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# Fuzzy Logic-Based Congestion Control in AODV Mesh Networks \*

\*Mitigating Traffic Congestion

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**Abstract**— Mesh networks refer to a wireless network capable of self-configuration that does not rely on a fixed infrastructure. The management of network congestion is a crucial concern in such networks owing to the restricted resources and the constantly changing topology of the network. Implementing a decentralized routing protocol, including the AODV routing protocol, is prevalent in mesh networks, where individual nodes are intermediaries for transmitting data packets. Congestion may arise due to network overload, leading to elevated packet loss, prolonged latencies, and suboptimal resource allocation. The present study suggests using a fuzzy logic approach to regulate the latest broadcast packet information within the AODV routing protocol. This technique aims to mitigate congestion in mesh networks and improve the performance of AODV. The study's main findings indicate that incorporating fuzzy logic into the routing protocol can enhance network performance and optimize the use of network resources. The results demonstrate a 97.78% to 96.43% PDR, a 4.41% to 5.93% PLR, and a routing overhead of 4.41% to 5.93% compared to other protocols. These outcomes suggest that fuzzy logic could effectively improve routing in mesh networks.

**Index Terms**—MANET, Mesh, AODV, network congestion, fuzzy logic, routing protocol

## I. INTRODUCTION

Wireless networks that conform to the IEEE 802.11 standard are considered one of the most effective ways to make networks accessible to users in all locations. Wireless technology has given rise to two fundamental wireless network models: infrastructure-based and infrastructure-less [1], [2]. In the absence of a pre-existing network backbone consisting of fixed base stations, conventional wireless networks take the

form of mesh networks, which consist of mobile nodes with varying degrees of mobility. Mesh, also known as multiple-hop networks, are characterized by each mobile node performing the functions of both a node and a router [2], [3]. In other words, each node in the Mesh network serves two purposes: a host and a router. Therefore, each node makes it possible to create a multi-hop path inside the network. Communication between wireless nodes occurs through wireless links. Since there are no restrictions on a node when it comes to joining or leaving the network, the mesh has a highly dynamic topology [4].

In several scenarios, there may be better options than an infrastructure network. For example, the primary purpose is Internet access or an application speaking in a local area network with many nodes that can move around. In that case, an access point may only be able to communicate with some mobile wireless nodes due to constraints such as transmission range. If routing is handled in the wireless domain, communication is feasible even under these conditions. Furthermore, the mesh network could better solve earthquakes, floods, natural disasters, or even military operations [5]. Therefore, a mesh is a suitable choice for such situations where quick reinstatement of communication is necessary.

Creating an effective routing protocol is one of the technological hurdles that must be overcome before the full potential of mesh can be realized. Multi-hop routing faces obstacles such as changing network topology, traffic, channel contention, and limited wireless bandwidth [6], [7]. Congestion control refers to the techniques and mechanisms to reduce or eliminate congestion. Congestion control improves a network's performance by reducing the time the network's resources

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are held up due to congestion and the chance that a buffer will overflow. Congestion control in wired networks is often implemented at the transport layer and is usually considered independent of the responsibilities of other tiers. Mesh networks face issues that fixed networks do not have, such as limited wireless bandwidth, power, and route failures due to the mobility of the nodes. Therefore, conventional congestion control methods cannot be directly applied to them. As more data is transmitted through a network, congestion increases the likelihood of packet loss, rerouting instability, resource and bandwidth waste, and the need to retransmit previously sent data [8].

As mentioned earlier, network congestion occurs when the number of packets travelling across a network exceeds the number of packets the network can process simultaneously. Therefore, selecting the routing protocol presents a critical and challenging issue. Consequently, various routing protocols, such as Ad-Hoc On-Demand Distance Vector Routing (AODV), Dynamic Source Routing Protocol (DSR), Optimized Link State (OLSR), AODV-based Adaptive Backup Routes (AODV-ABR) [9], have emerged to deal with these issues.

One of the link failure recovery methods that can be employed is the AODV-based Adaptive Backup Routes (AODV-ABR). Once a node discovers a link failure, it initiates a three-way handshaking procedure, as described in AODV-ABR (Adaptive Backup Routing) proposed by [9]. This method relies on the information in RREP packets containing the hop count to the destination node. This approach transfers data without sending many extra control messages.

The present study discusses techniques and methods to minimize routing overhead [10]. When a network's topology changes constantly, sending out data packets, such as RREQ packets, may result in excessive routing overhead. In order to tackle this matter, the research paper presents a routing framework that considers the quality-of-service (QoS) aspect. This framework incorporates three fundamental QoS mechanisms: the cross-layer communication mechanism, the session admission control (SAC) process, and the QoS-aware routing mechanism. This framework efficiently transmits real-life video traffic over mobile Ad-Hoc networks (MANETs).

This study presents an extension of the Ad-Hoc on-demand multipath distance vector (AOMDV) routing protocol for mobile ad-hoc networks (MANETs). A novel protocol called bandwidth-aware multipath reactive (BAMR) is also proposed. The suggested protocol aims to locate corridors with sufficient bandwidth and fewer instances of link failure. The proposed protocol's primary objective is effectively utilizing the bandwidth [11].

Several protocols have been developed to deal with the issue of congestion, such as those presented in [7], [12]–[18].

The present study focuses on congestion control in mesh networks. Due to the unique impacts of mesh and the distinct architecture of TCP, the two perform poorly together. TCP was developed for the Internet, which has different characteristics than today's networks. Therefore, proper congestion

control is a significant challenge for mesh. Specifically, the proposed paper presents a flow-controlled end-to-end approach that employs a novel method to control congestion dynamically. A congestion-tolerant path discovery approach enhances throughput, packet loss, end-to-end delay (E-2-E Delay), and normalized routing overhead (NRL), thereby preventing network overload.

