An Energy-Efficient Multicast Routing Protocol and Traffic Splitting in MANETs

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ABSTRACT:
A Mobile Ad hoc Network (MANET) is a decentralized, self-organizing network of mobile devices that communicate directly without depending on fixed infrastructure or centralized management. MANETs are defined by their dynamic topology and resource limitations, which result in uncertainty challenges. These uncertainties complicate the selection of the most efficient communication path. To tackle this issue, this paper introduces an effective multicast routing protocol for MANETs, taking into account energy, delay, and traffic constraints. The proposed approach combines all network metrics into a unified metric. Potential routes that meet the constraints are analyzed, and the one with the maximum cost is chosen as the optimal path. If no single route fulfills the constraints, traffic is distributed across multiple disjoint paths using the Traffic Splitting algorithm. Experimental findings reveal that the proposed protocol surpasses ODMRP and MAODV in terms of residual energy, packet delivery ratio, and packet delivery delay.

KEYWORDS: Mobile Ad-hoc Network, Multicasting, Multipath Routing, Service Quality, Traffic splitting, Energy-aware.

1. INTRODUCTION

MANETs represent a revolutionary approach to wireless communication, characterized by their decentralized structure and dynamic nature. Unlike traditional networks that rely on fixed infrastructure, MANETs allow mobile devices to connect and communicate directly with one another, forming an ever-changing network topology. This self-organizing capability enables rapid deployment in various environments, making MANETs particularly valuable for applications such as emergency response, military operations, classrooms and vehicular communication systems. The flexibility of MANETs comes with inherent challenges, including issues related to Restricted network resources (like bandwidth, delay, and energy), routing, scalability and security. As mobile devices move in and out of range, maintaining efficient communication becomes complex, necessitating advanced protocols and algorithms [1].

1.1. Multicast Routing

Multicast routing is a networking technique designed to efficiently transmit data from a single source to multiple destinations simultaneously. Unlike unicast routing, which delivers data to one specific recipient, multicast routing enables the distribution of information to a group of interested hosts. This approach is particularly beneficial for applications such as video streaming, online gaming, and virtual conferences, where the same content needs to be delivered to several users at once. By optimizing bandwidth usage and reducing network congestion, multicast routing plays a crucial role in modern network communications, enhancing the efficiency of data distribution across diverse applications.

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1.2. Load Balanced Routing

Load balancing in network routing is a crucial method for enhancing the efficiency and reliability of data transmission across networks. By distributing network traffic across multiple servers or pathways, load balancing ensures that no single route or server becomes overwhelmed, which can lead to slowdowns or failures. In the context of routing, load balancing helps optimize the flow of data packets, prevents bottlenecks, and supports higher availability by rerouting traffic when certain paths or servers are overloaded or down.

1.3. Multi-Path Routing

In the field of network routing, the primary goal is to discover efficient, reliable paths between source and destination nodes for data transmission. Traditional single-path routing methods often rely on a single, optimized path to handle all network traffic, which can lead to congestion, limited fault tolerance, and underutilization of network resources. As network demands and complexities grow, these limitations become more pronounced, particularly in environments such as wireless sensor networks, data centers, and high-traffic internet backbones. This is where multi-path routing comes into play.

Multi-path routing is a technique that establishes multiple routes from a source to a destination, allowing data packets to travel across diverse paths simultaneously. By utilizing multiple paths, this approach offers several advantages over single-path routing, including improved fault tolerance, enhanced load balancing, better bandwidth utilization, and reduced latency. In multi-path routing, if one path fails, traffic can be dynamically rerouted through alternative paths, making it particularly valuable for mission-critical applications that require high reliability and consistent quality of service (QoS).

1.4. Traffic splitting in MANETs

Traffic splitting involves dividing data packets into multiple streams and sending them across different routes. In MANETs, this technique helps balance the load across available network paths, reducing congestion, enhancing fault tolerance, and increasing overall data throughput. By sending data over multiple routes, traffic splitting also minimizes the risk of data loss due to node failures or link disruptions, common in highly mobile environments like MANETs.

