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RESEARCH ARTICLE

Optimization of Contention Window and Relay Selection for Efficient Routing Using Fuzzy Logic Model

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ABSTRACT The rapid increase in vehicle density on roads owing to urbanization and motorization has led to increased risks of roadblocks, traffic jams, and accidents. To ensure the reliability of transportation, it is crucial to have stable and timely transmission of safety messages through Vehicle Ad-hoc Networks (VANETs). However, frequent vehicle movement and changes in the network topology may cause link breakage and packet loss. This paper proposes a solution that uses a fuzzy logic system in both the Medium Access Control (MAC) layer and the network layer to broadcast safety messages efficiently. The proposed rule-based model optimizes the Contention Window (CW) and relay selection process to adapt to different traffic conditions. The dynamic CW MAC (DYCW-MAC) model selects the optimum size of CW based on network parameters such as density, velocity, and link quality factor. For multi-hop communication, the model determines the next forwarding relay by considering factors such as direction, velocity difference, coverage factor, and Fast-Expected Transmission Count (F-ETX) between the sender vehicle and surrounding vehicles within its transmission range. The simulation results indicate that the DYCW-MAC model enhances the network throughput and decreases the average packet delay in comparison to other models. On average, the proposed model has a 28% lower throughput standard deviation than other comparable models considered.

INDEX TERMS Broadcasting, fuzzy logic system, F-ETX, IEEE 802.11p, dynamic contention window, VANET.

I. INTRODUCTION

Vehicular ad hoc networks (VANETs), which are a key part of Intelligent Transportation Systems (ITSs), allow vehicles to communicate with each other and with infrastructure in a defined area despite their unpredictable movement. The Wireless Access in Vehicular Environments (WAVE) technology [1] was specifically designed for ITS and provides additional functionalities that enable the deployment of networks in vehicular environments. VANETs have multiple benefits, including enhancing road safety through the exchange of warning messages and increasing traffic efficiency by coordinating vehicle movement. VANET connections are classified into three parts: Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), and Infrastructure to Infrastructure (I2I) communication, as shown in Figure 1. VANETs disseminate various information, including road accidents, blind spots, emergency messages, and parking information, among nearby vehicles. For instance, in a contingency situation, broadcasting the message requires a time-sensitive and high-priority approach. According to Figure 1, in the event of an accident, a vehicle must immediately broadcast information to its neighboring vehicles to enable them to change lanes and prevent traffic congestion. Transmitting this information to the nearest hospital has the potential to save a life.

The main attribute of VANETs is the high vehicular mobility and dynamic nature of the topology, which leads to frequent disconnections and packet losses. To resolve this, each

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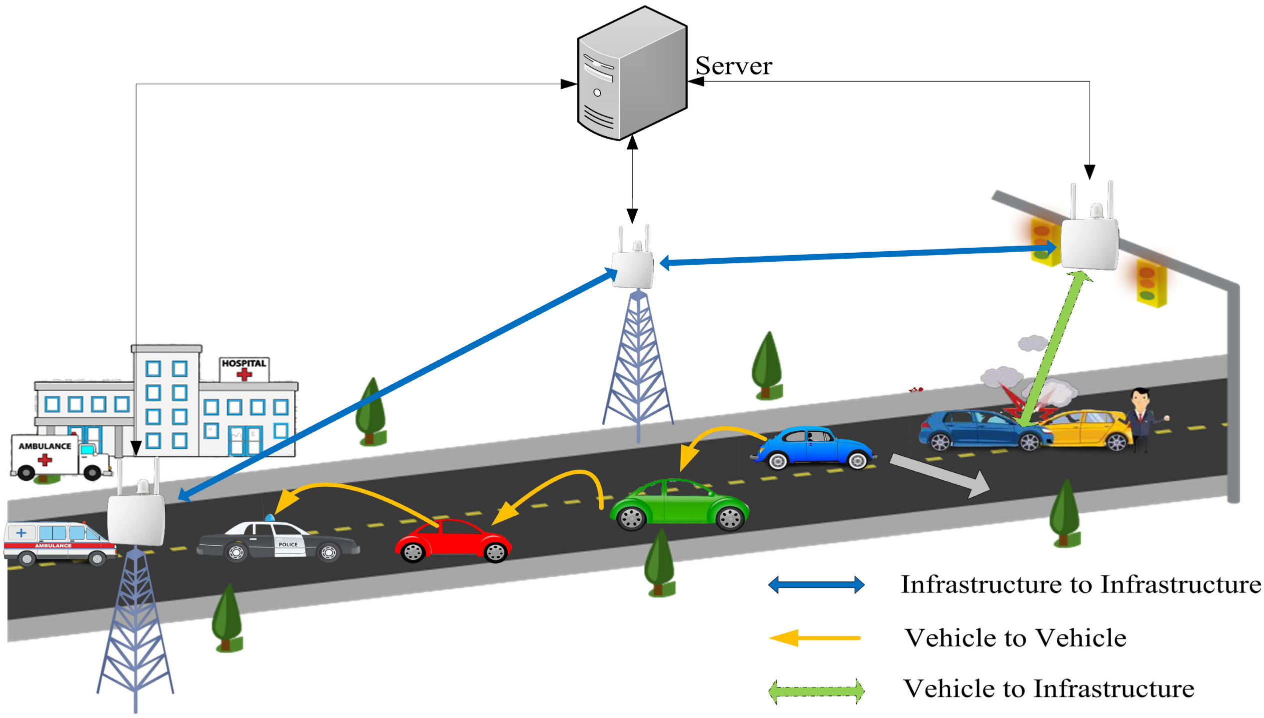

FIGURE 1. Illustration of VANET structure during an emergency situation, where an accident occurs, and a message needs to be conveyed to a hospital.

TABLE 1. List of abbreviations.

Acronym	Definition
VANET	Vehicular Ad-Hoc Network
ITS	Intelligent Transportation System
WAVE	Wireless Access in Vehicular Environments
MAC	Medium Access Control
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
I2I	Infrastructure to Infrastructure
CW	Contention Window
FLB	Fuzzy Logic-based Broadcast
BEFLAB	Bandwidth Efficient Fuzzy Logic Assisted Broadcast
WLAN	Wireless Local Area Network
DoM	Degree of Membership
D	Direction
VD	Velocity Difference
CF	Coverage Factor
ETX	Expected Transmission Count
F-ETX	Fast- Expected Transmission Count
VF	Velocity Factor
DF	Density Factor
LQF	Link Quality Factor
PDR	Packet Drop Ratio
SNVs	Set of Neighbouring Vehicle
ALS	Assessment of Link Stability
SUMO	Simulation of Urban Mobility

vehicle periodically disseminates a "Hello Message" [2] containing information about its location, direction, velocity, and vehicle ID, to update its status to surrounding vehicles.

Broadcasting refers to the transmission of a message from a source vehicle to multiple recipients within its communication range simultaneously. To prevent the broadcast storm problem [3], which is a network issue caused by the excessive transmission of broadcast packets, the best relay node (selected using the proposed relay selection model) is used for broadcasting the packet to surrounding nodes. Multi-hop extends the range by relaying the message through a chain of vehicles until it reaches its destination, thereby increasing overall V2V communication coverage. The multi-hop broadcast also uses intelligent relay selection for efficient transmission to the destination.

