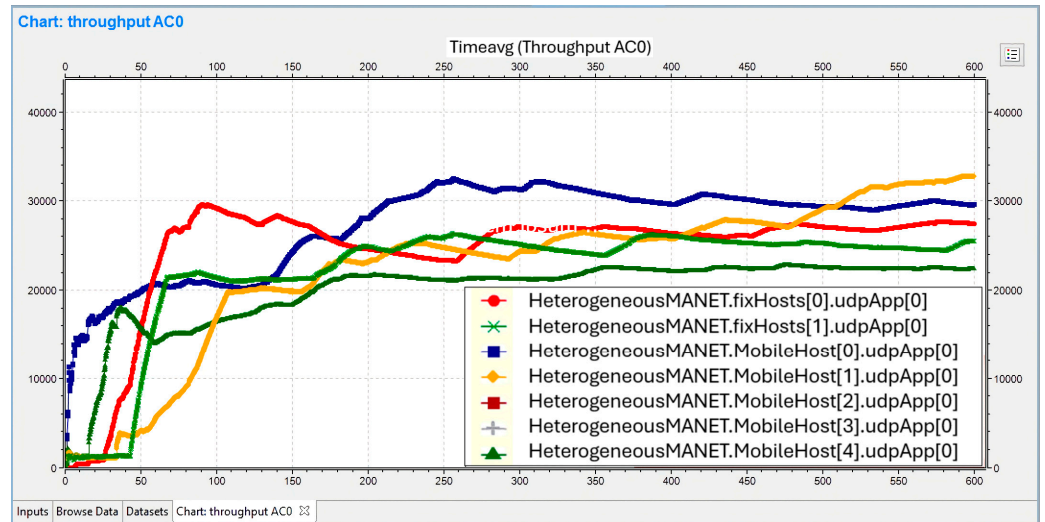


Figure 8. AODV’s throughput for mobile nodes.

AODV’s throughput performance for fixed nodes is shown in Figure 9. Throughout the simulation, the throughput shows a steady increase, eventually reaching approximately 20,000 kbps for both fixed nodes. The higher throughput for Node 0 compared to Node 1 indicates the influence of the individual node positioning or link quality, emphasizing the importance of network topology in static MANET environments.

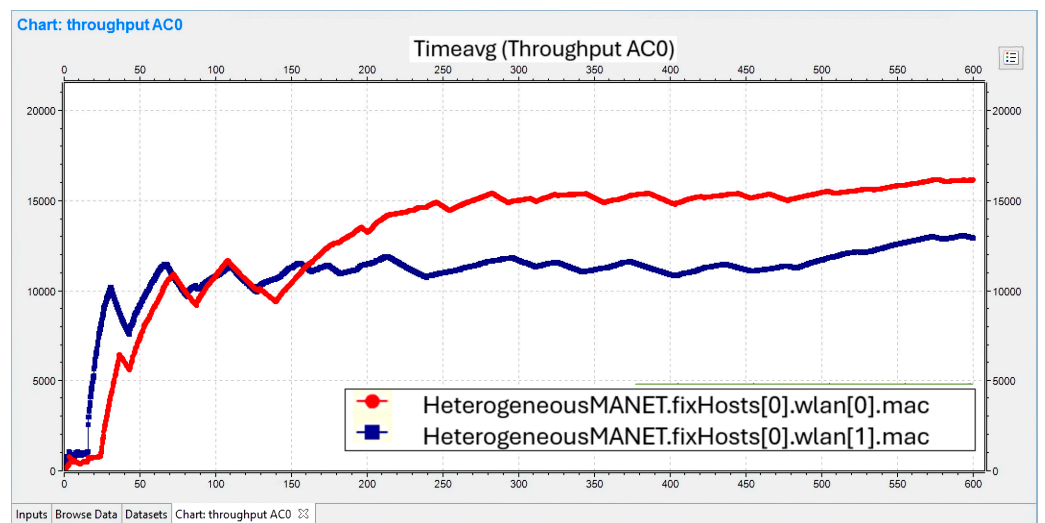


Figure 9. AODV’s throughput for fixed nodes.

4.2.2. Node Throughput for BATMAN Routing Protocol

Figure 10 shows the throughput performance of the laptop nodes for the BATMAN routing protocol. Throughout the simulation, the throughput stabilizes after an initial period of fluctuation, with all the nodes converging to similar throughput values around 500–1000 kbps. The close alignment of the throughput across the heterogeneous laptop nodes suggests effective load balancing and efficient routing across the network.