Building on this background, this paper presents a protocol called the Energy-Efficient Multicast Routing Protocol with Traffic Splitting for MANETs. The proposed protocol takes into account multiple QoS constraints simultaneously, including delay, energy, and path traffic. These constraints are then combined into a single metric. If a path meets the routing requirements, it is selected for transmitting data packets from the source node to a set of receiver nodes with the highest cost value. Otherwise, the Traffic Splitting algorithm is employed to distribute traffic across multiple disjoint paths.

The structure of this paper is as follows: Section 2 presents a review of related works on traffic splitting multicast and multipath routing protocols for MANETs. Section 3 offers an in-depth explanation of the proposed protocol. Section 4 presents the performance evaluation and simulation results, comparing our protocol with the MAODV and ODMRP. The final section concludes the paper. A list of abbreviations used in this paper can be found in Table 1.

Table 1. Notation table.

$\boldsymbol{S_{addr}}$	Source address
$\boldsymbol{MCD_{addr}}$	Multicast destination address
$\boldsymbol{U_{id}}$	Unique id
$\boldsymbol{RP_{info}}$	Routing path information
$\boldsymbol{REP_{info}}$	Reverse routing path information
$\boldsymbol{E_{path}}$	Minimum residual energy of the nodes
$\boldsymbol{E_{minr}}$	Minimum residual energy of the nodes
$\boldsymbol{E_{Total}}$	Total residual energy of path nodes
$\boldsymbol{D_S}$	The time to send the RREQ from the source
$\boldsymbol{Hop_{count}}$	Number of hops
$\boldsymbol{T_{Total}}$	Sum number of packets in the queue
$\boldsymbol{RT}$	Routing table
$\boldsymbol{RREQ}$	Route request packet
$\boldsymbol{RREP}$	Route reply packet

2. RELATED WORK

Multicast routing protocols in MANETs are generally classified into three main categories based on their route construction and maintenance strategies: Mesh-based protocols, Tree-based protocols and Hybrid protocols. Each category approaches routing differently to address the challenges posed by dynamic topology, limited bandwidth, and node mobility in MANETs. Tree-based multicast routing protocols in MANETs construct a single, shared multicast tree structure to connect all multicast group members. This tree-based approach minimizes redundancy in data transmission, which conserves network resources and reduces overhead. However, these protocols are often vulnerable to node mobility because a single broken link can disrupt connectivity for the entire group, so this type of protocol is not suitable for large wireless networks. Examples are Multicast Ad hoc On-demand Distance Vector routing protocol (MAODV) [2], Design of Load Balanced Multicast Routing Protocol for Wireless Mobile Ad-hoc Network (DLBMRP) [3], Ad Hoc Multicast Routing Protocol utilizing Increasing ID Numbers (AMRIS) [4].

Mesh-base Multicast Routing Protocols in MANETs establish a mesh structure for data transmission between multicast group members. Unlike tree-based multicast protocols, which rely on a single path, mesh protocols create multiple paths, forming a more resilient network capable of handling frequent topology changes due to node mobility. The redundancy provided by a mesh structure improves fault tolerance and reliability, as data can be rerouted if one path fails, so this type of protocol is suitable for large wireless networks and dynamic topology. Some mesh-based multicast routing protocols are: Pool ODMRP [5], the On- Demand Multicast Routing Protocol (ODMRP) [6] and its variations (Patch ODMRP) [7]. In MANET, nodes operate independently and have limited energy resources. Consequently, it is very important to focus on efficient multicast routing protocols for these networks. To address this issue, several efficient multicast routing protocols have been proposed, such as the efficient multicast routing algorithm based on network coding [8].

Soon Y. Oh et al. [9] proposed a multipath routing strategy with and without Network Coding to enhance reliability and robustness. This approach utilizes spatial redundancy by injecting duplicate data into the network, which improves robustness against channel and link errors caused by mobility. The dynamic routing mode switching adjusts the routing strategy based on current channel conditions. This method achieves a delivery ratio performance comparable to that of traditional multipath routing, but with significantly lower overhead in environments with high channel and link errors.

3. PROPOSED WORK

Our proposed protocol has two phases, route discovery and route reply, also each node has a RT and keeps several information about its neighbor node such as S_{add}, MCD_{add}, $Next-hop_{add}$, E_{path}. In addition, all nodes are equipped with GPS which can be used to synchronized with the GPS clock and each node knows its residual energy, which is calculated in Eqs. (1)-(4).

