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EVALUATING THE PERFORMANCE OF MULTIPATH ROUTING PROTOCOLS IN MOBILE AD-HOC NETWORKS: A COMPARATIVE STUDY

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Abstract: A Mobile Ad-Hoc Network (MANET) is a dynamic wireless network that links mobile devices without fixed infrastructure. All device in MANET acts as a node and a router, dynamically establishing and maintaining network connections as they move. Mobile Ad Hoc Networks find widespread application in scenarios where conventional network infrastructure is absent or unfeasible, including military deployments, emergency response efforts, and vehicle-to-vehicle communication systems. Routing in MANETs can be ambitious due to dynamic topologies, limited bandwidth, and power restraints. The protocols governing these networks fall into three basic categories, proactive, reactive, and hybrid routing protocols. Multipath routing in MANET involves establishing several paths between source and destination. This technique enhances network performance by providing numerous benefits. This research examines multipath routing protocols like MP-OLSR, SMR, AOMDV, ZRP, TORA and analyses key metrics including route discovery efficiency, route maintenance, end-to-end delay, packet delivery ratio, and energy usage.

Keywords: MANET; routing protocols; proactive; reactive; hybrid and AOMDV

I. INTRODUCTION

A Mobile Ad-Hoc Network (MANET) is a grouping of wireless mobile nodes that form a transitory network with any infrastructure. Every node within MANET was able to relocate, resulting in a dynamic topology. There is no central administrator, thus each node operates as a router, sending traffic to the other. The nodes continuously store the information needed to route traffic correctly. This decentralized structural design supports impromptu network involvement and device mobility within the network's spatial domain. It permits nodes to join, leave, and relay traffic opportunistically based on their proximity to other nodes [1]. Mobile Ad-Hoc Networks experience critical presentations in diverse fields, including vehicular telematics, industrial Internet of Things (IIoT), tactical military communications, residential mesh networks, and disaster response systems. The efficacy of these applications is fundamentally dependent on the implementation of robust and efficient routing protocols, which optimize network performance and ensure reliable data transmission under dynamic topological conditions [2].

In Mobile Ad-Hoc Networks numerous routing protocols have been created and proposed. In the Proactive Routing Protocols, each node maintains updated routing tables that store information about all routes that are available in the network so there would be immediate availability of a route when needed. Examples include OLSR, DSDV, and MP-OLSR. The Reactive Routing Protocols generate routes only when the source node requests them. A node invokes route discovery only when it wishes to communicate with another node, thus saving resources. Examples include AODV, DSR, SMR, and AOMDV. Hybrid Routing Protocols are an instance of together proactive and reactive approaches. These provide reactive routing, when necessary, outside of a designated zone and proactive routes within that zone. Example includes ZRP and TORA [3].

II. ROUTING PROTOCOLS

In a MANET, a routing protocol is an algorithm that specifies how network nodes choose the most efficient way to forward packets from a source node to a destination node. Proactive, reactive, and hybrid routing protocols are the three main types of routing protocols used in MANETs. For MANETs in particular, network designers have two options for choosing routes between a source and a destination naming, unipath and multipath routing. These two approaches distinctly differ concerning handling the communication paths. Both of these approaches have merits and demerits based on various network conditions such as reliability, load balancing, and fault tolerance. Unipath routing uses only a single route; hence, it is simple, but it is not fault-tolerant and fails in the context of load balancing. Multipath routing uses several paths to its advantage. This gives them better resilience to faults and ease of work in balancing loads and bandwidth usage at higher complexities and control overhead. The work uses a multipath routing protocol that selects the optimal path from available dual paths based on distance metrics. Popular multipath routing protocols include MP-OLSR, SMR, AOMDV, ZRP, and TORA [4]. The various MANET routing protocol types are depicted in Fig 1.

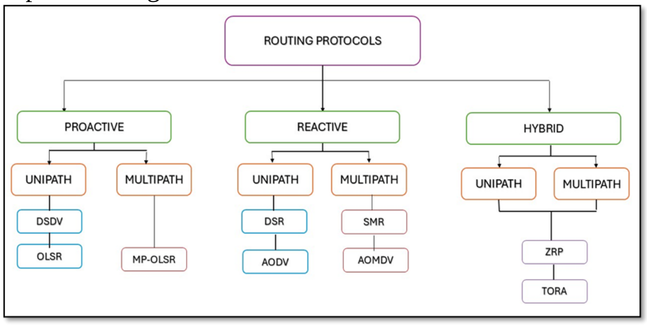

Figure 1. MANET-Routing Protocols.