The IEEE 802.11p uses an exponential backoff mechanism [1], in which the Contention Window (CW) of a station is doubled each time a collision occurs until it reaches the maximum value. In the traditional model, CW has a range of 16 to 1024. The CW is determined by the number of transmission attempts that have failed for a given packet. The backoff time counter varies from $[0, 1, 2, \ldots, (CW - 1)]$. It starts from the maximum value $(CW - 1)$ and decreases by 1 on each idle channel condition. The packet is broadcasted over the network when the counter reaches 0. Rising vehicle numbers on the road increase packet collision probability as the likelihood of multiple vehicles choosing the same backoff time increases. A counter-timer mechanism [4] has been proposed to avoid channel congestion during broadcasting. The counter pauses when the channel is busy and restarts only when the channel is idle. This improves communication efficiency by preventing multiple transmissions on the same channel.

In [5], a fixed size of CW is used for all types of vehicle density. However, a fixed size of CW may not be effective as different network densities require different CW sizes. In high-density network conditions, a larger CW is required

TABLE 2. Symbols used in DYCW-MAC model.

Symbol	Description
N	Vehicle density
v_r	Relative velocity of receiving
v_{min}	Minimum relative velocity of neighbouring vehicle
v_{max}	Maximum relative velocity of neighbouring vehicle
N_s	Sender vehicle density
N_r	Receiver vehicle density
S_i	Sender Node
W_o	Weighted output value
β	Sensitivity of the LQF
P_{sen}	PDR of sender node
P_{rec}	PDR of receiver node
$\vec{V_i}$	Velocity vector of the sender node
$\vec{V_j}$	Velocity vector of the relay node
S_r	Relay node
D_v	Destination node

to avoid packet collision, while a smaller CW can be selected to avoid unnecessary delay in low-density traffic conditions. To address this issue, a fuzzy logic model can be used to adjust the size of CW based on the prevailing network parameters. This paper presents a new fuzzy logic-based model to resolve problems in existing algorithms by selecting the best possible relay nodes and choosing an optimal CW based on the given network parameters.

The key contributions of the DYCW-MAC model are as follows:

1) A modified WAVE architecture is introduced, in which the performance of MAC and Network layers are enhanced using a fuzzy logic model.
2) To improve the performance of the network, the best relay is selected using a fuzzy logic model to efficiently transmit safety messages.
3) Optimization of the CW on the MAC layer based on vehicle density, velocity, and link quality between the corresponding nodes.

The rest of the paper is prepared as follows: Section II provides a discussion of multi-hop protocols and a review of papers based on the fuzzy logic model. In Section III, the modified WAVE architecture and complete flowchart of the DYCW-MAC are described. Section IV discusses the input metrics and procedure for relay selection. Section V explains the optimization process of CW for packet transmission using a fuzzy logic system. Section VI provides the performance analysis and comparison of the DYCW-MAC model with other models, and in Section VII, the conclusions are drawn.

A. ABBREVIATIONS AND ACRONYMS

The abbreviations and symbols used throughout the article are listed in Table 1 and 2, respectively.

II. LITERATURE REVIEW ON FUZZY LOGIC MODEL AND CW

To avoid the broadcast storm problem, the fuzzy logic model considered in [6]. When it comes to fuzzy logic systems, the key components are the input factors that are considered during the decision-making process. In the context of VANET, it is important to understand which parameters are crucial to consider. After reviewing several research articles, it is evident that various studies have identified a diverse set of factors, each having its own set of benefits and drawbacks.

The Fuzzy Logic-based Broadcast (FLB) protocol, presented in [7], analyzed a model in which the decision to rebroadcast a message was made using a fuzzy logic system that took into account three key metrics: mobility factor, coverage factor, and connectivity factor. These factors are computed regularly from the information (such as coordinates, direction, and vehicle ID) collected through the hello messages that are periodically exchanged between the vehicles in the network. However, the authors focus only on broadcasting the packet. In [8], the authors propose the Bandwidth Efficient Fuzzy Logic Assisted Broadcast protocol (BEFLAB), which incorporates coverage and mobility factors as the primary components of the system's decision matrix. The retransmission decision takes into account whether a receiving node is qualified for retransmission or not. The model effectively reduces the number of relay vehicles, resulting in significant bandwidth savings in dense network environments.

Ammar Hawbani et al. [9] have proposed a network-layer protocol called vehicular environment fuzzy router for road and relay selection based on network parameters - network size and vehicle density. The model shows considerable improvement in terms of end-to-end latency and the packet delivery ratio over other comparable models. To avoid congestion, [10] considered density metrics for rerouting traffic to decrease the traveling time of vehicles. The Expected Transmission Count (ETX) [11] is a commonly used network layer metric for estimating the link quality between nodes. However, as ETX is designed for static wireless networks, it is suggested that an advanced metric called Fast-ETX (F-ETX) [12] be used for mobile ad-hoc networks such as VANETs. F-ETX addresses the issue of increased loss rate in propagation channels caused by node mobility and network disturbances by estimating the inter-node link state based on link quality and stability assessment. The research articles mentioned above provide insights into the input metrics and the advantages they offer. An approach utilizing fuzzy logic has been developed to assess the likelihood of link failure [13], which is known as a link quality evaluation method. By implementing various pre-emption techniques, such as those outlined in [14], the model prioritizes routing decisions in a way that minimizes delay. In [15] and [16], authors have considered a fixed size of CW for both the dense and sparse vehicle density. However, [17] shows that a static CW for an estimator implies a trade-off between reactivity and accuracy since in a dense network multiple vehicles can use the same CW leading to increased packet collisions.

Optimizing the CW is another potential approach to mitigate the end-to-end delay [18], [19]. In [18] and [20], algorithms for adjusting the CW are presented. To adjust the CW, the authors of [20] derived a closed-form expression in accordance with the available active nodes in the coverage area of the sender vehicle. The model is proposed for Wireless Local Area Networks (WLANs) where the high mobility of VANET is not considered. In the research article [18], the authors proposed a method for modifying the CW size based on network density and message transmission probability. The vehicle first selects the smallest CW and then uses fuzzy logic to adjust the CW, which can either increase, keep, or decrease it relative to the initial value. However, this method is time-consuming, which can result in an increased delay when safety messages need to be transmitted in milliseconds. The authors of [19] considered adjustments on both the network layer and the MAC layer. For the MAC layer, this protocol utilizes the Q-learning approach to modify the size of the CW. At the network layer, the system, based on traffic conditions, uses common forwarder nodes, which leads to a reduction in the number of sender nodes and results in lower congestion.

The CW size is optimized in [21] for VANETs to improve the performance of the transmission of safety messages, taking into account traffic, vehicle velocity, and the number of vehicles. A comparison between IEEE 802.11 and IEEE 802.11p in terms of throughput and delay performance is presented, using a Markov Chain analytical model. However, it is important to note that the article overlooks the impact of fading channels or link quality between vehicles, which are critical factors in the transmission of safety messages. The paper [22] presents a method to enhance the utilization of channel bandwidth in transmitting safety messages through a time division multiple access scheme. In addition, the authors suggest adjusting the initial size of the CW to optimize throughput and delay performance. While the system has shown some progress, its throughput remains suboptimal, and the use of the fuzzy logic system and dynamic CW is recommended to further enhance its throughput.

The proposed DYCW-MAC model adjusts and finds the exact value of CW based on input metrics such as velocity, density, and link quality before the transmission happens, thus improving the CW optimization process. Furthermore, it also included a fuzzy logic model for optimum relay selection in multi-hop communication. As a result, the combination of the two fuzzy logic models for CW adjustment and relay selection is novel and original.