In a network where resources are shared, each sender must adjust their data transfer rate to keep the network from becoming overloaded. Packets that are unable to be forwarded upon arrival at a router are discarded. As a result, an excessive number of packets at a network bottleneck results in a significant occurrence of packet drops. These packets have earlier consumed significant resources by travelling a long way through the network. In addition, the occurrence of lost packets frequently initiates re-transmissions, resulting in an increased influx of packets being transmitted within the network. Network congestion has the potential to diminish network throughput considerably. Inadequate management of network congestion can result in a phenomenon known as "congestion collapse," characterized by a significant reduction in data transmission rates. The issue about the early Internet catalyzed the development of the congestion control mechanism within the Transmission Control Protocol.

The remainder of this article follows an ordered approach. Section II, presents a comprehensive overview of the literature review in this study. Section III, provides an introduction to the mesh routing protocols overview. The proposed approach, which includes a fuzzy technique model and dynamic congestion-tolerant routing, is presented in Section IV. In Section V, the simulation scenario is described. The findings from NS2 simulations are presented in Section VI, showing that the proposed protocol performs better in comparison to the current standard protocols in packet delivery rate, packet consumption control, and end-to-end delay. Finally, the conclusion is presented in section VII.

## II. LITERATURE REVIEW

Numerous proposals have been put forth concerning the implementation of congestion-avoidant commuting plans. As such, congestion in mesh networks has garnered significant attention and has been the subject of numerous studies. These investigations have put forward diverse approaches to address this issue, including clustering, hierarchical routing, and congestion control. Nevertheless, it is noteworthy that these approaches possess certain constraints, as they may lead to high overhead, heightened intricacy, and reduced scalability.

In [19], a fuzzy logic-based routing mechanism for AODV is proposed to enhance system stability. The trust value of the output variable is determined in this approach by utilizing input variables, specifically remaining energy, speed, and hop count. A trust value is determined for every intermediate node that plays a role in establishing a route between the source and destination nodes. The NS-2.35 simulator was used to compare the AODV, fuzzy AODV, and MBCR routing protocols so that the effectiveness of the proposed fuzzy AODV routing

protocol could be judged. The results of the experiments showed that the fuzzy AODV algorithm, as it was proposed, had the best performance in many ways, such as throughput, packet delivery ratio, average end-to-end delay, and average routing load. Significantly, even in environments characterized by high mobility, the fuzzy AODV demonstrated commendable performance.

To further augment the performance of the AODV routing protocol, a fuzzy-based approach is also proposed by Nihad I. Abbas. This method selects nodes with the highest level of credibility to determine the most suitable path between the source and destination nodes. The study of [20], have also proposed an alternative multipath protocol, termed the Fibonacci Multipath Load Balancing (FMLB). In this approach, the source detects  $K$  distinct routes, which are then arranged in ascending order based on the number of hops required. Next, the FMLB protocol assigns weights to each route, as follows:  $\text{Fibonacci}(K)$ ,  $\text{Fibonacci}(K - 1)$ ,  $\dots$   $\text{Fibonacci}(2)$ ,  $\text{Fibonacci}(1)$ . The number of packets transmitted down each path is contingent upon the size of data contained within each packet.

The Dynamic Load-Aware Routing (DLAR) protocol, as proposed by Sung-Ju Lee, is designed to address congestion management in Wireless Ad-Hoc Networks (WANETs) [21]. The protocol utilizes the number of packets buffered by intermediate nodes as a primary metric to determine the optimal path with the least amount of congestion. Notably, throughout the duration of an active data session, the destination node assumes the responsibility of monitoring the congestion level of the route. In the event of congestion, the destination node initiates the process of selecting a new path to avoid congestion.

The Dynamic Congestion Detection and Control Routing (DCDR) protocol, introduced by [7], proposes a congestion management approach based on the average queue length at each node. Specifically, the protocol considers a node to be safe when the average queue length is less than the minimum threshold ( $\text{Avgque} < \text{MinThreshold}$ ) and the instant queue length is less than half the maximum queue size ( $\text{Instque} < \text{QueueSize}/2$ ). In contrast, if the average queue length falls within the range of  $\text{MinThreshold}$  and  $\text{MaxThreshold}$  ( $\text{MinThreshold} < \text{Avgque} < \text{MaxThreshold}$ ), the node is deemed congested, and a substitute route selection process is initiated. Furthermore, the substitute route selection status is reset if the instant queue length exceeds the  $\text{MaxThreshold}$  due to incoming traffic. In this case, the  $\text{MaxThreshold}$  value is adjusted to ensure the accuracy of the substitute route selection process. When a node enters a congested state, it alerts its neighbouring nodes, which subsequently search for an alternate path to avoid traffic.

The Multipath Load Balancing Method for Congestion Control (MLBCC), introduced by [22], is designed to manage congestion in Mobile Ad-Hoc Networks (MANET) by ensuring even load distribution. The protocol leverages packet arrival and outgoing rates to detect congestion levels over a specific time interval. Furthermore, link and path costs are employed to

select the gateway node. When the path's throughput exceeds a predetermined threshold, the traffic is routed through the designated gateway node.

The ARCCRP, as proposed by [23], is a technique that enables Mobile Ad-Hoc Networks (MANETs) to resume normal operations by selecting different routes to avoid congested areas. Specifically, when a node encounters congestion on a local outbound connection  $L$ , and that path includes link  $L$ , it determines multipath routes to its destinations. Consequently, some of the node's traffic is redirected to an alternative route.

When the utilization of a local link surpasses a predefined local congestion threshold (T.H.), the link is classified as congested. The main aim of this endeavour is to decrease network utilization to a more controllable extent by redirecting specific traffic onto alternative pathways, referred to as bypass traffic. When a network node perceives congestion on a local link or receives an Explicit Congestion Indication (ECI) bit from an adjacent node, it computes a collection of alternative pathways. The distribution of bypass traffic is evenly allocated among the aforementioned routes.

The ECI bit serves as a means of communication among nodes. The authors compared ARCCRP, the Hop-by-Hop method, and the default TORA routing protocol [23], [24]. The study's findings indicated that the implementation of ARCCRP resulted in an enhancement of data transmission capacity, accompanied by a decrease in packet loss and a reduction in the associated overhead.