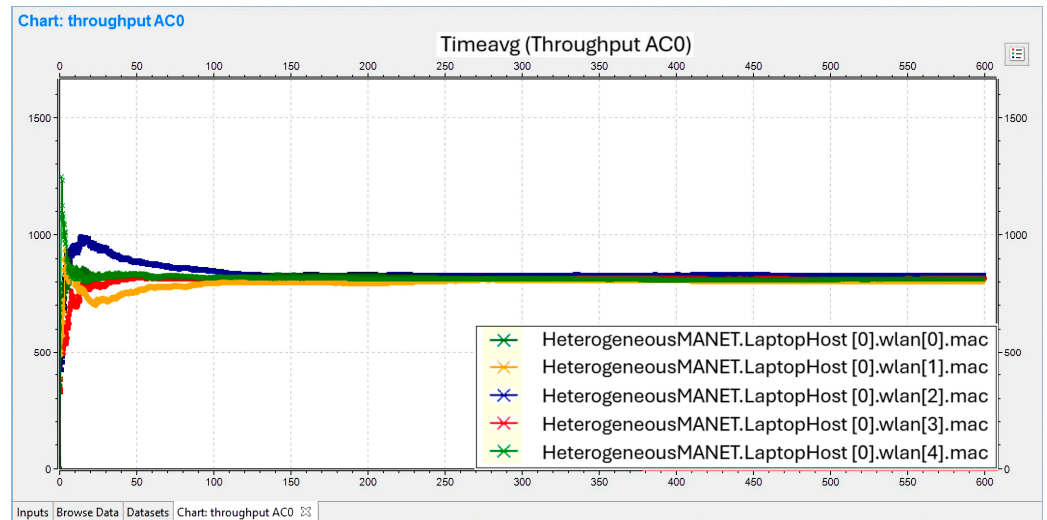


Figure 10. BATMAN’s throughput for laptop nodes (low mobility).

Figure 11 shows the throughput performance of the fixed nodes for the BATMAN routing protocol. The red and blue lines depict distinct fixed nodes, showcasing variations in throughput across the simulation time. Node 0 consistently maintains higher throughput compared to Node 1, with peaks exceeding 60,000 kbps. This contrast demonstrates the differential load distribution and routing efficiency, highlighting BATMAN’s ability to adapt to network conditions, although some performance disparities between nodes are evident.

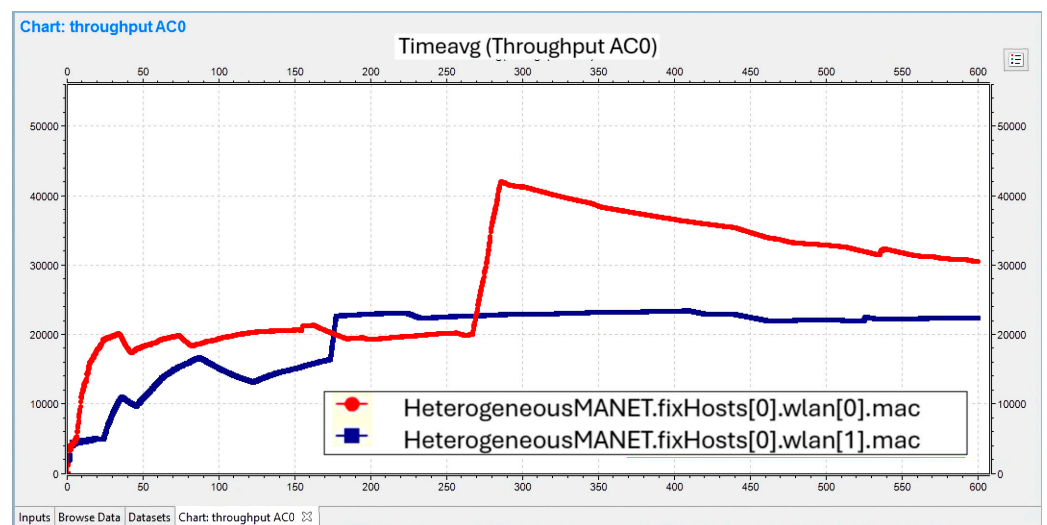


Figure 11. BATMAN’s throughput for fixed nodes.

Figure 12 illustrates the throughput performance of the mobile nodes for the BATMAN routing protocol. The data reveal variations in throughput across five different mobile hosts, with some hosts achieving peaks of nearly 60,000 kbps during the simulation period. These differences underscore the impact of mobility and node heterogeneity on the overall network performance, where frequent changes in the node positions influence the BATMAN protocol’s adaptive capabilities in managing route discovery and data transmission.

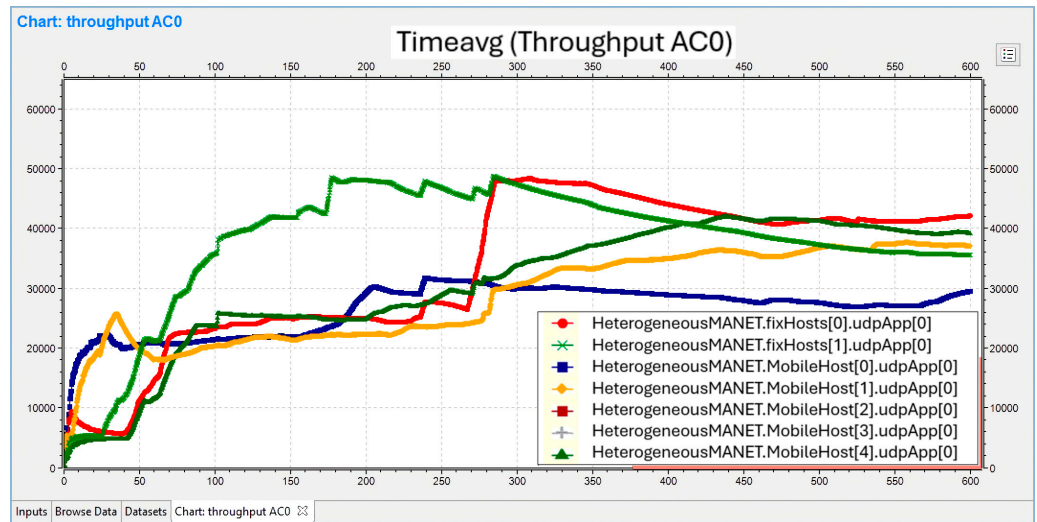


Figure 12. BATMAN’s throughput for mobile nodes.

