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Scalability and Reliability Analysis of Routing Techniques in Mobile Ad Hoc Networks

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Abstract: Mobile ad hoc networks (MANETs), with no infrastructure, changing topology and self-configuration capabilities, have created a new paradigm in wireless communication. The routing of data packets in a MANET environment is challenging, as there are constant changes to the topology, limited bandwidth, movement of nodes and energy limitations. This study provides a comprehensive analysis of the effectiveness, scalability and reliability of various routing techniques commonly used in MANETs under different network conditions. Through the use of performance metrics, such as packet delivery ratio, end-to-end delay, throughput, routing overhead and network reliability, the study compares the behaviour of proactive, reactive and hybrid routing protocols. The simulation of a MANET was accomplished by varying node density, mobility patterns and traffic loads, to assess protocol performance under highly dynamic and large-scale network conditions. The results demonstrate that routing protocol performance is significantly impacted by network scalability and mobility. Reactive protocols are more adaptable to changes in a dynamic network, whereas proactive protocols provide lower latency in stable networks. Hybrid routing protocols provide balanced performance as they increase scalability and reliability of communication. The results of this study contribute to identifying the most effective routing strategies for next generation wireless ad hoc communication systems, and assist in developing reliable MANET applications for disaster recovery, military communications, intelligent transportation and IoT enabled environments.

Keywords: Routing Protocols, Scalability Analysis, Network Reliability, Reactive Routing, Proactive Routing, Hybrid Routing, Packet Delivery Ratio.

I. INTRODUCTION

The evolution of wireless technology has completely changed the way we communicate using digital channels; providing users with ways to connect to one another wirelessly anywhere in the world without requiring any kind of fixed infrastructure. Mobile Ad Hoc Networks (MANETs) are among the most flexible types of wireless networks because they are decentralized; consist of many mobile autonomous nodes that communicate with each other dynamically over a wireless medium while being used as both a host and router in the network. These networks are self-configuring and allow for quick deployment when there is not only no existing networking infrastructure but also no viable options for establishing one either due to physical damage or prohibitive costs associated with building out a new fixed infrastructure. Because of this, there has been interest in using MANETs in multiple real-life applications such as military operations, disaster recovery efforts and emergency response systems, transportation intelligence, healthcare monitoring, and environments enabled by Internet of Things (IoT).

While there are many advantages of using MANETs, there are also several technical challenges that affect the efficiency and reliability of communication. Hariz etal. [1] introduced multipath routing as an efficient routing protocol with integration of genetic algorithm optimization and MANETs, placing emphasis on providing reliable routing and reducing packet transmission delay through selecting optimized communication paths. Experimental results were favourable and showed enhanced throughput and fewer packet losses Than conventional routing protocols. The highly dynamic nature of the topology makes it very difficult for nodes to establish stable communication links due to frequent breaks in routing from mobility of nodes in the network. To further complicate managing the network, limitations caused by bandwidth availability, energy resources, transmission range, and wireless channel interference will all need to be considered. Because of these conditions, routing is an important factor in enabling communication between mobile nodes. In contrast to traditional wired networks, the protocols used for routing in MANETs need to support constant adaptation to changes in the topology of the network while maintaining reliability of the packet delivery and minimizing routing overhead. Therefore, the design and performance evaluation of routing protocols is considered one of the most significant areas of research in mobile wireless communication systems. The routing protocols for MANETs can be classified into three general categories: proactive, reactive, and hybrid. Proactive routing protocols deliver up-to-date routing information on every node within the network through periodic updates of routing tables, so they reduce the amount of time needed to establish a route but create the highest routing overhead in terms of control traffic. Reactive routing protocols only create routes when they are needed for data transmission, thus reducing the amount of overhead caused by control traffic, but the routes may take longer to be established. Hybrid routing protocols possess characteristics of both proactive routing and reactive routing protocols and attempt to achieve a balance in the performance of the network during varying communication conditions. Examples of commonly used routing protocols include Destination-Sequenced Distance Vector (DSDV), Ad-hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), and Zone Routing Protocol (ZRP). Each of these routing protocols has distinct differences in terms of performance based on node density, mobility patterns, amount of traffic per node, and the scalability of the node. Scalability and reliability are two of the most important factors that affect the overall performance of the MANET routing protocol. Fig. 1. shows the framework proposed for the analysis of the routing protocols in order to evaluate scalability, reliability, and communication performance under dynamic conditions of the network.