The paper's author introduces a new routing protocol, Cross-Layer Design and Fuzzy Logic-Based Stability Oriented (CLDFL-SO), presenting a practical approach for establishing stable routes by eliminating unstable links and low-quality nodes [25]. In order to assess the stability of the link, a link residual lifespan estimate is utilized, which is based on a cross-layer interaction parameter. Furthermore, the utilization of fuzzy logic is employed in the evaluation of node quality through the integration of various parameters, including residual energy, node speed, and node degree. The link stability status (LSS) is determined using the link residual lifespan estimation within the cross-layer design. The study involves the utilization of simulations to evaluate and compare the efficacy of the proposed CLDFL-SO routing protocol with the AODV routing protocol. The obtained results support the CLDFL-SO protocol's superior performance in establishing and maintaining stable routes.

From the studies above, there have been several approaches to addressing the congestion problem in mesh networks. However, few studies have attempted several techniques to reduce congestion, but still, the AODV routing protocol raises the drawbacks of high overhead, increased complexity, and decreased scalability. This is the gap that this proposed work aims to fill by using fuzzy techniques to reduce congestion.

### III. MESH ROUTING PROTOCOLS OVERVIEW

Traditional mesh protocols might be categorized into two groups: pro-active and reactive routing protocols [26]. The categories mentioned earlier are derived from distinct routing

methodologies. The table-driven routing protocol is commonly called the initial category of routing protocols.

This protocol involves the maintenance of a routing table by each node, which includes information about all other nodes in the network. An example of such a protocol is the Optimized Link State Routing (OLSR) protocol, commonly used in this context. The routing protocol known as on-demand routing protocol is alternatively referred to as reactive routing protocol. This protocol establishes the routing path when a source node transmits data. Dynamic source routing protocol (DSR) [27], Ad-Hoc on-demand multipath distance vector (AOMDV), Ad-Hoc On-Demand Distance Vector (AODV) [28], and Fuzzy Control Energy Efficient (FCEE) protocols are commonly used to route data among connected devices.

#### A. Ad-Hoc On-Demand Distance Vector - AODV

The AODV protocol, widely employed in wireless networks, particularly within research networks, serves as a reactive routing protocol. This protocol facilitates both unicast and multicast routing operations. The route discovery process commences when an RREQ packet is to neighbouring nodes within its transmission range. Subsequently, upon receiving the RREQ packet, each node evaluates the availability of a novel route towards the intended destination or its own identity as the destination. In response, the node transmits a unicast route reply (RREP) packet exclusively to the source node [29].

The AODV protocol adheres to a standardized approach, selecting the path to target nodes based on the minimum hop-count parameter without considering the specific characteristics of the nodes involved in constructing the route. However, when the source node receives multiple RREP packets, it opts for the route with the minimum number of hops. In the event of a route link failure, an error packet named RERR (Route Error) is generated and conveyed back to the initiating node of the communication. Should the route remain essential or additional packets need to be transmitted, the source node initiates the route discovery process once again.

During the initial phase of the AODV protocol, the source node disseminates an RREQ (Route Request) packet through the broadcasting process. Assume that an intermediate node receives the Route Request (RREQ) packet but does not correspond to the destination node nor possess a direct path to the destination. The packet will be retransmitted in such an event while raising the HOP-COUNT argument by one. However, when the intermediate node acts as the destination, it abstains from retransmitting the RREQ packet. The intermediate node may receive multiple Route Request (RREQ) packets from neighbouring nodes. These packets may possess identical identification and sequence numbers, but their HOP-COUNT values may vary. The node evaluates each RREQ packet individually, modifies its reverse route table accordingly, and retransmits the RREQ packet only if its HOP-COUNT value is lower than that of previously received RREQ packets sharing the identical ID. If the RREQ packet possesses a sequence number that is either lower or equal, the node proceeds to discard the packet. An intermediate node can engage in

multiple repetitions of propagating a given identifier RREQ packet.

However, the standard AODV protocol wastes network bandwidth resources, increases network traffic, and unnecessarily consumes energy, particularly in high-density wireless mesh networks.

#### B. Stable-AODV (STAB-AODV)

This study offers an improvement upon the AODV routing protocol for Mobile Ad-Hoc Networks (MANETs) named Stable-AODV (STAB-AODV) [30]. Using the number of currently connected nodes, the STAB-AODV protocol offers a new metric termed the "route stability factor" to assess the reliability of a given path. To increase network speed and decrease the frequency of route failures, the protocol considers this stability factor when deciding which route to forward data packets. The study also presents a system for dealing with route failures and reducing the number of control messages needed for route discovery. Compared to the baseline AODV protocol, the proposed STAB-AODV protocol improves upon it regarding packet delivery ratio, end-to-end delay, and routing overhead, as shown by the simulation results.

#### C. Signal Strength AODV

The proposed routing protocol, Signal Strength-Based Ad-Hoc On-Demand Distance Vector (SSAODV), is designed specifically for the context of MANETs [31]. The SSAODV protocol incorporates a route selection mechanism that considers both signal strength and link quality to improve the network's overall performance. The protocol employs a threshold value to evaluate the signal strength and determine the quality of links. Afterwards, it determines the most efficient route for transmitting data by selecting paths with the highest signal strength. The authors have introduced a new metric, called the "Neighbourhood Knowledge Factor," to improve the process of selecting routes. This metric considers the number of nodes with information regarding the most efficient route. The study used NS-2 simulation to compare the proposed SSAODV protocol to the conventional AODV protocol. According to simulations, SSAODV outperforms AODV in packet delivery ratio, end-to-end delay, and routing overhead. The findings suggest that the SSAODV protocol exhibits potential as a viable approach to enhance the efficiency of Mobile Ad-Hoc Networks (MANETs) by utilising signal strength and link quality to determine more dependable routes.

### IV. THE PROPOSED ALGORITHM BASED ON FUZZY LOGIC

The AODV-based FUZZY CONTROL ENERGY EFFICIENT (FCEE) routing protocol has been enhanced to include a fuzzy logic inference mechanism. These changes aim to improve route selection and network performance. In the FCEE protocol, reactive computing is employed among the nodes to ensure that traffic congestion is mitigated effectively. This is achieved using fuzzy logic techniques that enable the nodes to make intelligent decisions based on the current network conditions. Therefore, the FCEE protocol demands

reactive computing for its effective implementation. This section of the paper presents a mechanism and provides a detailed description. The ensuing discussion has been methodically organized into distinct sections to enhance clarity and facilitate the searchers' comprehension.