3.1. Energy Model

The first priority of this paper is energy management in wireless sensor nodes communication. The receiver and transmitter nodes calculate their energy consumption according to Fig. 1.

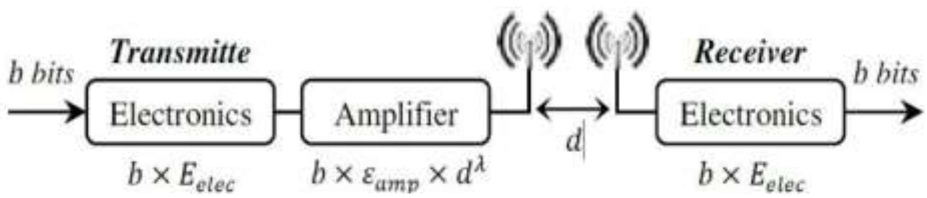

Fig. 1. First order communication mode.

A packet consisting of b bits is transmitted from the transmitter (T_x) to the receiver (R_x) over a distance of d meters, using the energy E_{T_x}. The transmission energy for the transmitter node is given by Eq. (1).

$$E_{T_x} = b \times E_{elec} + b \times \varepsilon_{amp} \times d^{\lambda} \quad (1)$$

Where, E_{elec} is the amount of energy consumed to send one bit by the transmitter circuit and $b \times E_{elec}$ is the energy required by the transmitter to propagate a packet with b bits. ε_{amp} refers to the energy consumed by the transmitter's signal amplifier over a given distance, while λ represents the route drop constant. A value of $\lambda = 2$ corresponds to the free space propagation model, whereas $\lambda = 4$ is associated with the multi-path fading propagation model.

The value of λ is determined based on the transmission distance d in relation to the threshold distance d_0 [10], and is typically calculated using Eq. (2).

$$d_0 = \sqrt{\varepsilon_{fs}/\varepsilon_{mp}} \tag{2}$$

Also, the receiver calculates the energy required to receive b bits using the Eq (3).

$$E_{R_x} = b \times E_{elec} \tag{3}$$

Thus, the energy required to transmit data between nodes s_i and s_j is represented by ei, as given in Eq. (4).

$$e_{i,j} = E_{T_x}(i) + E_{R_x}(j) \tag{4}$$

3.2. Multicast Route Discovery Phase

When a node intends to send a data packet to a group of receiver nodes, the source node first broadcasts the RREQ packet to discover a multicast routing path throughout the network. Nodes within its transmission range will then receive the RREQ. The RREQ packet contains several components in its header: $\{S_{add}, MCD_{add}, U_{id}, RP_{info}, D_S, E_{min}\}$ Where S_{add} refer source address, MCD_{add} is a set of destination addresses., U_{id} is unique message id used to identify duplicate RREQ packets, RP_{info} is used to record the complete routing path information while traveling from the source node S to a group of receiver nodes, D_S is the time to send the RREQ from the source, E_{min} is the minimum residual energy of the nodes on the path. Initially, the E_{min} is ∞ and D_S Its set by the node clock. The flow chart of the proposed algorithm is shown in Fig. 2.

When the nodes that are in the range of the transmitter, received the RREQ packet, they compare their node id with the multicast destination id (MCD_{add}) in its header. If the node id match with the multicast destination id (MCD_{add}), the route discovery process stops otherwise, they check if the RREQ is a duplicate or not:

If the RREQ packet is not duplicated, each node will compare its remaining energy with the value in the E_{min} field and the minimum value in the E_{min} will be overwritten (the newest E_{min} = min {Previous E_{min}, Current energy of the node}) and these nodes updates their RT with the current value of E_{min} in E_{path} and other fields for this RREQ. But when RREQ was duplicated:

The value in the E_{min} is compared with the previous value recorded in the E_{path} field in the RT belonging to the same RREQ and if the value in the E_{min} was less than or equal to the value in the E_{path} ($E_{min} \leq E_{path}$), The duplicate RREQ packet is discarded otherwise, ($E_{min} > E_{path}$) it records the value in the E_{min} instead of the value in the E_{path} ($E_{path} = E_{min}$) for this RREQ and it does not discard the packet and makes it broadcast again. the advantage of comparing the E_{min} field with the E_{path} field for duplicate RREQ packet is that: When nodes receiving RREQ packets from a longer path and discarded as duplicate RREQ packets, which may have better energy, traffic, and bandwidth (in this paper, we have considered only the residual energy and more parameters can be considered) And these paths are never or rarely used, be prevented and of all the nodes in the network are used almost equally. The same mechanism is followed by all nodes to locate the destination node.

