SMART BROADCAST PROTOCOL DESIGN FOR VEHICULAR AD HOC NETWORKS

by

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This dissertation was prepared under the direction of the candidate's dissertation advisor, Dr. Imad Mahgoub, Department of Computer & Electrical Engineering and Computer Science, and has been approved by the members of her supervisory committee. It was submitted to the faculty of the College of Engineering and Computer Science and was accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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ABSTRACT

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Multi-hop broadcast is one of the main approaches to disseminate data in VANET. Therefore, it is important to design a reliable multi-hop broadcast protocol, which satisfies both reachability and bandwidth consumption requirements.

In a dense network, where vehicles are very close to each other, the number of vehicles needed to rebroadcast the message should be small enough to avoid a broadcast storm, but large enough to meet the reachability requirement. If the network is sparse, a higher number of vehicles is needed to retransmit to provide a higher reachability level. So, it is obvious that there is a tradeoff between reachability and bandwidth consumption.

In this work, considering the above mentioned challenges, we design a number of smart broadcast protocols and evaluate their performance in various network density scenarios. We use fuzzy logic technique to determine the qualification of vehicles to be forwarders, resulting in reachability enhancement. Then we design a bandwidth efficient fuzzy logic-assisted broadcast protocol which aggressively suppresses the number of retransmissions. We also propose an intelligent hybrid protocol adapts to local network density. In order to avoid packet collisions and enhance reachability, we design a cross layer statistical broadcast protocol, in which the contention window size is adjusted based on the local density information.

We look into the multi-hop broadcast problem with an environment based on game theory. In this scenario, vehicles are players and their strategy is either to volunteer and rebroadcast the received message or defect and wait for others to rebroadcast. We introduce a volunteer dilemma game inspired broadcast scheme to estimate the probability of forwarding for the set of potential forwarding vehicles. In this scheme we also introduce a fuzzy logic-based contention window size adjustment system.

Finally, based on the estimated spatial distribution of vehicles, we design a transmission range adaptive scheme with a fuzzy logic-assisted contention window size system, in which a bloom filter method is used to mitigate overhead.

Extensive experimental work is obtained using simulation tools to evaluate the performance of the proposed schemes. The results confirm the relative advantages of the proposed protocols for different density scenarios.

To my beloved family.

SMART BROADCAST PROTOCOL DESIGN FOR VEHICULAR AD HOC NETWORKS

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Vehicular Ad hoc Network (VANET) recently attracts research interests in both academia and industry because of its potential role in improving Intelligent Transportation Systems (ITS). VANET is a form of Mobile Ad-hoc Networks (MANETs), where the nodes are vehicles. VANET has two types of applications, namely safety and non-safety (comfort). Safety applications are considered the more important due to their significant potential to prevent road accidents and save lives.

In VANET, a multi-hop broadcast protocol is required to support many safety applications such as road condition warning, post crash warning, breakdown warning, emergency vehicle at scene warning [1]. However, broadcast is also used for beaconing and in the other type of routing mechanisms like route discovery in Geocast.

Flooding is the simplest broadcast method in which all the nodes that receive the broadcast message will rebroadcast it to their neighbors. Blindly rebroadcast messages can lead to an explosive growth of traffic (broadcast storm) which wastes a significant amount of bandwidth [2]. Since in VANETs, broadcast is mostly used as the means of communication, solving the problem of broadcast storm is essential.

This work is a study of smart broadcast schemes design for VANET. Contained within this dissertation are presentation of research results on various proposed schemes.

1.2 BROADCAST IN VANET

Based on how the next forwarding vehicle is selected, multi-hop VANET broadcast methods can be classified into three: cluster-based, transmitter-based, and receiver-based broadcast methods. In cluster-based broadcast methods the message should always be delivered to a certain node. In other words, the next relay is a specified node (either mobile or fixed) [3], [4]. In transmitter-based broadcast methods, using exchanged neighbors information, the sending vehicle selects the next relay node [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], and [16].

The third type of broadcast methods is receiver-based in which each receiving vehicle itself determines how to act, rebroadcast the received message or remain silent [17], [18], [19], [20], [21], [22], [23]. All of these broadcast techniques have their advantages and disadvantages which can affect the broadcast efficiency. Table 1.1 summarized the advantages and disadvantages of each broadcast category.

Table 1.1: Multi-hop Broadcast Methods Classification

Method	**Advantage**	**Disadvantage**
Cluster-based	scalability	calculation overhead
Transmitter-based	bandwidth consumption	packet loss and end-to-end delay
Receiver-based	packet delivery	number of redundant rebroadcasts

1.3 PROBLEM STATEMENT

The most important class of applications in the context of vehicular networks is safety-related applications, in which emergency messages that are broadcasted to surrounding vehicles must have high reachability and minimum possible latency. Traditional broadcast techniques like flooding consume a significant amount of bandwidth by increasing the number of retransmissions (broadcast storm). In addition, due to nature of VANET, a broadcast protocol design needs to deal with frequent and rapid network topology changes, high vehicular mobility, and limited bandwidth.

Vehicle mobility affects the connectivity of vehicles in VANETs. In the sparse networks, this problem becomes much more challenging and can cause significant packet loss. The transmission range extension is one of possible strategies which can be utilized to achieve connectivity enhancement in sparse networks [24]. The transmission range extension potentially increases the interference, which increases the number of packet drops. Thus it is beneficial to increase the transmission range when vehicle density is low as the increase in interference level would be small. Alternatively, the transmission range can be reduced when vehicle density is found to be very high.

In addition, in a high traffic density, when the number of vehicles is large, traditional broadcast techniques lead to increased number of collisions and channel contention overhead. In IEEE 802.11p, to avoid ACK explosion, a vehicle does not acknowledge a broadcast MAC frame. In VANETs, since the vehicle density and data traffic pattern vary for different road types, the MAC protocol should be intelligent enough to be aware of this issue. When the number of sending vehicles is large, a relatively large CW (contention window) size is needed to avoid unnecessary collisions. In contrast, when the network traffic load is small, a small CW size is required to access the wireless medium with a short delay.

Since majority of existing broadcast protocols do not address all these points, it is necessary to design and evaluate a cross-layer protocol that can jointly and dynamically adapt the message forwarding mechanism at the network layer, transmission range at the physical layer, and the contention window size at the MAC layer.