4.2.3. Node Throughput for DYMO Routing Protocol

The node throughput performances of DYMO are illustrated through Figures 13–15. The effect of the laptop nodes (low mobility) on the throughput performance for the DYMO routing protocol is shown in Figure 13. The throughput shows significant variation in the early stages of the simulation but stabilizes after approximately 100 s. This stabilization indicates that DYMO effectively manages route discovery and traffic forwarding after the initial route setup, leading to consistent performance across all the laptop nodes, regardless of the network topology changes.

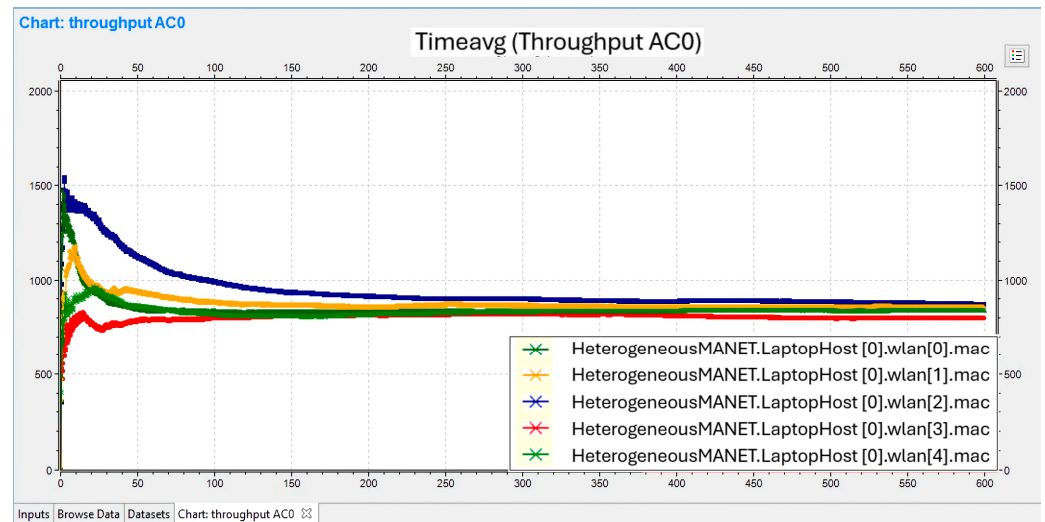


Figure 13. DYMO’s throughput for laptop nodes.

The effect of the mobile nodes on the throughput performance of the DYMO routing protocol is shown in Figure 14. The graph shows a significant increase in throughput as the simulation progresses, particularly between 50 and 200 s, where the network stabilizes. The variance in throughput across the different mobile hosts is reflected in the varying mobility levels and traffic loads within the network. After 200 s, the throughput becomes more stable, indicating effective route management by DYMO in dynamic conditions, although slight fluctuations can still be observed toward the end of the simulation.

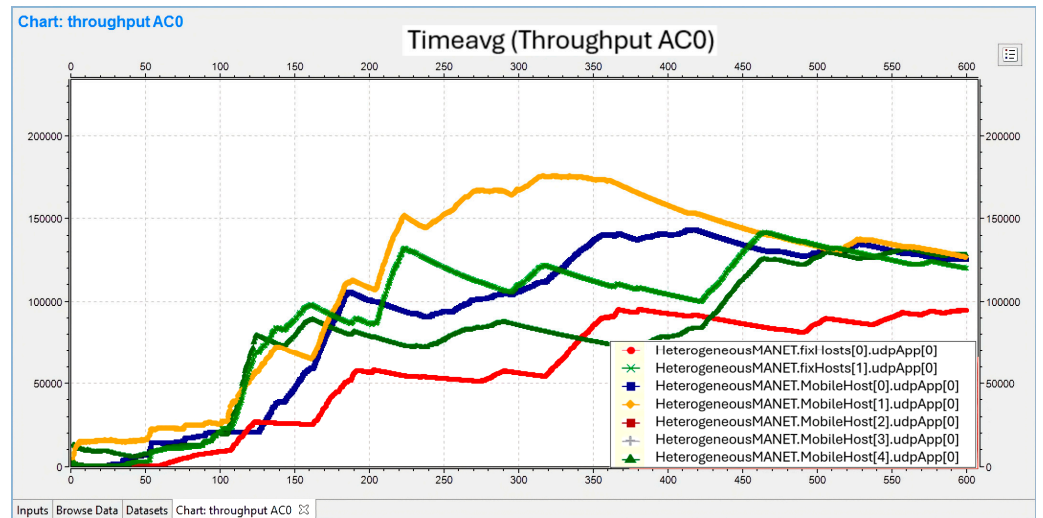


Figure 14. DYMO’s throughput for mobile nodes.

The effect of the fixed nodes on DYMO’s throughput is shown in Figure 15. The blue node exhibits significantly higher throughput compared to the red node, stabilizing after approximately 150 s. This result emphasizes DYMO’s capacity to maintain efficient routing for fixed nodes under heterogeneous conditions. In summary, DYMO maintains stable throughput even as the node mobility increases, unlike AODV. It outperforms the other protocols in delay and throughput, making it ideal for networks where devices move unpredictably.