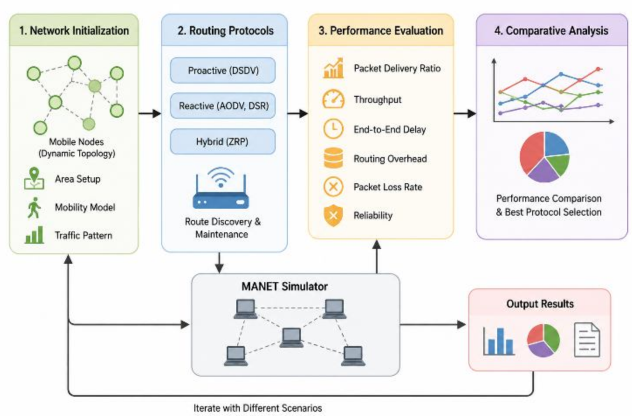

Fig. 1. Proposed Framework Architecture for Scalability and Reliability Analysis of Routing Protocols in MANETs

Scalability is the ability of a routing protocol to handle growth (addition of mobile nodes and request for communication) without significantly impacting network performance, while Reliability represents the successful delivery of data and communication continues even if the topology of the network changes dynamically or is disrupted in some manner. In terms of large-scale MANETs, routing protocols face various issues, including increased routing overhead, packet loss, increased latency, congestion, and energy consumption. This research focuses on evaluating the scalability and reliability of a variety of different routing techniques used for MANETs through an analysis of performance-based metrics. This research investigates the behavior and performance of various routing protocols in different network conditions by gathering information based on common network metrics (packet delivery ratio, throughput, end-to-end delay, routing overhead and reliability). Simulation experiments are performed to evaluate the performance of the protocol over different communication environments with different node densities and mobility patterns. Jumaa and Yadav [2] introduced a multicriteria relay selection algorithm to enhance the routing efficiency and stability of the network within MANETs. The rest of the paper is organized as follows.

Section II contains a summary of the literature review related to MANET routing protocols and performance evaluation. Section III presents the methodology used for the research, simulation environment, experimental results, and the performance comparison of the selected routing protocols. Section IV provides some of the findings of this study as well as some of the main observations that were produced. Lastly, Section V concludes the paper and discusses areas that should be researched in the future regarding scalable and reliable routing in MANETs.