1.4 CONTRIBUTION

In this work, we design and evaluate smart receiver-based broadcast schemes. To mitigate the broadcast storm, we utilize aggressive smart decision making systems to determine the forwarding vehicles and suppress the number of rebroadcasts. In order to enhance reachability and coverage, we utilize network distribution information based on nearest neighbor distance technique and introduce a transmission range adaptive broadcast scheme. We also deploy bloom filter technique to reduce overhead. To prevent packet collision, we introduce smart contention window size adjustment methods which adjust the level of contention window size based on local density and spatial distribution. The contributions are as follows:

1. The classification and survey of related multi-hop broadcast protocols in VANET (Chapter 2).
2. The design and evaluation of a Fuzzy Logic-based multi-hop Broadcast (FLB) protocol [25](Chapter 3).
3. The design and evaluation of a bandwidth efficient multi-hop broadcast using fuzzy logic techniques [26](Chapter 4).
4. The design and evaluation of an intelligent hybrid adaptive broadcast scheme [27] (Chapter 5).
5. The design and evaluation of a cross-layer statistical broadcast with density-adaptive contention window adjustment [28] (Chapter 6)
6. The design and evaluation of a volunteer dilemma inspired multi-hop broadcast scheme with contention window size adjustment [29] (Chapter 7).
7. The design and evaluation of a Transmission Range Adaptive Broadcast Scheme [30](Chapter 8)

1.5 ORGANIZATION

The reminder of this document is organized as follows. In Chapter 2 we present the literature review and survey of the broadcast protocols and related work. We introduce our fuzzy logic-based broadcast protocol in Chapter 3. Chapter 4 explains a bandwidth efficient multi-hop broadcast using fuzzy logic techniques. Chapter 5 introduces our proposed intelligent hybrid adaptive broadcast scheme. In Chapter 6, we describe our proposed cross-layer statistical broadcast with density-adaptive contention window adjustment protocol. In Chapter 7 we present volunteer dilemma inspired broadcast scheme with contention window size adjustment. Transmission range adaptive broadcast scheme is given in Chapter 8. Finally, Chapter 9 presents the conclusion along with future work.

CHAPTER 2

LITERATURE REVIEW

2.1 BROADCAST PROTOCOL CLASSIFICATION

Over the past few years, several broadcast protocols have been proposed. However, they can generally be classified into two main categories:

- Single-hop broadcast
- Multi-hop broadcast

The major contrast between two types of broadcast protocols is in the way that the messages are propagated through the network [31].

In single-hop broadcast, when a vehicle receives a message, it does not rebroadcast the information immediately. Instead, it keeps the information and updates its on-board database. Each vehicle carries the traffic information with itself as it travels and periodically sends this information to one-hop neighboring vehicles. In order to design this type of protocols, it is necessary to consider the broadcast interval and the information that needs to be broadcast.

In multi-hop broadcast, the message propagates through the network. Multi-hop broadcast is the most suitable communication mechanism for VANET safety applications. As mentioned earlier, flooding is the simplest multi-hop broadcasting method in which all the nodes that receive the broadcast message will rebroadcast it to their neighbors. But because of broadcast storm problem, many multi-hop broadcast protocols are proposed to provide high performance in vehicular communications. Based on how the next forwarding vehicle is selected, we classified broadcast protocols into three main classes:

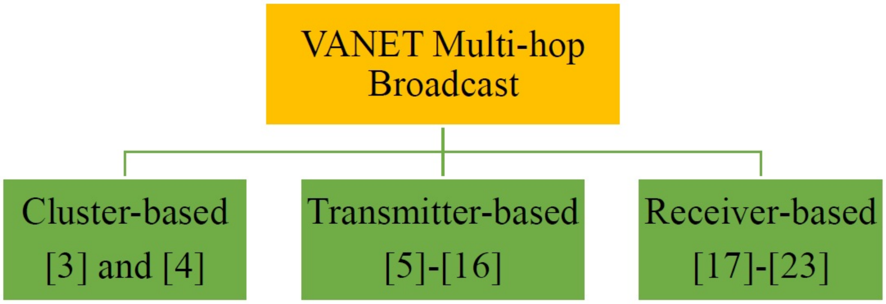


Figure 2.1: Multi-hop Broadcast Classification

- Cluster-based
- Transmitter-based
- Receiver-based

In cluster-based broadcast methods, the message should always be delivered to a certain node. In other words, the next relay is a specified node (either mobile or fixed). In transmitter-based broadcast methods, using exchanged neighbors information, the sending vehicle selects the next relay node. The third type of broadcast methods is receiver-based in which each receiving vehicle itself determines how to act, rebroadcast the received message or remain silent. In next sections we review these proposed broadcast protocols.

2.1.1 Cluster-based Broadcast Protocols

In cluster-based network protocols, vehicles near each other form a cluster and a virtual network infrastructure is created in order to provide scalability. Each cluster can select a cluster head, which is responsible for intra-cluster and inter-cluster coordination in the network management functions. Vehicles inside a cluster communicate via direct links. Inter-cluster communication is performed via the cluster heads. In [3], a distributed proactive clustering scheme is proposed for VANET broadcast. The proposed system dynamically establishes a virtual backbone infrastructure, taking robustness and lifetime of connections among backbone members into account. In [4], a mathematical modeling and analysis for a cluster-based safety message broadcasting in highway environment is presented. Due to constant topology changes in VANET, cluster formation and cluster head selection lead to an inefficient performance in terms of message overhead.

2.1.2 Transmitter-based Broadcast Protocols

In transmitter-based protocols, based on the exchanged hello messages information, each sending vehicle selects the next relay node. In [5]- [8], the farthest neighbor from the sending vehicle is considered the most suitable candidate for being the next forwarder node. Since all the nodes between the sending vehicle and its farthest neighbor have already received the broadcast message, selecting the farthest neighbor as the next relay vehicle can result in covering more area ahead or behind (depends on forward or backward messaging pattern). Obviously, geographical position information is used to evaluate this criterion. Due to the impact of wireless channel condition, the farthest node may not be considered the best relay node. Therefore, in [9] and [10], the transmitter node uses channel quality metrics (i.e. received signal strength) to evaluate the most suitable next relay node. In [11]- [14], based on a fuzzy logic system, relay node selection is done. In order to select the next rely node, the transmitting vehicle takes multiple metrics of inter-vehicle distance, node mobility and signal strength into consideration. In [15], a transmitter-based cross-layer broadcast protocol is introduced. In this protocol, fuzzy logic system is applied to select backbone nodes which considers the vehicle velocity, the number of neighboring vehicles moving in the same direction and the antenna height. Transmitter-based broadcast methods potentially have a higher probability of packet loss which causes increasing end-to-end delay.

2.1.3 Receiver-based Broadcast Protocols

Receiver-based broadcast protocols are shown to perform efficiently in terms of reliability and overhead. Each receiving vehicle decides whether or not to retransmit a received broadcast message. Statistical receiver-based broadcast methods compare a locally measured value to a threshold, to decide whether to rebroadcast in receiver side. As shown in Fig. 2.2, so far five fundamental statistical broadcast methods are introduced: stochastic, counter-based, distance-based, location-based, and distance-to-mean-based [17].

Stochastic method : The stochastic method is the simplest method in the context of statistical broadcast schemes. In the stochastic method, a receiving vehicle generates a uniform random number between 0 and 1 and compares this to a predefined threshold value. If this generated number is less than the threshold, the message is rebroadcast. Otherwise, the vehicle drops the message. Besides simplicity, this method reduces the number of rebroadcasting vehicles. External quantities such as traffic density can be used to define a threshold. If the threshold value is too small, there will be too few rebroadcasting vehicles [18]. In [19], a broadcast protocol based on the symmetric volunteer dilemma game is proposed. This protocol models volunteering's costs and benefits based on the distance to the sender. However, this protocol relies on a stochastic broadcast scheme and for each vehicle compares the probability of forwarding to a random generated value.