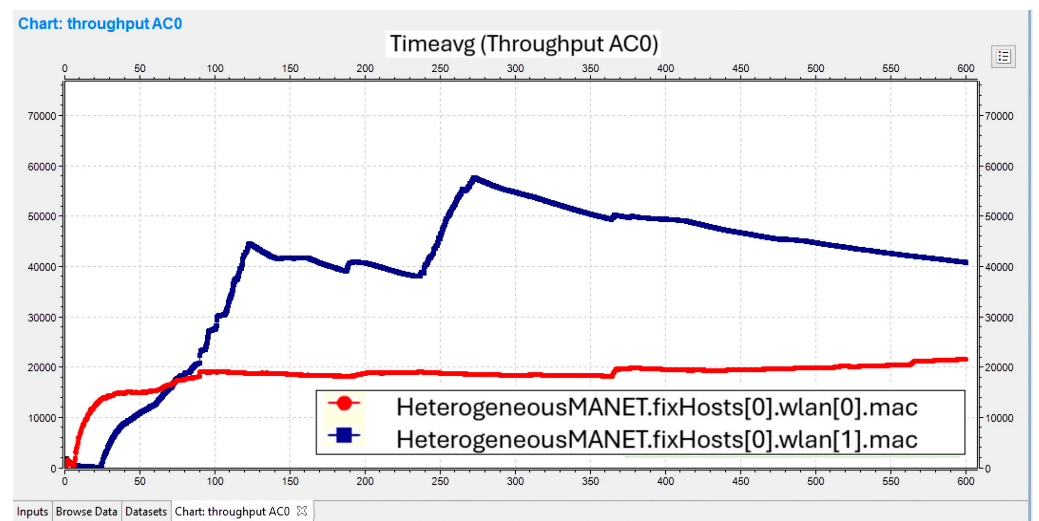


Figure 15. DYMO’s throughput for fixed nodes.

4.2.4. Node Throughput for OLSR Routing Protocol

Figure 16 shows the throughput performance of the laptop nodes for the OLSR routing protocol. The throughput stabilizes after the initial fluctuations, maintaining a steady rate around 800–1000 kbps across all the nodes. The OLSR protocol ensures consistent performance by leveraging its proactive nature, which helps sustain optimal throughput levels even in dynamic network conditions.

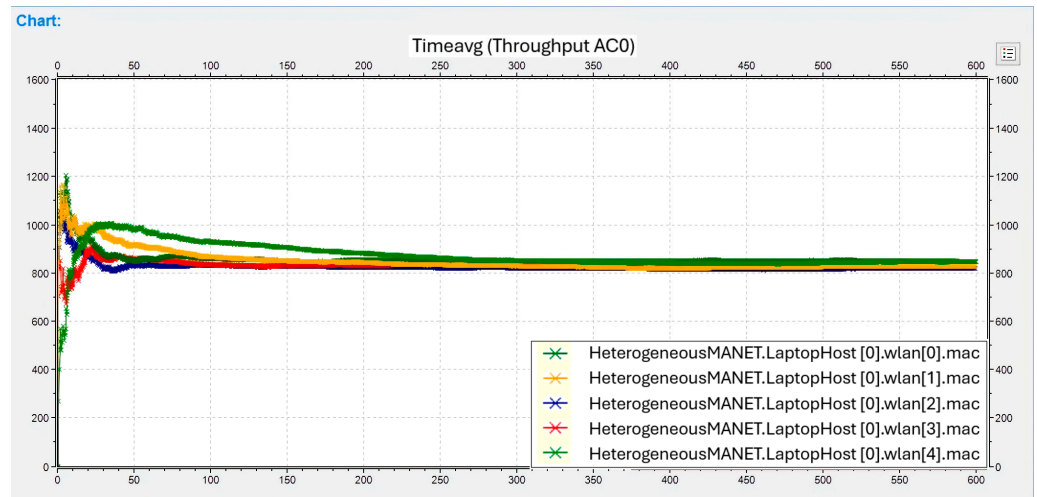


Figure 16. OLSR’s throughput for laptop nodes.

The effect of the fixed nodes on the throughput performance of the OLSR routing protocol is shown in Figure 17. The throughput steadily increases as the simulation progresses, reflecting the proactive nature of the OLSR protocol, which maintains routing information consistently. The fixed nodes exhibit a stable upward trend in throughput, indicating efficient data transmission over time, with minimal fluctuations.