#### A. An Overview of Fuzzy Logic

This study presents the design and performance of the Fuzzy Logic-based Congestion-Tolerant Routing Protocol, an approach routing protocol for wireless mesh networks. To better handle network congestion, this protocol makes use of fuzzy logic. The present subsection looks at fuzzy logic, a valuable tool for assisting humans in decision-making in the face of ambiguous or missing information.

Machines, on the other hand, typically lack this capability. Zadeh introduced fuzzy logic to incorporate human-like thought processes into a control system in 1965. Fuzzy logic is distinguished by its low processing overhead and ability to deal with nonlinear, time-varying, uncertain systems.

#### B. Fuzzy Logic System (FLS)

Fig. 1, depicts a control system that is based on fuzzy logic principles. The Fuzzy Logic System (FLS) is composed of several key components, which are enumerated below.

- **Fuzzifier:** A fuzzifier is a critical module within a Fuzzy Logic System (FLS) that converts crisp input data into fuzzy sets. This process transforms data from a classical (crisp) form into a fuzzy representation.
- **Knowledge Base:** All fuzzy rules are stored in knowledge-base.
- **Inference Engine:** Is responsible for deliberating and selecting an optimal course of action based on the input data that has been fuzzified. The output of the inference engine is represented in the form of a fuzzy set.
- **Defuzzifier:** It converts fuzzy set back to classical/crisp values.

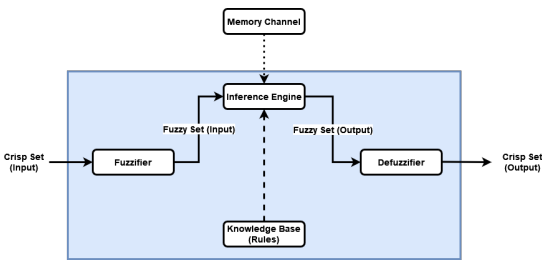


Fig. 1. Proposed Memory Channel based FLS.

#### C. Proposed Architecture of Fuzzy Control Energy Efficient (FCEE) Routing Protocol

This subsection outlines the proposed design for the Fuzzy Logic-based Congestion-Tolerant Routing Protocol (FCEE) for wireless mesh networks. Specifically, the paper presents an approach to fuzzy logic that leverages short-term memory, as detailed in subsection IV-D. Then the present work integrates the proposed architecture into the AODV routing protocol to

enhance its congestion management capabilities. As discussed in the following subsections, this integration enables the FCEE protocol to effectively manage network congestion and improve overall performance.

#### D. Proposed Short-term Memory Channel-Based FLS

This subsection introduces a novel Memory Channel module into the Fuzzy Logic System (FLS) to enhance its decision-making capabilities. The general architecture of the FLS is depicted in Fig. 1, which also features the proposed new design. Notably, the new design integrates a Memory Channel, which maintains a record of state variable(s), such as the last broadcast information. In conjunction with the knowledge-based fuzzy rules, the inference engine leverages this state information to generate a fuzzy output set. Subsequently, the fuzzy output set is fed into the Defuzzifier module to produce the final output.

The proposed model utilizes a memory channel to maintain node state information, specifically the broadcast packet parameter. The objective of the research is to design a congestion-tolerant routing protocol, which means that broadcast packets can affect network throughput and become a source of congestion and packet loss. The node's remaining energy level and the last broadcast packet sent information are used to decide whether or not to forward the broadcast packet. The inference engine uses fuzzy rules presented in Table I.

TABLE I  
FUZZY RULES

Rules	Energy Level	Last Broadcast	Decision (Forward Broadcast)
Rule 1	High	Yes	Yes
Rule 2	High	No	Yes
Rule 3	Good	Yes	No
Rule 4	Good	No	Yes
Rule 5	Average	Yes	No
Rule 6	Average	No	Yes
Rule 7	Low	Yes	No
Rule 8	Low	No	Yes

#### E. Fuzzification

The Fuzzifier module depicted in Fig. 1, is instrumental in performing the fuzzification process, which is achieved through the utilization of the membership function presented in equation (1). This equation plays a pivotal role in determining a given node's membership.

Specifically, the work presented in this paper defined four linguistic variables to express a node's energy level, namely: (i) high, (ii) good, (iii) average, and (iv) low. The graph of equation.1, is presented in Fig. 2, with scalar values  $p$ ,  $q$ ,  $r$ ,  $s$  used to shape the function accurately. The scalar values 'p' and 'q' are used to construct the trapezoid base, while 'r' and 's' are used to construct the top of the trapezoid. Furthermore, table II, which is presented in this paper, is leveraged to define the fuzzification process in greater detail.

$$\mu(x) = \begin{cases} 0 & \text{if } x \leq p \\ \frac{x-p}{r-p} & \text{if } p \leq x \leq r \\ 1 & \text{if } r \leq x \leq s \\ \frac{q-x}{q-s} & \text{if } s \leq x \leq q \\ 0 & \text{if } q \leq x \end{cases} \quad (1)$$

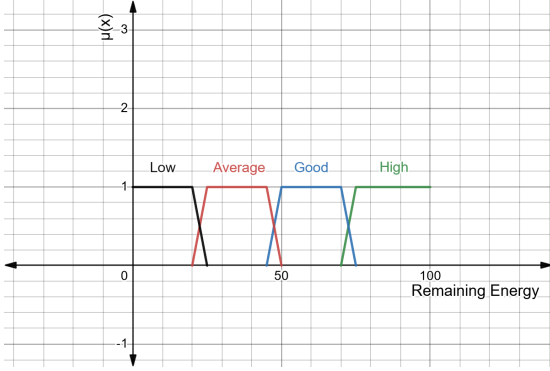


Fig. 2. Membership function for Proposed FLS.