III. PROPOSED WAVE ARCHITECTURE FOR THE OPTIMIZATION OF RELAY SELECTION AND CW

VANETs are dynamic in nature due to constantly changing network conditions, making it difficult to design a static mathematical model for the transmission link between the sender and receiver. It has been considered a flexible system model based on a fuzzy logic system [23] to address this challenge. It is used to broadcast safety messages, that optimize the CW and selects the best relay for multi-hop communication based on the prevalent traffic characteristics. It provides an intelligent routing mechanism that computes fuzzy rules based on node attributes to provide efficient and

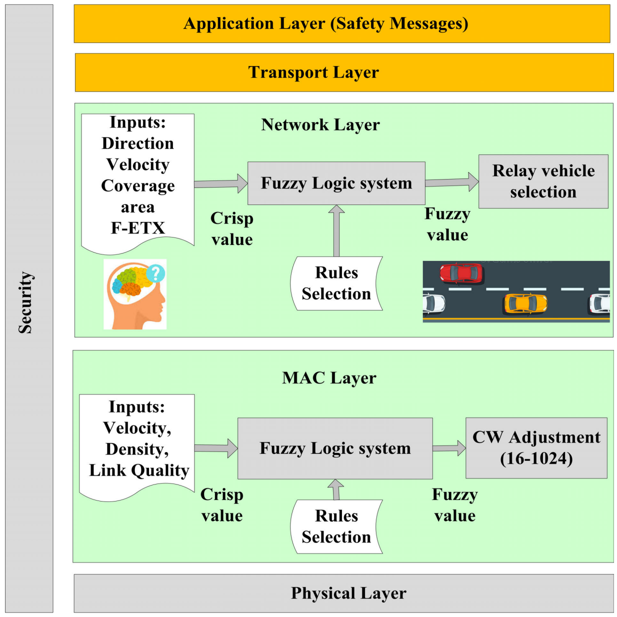

FIGURE 2. Illustration of the proposed modified WAVE architecture for enhanced DYCW-MAC performance.

reliable end-to-end transmission in the case of a multi-hop relay system. The proposed modified WAVE architecture is divided into two parts as shown in Figure 2. One is the network layer-based protocol which selects the best relay using the fuzzy logic system. The model considers the direction of the vehicle, the velocity difference between the corresponding vehicles, the coverage factor of the sender vehicle, and F-ETX (which gives information on link connectivity and link stability) as the input metrics of the fuzzy logic system. Second is the MAC layer-based protocol that decides optimal CW depending upon the fuzzy logic system. The model computes vehicle velocity, network density, and link quality based on the information gathered through the hello packets from the surrounding vehicles. The best relay and CW are selected according to the rule selection table.

The complete flow chart of the DYCW-MAC model is shown in Figure 3. In MATLAB simulation, a two-lane road with a total length of 1000 meters and width of 15 meters is utilized. The road is partitioned into 10 segments, with each segment measuring 200 meters in length and 7.5 meters in width. Vehicles (N) move unidirectionally in their lane with a velocity in the range of 5-25 meters/second. The simulation starts by identifying the vehicles in/out of each zone and assigning velocity and direction to each. An emergency message is generated from a randomly chosen vehicle. The optimum relay for multi-hop communication is selected for each zone using the Relay Selection Process (Explained in Section IV-B). The process determines the most suitable relay based on parameters such as Direction (D), Speed difference (SD), Coverage Factor (CF), and Fast Expected Transmission Count (F-ETX) using a fuzzy logic model. The CW is also adjusted (Explained in Section V-B) using fuzzy logic based on variables such as Velocity Factor (VF), Density

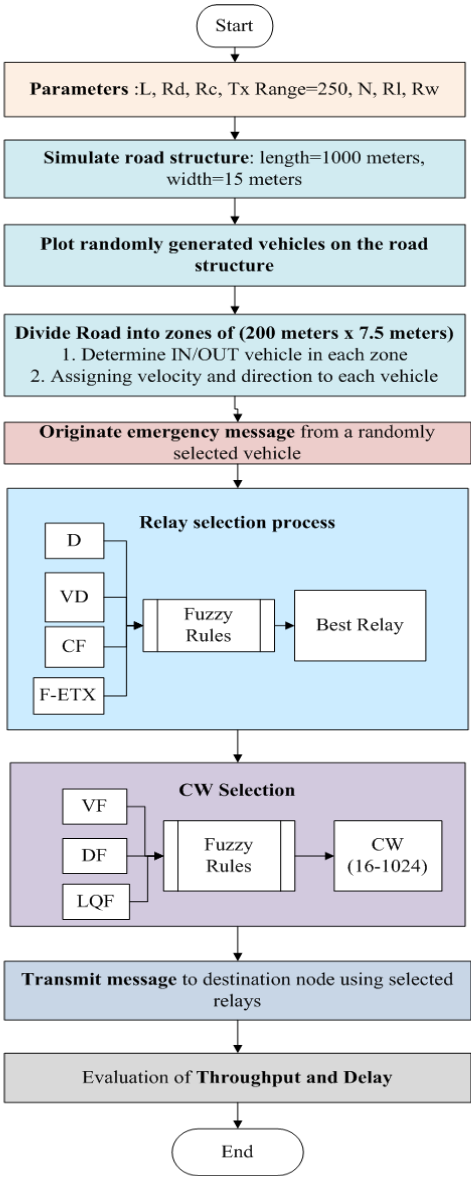

FIGURE 3. Complete flow chart of the DYCW-MAC with key processes.

Factor (DF), and Link Quality Factor (LQF). The message is transmitted to the destination using the selected relays and adjusted CW, ensuring maximum reliability and efficiency.

IV. NEXT FORWARDING RELAY SELECTION

The selection of the next forwarding relay vehicle from the Set of Neighboring Vehicles (SNVs) of the sender vehicle node for multi-hop communication using the fuzzy logic system as shown in Figure 4. The fuzzy logic system uses four input variables namely - Direction, Mobility, Coverage factor, and F-ETX, to select the best relay node among the SNVs. The selected relay should be such that it covers a large number of vehicles and form a stable network so that packet loss is minimized.

It consists of 4 layers: the first is the input layer (Direction, Velocity Difference, Coverage Factor, and F-ETX), and

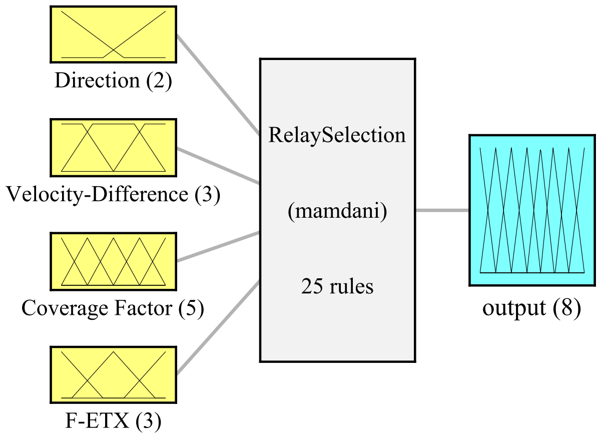

FIGURE 4. Fuzzy logic model for the relay selection.

the second shows the fuzzy logic system, which combines the fuzzifier, inference engine, rules, and defuzzifier. The popularity of triangular membership functions in fuzzy logic applications can be attributed to their simplicity, versatility, smoothness, and computational efficiency [18]. In this model, a triangular membership function is utilized. Different linguistic variables are considered for each input metric. For example, in the case of direction (D), two variables (opposite and same) are considered, three variables (less, intermediate, and more) for velocity difference (VD), five variables (too close, close, middle, far, too far) for coverage factor (CF), and three variables (excellent, intermediate, and poor) for F-ETX. It has been considered the Mamdani fuzzy system as the inference system [11]. Table 3 listed 25 fuzzy rules for selecting a relay vehicle. The operation of generating a numerical value in accordance with the output membership function is known as defuzzification. Some commonly used defuzzification processes [24] are Mean of Maximum (MOM), Center-of-gravity (CoG), largest of maximum (LOM), Bisector of area (BOA), and smallest of maximum (SOM). The CoG method was used to defuzzify the output because it is a popular defuzzification approach in real-world applications. The output layer displays the optimal relay.