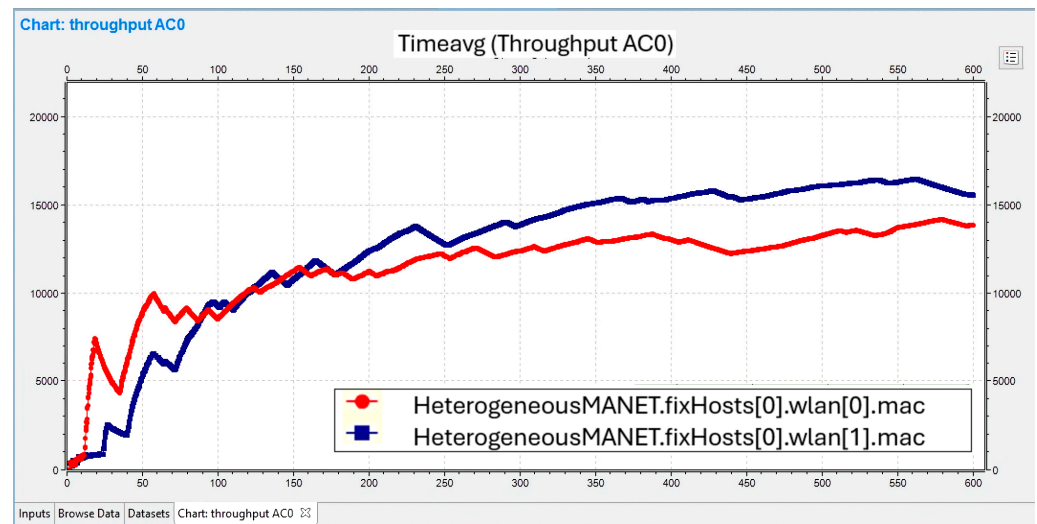


Figure 17. OLSR’s throughput for fixed nodes.

The effect of the mobile nodes on the performance of the OLSR routing protocol is shown in Figure 18. Throughout the simulation, there is a steady increase in throughput for the mobile nodes, although there are some fluctuations because of dynamic changes in the network topology. OLSR’s proactive nature helps to maintain relatively consistent throughput, despite the mobility of the nodes, reflecting its efficiency in routing updates and maintaining network stability.

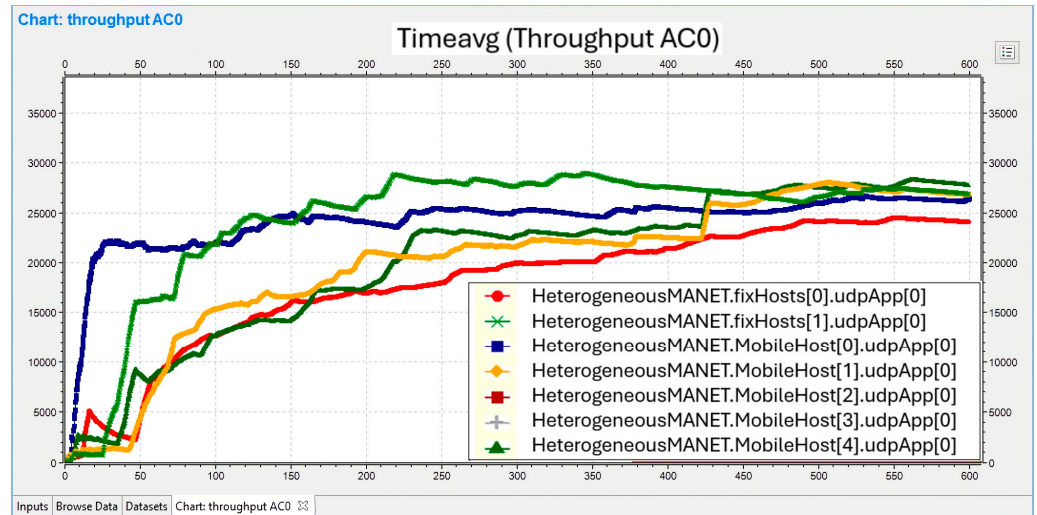


Figure 18. OLSR’s throughput for mobile nodes.

4.3. Packet Delivery Ratio

In this section, we present the packet delivery ratio (PDR) performance for all four MANET routing protocols that we considered in this study. The PDR is defined as the ratio of the number of packets successfully delivered to the destination to the total number of packets sent by the source. The UDP packet size was set to 512 bytes. Packet loss was primarily caused by wireless loss, which was modeled using a combination of free-space path loss and Rician fading to account for the mobility of the nodes. The buffer overflow was minimized by setting the buffer size to 64 KB per node. Figure 19 shows the PDR for the AODV routing protocol across various node types, including both fixed and mobile nodes. The chart highlights the consistency of the PDR between the sent and received packets for mobile hosts compared to fixed hosts, with only minor variations observed. AODV performs well in terms of maintaining a high PDR, particularly for mobile nodes, emphasizing its effectiveness in dynamic network environments.