TABLE II  
FUZZIFICATION

Remaining Energy (RE)	Level of Energy
If a node has RE greater than 75%	High
If a node has RE greater than (or equal to) 50% and less than 75%	Good
If a node has RE greater than (or equal to) 25% and less than 50%	Average
If a node has RE less than 25%	Low

Network congestion is a common challenge that often occurs at intermediate or routing nodes along the transmission path. These nodes are responsible for making routing decisions and are commonly called routing nodes. A routing node, also known as a router, determines the optimal path for a packet and forwards it to the next hop or destination. Broadcast traffic is another significant contributor to congestion, particularly on networks with high levels of broadcast traffic.

The Fuzzy Control Energy Efficient (FCEE) routing protocol was recently developed to mitigate this issue. This protocol utilizes fuzzy logic and memory channels to regulate broadcasting in an effective manner, resulting in a more efficient optimization of network load and a reduction in congestion levels within the network.

## V. SIMULATION SCENARIO

The present article employs Network Simulator 2 version 35 (NS2.35), which is a discrete event simulator designed explicitly for networking research. NS2 provides robust functionality for simulating a range of networking protocols, including TCP, routing, and multicast protocols for both wired and wireless networks, including local and satellite networks. Furthermore, NS2 includes extensive support for distributed systems and

simulated communication networks, enabling accurate representation of the latter's attributes by the former. The aim of the experiment is to conduct simulations for FCEE, STAB-AODV, and SSAODV routing protocols.

### A. Simulation Modelling

Several metrics can be employed to evaluate the efficacy of mesh routing protocols. This study employed a commonly utilized performance metric to simulate the performance of wireless mesh routing protocols.

The following study considers a scenario with a node count of 60 distributed over a 800 m × 900 m area. The simulation scenario was generated using the setdest utility available with NS2. The simulation was conducted on a mobile scenario, where each node randomly chooses a destination at the beginning of the simulation. Upon reaching the destination, the node pauses for a predetermined time before moving on to a new destination.

The simulation was run for 150 seconds, and the reported results are the average values obtained from 40 iterations. The channel bandwidth was set to 512 bytes, and each node had a transmission range of 250 m. The MAC layer was based on the 802.11 distributed coordination function. The source nodes generated a constant bit rate (CBR) traffic, with a packet size of 512 bytes. The MAC layer queue size was set to 450 packets. Table III, summarizes the parameter values of the simulation scenario. The results of the simulation are presented and analyzed in VI sections.

TABLE III  
SCENARIO SIMULATION PARAMETER VALUES

Mesh network Parameters	Values
Simulator of the Network	NS-2
Routing protocols	FCEE, STAB-AODV, SSAODV
No. of nodes	60
Network area size	800 × 900 m
Time	150 s
Transmission range	250 m
Mobility model of the network	RWP
Traffic type	CBR
Packet size	512 bytes
Node speed	10, 20, 30, 40, 50 m/s

The protocols were tested and evaluated based on the following performance metrics:

- **Packet delivery ratio (PDR):** The PDR is the ratio of the number of data packets successfully received at their intended destinations to the total number of data packets that were generated by sources. This ratio can be defined as the percentage of data packets that were successfully delivered. In other words, the average packet delivery ratio indicates the completeness and accuracy of routing protocols and reflects the reliability of network transmission. A network's PDR can be measured using equation (2).

$$PDR = \frac{\sum \text{Packets received at the destination}}{\sum \text{Packets send by node}} \quad (2)$$

- **Packet Loss Ratio (PLR)** In computer networking, the percentage of data packets lost while being sent from one device to another is measured by the Packet Loss Ratio (PLR). Information travels over a network and is typically packaged into smaller chunks known as packets. Data is packetized and transferred over the network.

However, some packets may get lost during transmission for numerous causes, which can cause data loss or communication delays. To determine the packet loss rate (PLR), we divide the total number of lost packets by the total number of packets sent and then multiply that by 100. If 10% of transmitted packets are lost, the PLR is 10%.

PLR is essential for maintaining reliable network performance in network monitoring and troubleshooting. Elevated PLR values may signify network congestion, hardware failure, or other issues that require attention to ensure dependable network functionality. PLR can be calculated using the following equation (3).

$$PLR = \frac{nSentPackets - nReceivedPackets}{nSentPackets} \times 100 \quad (3)$$

Where  $nReceivedPackets$  is the number of received packets, and  $nSentPackets$  is the number of sent packets.

- **Normalized Routing Load (NRL):** The ratio between control packets (e.g., RREQ and RREP) and delivered packets can be quantified as the aggregate count of routing control packets transmitted by all nodes within the mesh network throughout the simulation duration. Equation (4), is used to calculate it.

$$NRL = \frac{\sum \text{Routing packets}}{\sum \text{Packets received}} \quad (4)$$

- **Average end-to-end delay (E-2-E delay):** The average time taken for a data packet to travel from its source to its final destination can be represented as the mean duration elapsed between the source and destination nodes during transmission, accounting for the combined effects of queuing, buffering, and propagation delays. This value can be calculated using the following equation (5).

$$\text{Average End to End Delay} = \frac{1}{N} \sum_{i=1}^N (t_r - t_s) ms \quad (5)$$

- **Average network throughput:** One way to measure the success of data transmission during a simulation period is by calculating the throughput. Throughput represents the number of data packets that have reached their final destination within a given unit of time. This measure can be calculated using the following equation (6):

$$\text{Throughput} = \frac{(\text{Bytes Received}) * 8}{(\text{Simulation Time}) * 1024} \text{ Kbps} \quad (6)$$

The above equation will assess data transfer efficiency and identify potential bottlenecks. This data can help develop and optimize communication networks.

## VI. SIMULATION RESULTS & DISCUSSION

This section compares the proposed FCEE protocol, STAB-AODV, and SSAODV. Node speed affects mesh network performance, including throughput, Packet Loss Rate (PLR), Packet Delivery Ratio (PDR), Network Reachability Level (NRL), and End-to-End (E2E) delay. Mesh networks utilize mobile devices, often referred to as nodes, to establish communication channels in the absence of a fixed infrastructure. The velocities of these nodes influence the overall efficiency of the network. High-velocity nodes can increase network overhead due to route discovery and maintenance message transmission. One possible outcome of this situation may be a reduction in the overall efficiency of the network and a hindrance to effective communication. Additionally, high node velocities may increase PLR and decrease PDR as the likelihood of packet loss or drop during transmission increases.