A. *Proactive Protocols*

Proactive routing methods minimize latency by maintaining real-time data, they do so at the cost of higher resource use, including memory and bandwidth, as a result of constant table changes. This protocol is categorized into two further methods, unipath and multipath routing.

1) Unipath Routing in Proactive

. Unipath routing manages only one route, to connect the origin and their final destination. Route discovery and maintenance are the two phases that make up the routing protocol. When a source node needs to communicate with a destination node, the Route Discovery process is started. This mechanism functions in two sequential phases, first, it executes path discovery algorithms to determine feasible routing paths through the network, and subsequently, once a suitable route is established, it makes it easier for data packets to go from the nodes that are the source and destination along the identified path. The next phase is Route Maintenance, which occurs when the route between source and destination is blocked for any reason, and the node re-discovers the path to send the data packet. In unipath routing protocols, proactive routing approaches include DSDV and OLSR [5].

2) Multipath Routing in Proactive

The multipath routing technique involves maintaining multiple alternative paths between source and destination nodes. The network's nodes all keep track of each other's most recent routing information. The routing data is stored in several different tables. These tables are updated frequently when the network topology changes in order to maintain a consistent network perspective. A routing table stores the method of identifying and updating routing information, and each of these protocols has a different number of routing tables. The network overhead in this protocol rises as the node mobility and network size change. One method of proactive multipath routing is Multipath-Optimized Link State Routing (MP-OLSR) [6].

B. *Reactive Protocols*

Reactive routing protocols only construct links from the source node when they are needed. If nodes wish to connect to other nodes for which they have not yet constructed a route, they initiate the route discovery process. Once located, a route is kept just for the duration of the data transmission required. Researchers divide reactive routing protocols further into unipath and multipath based on their routing algorithms [7].

1) Unipath Routing in Reactive

Unipath routing creates only one path between the source and the destination in the reactive protocol. Route maintenance and route discovery are the two stages of this routing process. In route discovery, a source looks for a way to a destination and uses it to transmit the data packet. If the link between the source and the destination is broken for whatever reason, the node searches for a different path to carry on transmitting the data packet, and the route discovery process is invoked when needed. The reactive unipath routing protocols are DSR and AODV [8].

2) Multipath Routing in Reactive

Multipath routing in reactive protocols is a strategy that has been devised to enhance data transmission efficiency within networks. Multipath routing finds several routes between a source and a destination during the route discovery phase, and nodes create routes only when they require them. Nodes no longer have to commit network resources to idle routes, which removes overhead. The distribution of data over several paths improves fault tolerance, load balancing, and resilience. This reduces the chances of network congestion and routing failure especially in dynamic networks. The multipath routing in reactive protocols is Split Multipath Routing (SMR) and Ad-hoc On-demand Multipath Distance Vector (AOMDV) [9].

C. *Hybrid Protocols*

Hybrid protocols contain both proactive and reactive routing strategies. The protocol is a hybrid of the two, with nearby nodes preserving routing information proactively and remote nodes discovering routes reactively as needed. Thus, this balance helps optimize performance in dynamic networks. This model of combining proactive and reactive mechanisms highly increases implementation complexity, increases resource consumption, and is extremely expensive. The hybrid protocol is Zone Routing Protocol (ZRP) and Temporally Ordered Routing Algorithm (TORA) [10].

III. MULTIPATH ROUTING IN PROTOCOLS

Multipath routing protocols are network routing systems that use numerous alternate paths concurrently between a source and recipient node. In contrast to traditional single-path routing, multipath routing offers reliability and fault tolerance with effective load balancing. The basic concept of the method is redundancy, or tracking numerous routes so that, in case of failure, data transmission will continue without any interruptions. Multipath routing protocols are necessary for the transmission of communication using backup channels from the source to the destination. Although in end-end communication the route fails, it delivers the message efficiently to the destination through back routes. It includes four prominent features of multipath routing, multiple path setup for data flow, improvement in network reliability and robustness, traffic balancing over diverse potential paths in a network, and resource redundancy and diversity exploitation in networks that provide great advantages in MANETs for enhancing performance. This begins with the discovery of various paths between the source and destination, which improves redundancy and reliability. The protocol picks some of the found paths based on stated parameters, such as shortest distance. It then breaks up data packets and sends them across the selected multiple paths simultaneously. In other words, if there is a failure on one path, it can use the remaining active paths to reroute traffic for which data should not reach its destination without disruption [11].