A. INPUT METRICS FOR THE RELAY SELECTION PROCESS

The input factors considered for relay selection are discussed in detail below.

1) DIRECTION

It is important to consider the Direction (D) of movement of the relay node relative to the sender node, as it gives an idea about the stability of packet progression between them. Let $\vec{V}_i$ and $\vec{V}_j$ be the velocity vectors of the sender node and relay node, respectively. The direction between the movement of the two nodes can be expressed as (1)

$$D = cos(\theta) = \frac{\vec{V}_i \cdot \vec{V}_j}{\mid \vec{V}_i \mid\mid \vec{V}_j \mid} \tag{1}$$

Figure 5 (a) shows the direction's membership function. The degree of membership (DoM) is shown on the y-axis and the range of the input variable is shown on the x-axis for all input and output membership functions. The linguistic variable with two directional input elements set can be written as: T(D)={*Opposite*, *Same*}, where T(D) shows the movement direction of the relay vehicle with respect to the sender vehicle. Here, when $-1 \leq D < 0$, the relay vehicle is located in the *"Opposite"* direction i.e. moving in a different lane, whereas if $0 < D \leq 1$, the relay vehicle is located in the *"Same"* direction.

2) VELOCITY DIFFERENCE

The Velocity Difference (VD) between the sender and the relay vehicle should be low as a lower velocity difference between the nodes leads to better link stability by reducing packet delay and minimizing packet loss in transmission. The primary goal of this metric is to obtain the similarity of mobility and assign the highest priority to the vehicle node which has less mobility difference in the coverage area of the sender node. Let $\vec{V_r}$, $\vec{V_{max}}$, and $\vec{V_{min}}$ be the velocity of the relay vehicle, the maximum velocity, and the minimum velocity of the vehicle, respectively, relative to the sender vehicle's velocity. The normalized velocity difference is calculated using (2)

$$VD = \frac{\vec{V_r} - \vec{V_{min}}}{\vec{V_{max}} - \vec{V_{min}}} \tag{2}$$

Let VD be a linguistic variable with three input elements set T(VD)=T(VD)={*Less*, *Intermediate*, *More*}, where T(VD) shows the velocity difference of the relay vehicle relative to the sender vehicle. The membership function for the VD is shown in Figure 5 (b). The value of VD can be categorized based on the range in which it falls. If VD falls within the range of 0 to 0.5, it indicates that VD is *"Less"*. If VD falls within the range of 0.1 to 0.9, it suggests that VD is *"Intermediate"*. Finally, if VD falls within the range of 0.5 to 1, it signifies that VD is *"More"*.

3) COVERAGE FACTOR

The Coverage Factor (CF) measures the nearness of a relay node with respect to the sender node. Due to fading problem which mitigates the signal strength as the radio wave travels through the distance, the relay node nearer to the sender node is preferred. The sender node computes a point-to-point distance between itself and all the nodes in its coverage area. Let $Dist_r$ be the distance of the relay vehicle from the sender vehicle and $Dist_{max}$, and $Dist_{min}$ be the maximum and minimum distance in the SNVs of the sender node respectively. The distance is then normalized to get a number between 0 and 1 as per the (3)

$$CF = \frac{Dist_r - Dist_{min}}{Dist_{max} - Dist_{min}} \tag{3}$$

The Membership function for the CF is described in Figure 5 (c) as a linguistic variable expressed by a fuzzy set T(CF)={*Too Close*, *Close*, *Middle*, *Far*, *Too Far*}. If the value falls between -0.4 and 0.25, it is considered *"Too-Close"*. If the value falls between 0 and 0.5, it is considered *"Close"*, while a value between 0.25 and 0.75 is considered *"Middle"*. A value between 0.5 and 1 is considered *"Far"*, and a value between 0.75 and 1.8 is considered *"Too-Far"*.

4) F-ETX

The F-ETX metric is an enhanced version of the traditional ETX metric that also captures the dynamic environment variables of VANET. In VANET, the link quality estimator needs to have high accuracy and reactivity since routing decisions are made based on link quality evaluated from multiple parameters collected from neighboring nodes [17]. F-ETX performs well in link quality evaluation as it also takes link stability into account. In the DYCW-MAC model, F-ETX can be estimated by the following three factors named as link quality factor, drift in link quality, and Assessment of link stability (ALS). Each of these factors is discussed below.

I) **Link Quality Factor:** In VANET, vehicles move in different directions and therefore, links may break at any time due to the dynamic nature of the network. It is challenging to predict how long a node will be connected for data transmission because of this. To address this issue, a link quality factor that is inversely proportional to the packet drop ratio (PDR) of both the sender and receiver nodes is considered. Every node keeps a count of the number of hello messages sent to and from each of the neighboring vehicles. Using that along with actual hello packets received at each end within a rolling period window (say the last 10 seconds). Using this data, each node calculates its own PDR (refer (4)) at sender P_{sen}, defined as, the ratio of successful packets received at neighbors to total packets sent from the sender to all the neighboring nodes. Similarly, each node also calculates its own PDR at receiver P_{rec}, defined as, the ratio of total packets received by the node to total packets sent to the node from all the neighboring nodes. In this DYCW-MAC model, both of these data points are part of hello messages and hence are constantly shared among all the nodes in the network.

$$P_{sen} \text{ or } P_{rec} = \frac{Received\ Hello\ packet}{Transmitted\ Hello\ packet} \tag{4}$$

The higher the PDR of both sender and receiver, the lower the link quality between them. Using this factor, every node assesses and selects the link which has higher throughput and lower PDR. The probability that the packet is sent and correctly received is given by $P_{sen} \times P_{rec}$. As shown in (5), the link quality factor of packet transmission for a Bernoulli process is provided.

$$LQF = \frac{1}{(1 - P_{sen}) \times (1 - P_{rec})} \tag{5}$$

II) **Drift in Link Quality:** It computes the change in present link quality factor ($LQF(t)$) with respect to the previous link quality factor ($LQF(t-1)$) using Exponentially Weighted Moving Average (EWMA) filter as stated in (6)

$$\nabla_t^{LQF} = LQF(t) - LQF(t-1) \tag{6}$$

$$LQF_t^{drift} = \beta \times \nabla_t^{LQF} + (1-\beta) \times LQF_{t-1}^{drift} \tag{7}$$

In (7), LQF_t^{drift} represents the change in the link quality factor over time. The sensitivity of the link quality factor is impacted by the parameter β. To attain a long-term estimate, it is advisable to choose a low value for β. It has been considered a smaller value of $\beta = 0.1$ as given in [17].