Conversely, high node velocities may also increase network throughput due to nodes' ability to expedite data transmission while in motion at higher speeds. Thus, it is imperative to understand the influence of node velocity on the parameters above' performance while designing and evaluating mesh networks. By considering node speed, network designers can optimize the network to enhance performance across various operational circumstances.

Figs. 3 to 7, Show the effect of varying node speed on PDR, PLR, throughput, NRL, and E-2-E delay, respectively. In these cases, node speed varies from 10 m/s to 50 m/s, such as 10, 20, 30, 40, and 50. The node number is taken as 60. The term (PDR) refers to the percentage of packets successfully transmitted to their intended destination compared to the total number of dispatched packets. Through data analysis, it has been determined that the FCEE protocol exhibited the highest packet delivery ratio, with STAB-AODV and SSAODV following closely behind. These findings suggest that FCEE was able to transmit the most significant number of packets successfully, which can be attributed to its efficient routing mechanism 3.

On the other hand, it can be deduced that SSAODV exhibited a relatively lower packet delivery ratio due to its less efficient routing mechanism. The acronym PLR represents the ratio of lost packets to the total number of packets transmitted. The data analysis reveals that STAB-AODV and SSAODV demonstrated comparable performance. Nevertheless, the STAB-AODV protocol displayed a marginally increased packet loss ratio when the node speeds were lower. In contrast, the SSAODV protocol exhibited a slightly higher ratio when the node speeds were higher. The observed phenomenon can be attributed to the disparity in routing mechanisms utilized by the two protocols. The packet loss ratio is a critical metric that can determine the suitability of a routing protocol for specific applications, particularly those that require dependable and prompt packet transmission.

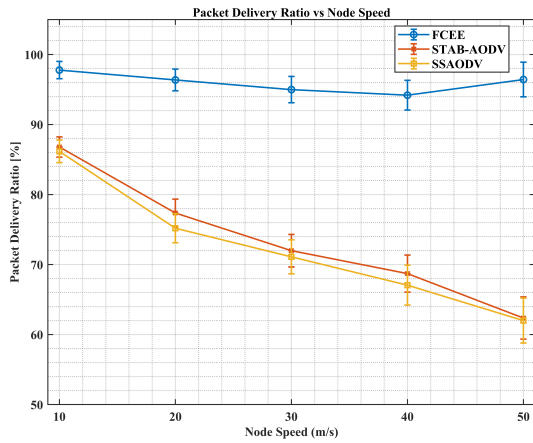


Fig. 3. Packet Delivery Ratio.

The term PLR pertains to the proportion of lost packets concerning the overall quantity of transmitted packets. According to the data analysis, it can be observed that STAB-AODV and SSAODV exhibited comparable performance. However, STAB-AODV demonstrated a marginally elevated packet loss ratio at lower node speeds. In comparison, SSAODV displayed a slightly higher ratio at higher node speeds, as shown in Fig. 4. The dissimilarity in routing mechanisms employed by the two protocols will likely cause this phenomenon. Evaluating the efficacy of the routing protocol for applications that demand reliable and timely packet transmission is contingent upon the packet loss ratio. This particular metric holds significant importance in evaluating network performance and dependability.

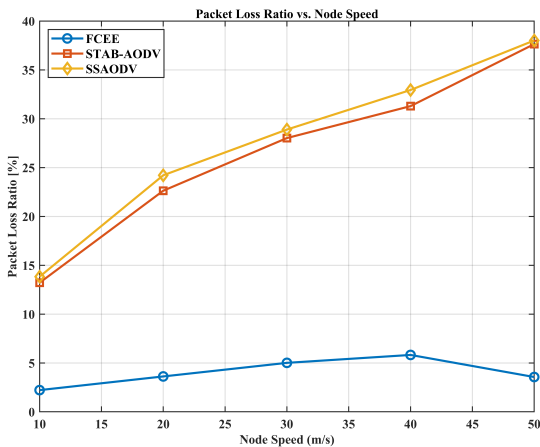


Fig. 4. Packet Loss Ratio.

Fig. 5, presented, depicts the NRL of three distinct routing protocols, namely FCEE, STAB-AODV, and SSAODV, as a function of node speed in a mesh network. NRL measures the average number of control packets dispatched by a node for each data packet transmitted, representing the overhead of the routing protocol.

The graph reveals that node speed increases NRL for all

three protocols. For FCEE, the NRL ranges from 4.41 at 10 m/s to 5.93 at 50 m/s. For STAB-AODV, the NRL ranges from 360.39 at 10 m/s to 585.54 at 50 m/s, while for SSAODV, it ranges from 382.81 at 10 m/s to 627.42 at 50 m/s. The observed phenomenon can be attributed to increased node mobility at higher speeds, leading to more frequent network topology changes and more control packets to maintain routing information.

Notably, FCEE exhibited the lowest NRL among the three protocols, followed by SSAODV and STAB-AODV, across all node speeds. Specifically, FCEE consistently exhibited the lowest NRL, indicating its superior efficiency in controlling packet overhead compared to the other two protocols. Conversely, STAB-AODV consistently exhibited the highest NRL, highlighting its inefficiency in controlling packet overhead. SSAODV performed relatively better than STAB-AODV but demonstrated a higher NRL than FCEE.

The presented graph underscores the criticality of efficient routing protocols in mesh networks, particularly in high-speed scenarios where control packet overhead can significantly impact network performance.