A. *Multipath-Optimized Link Sttate Routing (MP-OLSR) Protocol*

The Multipath Optimized Link State Routing uses a technique wherein every network node establishes multiple paths. Each node regularly exchanges Topology Control (TC) and HELLO messages to retain topology information. Using a Multipoint Relays (MPR) selection mechanism, MP-OLSR reduces TC message traffic. Unlike several other protocols, MP-OLSR does not maintain current routing tables for each network node that can be reached. Instead, it uses an on-demand approach for multipath computation. The multipath computation in MP-OLSR utilizes a modified version of Dijkstra's Algorithm. This algorithm operates on the network topology database and does not eliminate nodes that are part of the processed paths. Even when the ad-hoc network lacks precisely node-disjoint pathways, this method creates many paths. This strategy allows MP-OLSR to adapt to various network topologies and provide multiple routing options, enhancing the protocol's flexibility and resilience in diverse ad hoc network environments [12].

The MP-OLSR protocol, while enhancing network performance, has certain limitations. The phenomena of route demand is one important problem. In this scenario, multipath reactive protocols can generate an excessive number of route request (RREQ) messages. These RREQ messages include a hop-limit field, which, when it reaches zero before arriving at the destination, causes the node to discard the request rather than forward it. This process results in increased latency. Another challenge is the inefficiency in route discovery. This problem manifests in the source node's management of a buffer. The buffer stores copy of packets that cannot be transmitted because no available route exists. Each packet in the buffer is assigned a time stamp and is eliminated after a predetermined period if it remains unforwarded. These drawbacks highlight areas where the MP-OLSR protocol could be improved to enhance overall network efficiency and reduce unnecessary data traffic [13].

B. *Split Multipath Routing (SMR) Protocol*

Split Multipath Routing (SMR) is an adaptive multipath routing protocol. Several routes having maximally discontinuous paths are created to minimize the discovery of routes and control message overhead. To avoid congestion, this method divides the data transmission across multiple pathways. The destination node makes two very good path selections. It is believed that the very initial path is the shortest. It reduces the amount of time needed to identify a route by finding the earliest path. It moves on to the second path after picking the first. After a predetermined amount of time, the destination node awaits new requests. It finds every route that could lead from a source to a destination. In this way, it chooses between two paths. Two discrete routes, one for the shortest path and the other for is alternative approach. When compared to a most discontinuous path, the path that distributes route requests to the destination most quickly is selected as the first path. The SMR protocol uses the less frequent discovery of route procedures, however, one of its disadvantages is that it does not use overhead packets [14].

C. *Ad-hoc On-demand Multipath Distance Vector (AOMDV) Protocol*

The Ad-hoc On-demand Multipath Distance Vector (AOMDV) Protocol is the best-known multipath routing mechanism for ad-hoc wireless networks. AOMDV finds many pathways from the source to the final destination, all loop-free and link-disjoint. The hop count measure is the primary tool used by AOMDV to identify the best routes. The advertised count of hops is used in AOMDV in place of the traditional hop count. The subsequent hop was restored by a route listing, this modification affects the number of subsequent hops and their accompanying hop counts. However, the destination sequence number remains the same for all subsequent hops. Every time the sequence number is changed, the hop count is initialized. AOMDV searches for several routes and sends the packet over to the one with the fewest hops. AOMDV chooses discontinuous paths to increase fault tolerance. The routing table in AOMDV contains the following key components route list, destination, advertised hop count, sequence number, and expiration time out [15]. Table I shows the functions of key components in AOMDV.

Figure 1. Key Components and their Functions of AOMDV

Key Components	***Functions***
Destination	The destination node or address to which data packets are being routed in the network
Sequence Number	A distinctive number is assigned to identify the route and to make sure that transmitting information is fresh. This is often employed to prevent routing loops and to maintain the most recent route.
Advertised Count of Hop	The sum of intermediate nodes from source to destination. A smaller hop count means a more direct route.
Route List	This field contains a list of potential routes or intermediate nodes through which data can travel to reach the destination.
Expiration Time-Out	This represents the time limit after which a route becomes invalid. The network removes a route from the routing table if nodes do not use or refresh it within the specified time, considering it expires.