Counter − based method : In the counter-based statistical methods, the key point is to determine the number of neighbors that the broadcast message has been received from. If this number is more than a threshold, there is no benefit by rebroadcasting the message.

Distance − based method : Basically, all broadcast schemes attempt to cover as much as possible additional area to improve the performance. In distance method, vehicles can rebroadcast the message if they have not received the message from

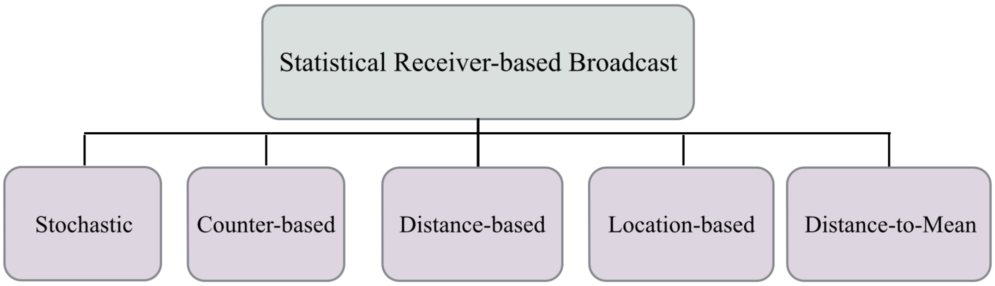


Figure 2.2: Statistical Broadcast Methods

another vehicles nearby. In other words, more distance between receiving vehicle and transmitting neighbors, more benefit to rebroadcast the message.

$Location - based\ method$: Typically, the location-based methods rely on a covered area calculation and estimation of the amount of area that would be covered by potential new transmissions. To make the retransmission decision, the receiving vehicle utilizes an assessment delay method to observe the location of the transmitting neighbors. It then calculates the intersection of those transmitting neighbors' covered areas with its own transmission area. Finally it estimates the potential new area, which will be covered if the vehicle rebroadcasts. If this calculated area is greater than a given threshold, the vehicle rebroadcasts the message.

$Distance - to - mean - based\ method$: In [17] and [20], the distance-to-mean broadcast method is proposed and a straightforward broadcast protocol based on this method (DTM) is evaluated. Utilizing exchanged neighbors' position information, DTM calculates the spatial mean of the receiver's transmitting neighbors. Then, the receiver determines its distance to the spatial mean. The vehicle decides to rebroadcast the message if this distance-to-mean value is greater than a defined threshold, which is a function of the number of neighbors. DTM is shown to surpass the distance-based method and to have similar performance to the location method, even though it is much easier to calculate than the location method.

In all statistical broadcast methods, it is very important how to select the threshold value. If the threshold value is too small, the number of transmissions will increase. A large threshold value aggressively reduces the number of transmissions and can hurt reachability.

In the context of receiver-based multi-hop broadcast for VANET, several techniques have been proposed based on statistical methods. In [21], using a combination of the counter and stochastic methods and distance- biased assessment delay, the Weighted p-Persistence protocol is presented. When a vehicle receives a packet for the first time, it computes its own probability based on the distance between itself and the transmitter. The rebroadcast probability is function of the distance between transmitter and receiver, and also the transmission range. Based on this function, the vehicles that are farther from the transmitter will be given higher probability. This protocol does not take traffic density into consideration, therefore, in high traffic density it experiences a large value of the number of rebroadcasts. The Distribution-Adaptive Distance with Channel Quality (DADCQ) protocol proposed in [22] is a statistical broadcast protocol that utilizes the distance method to select forwarding nodes. DADCQ creates a decision threshold function which is simultaneously adaptive to the node density, the spatial distribution pattern and the wireless channel quality. With varying node density and fading intensity, DADCQ is shown to utilize bandwidth efficiently while achieving high reachability in both urban and highway scenarios. The Statistical Location Assisted Broadcast (SLAB) protocol is presented in [23]. SLAB uses the distance-to-mean method and further enhances DADCQ by utilizing machine learning techniques-based optimization algorithms to automatically create an efficient decision threshold function.

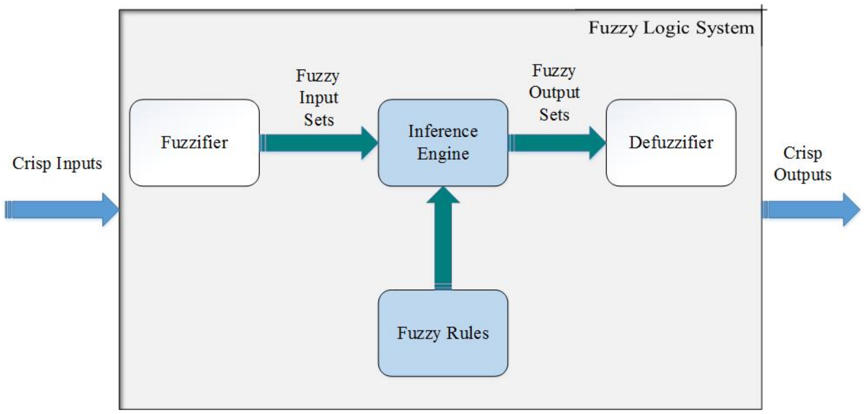


Figure 2.3: Fuzzy Logic System Structure

2.2 FUZZY LOGIC TECHNIQUE

Fuzzy logic, introduced by Lotfi zade in 1965 [32], accepts a range of values and returns estimated results. As shown in 2.3 Generally, each fuzzy logic system has three main components:

- Fuzzifier
- Inference engine
- Defuzzifier

Basically, the fuzzifier is used to map the crisp input into fuzzy set, the fuzzy rule based processor implements an inference engine to obtain the solution based on IF-THEN sets of rules. The defuzzifier is applied to transform the solution to the crisp output. Basically, three defuzzification techniques are commonly used: Mean of Maximum method, Center of gravity method and Height method.