II. LITERATURE SURVEY

Over the last few years, researchers have put together many different strategies for making Mobile Ad Hoc Networks (MANETs) work better by increasing routing efficiencies and providing us with new ways to connect by improving scalability, reliability and security while maintaining the Quality of Service (QoS) we expect when connecting to each other. For example, Raman et al. [3] looked into ways to make it easier to provide QoS of MANETs through the use of a secure routing protocol that could provide multi-constrained network feature approximation. Similarly, Alkhayyat et al. [4] created a clustering and routing framework based on the Golden Jackal Optimization Algorithm for MANET communications. Their application of a novel escaping strategy greatly improved routing efficiency and energy consumption by optimizing the selection of cluster heads and by optimizing the selection of routes to communicate. The results of their simulations indicated that their framework enhanced network life and reduced the overhead associated with routing. However, the overhead created from using clustering optimization-based frameworks presents challenges with the scalability of these types of networks due to their highly dynamic nature. Hussein et al. [5] created an Artificial Neural Network based intent prediction secure routing model that would be used in supporting the communication protocols used in VANETs; VANETS have several similarities with the MANET architecture. The use of an AI based methodology allowed Their results demonstrated an improvement in reliability of communications as well as improved security with respect to data transmitted over a communication medium, reinforcing the increasing reliance on machine learning as another means to support the use of wireless ad hoc communications systems. According to Alrwbaye & Alzahrani [6], node density-based routing algorithms were introduced in order to optimize routing decisions due to the variability of node distributions that can occur within a MANET environment. Their results demonstrate that using adaptive routing mechanisms based upon the density of nodes in a given area can improve both the scalability and throughput of that area significantly. The new model also minimizes routing overheads and congestion for large-scale networks. Vikas et al. [7] proposed a hybrid Deep Belief Network (DBN) and Harris Hawks Optimizer-based Intrusion Detection Framework (IDF) for Wireless Sensor (WSN) applications. The research conducted was focused on WSN; however, the Intelligent Security Model provided many insights into securing MANET routing communications from malicious attacks. Their findings pointed to the ability of deep learning and optimization algorithms to enhance network security and performance in the forms of improved detection accuracy as well as improved performance of network security. Aslam & Shahnawaz [8] proposed a cryptographic enhancement to the Ad Hoc On-Demand Distance Vector (AODV) routing protocol to improve security for voice over IP (VoIP) communications in MANETs. Their enhancements were shown to enhance the protection of VoIP communications against unauthorized access and routing attacks. Their experimental analyses indicated that the performance of secure AP/dynamic route transmission of packets was better than that of the AODV protocol alone; however, additional computation time was incurred due to the introduction of cryptographic operations. Al-Mashhadani & Karoui [9] completed a comparative review between rule-based and artificial intelligence (AI)-based routing protocols for use in MANETs. The authors identified the limitations of traditional routing protocols for high dynamic communication environments and emphasized the advantages of intelligent (i.e., machine learning or AI) routing protocols. The authors concluded that AI integrated routing protocols provide superior efficiency, scalability, and adaptability for use in current day MANETs. Nagaraju et al. [10] introduced a decision-making model for routing in urban wireless ad-hoc networks based on graph attention networks and deep learning. This new routing framework can make better routing decisions by dynamically analyzing the network topology and the current traffic state. In comparison to traditional routing methods, this technique showed improved packet delivery performance and reduced communication delays, especially in high-density delivery environments. Sengar et al. [11] researched the simulation and analysis of MANET routing protocols under non-ideal conditions such as interference, mobility, and packet transmission instability. They concluded that environmental conditions and channel imperfections greatly impact the performance of routing protocols and the reliability of the overall MANET. This study also demonstrates that adaptive routing techniques are necessary to provide stable communication in real-world MANET deployments. Sharma et al. [12] provided a detailed overview of Enhanced Optimized Link State Routing (EOLSR) protocols for secure routing communications in MANETs. Their analysis discussed improvements with regard to the security of routing, the efficiency of packet forwarding, and the resistance to routing attacks. Enhanced OLSR methods displayed to be effective means of enhancing the reliability of communication in dynamic mobile communication environments.

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Reddy et al. [13] researched the utilization of deep learning techniques to detect malicious network traffic. Their findings illustrate the effectiveness of intelligent analysis of traffic as a means of detecting threats to the network and identifying abnormal communications.

III. PROPOSED METHODOLOGY

This research proposes a comprehensive evaluation framework for routing performance to assess the reliability and scalability of routing techniques within Mobile Ad Hoc Networks (MANETs). The objective of the proposed methodology is to examine the behaviour of proactive (table-driven), reactive (on-demand), and hybrid routing protocols when exposed to a variety of dynamically changing communication conditions, such as nodes moving at different speeds, different patterns of mobility, using different traffic loads, and in various types of transmission environments.

A. MANET Network Initialization and Topology Configuration

In this first stage of the methodology proposed for the establishment of a MANET simulation environment/creating a dynamic network topology, the establishment of a wireless ad hoc communication network will be accomplished by deploying numerous mobile nodes throughout a defined area of simulation. The mobile nodes operate independently, meaning there is no centralized infrastructure or fixed base stations. Each mobile node acts both as a host for communication and as an intermediate routing device that forwards packets to neighbouring nodes in a network. The topology of the network is generated dynamically using the random placements of nodes and their movements based on their mobility patterns. There are multiple node density scenarios considered to determine the efficacy of scalability under small, medium, and high-density environments; the models utilized are those which mimic real-world movement patterns of objects in motion on a wireless communication system. Various configurations of speed of mobility and pause times can be established in order to evaluate how stable routing will be under different degrees of topology changes. The communication links between nodes will be established according to their transmission ranges and the availability of a wireless signal. Additionally, the simulation framework supports various traffic generation patterns such as constant bit rate (CBR) and variable bit rate (VBR) communications flows so that routing behavior can be observed and measured under a range of different traffic patterns. The initialized network environment provides a realistic testbed for the evaluation of routing protocols in a dynamic MANET scenario.