The attributes of AOMDV are, the acceptance of RREQs from various source neighbors at intermediate nodes, the creation of multiple link-disjoint (node-disjoint) routes, the creation of many routes in a single route discovering process, the usage of the maximum advertised count of hop for preventing loops, and the maintenance of next-hop data regarding destinations by nodes, a source lacks route data, and the removal of frequent route interruptions and link failures in extremely dynamic ad hoc networks [16]. AOMDV is suited for high-link breakage rates and high-performance requirements. The benefit is being able to control network load, prevent congestion, and increase reliability. To plan many routes from the source to the desired destination, AOMDV ensures a suitable and reliable connection. It includes several sophisticated capabilities, including the ability to create routes on demand, create nodes free of loops, maintain connectivity, and recover faults quickly and effectively. Fig 2. describes the route discovery process in the AOMDV protocol [17].

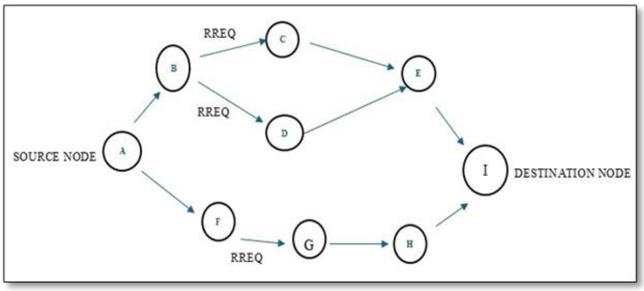

Figure 2. Route Discovery Process in AOMDV Protocol

D. Zone Routing Protocol

The Zone Routing Protocol, or ZRP, effectively controls communication in mobile ad-hoc networks by combining aspects of proactive and reactive routing techniques. The benefits of proactive and reactive routing techniques are combined in this method. The Zone Routing Protocol segments the network into distinct areas concentrated on individual nodes. Every node in the network is surrounded by its zone, which is determined by a specified radius measured in hop counts. Inside the zone, routing is managed proactively and outside the zone, routing is handled reactively. In a proactive approach, nodes maintain the latest routing tables by periodically exchanging routing information. When communicating with nodes beyond its local zone, ZRP employs on-demand routing techniques. If a node wants to reach a remote node outside of its zone, it initiates a path discovery method to dynamically construct a way, demonstrating the idea of reactive routing techniques [18].

The Zone Routing Protocol (ZRP) integrates three key components, IntrA-zone Routing Protocol (IARP), IntEr-zone Routing Protocol (IERP), and Bordercast Resolution Protocol (BRP). The IntrA-zone Routing Protocol (IARP) operates proactively, continuously updating routing tables. This approach ensures that each node can instantly determine the optimal route to any other node within its zone, eliminating the need for on-demand route discovery processes. IARP dynamically adapts to network topology changes by facilitating regular routing update exchanges among intra-zone nodes, thereby maintaining current and accurate routing information. Because the IntEr-zone Routing Protocol (IERP) is reactive, a node will only search for a route when it is expected. The route discovery process begins when a node wants to deliver data to a target that is outside of its zone. The node does not send out an enormous number of route requests to the whole network. Rather, it simply transmits the route request to its zone's boundary nodes. Once the destination is within their zone, these border nodes verify it or forward the request to one of their border nodes. BRP is used to border cast the request to the border nodes, who then view the target within their zone. If the target is still not found, the border nodes keep sending the request to their border nodes in other zones. Once the destination has been determined, a route reply is returned to the source node, establishing a path [19].

E. Temporarily Ordered Routing Algorithm (TORA)

The Temporally Ordered Routing Algorithm (TORA) is a versatile approach that combines reactive and proactive elements. It is designed for efficiency, adaptability, and scalability in mobile ad-hoc networks. TORA implements a distributed routing paradigm utilizing link-state topology, wherein route initialization is source-triggered, facilitating the establishment of multiple node-to-node path vectors [20]. TORA includes three basic operations, route creation, route maintenance, and route erasure. By building a directed acyclic graph (DAG), the route generation function creates a path to a destination and ensures every node has a path there, it maintains the established route while adapting to network changes by changing routes as necessary to provide constant connectivity even in dynamic topologies. The protocol can detect a network division and eliminate any invalid routes if one happens. TORA does not scale well in large networks with many traffic connections, which affects its performance in more extensive network environments. It has high end-to-end delays when establishing routes, which makes it slower compared to other protocols [21].

IV. ANALYSIS OF MULTIPATH ROUTING PROTOCOLS

Key observations are made after examining the protocols covered in this multipath routing protocols analysis and their associated metrics. The analysis of the various multipath routing protocols is presented in Table II.