III) **Assessment of Link Stability (ALS):** The difference in the value of CW of a node with respect to time gives information about its link stability. Since a stable value of CW is a sign of stable link quality, any absolute change in the CW of a node with time is considered a deterioration of link stability, which can be expressed as in (8). The higher the difference in CW value, the worse the link stability between the nodes. Hence, to avoid transmission overhead, this metric can be used to identify the optimal relay node that maintains a constant CW for a longer time, resulting in a more stable link.

$$ALS(t) = \mid log_2(CW_t) - log_2(CW_{t-1}) \mid \tag{8}$$

The balanced consideration of LQF, drift in link quality, and ALS highlights the significance of each factor in evaluating the overall quality of the link. Finally, a single value for F-ETX is arrived at by giving equal weights to each of the three normalized factors. Let F-ETX be a linguistic variable with three input elements set T(F-ETX)={*Excellent*, *Intermediate*, *Poor*} where T(F-ETX) estimates the link condition of the relay vehicle corresponding to the sender vehicle. Figure 5 (d) depicts the membership function for the F-ETX. When the value of F-ETX falls within the range of -0.4 to 0.4, it is considered to be in the *"Excellent"* category. If the value falls within the range of 0.1 to 0.9, it is categorized as *"Intermediate"*. However, if the value falls within the range of 0.6 to 1.4, it is classified as *"Poor"*.

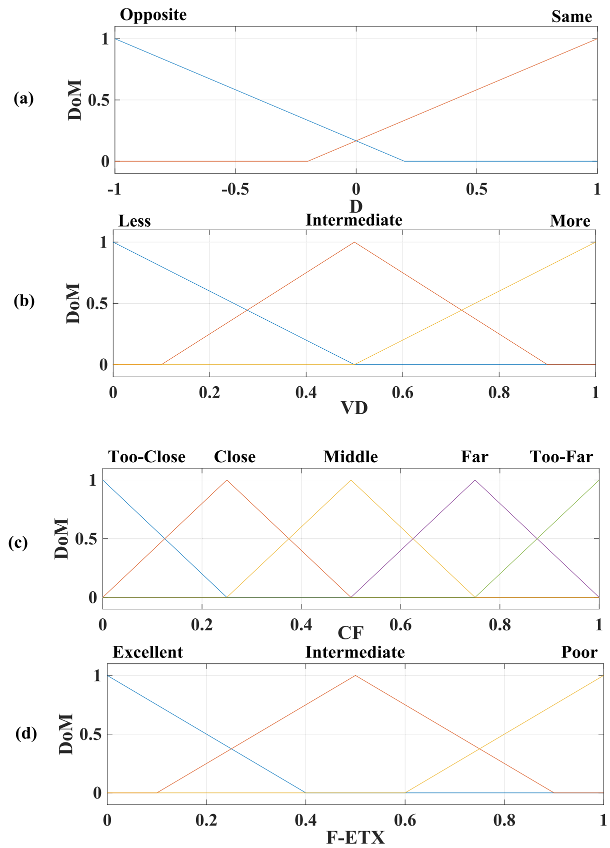

FIGURE 5. Membership function for the input metrics of relay selection (a) Membership function for the direction (b) Membership function for the velocity difference (c) Membership function for the coverage factor (d) Membership function for the F-ETX.

B. RELAY SELECTION PROCESS

Whenever an emergency situation occurs, the origin/sender vehicle needs to disseminate the packet to the surrounding vehicles using the broadcasting protocol and using multi-hop communication to deliver the message to a fixed destination. The protocol calculates the link attributes of individual nodes based on their direction, velocity difference, coverage factor, and F-ETX. The fuzzy logic system considers all these factors jointly and selects optimal relay nodes for transmission. The relay vehicle selection for forwarding the packet is explained in Figure 6. Table 3 contains 25 rules for relay selection. The sender vehicle uses a Table 3 of IF/THEN rules to choose the optimal relay vehicle from a set of neighboring vehicles. The selection is based on the fuzzy values of D, VD, CF, and F-ETX, which are calculated and analyzed by the sender vehicle. The first rule defines the best relay vehicle for disseminating a message as follows:

IF D is *Same*, VD is *Less*, CF is *Too Close* and, F-ETX is *Excellent* **THEN** relay node is *Excellent*.

The last rule defines the worst relay vehicle for broadcasting a message as follows:

IF D is *Opposite*, VD is *More*, CF is *Too Far* and, F-ETX is *Poor* **THEN** relay node is *Worst*.

The relay selection process produces output that is described using the linguistic variables [*Excellent*, *Too-Good*, *Good*, *Satisfactory*, *Undesirable*, *Poor*, *Too-Poor*, *Worst*]. Figure 7 provides a visual representation of the fuzzy weight output membership function for the relay selection process. It has a value range of 0 to 10, with 0 being the best neighbor weight and 10 being the worst. If the weighted output values of multiple surrounding vehicles are the same, the vehicle closest to the destination node (D_v) is selected as the next vehicle in the routing protocol.

V. OPTIMIZATION OF THE CONTENTION WINDOW SIZE

This section discusses the design of the algorithm that decides the best possible CW in the MAC layer under dynamic

TABLE 3. Rule-based table for relay vehicle selection for next broadcasting node.

D	VD	CF	F-ETX	W_O
Same	Less	Too Close	Excellent	Excellent
Same	Intermediate	Too Close	Excellent	Too Good
Same	More	Too Close	Intermediate	Satisfactory
Opposite	Intermediate	Too Close	Intermediate	Undesirable
Opposite	More	Too Close	Poor	Too Poor
Same	Intermediate	Close	Excellent	Too Good
Same	More	Close	Poor	Too Poor
Opposite	Intermediate	Close	Excellent	Good
Opposite	Intermediate	Close	Intermediate	Satisfactory
Opposite	More	Close	Intermediate	Undesirable
Same	less	Middle	Excellent	Too Good
Same	Intermediate	Middle	Poor	Poor
Same	More	Middle	Poor	Too Poor
Opposite	Less	Middle	Excellent	Satisfactory
Opposite	More	Middle	Intermediate	Poor
Same	Less	Far	Excellent	Good
Same	More	Far	Intermediate	Undesirable
Opposite	Less	Far	Excellent	Undesirable
Opposite	More	Far	Intermediate	Too Poor
Opposite	More	Far	Poor	Worst
Same	More	Too Far	Excellent	Undesirable
Same	More	Too Far	Poor	Too Poor
Opposite	Less	Too Far	Excellent	Undesirable
Opposite	More	Too Far	Intermediate	Worst
Opposite	More	Too Far	Poor	Worst

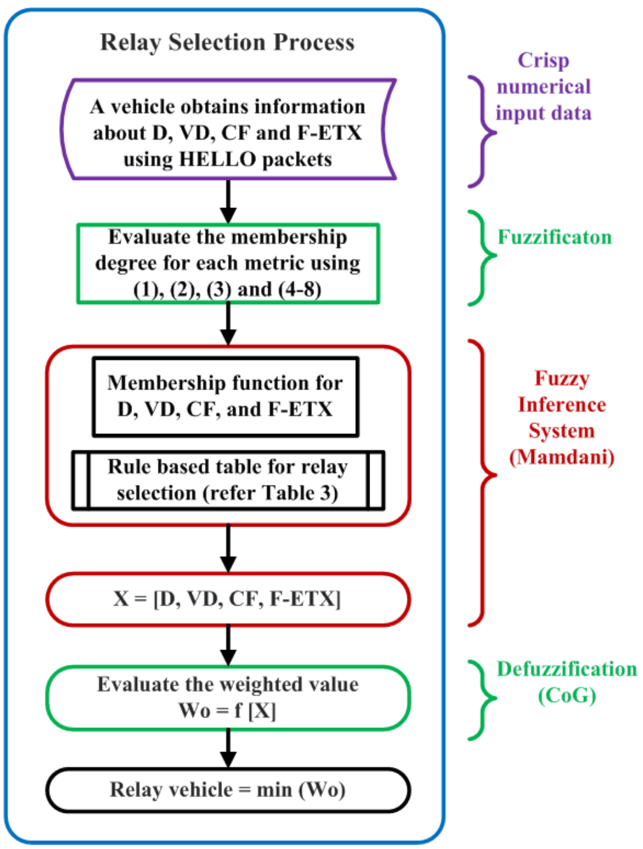

FIGURE 6. Illustration of the process of relay selection using fuzzy logic model.