2.2.1 Fuzzy Logic Application in VANET

In VANET, fuzzy logic has been used to improve the decision making process and reduce computation delays. Some of the areas that fuzzy logic has been applied to are:

- Routing algorithm
- Broadcasting
- Cluster head selection
- Localization

In [33], a novel stability and reliability routing protocol is presented. This routing mechanism uses fuzzy logic with geographical routing in making packet forwarding decisions. Direction and distance are considered as fuzzy system inputs to select the best neighboring vehicle. Recently, it comes as no surprise that fuzzy logic has been shown to be effective for VANET broadcast [11]- [14]. In [15], fuzzy logic technique is utilized to select the backbone node in a cross-layer broadcasting method. This method considers the vehicle velocity, the number of neighboring vehicles moving in the same direction, and the antenna height as fuzzy logic system inputs. The cluster head selection method presented in [34], cluster heads are selected according to their speed and distance from the cluster members. The fuzzy logic inference system predicts the future speed and position of cluster members to improve cluster head lifetime and more stable topology. In [35], a fuzzy logic-based localization for VANET is presented. In this method, fuzzy logic and weighted centroid localization (WCL) are combined. Two input parameters are fed to the fuzzy logic system, distance between the neigh- boring vehicles and heading information. Periodic messages (beacons) are used to exchange such information. The output of the fuzzy logic system is weight values. Using WCL, each neighboring vehicle will be assigned to a weight value. The weighted coordinates of the neighboring vehicles are then used to estimate the location of the vehicle.

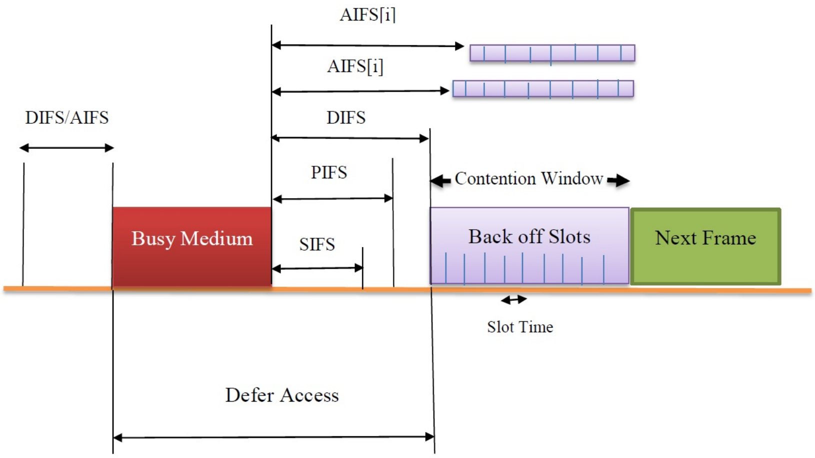


Figure 2.4: WAVE MAC Frame

2.3 CONTENTION WINDOW SIZE ADJUSTMENT

IEEE 802.11p is a modification of the IEEE 802.11 standard to provide Wireless Access in Vehicular Environments (WAVE) [36]. Based on IEEE 802.11p, each vehicle uses the Distributed Coordination Function(DCF), or an Enhanced Distributed Channel Access (EDCA) function to contend for channel access. Each vehicle checks the status of the wireless medium before transmission. If the medium is idle for longer than DCF Inter-Frame Space (DIFS) or Arbitration Inter-Frame Space (AIFS), it can transmit immediately. Otherwise, each vehicle needs to defer until the medium is determined to be idle after a DIFS/AIFS period. After this period, the vehicle generates a random backoff period as an additional deferral time before it transmits. The backoff time is relative to a random integer which is drawn from a uniform distribution over the interval of [0,CW], where CW is the current contention window size. CW is a value determined by aCW_{min} and aCW_{max} depending on the access category. According to the IEEE 802.11p, aCW_{min} is 15, and aCW_{max} is 1023. If multiple neighboring vehicles (which are in the communication range of each other) choose the same backoff time, collisions may happen.

Since in IEEE 802.11p, there is no acknowledgment for broadcast MAC frame, and also there is a different vehicle density for different road types or road segments, the MAC protocol should take these issues into consideration. The solution can be addressed by a CW (contention window) adaptive MAC protocol. This means when the number of transmitting vehicles is large, a proportionally large CW size reduces the number of collisions, while in a low traffic density a small CW size is needed to access the medium.

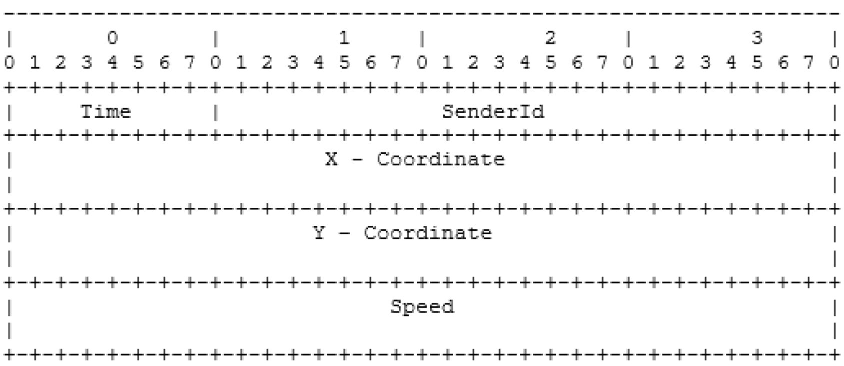
CHAPTER 3

FUZZY LOGIC-BASED BROADCAST (FLB) PROTOCOL

In this chapter using fuzzy logic techniques, we propose a receiver-based intelligent broadcast protocol [25]. Relying on coverage, connectivity and mobility factors calculated by a receiving vehicle, the fuzzy logic system decides if the node is required to rebroadcast or not. Material in this chapter is published in [25].

3.1 SYSTEM MODEL

We assume all the vehicles are equipped with a half-duplex transceiver and a Global Positioning System (GPS), so each vehicle is aware of its position and moving velocity information and exchanges this information with its neighbors using hello messages. The proposed method is designed for highway environment. Each vehicle is able to keep track of its neighboring vehicles using periodic hello messages. These broadcasted hello messages contain position, velocity and vehicle's ID information. Based on the received hello messages, vehicles construct and update their own neighbors



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-----------------------------------------------------------------
|       0       |       1       |       2       |       3       |
0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7 0
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Time      |                   SenderId                    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        X - Coordinate                         |
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Y - Coordinate                          |
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                             Speed                             |
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3.1: Hello Message Contents

information table. When a vehicle receives a warning message for the first time, it calculates a delay time t_{max} based on equation 3.1.

$$t_{max} = T_{max}\ (1 - \frac{d}{r}) \tag{3.1}$$

where, d is the distance from the closest vehicle that the message received from and r is the maximum transmission radius. If the message is received before the timer expires, the timer will be reset. When the timer expires with no new received messages, the protocol will continue to make a rebroadcast decision. Then to decide whether to rebroadcast or not, it calculates the following factors:

- Coverage
- Connectivity
- Mobility

If the same warning message is received again, it will be dropped. The factors can be defined as follows:

Coverage Factor: We use the distance-to-mean method proposed in [20], to estimate coverage. The distance-to-mean method considers distance from the vehicle to spatial mean of the neighbors from which the broadcast message has been received. In order to calculate this metric, position information is used .The spatial mean of a set of points (x_i,y_i) is calculated as:

$$(\bar{x}, \bar{y}) = (\frac{1}{n}\sum_{i=1}^{n} x_i, \frac{1}{n}\sum_{i=1}^{n} y_i) \tag{3.2}$$

If the vehicle is positioned at (x,y), then the normalized distance to mean variable, M, is measured as in Equation 3.3.

$$M = \frac{1}{r}\sqrt{(x-\bar{x})^2 + (y-\bar{y})^2} \tag{3.3}$$

where, r is the transmission radius. When M is small, it means the neighboring transmitters are distributed evenly around the vehicle, indicating that it should favor not rebroadcasting.