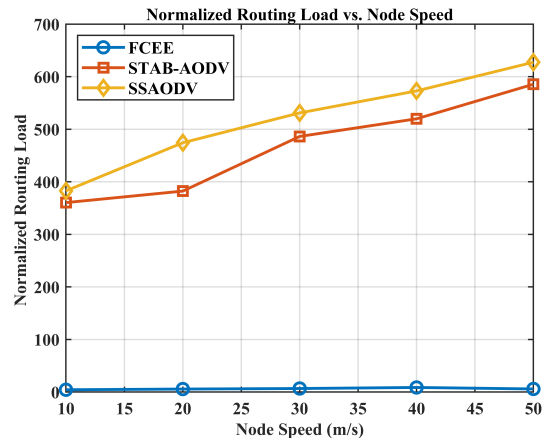


Fig. 5. Normalized Routing Load.

The study demonstrates that as the speed of nodes increases, the throughput of all considered schemes experiences a decline. However, the proposed protocol performs better than the others, as shown in Fig. 6. This can be attributed to the fact that with an increase in node speed, node mobility accelerates, leading to connectivity loss and consequent degradation in throughput. In this regard, the FCEE scheme, which incorporates residual energy and congestion of intermediate nodes in path selection, offers more stable paths, resulting in reduced congestion.

The end-to-end delay results show in Fig. 7, that FCEE has the lowest delay among all the protocols at all speeds, with an average delay of 0.054 seconds. STAB-AODV and SSAODV have similar delay performance, with average delays of 0.062 milliseconds and 0.076 seconds, respectively. At lower speeds (10 and 20 m/s), STAB-AODV has a slightly lower delay than SSAODV; as the node speed increases, SSAODV performs better in delay. Overall, the end-to-end delay results suggest

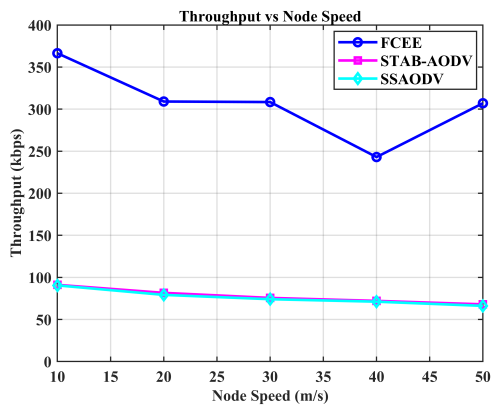


Fig. 6. Throughput in kbps vs node speed.

that FCEE is the best protocol for minimizing delay, while STAB-AODV and SSAODV have comparable performance with slightly higher delay.

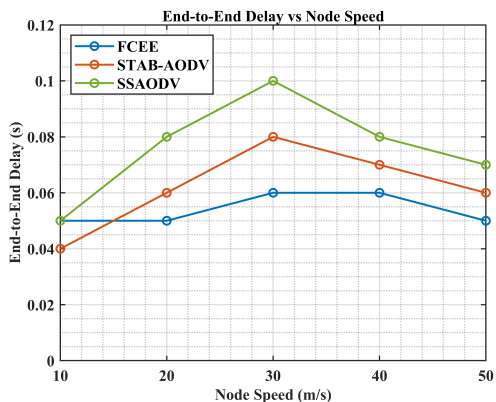


Fig. 7. End-2-End Delay.

## VII. CONCLUSION

In this paper, a routing protocol named FCEE has been proposed for mesh networks. The protocol was designed to improve the performance of the networks with a focus on normalized routing overhead.

Upon analysis of the provided data, it is evident that the performance of the three mesh routing protocols (FCEE, STAB-AODV, SSAODV) varies across metrics with varying node speeds. Among these metrics, throughput is a crucial parameter that determines the overall performance of the routing protocol. From the data, it is clear that FCEE outperformed STAB-AODV and SSAODV regarding throughput across all node speeds, while STAB-AODV and SSAODV exhibited similar performance.

Furthermore, normalized routing load is an essential metric that measures the overhead of the routing protocol. FCEE demonstrated the lowest load, followed by STAB-AODV and SSAODV, with the gap between FCEE and the other two protocols becoming wider as node speed increased.

The packet loss ratio is another crucial metric that determines the appropriateness of a routing protocol for specific applications. STAB-AODV and SSAODV exhibited similar performance in this metric, with STAB-AODV having a slightly higher packet loss ratio at low node speeds and SSAODV having a slightly higher ratio at high node speeds. Conversely, FCEE demonstrated the lowest packet loss ratio at all node speeds.

Finally, end-to-end delay is a vital metric that can impact the performance of a mesh routing protocol. From the data, all three protocols demonstrated similar performance, with STAB-AODV having the lowest delay at low node speeds and SSAODV having the lowest delay at high node speeds.

In summary, choosing the most suitable mesh routing protocol depends on the application's specific requirements and the environment. For instance, if low packet loss is a crucial requirement, FCEE may be the best choice, while if low routing overhead is a priority, STAB-AODV may be preferable. Ultimately, selecting the most appropriate routing protocol is a critical decision that can impact the overall performance of the mesh network.