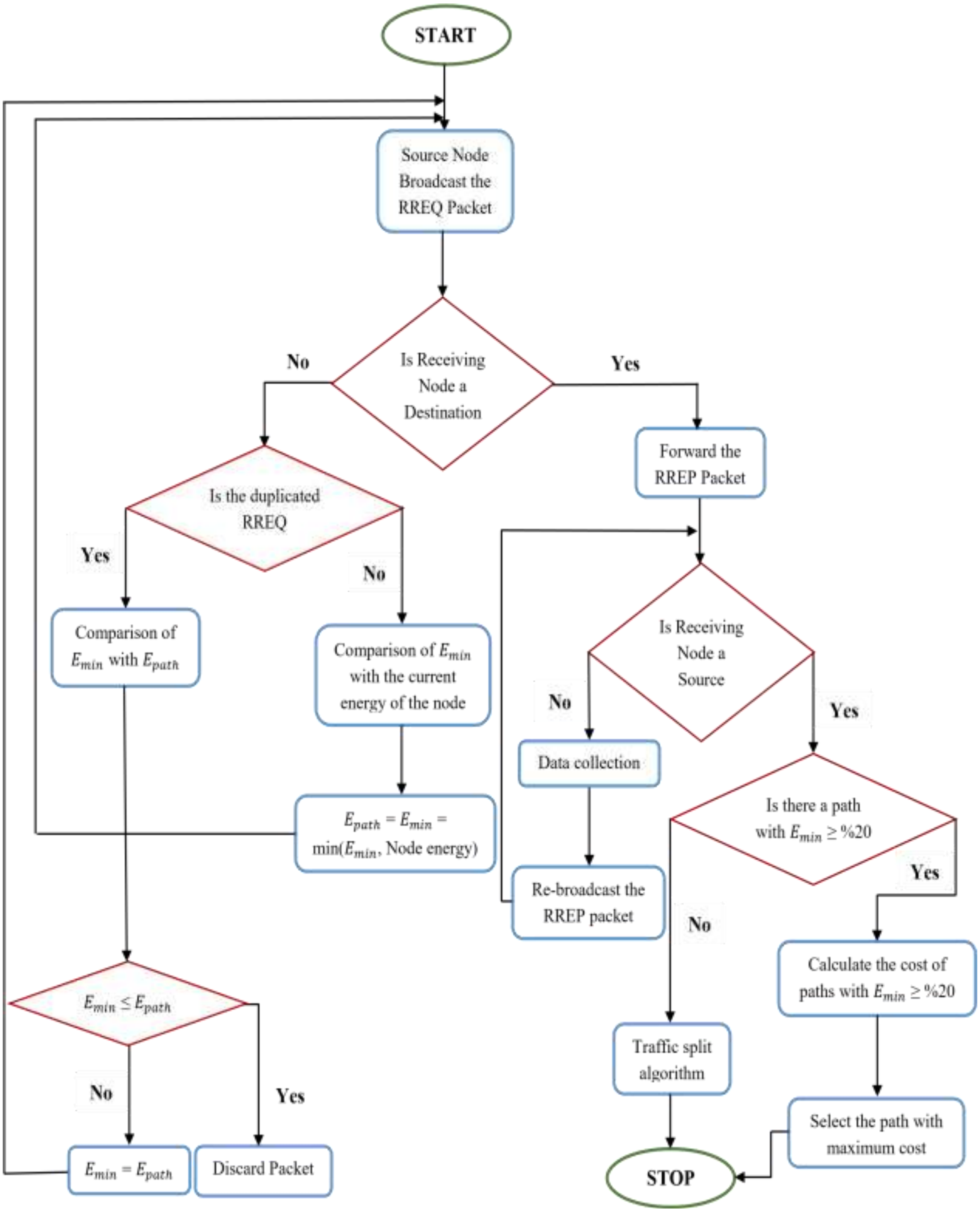

Fig. 2. Multicast routing flow chart.