$ConnectivityFactor$: We use the number of neighbors of a receiving vehicle, which are not common with its neighboring retransmitters to estimate connectivity. In our proposed method, each node before broadcasting the warning message, adds its neighbors ID list in a header to the message. After receiving the message, the next retransmitter vehicle updates this header before it broadcasts. According to this procedure, each receiving vehicle is aware of its 2-hop neighbors. So, it compares this neighbor's neighbors list with its own neighbors list to calculate the number of uncommon neighbors. The normalized number of uncommon neighbors (uncommon neighbors divided by number of 2-hop neighbors) value is considered the connectivity factor. Vehicles with more number of uncommon neighbors are more qualified to retransmit the message.

$MobilityFactor$: The definition of the third factor, mobility, is given in Equation 3.4.

$$MobilityFactor = \frac{v_r - v_{min}}{v_{max} - v_{min}} \tag{3.4}$$

where v_r denotes the velocity of the receiveing vehicle and v_{min} and v_{max} indicate the minimum and maximum velocity among neighboring transmitter vehicles and receiving vehicle, respectively. A lower mobility factor indicates a lower velocity. This work is based on a backward warning message rebroadcast pattern, so in this case vehicles with lower velocity are more qualified to rebroadcast the message.

3.1.1 Fuzzy Logic for Broadcasting

The membership functions of coverage, connectivity, and mobility factor for this proposed Fuzzy Logic-based Broadcast (FLB) scheme, are defined in Figs.4.5, 3.3, and 4.4, respectively. A vehicle uses the coverage membership function to calculate which degree the coverage belongs to $low, medium$ or $high$. Similarly, it calculates the degree of both the connectivity and the mobility, which are $low, medium, high$ and