B. Routing Protocol Deployment and Communication Modeling

The second phase of the proposed framework consists of deploying and configuring a number of different MANET routing protocols for comparison of their performance characteristics. The goal of the study is to include a sample of representative routing techniques from the proactive, reactive, and hybrid routing groups to evaluate their scalability and reliability attributes in an identical network environment. Proactive routing protocols maintain current routing knowledge (about each node in the network) at all times by periodically exchanging routing tables with other nodes on the network. These routing protocols incur less delay when communicating with each other compared to reactive routing protocols however they incur more overhead due to the requirement to maintain routing tables on all nodes in the network. Reactive routing protocols establish a communication path only when there is a need to do so, thus reducing the amount of control traffic generated and increasing the time required to discover and establish a communications path. Hybrid routing protocols combine features of both proactive and reactive routing approaches to provide a balance between efficient communication and adaptable routing. The communication framework continuously monitors the process of route discovery, route maintenance, packet forwarding, handling link breakage, and updating the network topology while the network is operating. Dynamic route selection will be carried out based upon several attributes such as node availability, transmission reliability, and stability of route.

C. Scalability and Reliability Performance Evaluation

The third step in the methodology examines and analyses the performance of the nominated routing methods in terms of scalability and reliability by measuring their communication performance metrics. The proposed method is designed to measure routing Performance based on efficacy under dynamic conditions, such as increases in size of a network, intensification of mobility of users, or the addition of communication traffic to a network of mobile ad hoc nodes (MANET). During execution of the simulation, the performance of routing methods used will be analysed based on measurements of; Packet Delivery Ratio (PDR), overall throughput of the network and its average delay times for packets delivered through the various routes of the network, amount of routing overhead, number of packets lost in transit between the communicating nodes, and the overall reliability of the network.

Packet Delivery Ratio measures the success or failure of delivery of all packets transmitted from one node to another via a communication link, whereas throughput provides an arithmetic assessment of the total capacity of the network to transmit data from one node to another node over the entire network. Average delay in end-to-end packet delivery will measure the average time it takes for a packet transmitted from node A to arrive at node B across all paths in the network. Routing overhead is the measure of control information generated by routing protocols as they process communication events.

D. Comparative Analysis and Adaptive Routing Assessment

The final stage of the proposed methodology provides a comparison of the adaptive assessment of various routing protocols for identifying efficient routing strategies in MANET communication systems. The simulation results for the different routing protocols will be compared using both graphical and statistical techniques to assess their performance. The results of this assessment will provide an evaluation of the performance of each WAN protocol based on their strengths and weaknesses in terms of varying degrees of mobility, communication loads, and the ability to support large-scale networks. The assessment of adaptive performance will include the evaluation of how fast the routing protocols can respond to network topology changes, how well they can recover from route failures and congested traffic conditions, as well as how consistently they can transmit data in a dynamic networking environment. The framework will also consider the tradeoffs between routing overhead and the reliability of communications in order to determine what form of routing behaviour should be employed within the constraints of resource-limited MANET environments.

IV. RESULT AND ANALYSIS

The performance assessment of the proposed MANET (Mobile Ad-hoc Network) Routing Evaluation Framework encompasses a number of criteria, including scalability, routing reliability, communication efficiency, and adaptability to dynamic mobile networking conditions. The proposed methodology's effectiveness is demonstrated through simulation-based comparative analysis of various proactive, reactive and hybrid routing protocols based on multiple metrics for evaluating communication performance.