3.3. Multicast Route Reply Phase

When the receiver nodes receive the RREQ packet, it create the RREP and forward it to the source node S along the routing path indicated in the header of the RREQ packet. An RREP packet contains several components in its header: $\{S_{addr}, RevPath_{info}, U_{id}, MCD_{addr}, E_{minr}, E_{Total}, Hop_{count}, T_{Total}, D_{e\ to\ e}\}$. Where S_{addr} is source address, the reverse path is referred to by the $RevPath_{info}$ field to carry the RREP packet, U_{id} is the reply packet unique id, MCD_{addr} refer the multicast destination address, E_{minr} refer to the minimum residual energy of the node in the path, E_{Total} the total energy residualing in the nodes of the return path (when each node receives an RREP packet, it sums its current residual energy with the value in the E_{Total} field), Hop_{count} is the number of hop from the destination to the source (each node increments the Hop_{count} field in the RREP packet by one unit when receiving the RREP packet), T_{Total} the sums of the packets in the queues of the return path nodes (when each node receives an RREP packet, it sum the number of packets in its queue to the value in the $\mathrm{T_{Total}}$ field), $D_{e\ to\ e}$ subtracting the time to send the packet (D_S) and the time to receive the packet $\{Time_{sender}(D_S) - Time_{receiver}\}$. Initially, $E_{Total}, Hop_{count}, T_{Total}$ is zero. As soon as the RREP packets are received by the source node S:

It makes two groups (A and B), the paths that have the E_{minr} value in the RREP packet greater than or equal to 20% (the paths with $E_{minr} \geq \%20$, in group A) will be placed in group A and other paths in group B (the paths with $E_{minr} < \%20$, in group B).

From the paths that are in group A, the cost of each path is calculated using eqs (5)-(9) and the highest cost is identified as the optimal path, after which the data packet becomes ready for transmission to a group of receiver nodes.

$$N_{mid_i} = Hop_{count_i} - 1 \tag{5}$$

Where N_{mid_i} is the number of nodes between source and destination in a particular path.

$$T_{emty_i} = 1 - \frac{T_{Total_i}}{N_{mid_i} \times Q} \tag{6}$$

Q is the buffer size of each node and T_{emty_i} is the percentage of empty traffic of a particular path.

$$E_{path_i} = \frac{E_{Total_i}}{N_{mid_i} \times E_{initial}} \tag{7}$$

$E_{initial}$ is the maximum energy of each node (initial energy) and E_{path_i} is the percentage of residual energy of a particular path.

$$D_{path_i} = \frac{D_{e\ to\ e_i}}{\sum_{i=1}^{n} D_{e\ to\ e}} \tag{8}$$

$$Cost_{path_i} = 0/36\, T_{emty_i} + 0/36\, E_{path_i} + 0/28\, D_{path_i} \tag{9}$$

$Cost_{path_i}$ is the cost of a particular path and if there are multiple paths with the same cost, one of the paths is randomly selected.

But if there is no path in group A, the data packets are distributed among all the paths in group B to send the data packet to a group of receiver nodes using Eqs. (10)-(11).

$$T_{allocate_i} = 0/5\, \frac{T_{emty_i}}{\sum_{i=1}^{n} T_{emty_i}} + 0/5\, \frac{E_{path_i}}{\sum_{i=1}^{n} E_{path_i}} \tag{10}$$

Where $T_{allocate_i}$ is the percentage of all data packets that are allocated to a particular path.

$$Packet_{allocate_i} = T_{allocate_i} \times Data_{all} \tag{11}$$

$Packet_{allocate_i}$ is the number of total data packets that must be sent through a particular route and $Data_{all}$ is total number of data packets to be sent to destinations. If the value of $Packet_{allocate_i}$ is decimalized: A decimal greater than or equal to 0/5 should be rounded up, otherwise it should be rounded down.

4. PERFORMANCE ASSESSMENT

In this section, the proposed protocol is evaluated using the Network Simulation 2 (NS-2) and to show the capability of the proposed protocol, this method is compared with the MAODV and ODMRP multicast routing protocols in terms of packet delivery ratio, packet delivery delay and residual energy..