network conditions. The basic building block of a fuzzy logic model used for optimizing the CW is illustrated in

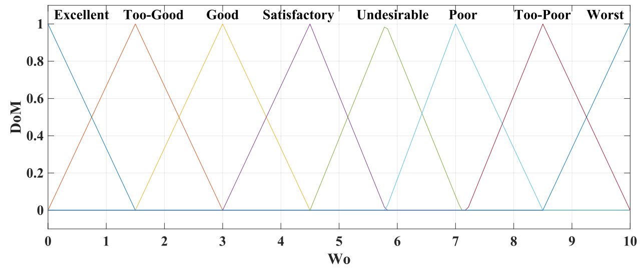

FIGURE 7. Membership function for the output metric (Relay Selection).

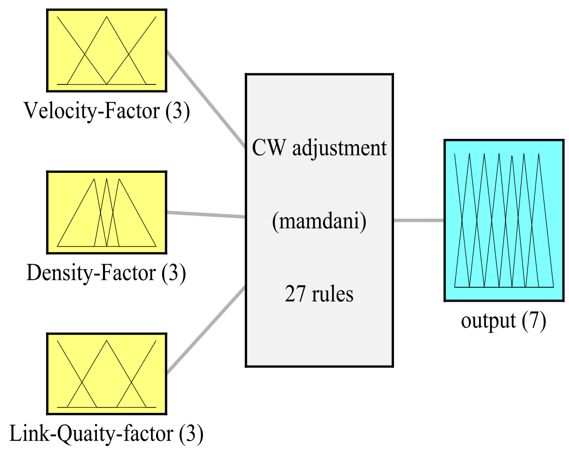

FIGURE 8. Fuzzy logic model for the optimization of CW.

Figure 8. It consists of 3 layers, one is input (velocity factor, density factor, and link quality factor), the middle one shows the fuzzy logic system which combines the fuzzifier, and inference engine with rules and defuzzifier. A Mamdani fuzzy system has been used as the inference system in this process [11]. The third component is the output layer, which displays the CW. Here 27 fuzzy rules are listed in Table 4 for CW adjustment.

A. INPUT METRICS FOR THE CW SELECTION PROCESS

The membership function of the CW optimization model consists of three factors namely- Velocity Factor (vehicle velocity), Density Factor (The similarity of density between the two nodes), and Link quality factor (quality of link between neighboring vehicles) as shown in Figure 9. These factors are normalized, so that the values lie between 0 and 1, before passing them through the fuzzy logic system.

1) VELOCITY FACTOR

Multiple research papers, including [9], [24], [25], and [26], have discussed that the smaller the change in the level of node mobility, the lower the chances of link disconnection and packet loss. To capture this aspect, the paper defines a velocity factor that captures the normalized velocity differential between any two nodes.

The first element of the fuzzy logic system for the CW selection is the Velocity factor (VF) which can be calculated as (9)

$$VF = \frac{v_r - v_{min}}{v_{max} - v_{min}} \tag{9}$$

where v_r shows the relative velocity of the receiving vehicle and v_{max} and v_{min} denotes the maximum and minimum relative velocity of neighboring vehicles with respect to the sender node. A smaller VF indicates lesser mobility meaning a relatively stable node that can disseminate messages to a higher number of neighboring vehicles. Let VF be a linguistic variable with three input elements set T(VF)={*Slow*, *Medium*, *Fast*} where T(VF) shows the velocity of the relay vehicle with respect to the sender vehicle. For VF, a triangular membership function is used, as shown in Figure 9 (a). The normalization process narrows down the velocity factor range to between 0 and 1. Values lower than 0.5 (-0.4 to 0.5) indicate *"Slow"* relative movement between the given nodes, while values between 0.1 and 0.9 represent *"Medium"* relative movement. Higher values between 0.5 and 1.4 indicate *"Fast"* relative movement between the given nodes.

2) DENSITY FACTOR

An increased variation in the number of surrounding nodes within the range of a sender and receiver node increases the chances of packet collision. A higher vehicle density difference between the nodes requires a higher value of the CW for transmission to reduce latency issues. The second input metric of the fuzzy logic system is Density Factor (DF) which can be expressed as (10)

$$DF = \frac{N_s - N_r}{max\,(N_s, N_r)} \tag{10}$$

where N_s is the sender vehicle density (i.e. vehicle density at the sender's end) and N_r is the receiver vehicle density (i.e. vehicle density at the receiver's end). It is clear from the equation that the range of DF varies from -1 to $+1$. DF will be negative when the receiver vehicle's density N_r is greater than that of the sender vehicle N_s and vice versa. When the DF value comes in the range of (0 to 1), the sender vehicle needs to increase its CW, whereas if the DF value is in the range of (-1 to 0), the sender vehicle needs to decrease the size of its CW correspondingly. The triangular membership function is used for the density factor, as shown in Figure 9 (b). Let DF be a linguistic variable with three input elements set T(DF)={*Low*, *Moderate*, *High*} where T(DF) shows the density of the relay vehicle with respect to the sender vehicle.

3) LINK QUALITY FACTOR

Before any transmission, the link quality factor between the two nodes is calculated which acts as an input for the fuzzy logic model for CW selection. The Link Quality Factor (LQF) is computed the same as (5).

The calculated LQF is normalized using the min-max scaling before it is passed through the fuzzy rules. For LQF, a triangular membership function is used, as shown in Figure 9 (c). Let LQF be a linguistic variable with three input elements set T(LQF)={*Good*, *Medium*, *Bad*} where T(LQF) shows the link quality factor of the relay vehicle with respect to the sender vehicle.

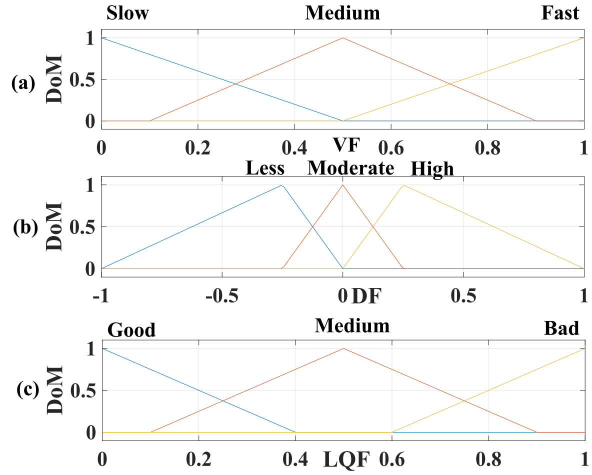

FIGURE 9. Membership function for the input metrics of CW selection (a) Membership function for the velocity factor (b) Membership function for the density factor (c) Membership function for the link quality factor.