A. System Configuration and Simulation Environment

The finding of the MANET routing system development was derived from experimental testing carried out in a virtual wireless network that simulated realistic scenarios of mobile ad hoc communications. In addition, the wireless communication simulation system consisted of one computer with an Intel Core i7 processor, 16 GB RAM, and Ubuntu-based support for network simulations. All routing systems tested were implemented and analysed in the NS-3 network simulator, which provides simulation support for mobility and wireless communication. The simulation system used multiple mobile wireless nodes assigned to the communication area within the wireless communication area (1000 m × 1000 m) that are deployed dynamically across the area. The mobile wireless nodes were assigned to different numbers of mobile wireless nodes per simulation to determine the scalability performance of the route protocols. The number of mobile wireless nodes per simulation were 25, 50, 75, 100, and 150. For the realistic simulation of the nodes' mobility behavior, a Random Waypoint mobility model was implemented to simulate realistic node movement, and each node's assigned mobility speed ranged from 5 m/s up to 25 m/s. The transmission ranges for each mobile wireless node were configured to provide multi-hop transmission between adjacent wireless nodes. The simulation framework was used to evaluate representative proactive, reactive, and hybrid route protocols (e.g., Destination Sequenced Distance Vector - DSDV, Ad Hoc On-Demand Distance Vector - AODV, Dynamic Source Routing - DSR, and Zone Routing Protocol - ZRP). Constant bit rate (CBR) traffic patterns were generated, resulting in the continuous transmission of packets for different load levels of traffic. Each packet was configured to be 512 bytes in size, and the simulation time was fixed at 300 seconds for each test scenario.

B. Performance Evaluation Metrics

The routing performance analysis was conducted using standard MANET evaluation metrics represented through equations (1) to (5). Packet Delivery Ratio determines the percentage of successfully delivered packets:

$$PDR = \frac{Packets\ Received}{Packets\ Sent} \times 100 ------(1)$$

Throughput measures the successful data transmission rate within the communication network:

$$Throughput = \frac{Total\ Data\ Received}{Simulation\ Time} ------(2)$$

Average End-to-End Delay represents the average transmission delay experienced by packets:

$$Delay = \frac{\sum(PRT - PST)}{Total\ Packets\ Received} ------(3)$$

Routing Overhead evaluates the amount of routing control packets generated during communication:

$$Routing\ Overhead = \frac{Control\ Packets}{Total\ Data\ Packets} ---(4)$$

Packet Loss Rate measures the percentage of packets lost during transmission:

$$PLR = \frac{PS - PR}{PS} \times 100 -------(5)$$

The collective evaluation of these metrics provides a detailed analysis of routing scalability and communication reliability in MANET environments.

TABLE I. PERFORMANCE COMPARISON OF MANET ROUTING PROTOCOLS

Routing Protocol	Packet Delivery Ratio (%)	Throughput (Kbps)	End-to-End Delay (ms)	Routing Overhead (%)
DSDV	89.4	512	48	31.5
DSR	92.1	548	41	24.8
AODV	94.6	586	36	20.7
ZRP	96.2	603	32	18.3

The results shown in TABLE I illustrate that the hybrid routing protocol (ZRP) provides significantly better communication performance than other Proactive or Reactive routing solutions. Improved Packet Delivery Ratio and throughput indicate that both scalability and reliability of packet transmission will be enhanced under changing communication conditions. The adaptability of the reactive routing protocols (AODV/DSR) is better than that of DSDV, a proactive routing protocol, because DSDV generates a greater amount of routing overhead from the need to continually update its routing table. The lower end-to-end delay value of ZRP indicates that it can manage routes and recover rapidly from disruptions in communication due to topology changes.