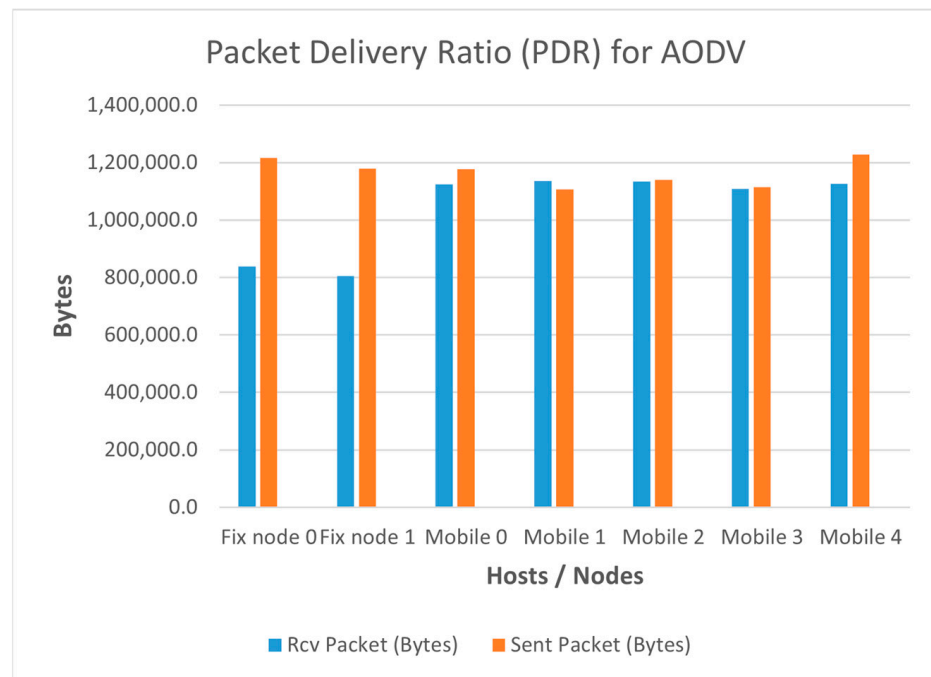


Figure 19. Packet delivery ratio for AODV.

Figure 20 focuses on the PDR for the BATMAN routing protocol. As with AODV, the mobile nodes generally show a slightly better PDR compared to the fixed nodes. However, the differences between the fixed and mobile nodes are more pronounced in the case of BATMAN, with the mobile nodes consistently achieving higher sent and received packet values. This result emphasizes the effectiveness of BATMAN’s approach in managing packet delivery for varying mobility conditions, with the mobile nodes being better equipped to handle dynamic topology changes. Despite this, the overall PDR remains consistent across both the fixed and mobile nodes, highlighting BATMAN’s robustness in diverse environments.

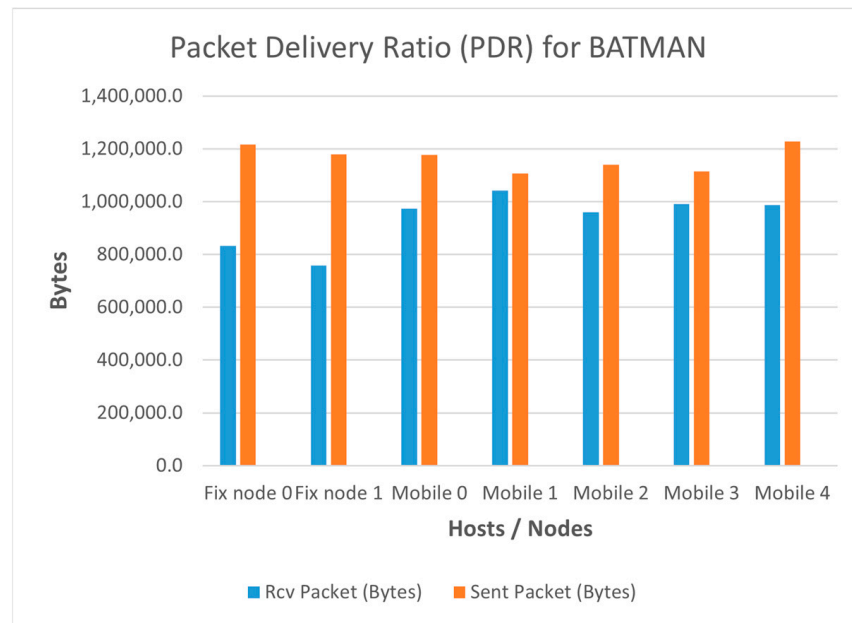


Figure 20. Packet delivery ratio for BATMAN.

Figure 21 shows the PDR for DYMO for various node types. The PDR is relatively consistent across both the fixed and mobile nodes, showing minimal variance in the sent and received packets. This indicates the reliability and efficiency of DYMO in maintaining data delivery across diverse network configurations.

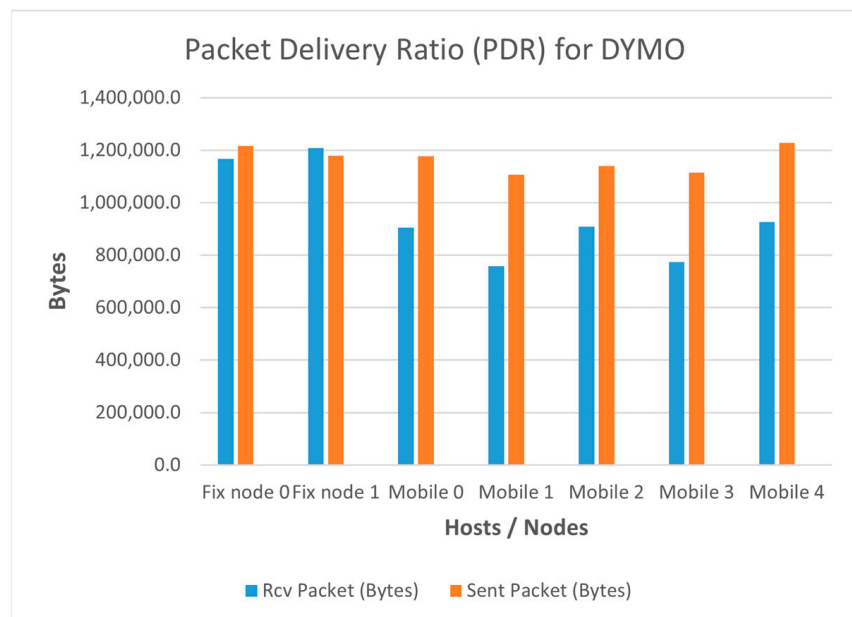


Figure 21. Packet delivery ratio for DYMO.