B. CW SELECTION PROCESS

Firstly, the optimal relay for data transmission is selected from the set of neighboring vehicles (SNVs) of the sender vehicle node for multi-hop communication using Figure 6. After the set of relays has been identified, the CW algorithm runs in a loop for each sender node in the set to select the optimal CW size for each sequential communication. The method for CW selection for packet forwarding is explained in Figure 10. The CW selection process takes as input the prevailing parameters between the sender and the relay node and provides as output the appropriate CW size for transmission between them. Before transmitting any packets, the sender node computes three input values namely- VF (refer (9)), DF (10), and LQF (5) using the network data periodically collected from the HelloPackets. Details of how each input value is computed have already been discussed in Section V-A. Each relay node follows the IF/THEN criteria provided in Table 4 to select the optimal CW with the aim of minimizing packet loss and packet delay. The table contains 27 rules for CW selection.

For instance, the first rule in the table dictates that a smaller CW should be chosen when the criteria is met, as stated:

IF VF is *Slow*, DF is *Less*, and LQF is *Good* **THEN** CW is *Extremely Low*.

The last rule to set a large CW for disseminating a message is as follows:

IF VF is *Fast*, DF is *High*, and LQF is *Bad* **THEN** CW is *Extremely High*.

After that, the sender node transmits the message to the next relay node using an optimized size of CW. Each relay node in the set of relays calculates its weighted value output (CW_O) using the computed input values and a fuzzy logic function. The output metric for CW selection is bounded by

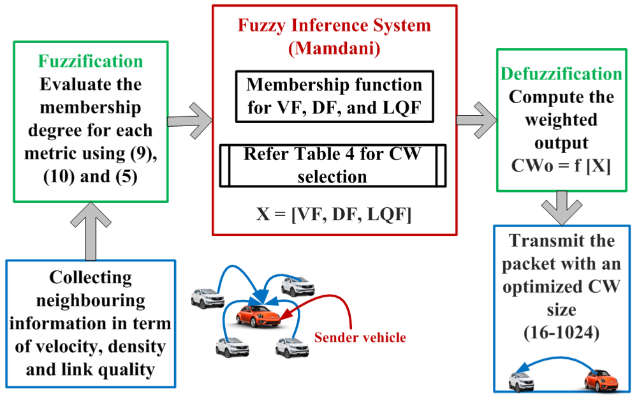

FIGURE 10. Illustration of the process of CW selection using fuzzy logic model.

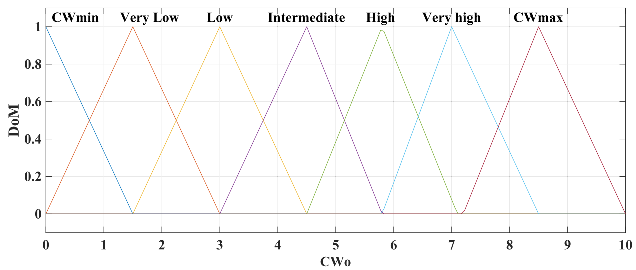

FIGURE 11. Membership function for the output metric (CW selection).

linguistic variables [*Extremely low* or (CW_{min}), *Very Low*, *Low*, *Intermediate*, *High*, *Very High*, *Extremely High* or (CW_{max})] as shown in Figure 11.

The calculated CW_O lies within a range of 0 to 10. Subsequently, S_r sets the CW using the computed CW_O, based on a predefined rule-based logic system. These values are further defuzzified to a crisp numerical value, which is used to select an exact CW from the range [16, 32, 64, 128, 256, 512, 1024] before sending any packet. Each relay updates the message header and transmits the packet to the next relay using the set CW. The process ends after running the loop for all sender nodes in the network.

VI. PERFORMANCE EVALUATION OF THE DYCW-MAC MODEL

To analyze the performance of this DYCW-MAC model, a simulation was carried out in MATLAB as shown in Figure 3. Further same analysis was carried out in NS 3.23 under real-world traffic conditions. For simulation results, a trace file is generated in Simulation of Urban MObility (SUMO) software that shows the movement of the vehicles i.e. the microscopic mobility model. The simulation incorporates a car following model that considers various factors such as vehicle acceleration, lane changing, and traffic jams. Here, the transmission range and co-channel interference range are considered to be 250 meters and 550 meters. Each packet has a data size of 512 bytes. The simulation time is 200 seconds. To address the fluctuation in signal strength due to multipath fading Nakagami-m propagation loss model is considered, where $m = 1$. It has been utilized the WAVE model which

TABLE 4. Rule-based table for CW adjustment before broadcasting message.

VF	DF	LQF	CWo
Slow	Less	Good	Extremely Low
Slow	Less	Medium	Very Low
Slow	Moderate	Good	Very Low
Medium	Less	Good	Very Low
Slow	Less	Bad	Low
Slow	Moderate	Medium	Low
Slow	High	Good	Low
Medium	Moderate	Good	Low
Medium	Less	Medium	Low
Fast	Less	Good	Low
Slow	Moderate	Bad	Intermediate
Slow	High	Medium	Intermediate
Medium	Less	Bad	Intermediate
Medium	High	Good	Intermediate
Medium	Moderate	Medium	Intermediate
Fast	Moderate	Good	Intermediate
Fast	Less	Medium	Intermediate
Slow	High	Bad	High
Medium	High	Medium	High
Medium	Moderate	Bad	High
Fast	High	Good	High
Fast	Moderate	Medium	High
Fast	Less	Bad	High
Medium	High	Bad	Very High
Fast	High	Medium	Very High
Fast	Moderate	Bad	Very High
Fast	High	Bad	Extremely High

TABLE 5. The simulation parameters used to obtain results.

Parameters	Value
Simulator	NS 3.23, MATLAB 17b
Traffic Simulator	SUMO
Topology	VJTI MAP, Open Street Map (OSM)
MAC/ PHY protocol	IEEE 802.11p
Propagation Model	Nakagami -m
Transmission Range	250 meters
Co-Channel Interference Range	550 meters
Header, Packet Size	50,512 bytes
WiFi Data Rate	6 Mbps
Vehicle Velocity	5-25 meter/second
Hello Packet Interval	1 second
Vehicle Density (N)	0-100 veh/km
Duration	200 second

supports 802.11p PHY and MAC layers. All vehicles that are part of the network can accomplish a CSMA/CA back-off mechanism accurately. All vehicles regularly create and update periodic tables based on their neighbors' information collected via a special type of HELLO packet periodically exchanged between all the nodes at predetermined time intervals (T). These HELLO messages contain information about the location, mobility, density, link quality factor, and identity of the vehicle. Each node maintains a cooperative table where information about neighboring vehicles is gathered through hello packets. This data is used to compute parameters that assist the vehicle node in making relaying judgments.

The paper has considered the traffic simulation area around VJTI College, Mumbai that is generated in Open Street Map as shown in Figure 12. The traffic simulation results

FIGURE 12. **Illustration of traffic simulation around VJTI college, Mumbai in SUMO 1.2.0.**

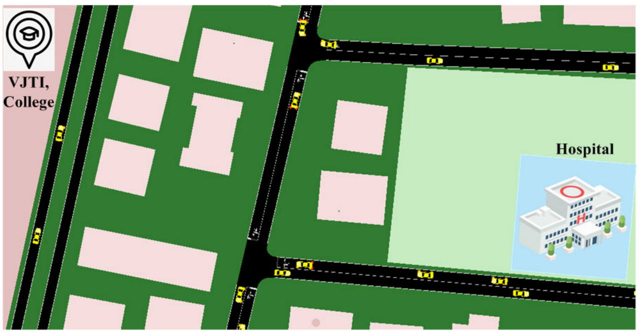

FIGURE 13. **Visualizing dynamic traffic patterns in SUMO 1.2.0: A close-up perspective.**

are presented in Figure 13, which provides a detailed and close-up view of the dynamic traffic flow using SUMO 1.2.0. The simulation shows vehicles in yellow color, allowing for easy visualization and analysis of their movements and interactions on the road network. The various network parameters considered for the simulation are listed in Table 5.