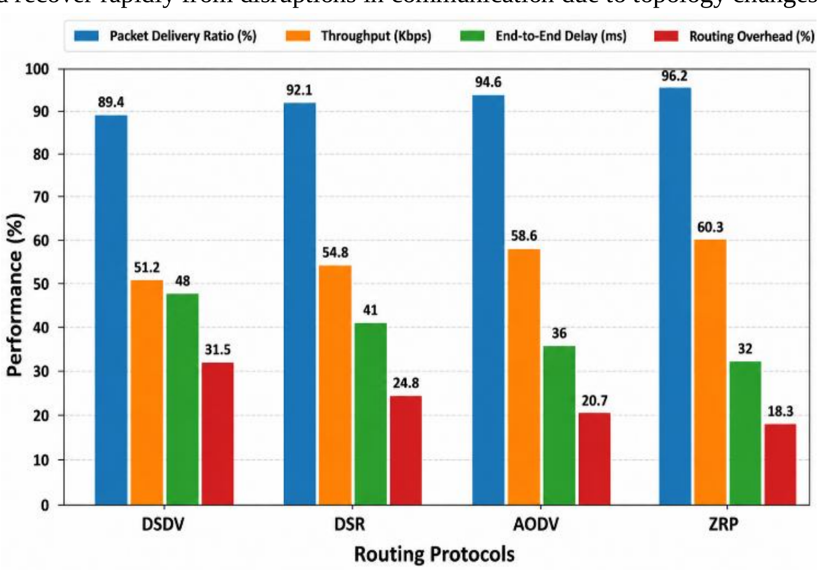

Fig. 2. Comparative Performance Analysis of MANET Routing Protocols

Fig. 2 illustrates that hybrid routing techniques maintain balanced performance across multiple communication parameters, making them more suitable for large-scale and highly mobile wireless ad hoc networks.

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D. Scalability Analysis under Varying Node Density

TABLE II demonstrates how increasing the density of mobile nodes impacts the performance of routing protocols in MANETs. Increased density negatively affects the performance of routing due to increased routing overhead, congestion, and communication interference. However, ZRP utilizes an adaptive routing protocol that allows for greater communication reliability than reactive routing protocols such as AODV, even in highly dense networks. Reactive routing protocols can also provide scalability by establishing routes dynamically when needed but experience reduced overall performance; proactive routing protocols will experience degraded performance due to the large number of routing updates required in large-scale communication systems.

TABLE II. SCALABILITY ANALYSIS WITH DIFFERENT NODE DENSITIES

Number of Nodes	AODV PDR (%)	DSR PDR (%)	DSDV PDR (%)	ZRP PDR (%)
25	97.2	95.8	94.6	98.1
50	95.4	93.6	91.8	97.0
75	94.6	92.1	89.4	96.2
100	92.8	90.5	87.3	95.1
150	90.6	88.4	84.7	93.8

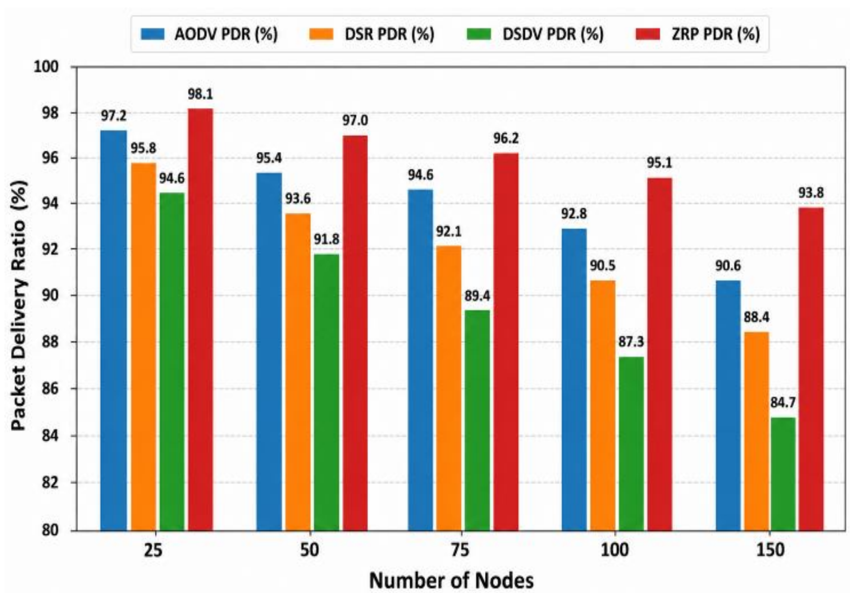

Fig. 3. Scalability Performance Analysis under Different Node Densities

Fig. 3 demonstrates that hybrid routing mechanisms provide improved scalability and communication consistency in dense MANET deployments.