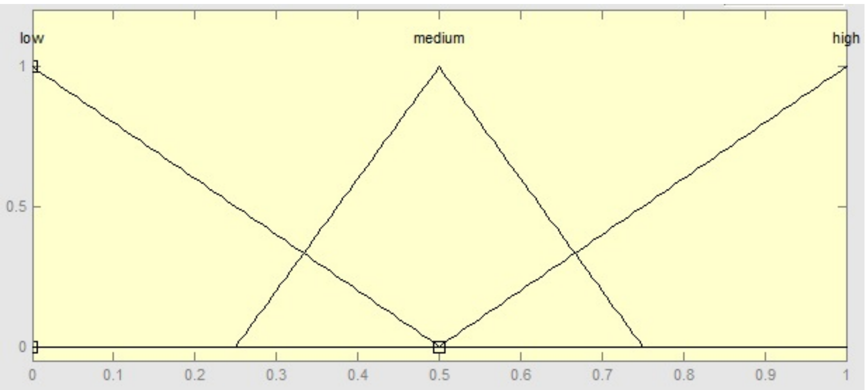


Figure 3.2: Membership Function for Coverage Factor

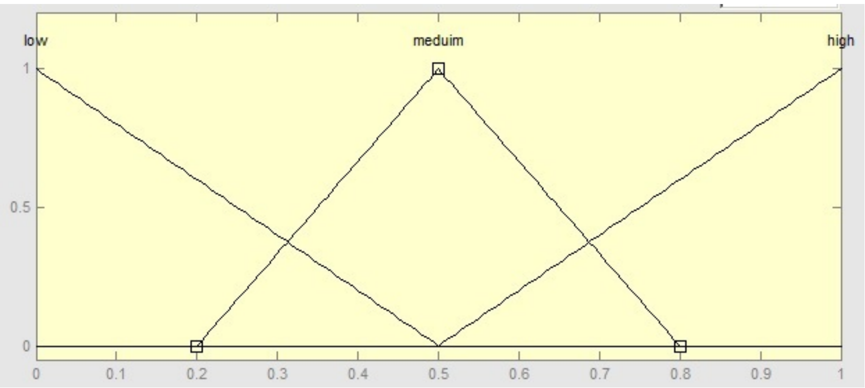


Figure 3.3: Membership Function for Connectivity Factor

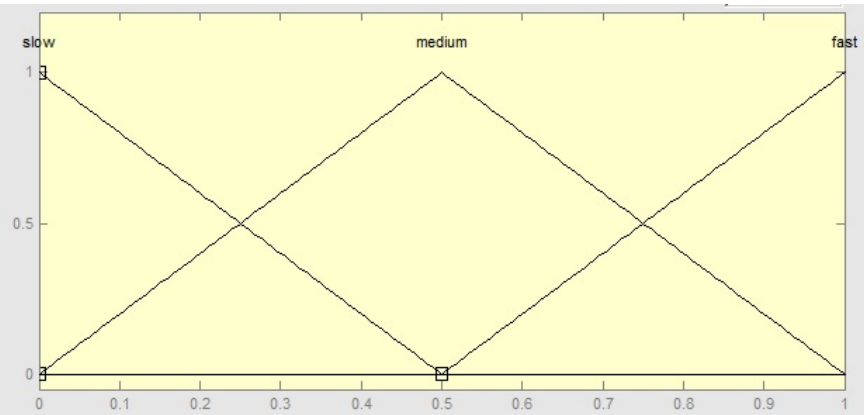


Figure 3.4: Membership Function for Mobility Factor

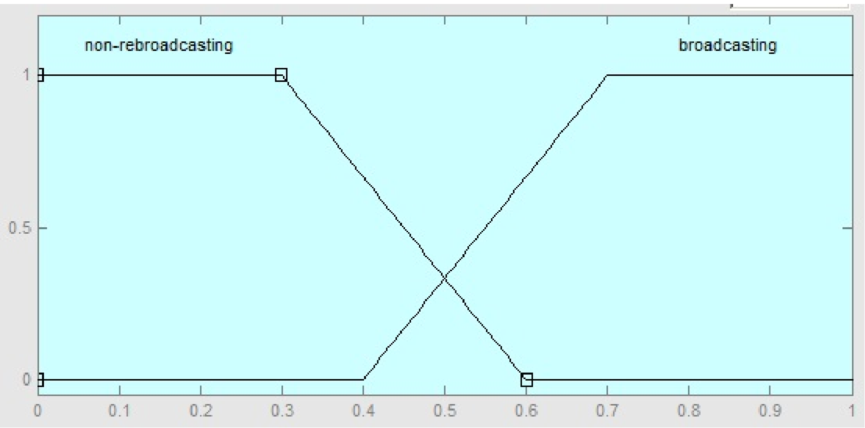


Figure 3.5: Output Membership Function

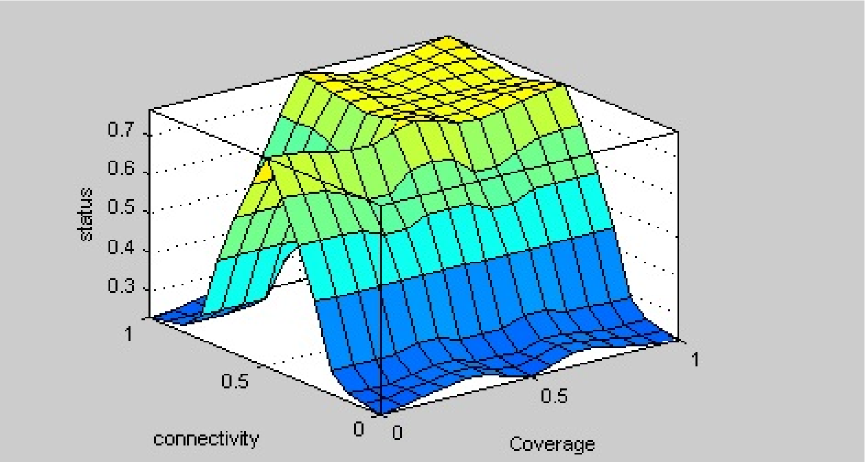


Figure 3.6: Correlation Between Coverage and Connectivity and Output

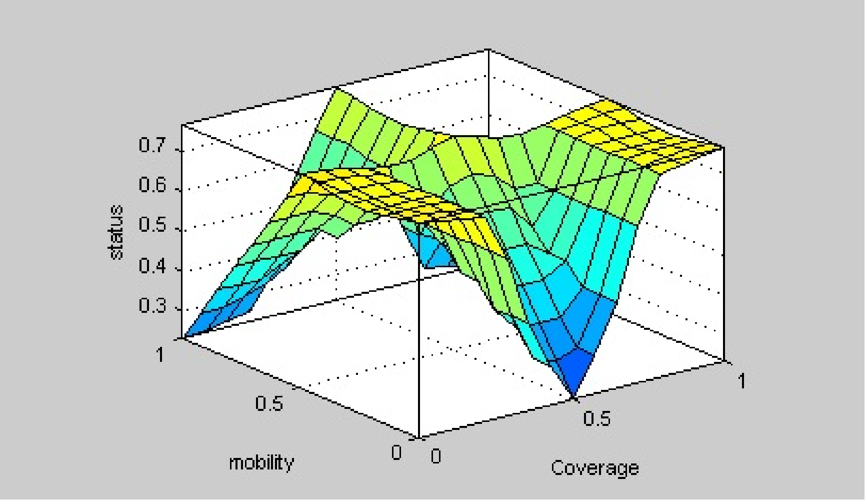


Figure 3.7: Correlation Between Coverage and Mobility and Output

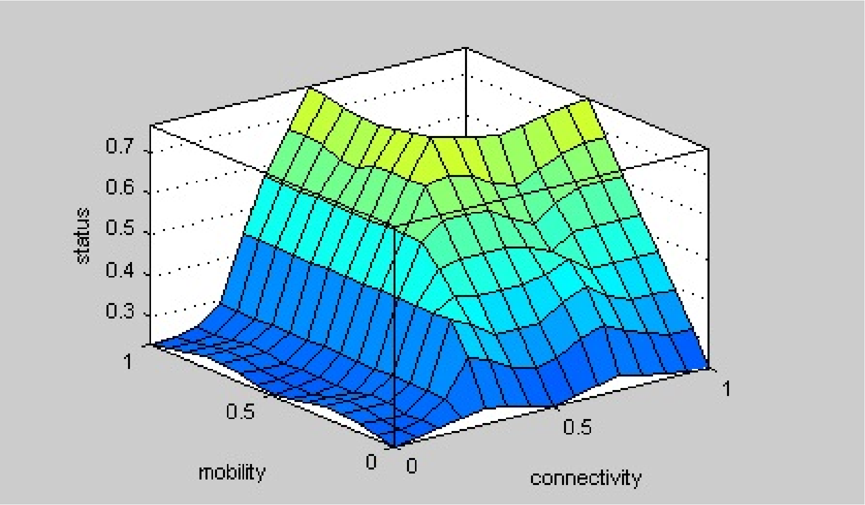


Figure 3.8: Correlation Between Connectivity and Mobility and Output

$slow, medium, fast$, respectively. The Max-Min fuzzy inference method is applied which means the fuzzy operator AND takes the minimum value of the antecedents [37]. Based on fuzzy values of input variables and using If-Then rules (as given in Table. 3.1), vehicle status as being rebroadcaster or non-rebroadcaster is calculated. The output membership function is demonstrated in Fig. 4.6. In this work, we use Center of Gravity (COG) which is the most popular defuzzification technique and widely utilized in actual applications.

3.2 SIMULATION AND RESULTS

We evaluate the efficiency of our proposed broadcast protocol using ns-3, a simulation tool based on C++ [38]. The simulations are run with the parameters stated in Table 3.2.

3.2.1 Highway Environment

The vehicles' mobility is generated based on ns-3 constant speed mobility model and the position allocation is based on ns-3 random rectangle position model, which places vehicles uniformly on a straight line (highway road scenario). We use the WAVE model [39], which is the overall system architecture for vehicular communications implemented in ns-3. The performance of our proposed protocol, Fuzzy Logic-based Broadcast (FLB), is compared with a straightforward broadcast protocol built on the distance-to-mean method (DTM) [20], Distribution-Adaptive Distance with Channel Quality (DADCQ) [22] and Statistical Location Assisted Broadcast (SLAB) [23] protocols. In order to evaluate scalability, we run the simulation for different traffic densities: low, medium, and high. Three sets of results are presented for each protocol using the following metrics:

- Reachability: Average fraction of vehicles that receive source messages

Table 3.1: Fuzzy Rules of FLB

Coverage	**Connectivity**	**Mobility**	**Status**
low	low	slow	non-rebroadcasting
low	low	medium	non-rebroadcasting
low	low	fast	non-rebroadcasting
low	medium	slow	rebroadcasting
low	medium	medium	rebroadcasting
low	medium	fast	non-rebroadcasting
low	high	slow	rebroadcasting
low	high	medium	non-rebroadcasting
low	high	fast	non-rebroadcasting
medium	low	slow	non-rebroadcasting
medium	low	medium	non-rebroadcasting
medium	low	fast	non-rebroadcasting
medium	medium	slow	rebroadcasting
medium	medium	medium	rebroadcasting
medium	medium	fast	non-rebroadcasting
medium	high	slow	rebroadcasting
medium	high	medium	non-rebroadcasting
medium	high	fast	non-rebroadcasting
high	low	slow	rebroadcasting
high	low	medium	non-rebroadcasting
high	low	fast	non-rebroadcasting
high	medium	slow	rebroadcasting
high	medium	medium	rebroadcasting
high	medium	fast	non-rebroadcasting
high	high	slow	rebroadcasting
high	high	medium	rebroadcasting
high	high	fast	rebroadcasting