4.1. Simulation Setting

This protocol is simulated in a wireless MANET in the area of 800 × 800 m^2 which has 15–300 mobile nodes. In the simulation, for the node mobility model, the random waypoint network model has been used, in which the nodes randomly choose their direction of movement. The free space propagation model has been used for the simulation propagation model, which shows the communication range as a circle around the nodes. The type of traffic used in the simulation is Constant Bit Rate (CBR). The initial energy is 100 joules (J) for each node and also, the energy consumption of sending packets for each node is 0/66 J and the energy consumption of receiving packets for each node is calculated as 0/395 J. Table 2 provides all the parameters used in the simulation.

- Packet delivery ratio (PDR): PDR measures the success rate of packet transmissions in the network by comparing the number of data packets successfully received by the destination nodes to the total number of packets sent by the source nodes. It is an indicator of the reliability and effectiveness of a routing protocol in maintaining stable paths and ensuring data delivery across a network.

$$Packet\ delivery\ ratio = \frac{\sum Number\ of\ packet\ receive}{\sum Number\ of\ packet\ send} \tag{12}$$

- Packet delivery delay: Packet Delivery Delay in MANETs refers to the average time taken for a data packet to travel from the source node to the destination node. This delay is a critical performance metric in MANETs as it directly affects the QoS for applications, especially those that are time-sensitive, such as real-time video streaming, voice communication, or other delay-sensitive tasks.

$$Packet\ delivery\ delay\ = \frac{\sum (arrive\ time - send\ time\ )}{\sum No.of\ connection} \tag{13}$$

Table 2. Parameters used in the simulations.

Parameters	Values
Examined protocols	Proposed protocol, MAODV, ODMRP
Simulation area	1000 m × 1000 m
MAC protocol	IEEE 802.11
Number of nodes	15–300
Multicast group size	5–40
Mobility speed	1–100 m/s
Initial energy	100 J
Mobility model	Random waypoint model
Propagation model	Free space
Node transmission ranges	250 m
Simulation time	150 s, 450 s
Data packet size	512 bytes
Queue length	150
Energy consumption of packet sending	0/66 J
Energy consumption of packet reception	0/395 J

4.2. Simulation results and analysis

In this section, we evaluate the proposed protocol in terms of parameters like residual energy, control overhead, PDR and packet delivery delay.

Due to the high mobility of MANETs, which creates uncertainty issues, the network metrics often change, which makes the source node unable to select an optimal multicast routing path, and Fig. 3 also shows that as the mobility of the node increases, the PDR decreases. The proposed protocol addresses uncertainty issues by making a more optimal selection from a larger set of discovered paths, allowing it to choose the best multicast routing path. As a result, the performance of the proposed protocol surpasses that of MAODV and ODMRP protocols in terms of packet delivery ratio.

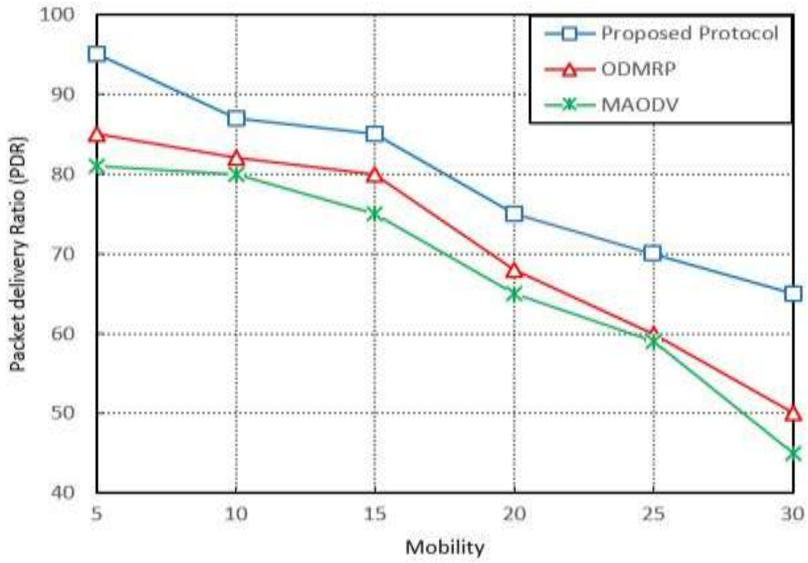

Fig. 3. Packet delivery ratio vs. mobility.