E. Reliability and Mobility Performance Analysis

TABLE III shows that the increase in node mobility impacts both route stability and communication reliability in MANETs. High mobility levels lead to frequent route breaks and interruptions to communication, thereby decreasing the overall routing performance. Due to the efficiency of the hybrid routing protocol's route recovery capabilities and adaptive communication management, this protocol provides a higher level of reliability than the other routing protocols discussed. Reactive routing protocols provide superior performance compared to proactive routing protocols when there exist high levels of dynamic mobility; on-demand routing techniques create routes as needed. Because of outdated routing information due to the rapid rate at which topology changes occur, proactive routing protocols are expected to experience reduced reliability rates than reactive routing protocols.

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TABLE III. ROUTING RELIABILITY ANALYSIS UNDER DIFFERENT MOBILITY SPEEDS

Mobility Speed (m/s)	AODV Reliability (%)	DSR Reliability (%)	DSDV Reliability (%)	ZRP Reliability (%)
5	96.5	95.1	93.8	97.4
10	95.2	93.7	91.6	96.8
15	93.4	91.8	89.2	95.6
20	91.9	89.6	86.5	94.3
25	89.8	87.2	83.7	92.7

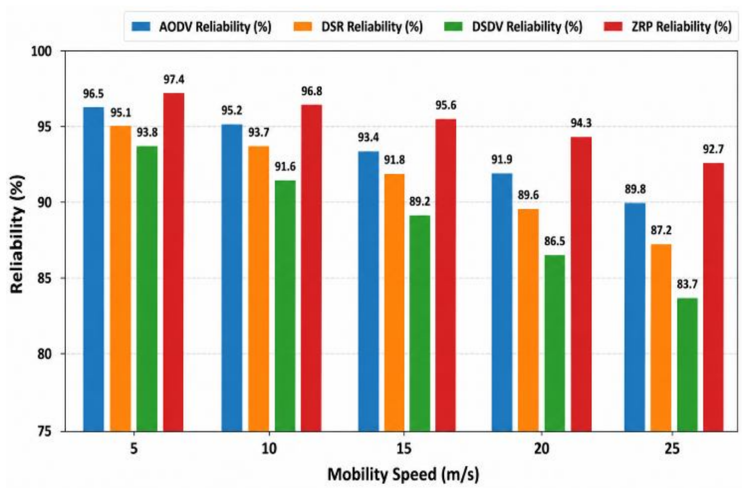

Fig. 4. Reliability Analysis of Routing Protocols under Dynamic Mobility Conditions

The comparative analysis in Fig. 4 confirms that hybrid and reactive routing techniques offer better communication reliability and scalability for next-generation MANET applications operating under highly dynamic wireless communication environments.

V. CONCLUSION AND FUTURE SCOPE

Using various communication criteria for the evaluation of proactive, reactive, and hybrid routing protocols, i.e. PDR, throughput, end-to-end delay, routing overhead, and network reliability and using experimental analysis, the hybrid routing protocol called ZRP showed a better overall performance result than the DSDV, DSR, and AODV routing protocols. The study demonstrated that ZRP achieved the highest PDR of 96.2%, throughput of 603Kbps, end-to-end delay of 32ms (lowest end-to-end delay recorded), and minimum routing overhead of 18.3%, which indicate that ZRP performed the best for routing in large-scale dynamic MANET environments in terms of scalability and communication efficiency. Furthermore, the scalability evaluation demonstrated that as node density increased, ZRP maintained stable routing performance with a PDR of 93.8% up to 150 nodes, whereas all other routing protocols experienced some degree of performance deterioration due to increased congestion and routing complexity. Reliability evaluation of the different routing protocols at different mobility speeds was also performed, with ZRP providing the highest reliability of communications at 92.7% at 25m/s of mobility speed, thereby demonstrating ZRP's adaptability and stability under rapidly changing topology conditions. From the comparative evaluation among all routing protocols in varied mobility conditions, it was established that reactive routing protocols (AODV) outperformed proactive routing protocols in highly mobile conditions; however, hybrid routing protocols provided well-balanced, consistent communication performance with varied network conditions. Future research can also include exploration of energy-efficient routing optimization, blockchain-based secure routing, congestion-aware communications, and real-time MANET deployment on 5G and 6G mobile wireless communications to further enhance scalability and security, as well as reliable communication performance in the next generation of mobile ad hoc networks.

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