Table II. Analysis of Multipath Routing Protocols

Protocol	***Route Discovery***	***Route Maintenance***	***Packet Delivery Ratio***	***End-To-End delay***	***Energy Consumption***
MP-OLSR [13]	Medium, as routes are pre-determined	Low, needs regular updates	High, proactive routing have lesser delays	Low, precomputed paths for all nodes	High, maintain routing table
SMR [14]	Medium, focus on disjoint links	High, multiple paths maintained	Medium, due to disjoint routes	Medium, locating a path requires time	Medium, based on path utilization
ZRP [18]	High, hybrid in nature	Medium, based on zone maintenance	High, by optimizing the paths	Vary, depends on zone radius	Vary, based on network infrastructure
TORA [20]	High, implement loop free nodes	High, regular routing updates	Low, due to link stability	High, increase in link failures	High, due to high frequency update
AOMDV [15]	High, multipath discovered	Low, maintains disjoint link	High, due to reliable path	Low, due to route calculations	Medium, depends on route computed

A. Protocols and their Characteristics

According to Table II, MP-OLSR offers a medium route discovery capability and low efficiency in route maintenance. However, it excels in packet delivery, boasting a high packet delivery ratio and low end-to-end delay, making it suitable for applications where timely delivery is critical. Its primary drawback is high energy consumption, which may limit its use in energy-sensitive environments. While its route maintenance efficiency is low, its high delivery efficiency makes it a strong candidate for networks prioritizing communication reliability.

SMR provides a well-rounded approach, balancing its route discovery and maintenance capabilities. It excels in route maintenance with high efficiency and offers a high ratio of packet delivery. Its end-to-end delay is moderate, and its power consumption is reasonable, making SMR a versatile choice for scenarios where both reliability and power efficiency are important. The balance between its metrics, particularly in packet delivery and route maintenance, makes it a solid all-around protocol, even though it may not lead in any single category.

AOMDV stands out for its high route discovery and packet delivery capabilities, ensuring fast and reliable communication. It also features low end-to-end delay, making it ideal for time-sensitive applications. However, its high route discovery efficiency can come at the cost of increased energy consumption, which, although moderate, might still be a factor to consider in resource-constrained environments. Overall, AOMDV excels in providing reliable, low-latency communication but may require careful management of energy resources.

ZRP is highly efficient in route discovery and packet delivery, making it suitable for networks requiring high reliability. However, its performance in terms of total delay and consumption of energy is variable, which may lead to unpredictable results depending on network conditions. ZRP’s adaptability can be advantageous, but its variable characteristics mean it may not consistently perform as well as protocols with more predictable behavior. This makes it a flexible but unpredictable choice.

TORA offers high route discovery and maintenance efficiency, ensuring stable network connectivity. However, it suffers from low packet transmission efficiency and high end-to-end delay, making it less suitable for time-sensitive or reliability-critical applications. Additionally, its high energy consumption could be problematic in environments where power is limited. TORA’s strength lies in its robust route maintenance, but its performance trade-offs in terms of delivery and energy usage limit its applicability in certain scenarios.

Among the protocols, **AOMDV** and **MP-OLSR** emerge as the most effective in terms of packet delivery ratio and minimizing total delay, making them ideal for time-sensitive and reliable communications in MANETs. **TORA**, while providing strong route maintenance, is hindered by high energy consumption and delay, making it less effective in energy-constrained environments. **ZRP** offers flexibility but suffers from unpredictable performance in terms of energy and delay, depending on network conditions. **SMR** strikes a balance across multiple factors, making it a versatile option, though it does not lead in any specific metric.

V. CONCLUSIONS

In conclusion, AOMDV and MP-OLSR stand out as the top-performing protocols for mobile ad-hoc networks (MANETs) due to their minimal end-to-end latency and an extremely high delivery ratio of packets, making them well-suited for applications that require timely and reliable communication. While TORA excels in route maintenance, its high energy consumption and delay limit its effectiveness in energy-constrained environments. ZRP provides flexibility, but its performance can be inconsistent, particularly in terms of energy efficiency and delay. SMR, on the other hand, offers a balanced performance across several metrics, making it a versatile but not exceptional choice for most scenarios. The selection of protocol will depend on individual network constraints, including energy constraints, reliability, and delay sensitivity. The future work includes the enhancement of AOMDV in efficient routing, load balancing, increasing the network lifetime and better performance in dynamic environments.

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