Table 3.2: The Simulation Parameters

Parameter	**Value**
Number of vehicles	20, 40, 80, 120, 250, 400
Duration	1800 seconds
Packet size	500 bytes
Max speed	30 m/s
Hello message interval	10 seconds
Signal propagation	Nakagami
MAC/PHY protocol	IEEE 802.11p
Transmission range	250 meters
Layer 3 addressing	IPv4

- Rebroadcasts per covered node: Number of retransmissions to number of vehicles that receive the message ratio (ignoring overhead from beacons)
- Bytes sent per covered node: Total number of bytes sent to number of vehicles that receive the message ratio (including overhead from beacons)

Fig. 3.9 proves FLB's ability of successful message delivery in terms of reachability. According to the graphs, FLB consistently shows high levels of reachability in all traffic densities. From Fig. 3.10, we observe that FLB can provide significantly lower number of retransmission for various numbers of vehicles. Fig. 3.11 demonstrates bandwidth consumption in terms of bytes sent per covered node. It is observed that FLB, for all densities, has the lowest bytes sent in comparison with other protocols. This can be attributed to taking into account both the mobility and connectivity factors.

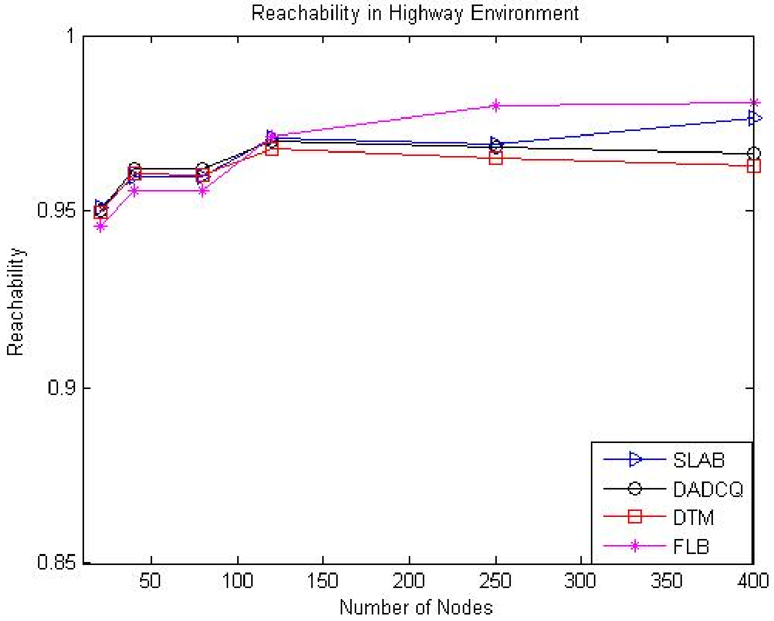


Figure 3.9: Reachability in Highway

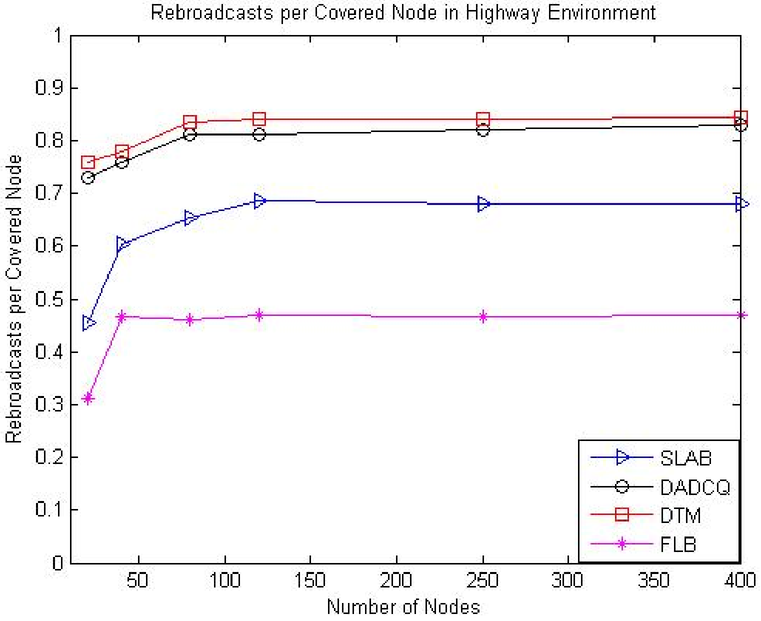


Figure 3.10: Rebroadcasts per Covered Node in Highway

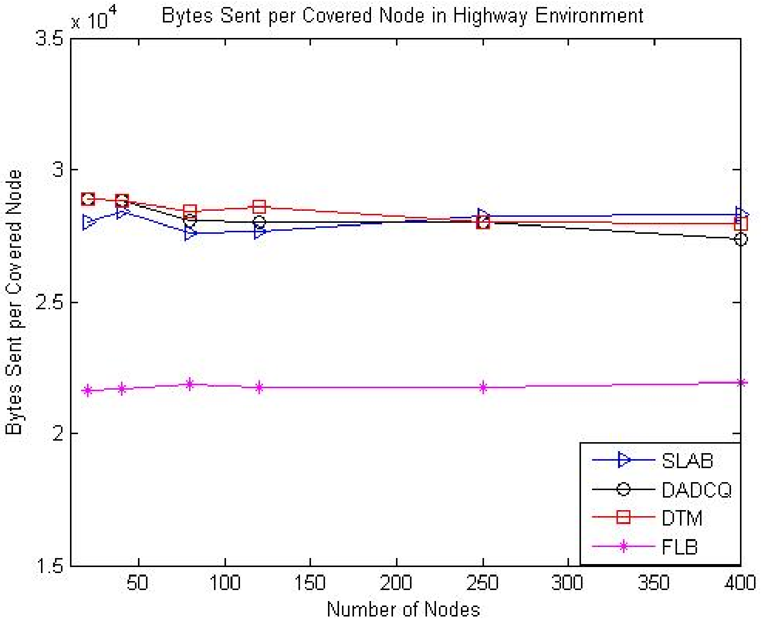


Figure 3.11: Bytes Sent per Covered Node in Highway

3.2.2 Urban Environment

We use Simulation of Urban MObility (SUMO) [40] to generate the vehicles' mobility in urban environment. In our simulation, a 3x3 Manhattan Grid Road with an edge length of 1000 meters and equal distances between neighboring intersections. The simulation parameters are stated in Table 6.1. In the car-following model, used in SUMO, each vehicle adapts its speed based on the leading vehicle's speed. Basically, vehicles' distribution and routes are generated randomly using the "randomTrips.py" in SUMO. After generating the mobility traces, using Ns2MobilityHelper class, they are imported into ns-3 to generate node mobility (Fig. 3.12).