Figure 22 illustrates the PDR for OLSR across various fixed and mobile nodes. The graph shows a stable PDR with minor variations between the sent and received packets for the different nodes, indicating OLSR's efficiency in maintaining reliable packet delivery across the network, especially for mobile hosts.

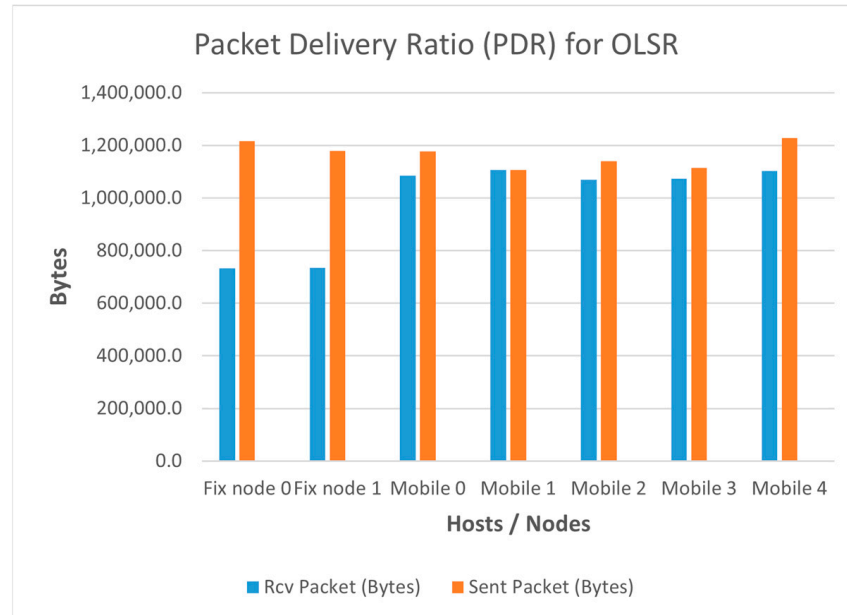


Figure 22. Packet delivery ratio for OLSR.

4.4. Model Validation

To gain confidence in the simulation outcomes, the simulation models must be validated to ensure that the results are valid with statistical accuracy. All the results presented in this paper are obtained with a 95% confidence interval and $\leq 5\%$ statistical errors. We validate the simulation model in the following ways. We first ensure that the OMNeT++ simulation parameters and configuration are working for $N = 2$ nodes. We also check the log files to ensure that there are no runtime errors. Second, all the assumptions, representations, and relationships are checked. Finally, the model is validated in terms of how it reacts to its inputs and the model's output behaviors [19]. We also validate our simulation model using the following methods.

- Animation—simulating the average speed yielded information about the types of messages being sent across the network—contents, their sources, and destinations.
- Parameter variability and sensitivity analysis—systematically varying the simulation parameters and analyzing the impact that they have on the outputs (results).
- Face validity—seeking advice and opinions from experts to see whether a model concept is acceptable and reasonable to use for simulation.

The adopted validation techniques not only help us in developing and building a network model that is appropriate and near accurate but also improve the quality of the simulation results, which makes analysis and evaluations of results more meaningful.

5. Summary of Research Findings and Practical Implications

There has been increasing research on mobile ad hoc networks (MANETs) and performance evaluation is performed by network simulators. A considerable number of studies show the importance of MANETs in critical emergencies. MANETs are wireless networks where the nodes are mobile constantly, and their infrastructures have no central routing resources in place. The nodes in heterogeneous MANETs have different resources and

capabilities for each node within the network. Heterogeneous MANETs have rarely been explored through network simulation tools, so this work helps to shed some light on the functionalities of heterogeneous networks. In this work, we analyze and compare four MANET routing protocols—AODV, OLSR, BATMAN, and DYMO—in a heterogeneous network environment. The simulations and evaluations of these protocols are conducted using the OMNeT++ simulator. The results are summarized next.

- *End-to-end delay performance*

We have one abnormality that occurs during the test of AODV, which is the blue line. This is a mobile node. It does not follow the same arc as the other mobile hosts. We believe this to be because it was further away from the gateway and could not communicate with the gateway until it moved into range. We set the playground size for all these tests to 1 km.

AODV reacted well, though, with its fixed nodes. The end-to-end delay was minuscule compared to the mobile hosts, which had a more significant delay in a talk at the beginning of the scenario. This could be due to AODV being a reactive protocol. DYMO is a hybrid protocol that can use both proactive and reactive routing protocols. For evaluating end-to-end delays, it would produce good results as it should be able to figure out what protocol is the best for this simulation.

As we hypothesized, the graphs for DYMO show that it has a rapid connection time between end-to-end connections. The static hosts are extra fast yet again, followed closely by the mobile hosts. All the nodes stay below 0.02 except one mobile host, which initially takes a long time to send and receive the packets. As seen in the graph above, OLSR has terrible end-to-end delays. Both the mobile and fixed hosts have had the same problem. We believe this is due to the proactive nature of OLSR, causing the network to be flooded with control messages, which causes a more significant delay.