## VIII. ACKNOWLEDGMENT

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## REFERENCES

- [1] N. Mast, M. A. Khan, M. I. Uddin, S. A. Ali Shah, A. Khan, M. A. Al-Khasawneh, and M. Mahmoud, "Channel contention-based routing protocol for wireless ad hoc networks," *Complexity*, vol. 2021, pp. 1–10, 2021.
- [2] G. A. Walikar and R. C. Biradar, "A survey on hybrid routing mechanisms in mobile ad hoc networks," *Journal of Network and Computer Applications*, vol. 77, pp. 48–63, 2017.
- [3] I. Alameri, J. Komarkova, and M. K. Ramadhan, "Conceptual analysis of single and multiple path routing in manet network," in *2021 International Conference on Information and Digital Technologies (IDT)*. IEEE, 2021, pp. 235–244.
- [4] M. Naravani, D. Narayan, S. Shinde, and M. M. Mulla, "A cross-layer routing metric with link prediction in wireless mesh networks," *Procedia Computer Science*, vol. 171, pp. 2215–2224, 2020.
- [5] I. Alameri, Š. Hubálovský, and J. Komarkova, "Evaluation of impact of mobility, network size and time on performance of adaptive routing protocols," in *2021 International Conference on Information and Digital Technologies (IDT)*. IEEE, 2021, pp. 245–253.
- [6] M. M. Christian Lochert, Björn Scheuermann, "A survey on congestion control for mobile ad hoc networks," *Wireless communications and mobile computing*, vol. 7, no. 5, pp. 655–676, 2007.
- [7] T. Senthikumar and V. Sankaranarayanan, "Dynamic congestion detection and control routing in ad hoc networks," *Journal of King Saud University-Computer and Information Sciences*, vol. 25, no. 1, pp. 25–34, 2013.
- [8] Y.-S. Yen, H.-C. Chang, R.-S. Chang, and H.-C. Chao, "Routing with adaptive path and limited flooding for mobile ad hoc networks," *Computers & electrical engineering*, vol. 36, no. 2, pp. 280–290, 2010.
- [9] W. K. Lai, S.-Y. Hsiao, and Y.-C. Lin, "Adaptive backup routing for ad-hoc networks," *Computer Communications*, vol. 30, no. 2, pp. 453–464, 2007.
- [10] C. Lal, V. Laxmi, M. S. Gaur, and S.-B. Ko, "Bandwidth-aware routing and admission control for efficient video streaming over manets," *Wireless Networks*, vol. 21, pp. 95–114, 2015.
- [11] S. K. Prasad and K. Bhatia, "Bamr: a novel bandwidth aware multipath reactive routing protocol for mobile ad hoc network," *International Journal of Systems, Control and Communications*, vol. 9, no. 1, pp. 75–84, 2018.

- [12] G. Singh, A. K. Sharma, O. S. Bawa, and H. Kaur, "Effective congestion control in manet," in *2020 International Conference on Intelligent Engineering and Management (ICIEM)*. IEEE, 2020, pp. 86–90.
- [13] N. Sharma, A. Gupta, S. S. Rajput, and V. K. Yadav, "Congestion control techniques in manet: a survey," in *2016 Second international conference on computational intelligence & communication technology (CICT)*. IEEE, 2016, pp. 280–282.
- [14] B. Bhatia, "Performance analysis of aodv based congestion control protocols in manet," in *2015 international conference on futuristic trends on computational analysis and knowledge management (ABLAZE)*. IEEE, 2015, pp. 453–458.
- [15] M. Y. Suraki, A. T. Haghghat, and M. Gholipour, "Fclcc: fuzzy cross-layer congestion control in mobile ad hoc networks," *IJCSNS*, vol. 18, no. 1, p. 155, 2018.
- [16] G. Suresh, S. Kumar, V. Kavitha, and S. Lekashri, "Forecast function based congestion control in manet routing," in *IOP Conference Series: Materials Science and Engineering*, vol. 925, no. 1. IOP Publishing, 2020, p. 012074.
- [17] S. Dalal, B. Seth, V. Jaglan, M. Malik, N. Dahiya, U. Rani, D.-N. Le, and Y.-C. Hu, "An adaptive traffic routing approach toward load balancing and congestion control in cloud-manet ad hoc networks," *Soft Computing*, vol. 26, no. 11, pp. 5377–5388, 2022.
- [18] M. Gowtham and K. Subramaniam, "Congestion control and packet recovery for cross layer approach in manet," *Cluster Computing*, vol. 22, no. Suppl 5, pp. 12 029–12 036, 2019.
- [19] N. I. Abbas, M. Ilkan, and E. Ozen, "Fuzzy approach to improving route stability of the aodv routing protocol," *EURASIP Journal on Wireless Communications and Networking*, vol. 2015, no. 1, pp. 1–11, 2015.
- [20] Y. Tashtoush, O. Darwish, and M. Hayajneh, "Fibonacci sequence based multipath load balancing approach for mobile ad hoc networks," *Ad Hoc Networks*, vol. 16, pp. 237–246, 2014.
- [21] S.-J. Lee and M. Gerla, "Dynamic load-aware routing in ad hoc networks," in *ICC 2001. IEEE International Conference on Communications. Conference Record (Cat. No. 01CH37240)*, vol. 10. IEEE, 2001, pp. 3206–3210.
- [22] S. V. Mallapur, S. R. Patil, and J. V. Agarkhed, "Load balancing technique for congestion control multipath routing protocol in manets," *Wireless Personal Communications*, vol. 92, pp. 749–770, 2017.
- [23] R. Vadivel and V. M. Bhaskaran, "Adaptive reliable and congestion control routing protocol for manet," *Wireless Networks*, vol. 23, pp. 819–829, 2017.
- [24] Y. Yi and S. Shakkottai, "Hop-by-hop congestion control over a wireless multi-hop network," *IEEE/ACM Transactions On Networking*, vol. 15, no. 1, pp. 133–144, 2007.
- [25] S. Patel and H. Pathak, "A cross-layer design and fuzzy logic based stability oriented routing protocol," *International Journal of Computer Network & Information Security*, vol. 14, no. 2, 2022.
- [26] N. Jabbar and G. Lencse, "An verview of the ultipath echnologies, their importance and types," *Proceedings of The Technical University of Sofia*, vol. 72, no. 1, pp. 21–28, 2022.
- [27] T. A. Ramya, J. Mathana, R. Nirmala, and R. Gomathi, "Exploration on enhanced quality of services for manet through modified lumer and fai-eta algorithm with modified aodv and dsr protocol," *Materials Today: Proceedings*, 2021.
- [28] D. Narayan, M. Naravani, and S. Shinde, "Cross-layer optimization for video transmission using mdc in wireless mesh networks," *Procedia Computer Science*, vol. 171, pp. 282–291, 2020.
- [29] I. Alameri, J. Komarkova, T. Al-Hadhrami, and A. Lotfi, "Systematic review on modification to the ad-hoc on-demand distance vector routing discovery mechanics," *PeerJ Computer Science*, vol. 8, p. e1079, 2022.
- [30] P. Pandey and R. Singh, "Efficient ad hoc on demand distance vector routing protocol based on route stability in manets," *International Journal of Wireless Information Networks*, vol. 29, no. 3, pp. 393–404, 2022.
- [31] N. Manjhi and N. Patel, "Signal strength based route selection in manets," *International Journal of Computer Science and Telecommunications*, vol. 3, no. 7, pp. 27–30, 2012.