Fig.. 4 shows that the proposed protocol has a better performance than the other two protocols in terms of packet delivery ratio with increasing number of nodes. The PDR increases as the number of nodes in a MANET grows. This is because a higher node count provides more opportunities to establish stable routing paths, reducing the likelihood of data loss. The proposed protocol achieves a higher PDR than MAODV and ODMRP by distributing the workload more evenly across network nodes, preventing rapid depletion of any particular node's energy. As nodes approach low energy levels, the protocol utilizes traffic splitting to send more packets to their destinations, thereby extending the overall network lifespan.

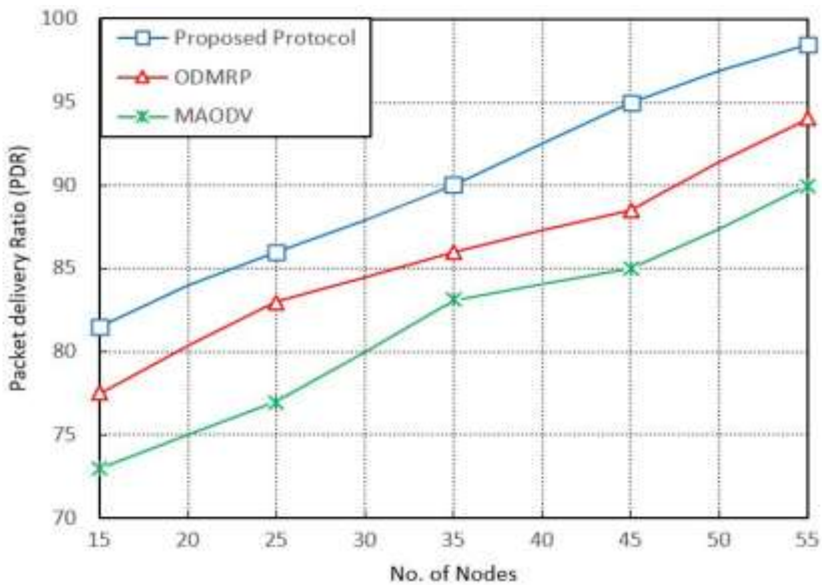

Fig. 4. Packet delivery ratio vs. number of nodes.

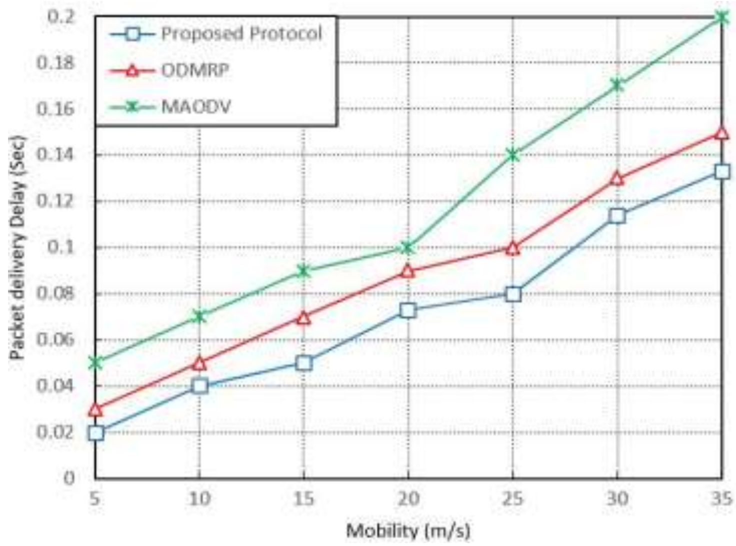

Fig. 5. Packet delivery delay vs. mobility.

Fig. 5 illustrates the impact of different mobility speeds on packet delivery delay. As node mobility increases, packet delivery delay also rises. This is because high mobility causes network metrics to change frequently, making it challenging to select a stable and optimal multicast routing path. As a result, additional time is spent on finding the best routing path due to uncertainty, which contributes to the overall packet delivery delay. The proposed protocol performs better than both MAODV and ODMRP.