BATMAN is a proactive routing protocol as well. It has been simulated with the same sort of results as OLSR. The network is flooded with so many control packets that it has slowed the network down. Two of the mobile hosts are intermittent because at 240 s into the simulation, this mobile host has moved to the edge of its transmission range. It also explains why it slowly increases and then comes back down. Since these hosts are not set to move in any set pattern, it has moved outside the range for a second and come back in at 260 s, so for 20 s, we have lost communication with this node.

- *Throughput performance*

The DYMO and BATMAN fixed nodes proved to have a higher throughput rate than that of their predecessors, which is not surprising considering that both protocols share reactive and proactive routing capabilities. BATMAN's fixed nodes proved to have more packets delivered than the rest, whilst AODV and OLSR managed to deliver the most miniature packets. The same was the case with the mobile nodes. DYMO proved to have a better throughput rate in its mobile nodes than the other routing protocols. BATMAN had more of a variance in results than the rest of the protocols, particularly the spike in packet throughput midway through running the simulation. This happened with the fixed nodes and could only come down to the significance of the distance between the two nodes. Since there is high throughput, the nodes must be near each other in space.

The laptop nodes for all the protocols proved stable on all the accounts, and all had similar throughput of packets across the board, which was surprising considering we thought there would be more of a variance in the results.

- *Packet delivery ratio performance*

The graphs show how many packets are being sent and received in bytes for each routing protocol. The result indicates that each protocol is nearly identical, and there is

not much gap difference in the ratios. This result is based on running a mobility scenario with two fixed hosts, five mobiles and five laptops, with a simulation time limit of 600 s (10 min), random mobility in an area 600×600 m, and random nodes in every protocol. As you can see, the laptop nodes are not included in the graph because the configuration parameters are not correctly configured. Therefore, AODV has the most significant packet delivery ratio amongst the other protocols in the mobility scenario, which means AODV has the most successful rate when delivering packets to the destination.

5.1. Real-World Implications

The findings of this study have significant implications for real-world applications, particularly in scenarios where heterogeneous networks are essential. For instance, DYMO's superior performance in handling mixed-device networks makes it a strong candidate for disaster recovery operations, where communication between devices with varying capabilities (e.g., drones, smartphones, and laptops) is critical. Similarly, in military field operations, DYMO's ability to maintain low latency and high throughput under dynamic conditions could enhance mission-critical communication. Furthermore, the protocol's adaptability to varying node mobility and transmission rates makes it suitable for IoT deployments in smart cities, where devices with diverse energy and computational capabilities must interact seamlessly. These real-world applications underscore the practical relevance of our findings and highlight the potential for DYMO to address communication challenges in heterogeneous environments.

5.2. Limitations

While this study provides valuable insights into the performance of MANET routing protocols in heterogeneous networks, it is important to acknowledge its limitations. First, our simulations were conducted with a relatively small number of nodes (two PDAs, five laptops, and five mobile phones). The scalability of DYMO and other protocols in larger networks (e.g., 1000+ nodes) remains untested and warrants further investigation. Second, real-world factors such as urban Wi-Fi congestion, signal interference, and energy constraints were not fully accounted for in our simulations. Moreover, our study focused on small to medium-sized networks, so the scalability of DYMO in large-scale deployments (e.g., smart cities with 500+ IoT devices) remains an open question. Future work should evaluate the protocol performance in such scenarios to assess its suitability for real-world applications. These factors could significantly impact the protocol performance in practical deployments. Finally, this study focused on a specific set of mobility and transmission parameters, which may not fully capture the variability of real-world scenarios. Future work should explore these limitations to provide a more comprehensive understanding of the protocol performance in large-scale, real-world environments.

6. Conclusions and Future Directions

In this paper, we studied and compared the performance of four selected routing protocols—AODV, OLSR, BATMAN and DYMO—in a heterogeneous MANET network setting comprising nodes with varying capabilities, including fixed, mobility, data transmission rates, and power consumption. The system performance was evaluated by an extensive OMNeT++-based simulation model. We measured QoS parameters such as the packet delays, throughput, and packet delivery ratios. Our research findings are discussed below.

Of the four routing protocols we studied, DYMO was the best-performing routing protocol in heterogeneous network environments with fixed as well as mobile nodes. Across all three performance metrics (i.e., delay, throughput, and packet drop ratio) that we evaluated, DYMO achieved lower delays, higher throughputs, and higher packet delivery

ratios. AODV proved to be stable with respect to packet delays, but DYMO performed much better. This establishes that reactive and hybrid protocols demonstrate the capability of handling delays much better than proactive protocols do. We observed that DYMO was more efficient in achieving higher throughputs than the other three routing protocols as it delivered more packets over the network. Therefore, it is recommended that the DYMO routing protocol would be the best one to use in heterogeneous networks. Developing a new technique to improve the performance of multi-hop routing for post-disaster recovery in MANETs is suggested as one of the future works. This study also opened up several avenues for future research. First, machine learning techniques could be integrated into DYMO to fine-tune the routing decisions in real time, further enhancing its performance in dynamic environments. Second, the performance of these protocols in 5G-integrated MANETs should be evaluated to assess their compatibility with next-generation wireless technologies. Finally, the security vulnerabilities introduced by heterogeneous nodes in IoT deployments must be addressed to ensure robust and reliable communication. These directions will contribute to the development of more efficient and resilient MANETs for real-world applications.

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