A. ANALYSIS AND DISCUSSION OF THROUGHPUT RESULTS FOR THE DYCW-MAC MODEL

The DYCW-MAC model was presented and analyzed for relay selection and CW adjustment using simulation. The achieved throughput and delay were compared with other comparable models, including VCAR-MAC [22], RECV-MAC [5], Traditional MAC, and a Clustering model [4].

As demonstrated in Figure 14, the DYCW-MAC model has the highest throughput (19.17 Mbps) when compared to other models. This is because the DYCW-MAC model determines the precise value of CW for broadcasting and selects the best possible relays for multi-hop communication using a fuzzy logic system.

This reduces the possibility of packet collisions, resulting in higher throughput. In contrast, the RECV-MAC model [5] uses a fixed CW, leading to a lower throughput of 14.37 Mbps when vehicle density is low. However, as vehicle density increases, the packet drop ratio increases, resulting in a decrease in throughput. In the case of the Clustering

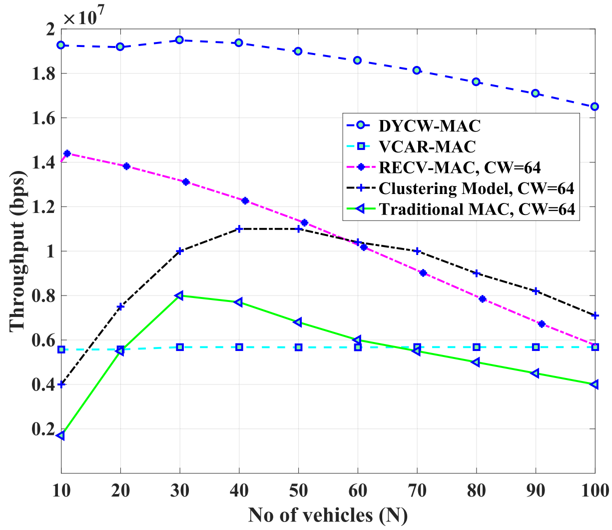

FIGURE 14. **Comparison of throughput performance of the DYCW-MAC model with other models with the number of vehicles.**

model [4], for a low-density network setting, the throughput performance is positively correlated with the number of vehicles but beyond a point, the throughput starts to decrease with an increase in the number of vehicles as can be seen in Figure 14. In the DYCW-MAC model, when the vehicle density increases, a comparatively smaller reduction is seen in the throughput performance due to CW adjustment. The variability of throughput is significantly lower as compared to other models, the highest to lowest throughput variation for the DYCW-MAC model is only 16.32% whereas for RECV-MAC, the Clustering model, and the Traditional model it is 59%, 38%, and 38% respectively.

B. ANALYSIS AND DISCUSSION OF AVERAGE PACKET DELAY RESULTS FOR THE DYCW-MAC MODEL

From Figure 15, one can infer that the average packet delay of the DYCW-MAC model is notably less compared to VCAR-MAC [22], RECV-MAC model [5], Clustering [4] and the Traditional model. The reason for this out-performance is the mechanism to dynamically adjust the CW and to select the most optimal relay via the fuzzy logic system due to which the system can access the channel quickly leading to a decrease in the packet collision probability and avoidance of latency at the MAC layer. Other compared models have assumed the same CW for all vehicle densities, resulting in increased packet collisions for the higher-density networks. Hence, such models are only accurate for low-density networks. However, in the DYCW-MAC model, the CW is dynamically adjusted before data transmission. In the fuzzy logic system for relay selection, the paper has considered the F-ETX metric, which performs better in VANETs [17] because F-ETX takes both link connectivity and link stability between the vehicles as its input. This makes the system more trustworthy. As shown in Figure 15 for the low-density network, the average packet delay for all the models is nearly the same, but as the number of vehicles increases, a marked

TABLE 6. Comparison of numerical results with the updated model.

	N	Proposed Model (DYCW-MAC)	VCAR-MAC [22]	RECV-MAC (CW=64) [5]	Clustering model(CW=64) [4]	Traditional Model (CW=64) [4]
Throughput (Mbps)	20	**19.17**	5.51	14.37	7.50	5.50
	40	**19.35**	5.57	12.26	11.51	7.71
	60	**18.56**	5.66	10.17	10.40	6.01
	80	**17.60**	5.67	7.84	9.02	5.11
	100	**16.48**	5.68	5.66	7.12	4.16
Average Packet Delay (ms)	20	**7.68**	10.25	17.10	7.50	20.01
	40	**17.74**	19.87	33.68	48.30	45.04
	60	**32.34**	34.67	55.40	78.02	85.06
	80	**40.44**	42.38	74.63	110.10	130.12
	100	**42.71**	48.13	91.57	145.30	175.40

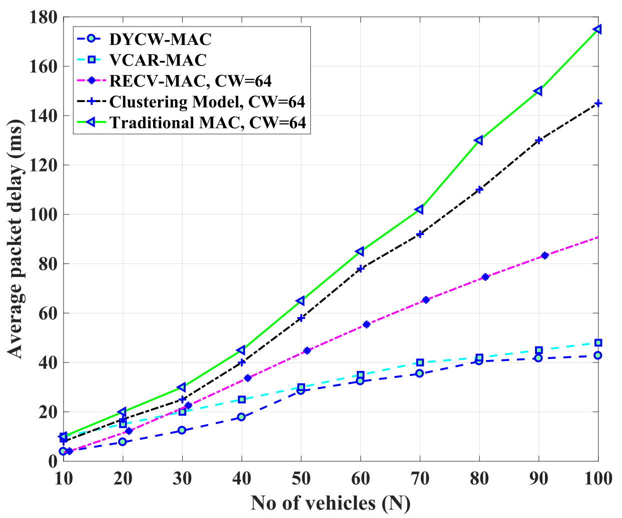

FIGURE 15. Comparison of average packet delay performance of the DYCW-MAC model with other models with the number of vehicles.

difference in average packet delay is seen. Table 6 shows the numerical results of all the discussed models.

After the complete analysis of the results, it can be said that the DYCW-MAC protocol outperforms other models in terms of the network throughput and the average packet delay under different vehicle densities (Highlighted in bold in Table 6). The fuzzy logic system based on different metrics performs well in VANETs by selecting the best CW and suitable relay vehicles for data transmission. The reliability and stability of the link increase due to analyzing and combining various metrics with a fuzzy logic rule-based system.

VII. CONCLUSION

The application of the fuzzy logic system on both the MAC and the Network layer suggests that the DYCW-MAC model is a reliable and time-efficient mechanism for safety message transmission. The optimal CW selection method is effective in sparse as well as dense networks since VANET's network condition and mobility are volatile, causing the link quality factor between the two nodes to degrade. The DYCW-MAC model dynamically adjusts CW and selects the best relay among nearby vehicles by considering four parameters: direction, velocity difference, coverage factor, and F-ETX, which takes into account link quality and stability. Such metrics help to select the best relay among numerous vehicles, resulting in the desired network throughput and reduced latency. The use of a fuzzy logic system on both layers leads to improved throughput and average packet delay under various network conditions, as demonstrated by the analysis and simulation results. These results outperform those obtained using the VCAR-MAC, RECV-MAC, Clustering Model, and traditional models.

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