Fig. 6 shows that packet delivery delay gradually rises as the number of nodes increases. This is due to the higher traffic load, which leads to more time spent selecting an optimal multicast routing path. As node numbers grow, additional time is required for this path selection process. To address network uncertainty, counting packets in queues and calculating both packet delay and end-to-end delay can help identify better paths. The proposed protocol effectively reduces packet delivery delay by selecting an optimal multicast routing path based on a proposed equation, unlike MAODV and ODMRP, which do not account for this factor.

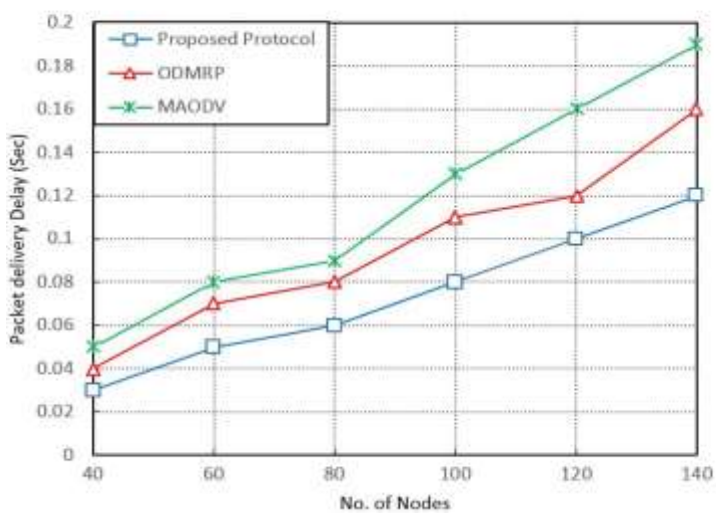

Fig. 6. Packet delivery delay vs. no. of nodes.

Network lifetime or network (link) stability time, is the length of time the network is stable and can send data packets. The amount of residual energy in mobile nodes, directly affects the network lifetime. As shown in Fig. 7 By choosing the high-energy path, it prevents network nodes from dying quickly. Since the paths are selected based on the residual energy and the average energy consumption, the network lifetime is increased and the network stability and link stability are better than the other two methods.

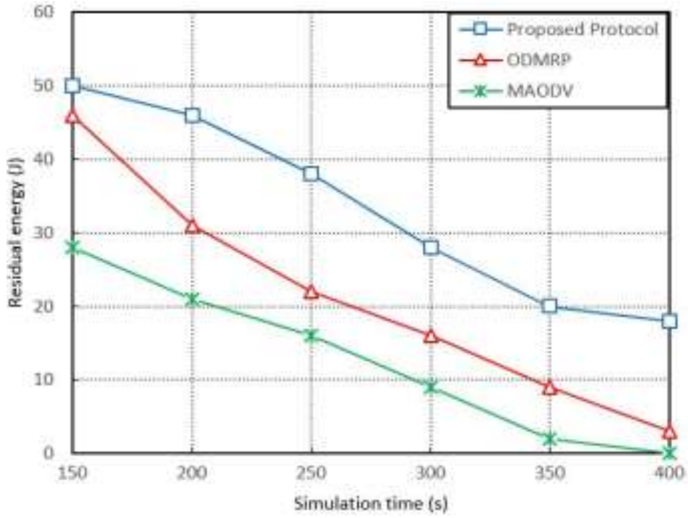

Fig. 7. Residual energy vs. simulation time.

5. CONCLUSIONS

This paper introduces an energy-efficient multicast routing protocol for MANETs that incorporates traffic splitting and addresses multiple constraints. In wireless networks, the high mobility of devices causes frequent changes in network metrics, leading to uncertainty and inefficient resource utilization. These challenges often result in suboptimal multicast routing paths for data transmission. To tackle these problems, the proposed protocol utilizes traffic splitting and selects multicast routes based on the maximum cost value, aiming to enhance overall network performance. The protocol's effectiveness is evaluated against existing multicast routing protocols (MAODV and ODMRP) by comparing key metrics such as PDR, residual energy, and packet delivery delay, demonstrating superior performance over the alternatives.

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