Fig 5.10 shows the road network we use. The simulations are run with the parameter stated in Table 6.1. The vehicles' mobility is generated using SUMO. In the car-following model, which is used in SUMO, the speed of a vehicle is adapted to the speed of the leading vehicle. Vehicles in the simulation are randomly distributed and routes are randomly generated using the randomTrips utility in SUMO. Then,

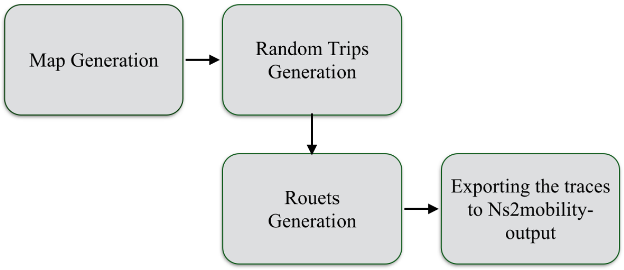


Figure 3.12: Map and Traces Generation Modules in SUMO

the generated mobility traces are imported into ns-3 to generate node mobility using Ns2MobilityHelper class.

The simulation results for urban environment are shown in Figs. 3.14 - 3.16. Similarly, in urban environment, FLB reaches more number of vehicles in comparison with DTM, DADCQ, and SLAB while it consumes less amount of bandwidth in terms of number of rebroadcast per covered node and bytes sent per covered node.

3.3 SUMMARY

We proposed a fuzzy logic-based broadcast method for vehicular ad hoc networks. In the proposed protocol, each vehicle after receiving a broadcasted warning message, decides whether to rebroadcast the message or not. Rebroadcasting decision is made by the fuzzy logic decision maker system, using the calculated coverage factor, connectivity factor and the mobility factor. These principal factors are calculated based on exchanged hello messages information between the vehicles. The simulation results confirmed the advantage of the proposed method over DTM, DADCQ and SLAB in highway and urban environment. FLB performed well in terms of reachability and bandwidth consumption compared to the other protocols in both highway and urban environments. The other protocols, either did not have the same level of reachability as FLB or did consume more bandwidth.

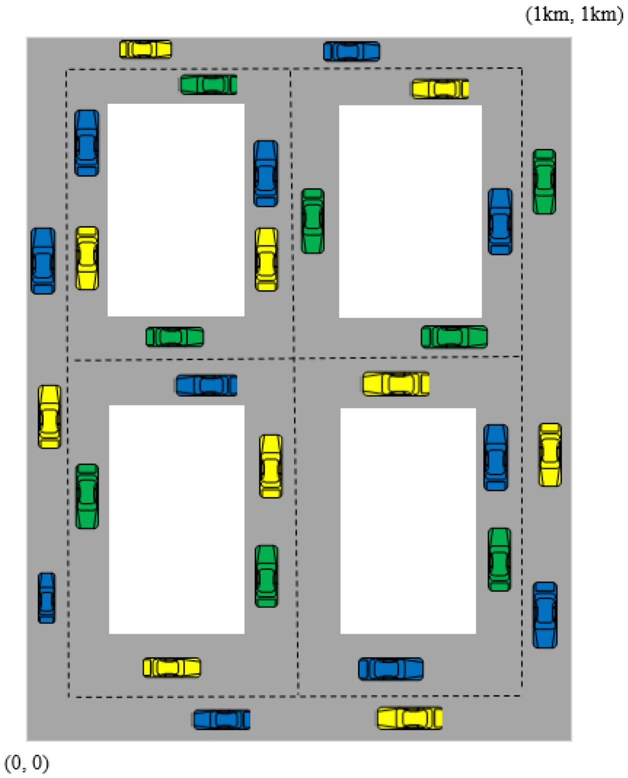


Figure 3.13: 3x3 Manhattan Grid Road Network

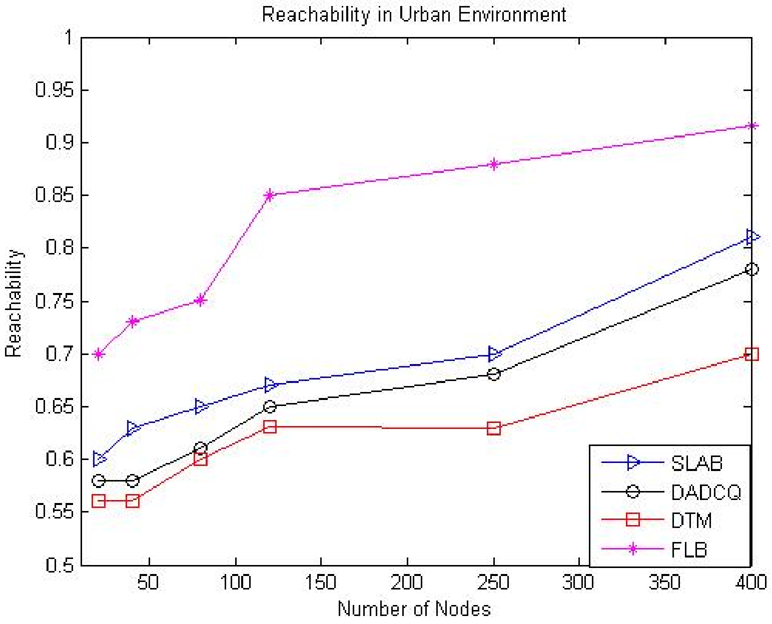


Figure 3.14: Reachability in Urban

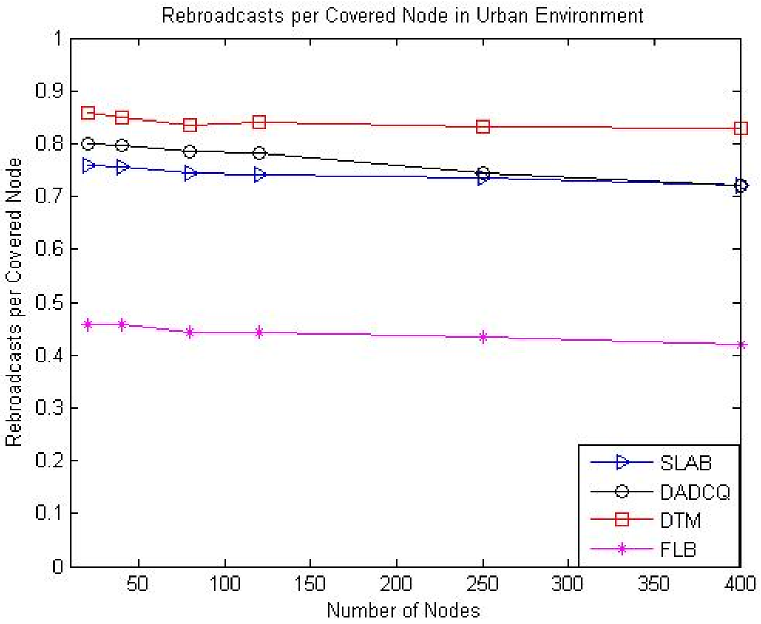


Figure 3.15: Rebroadcasts per Covered Node in Urban

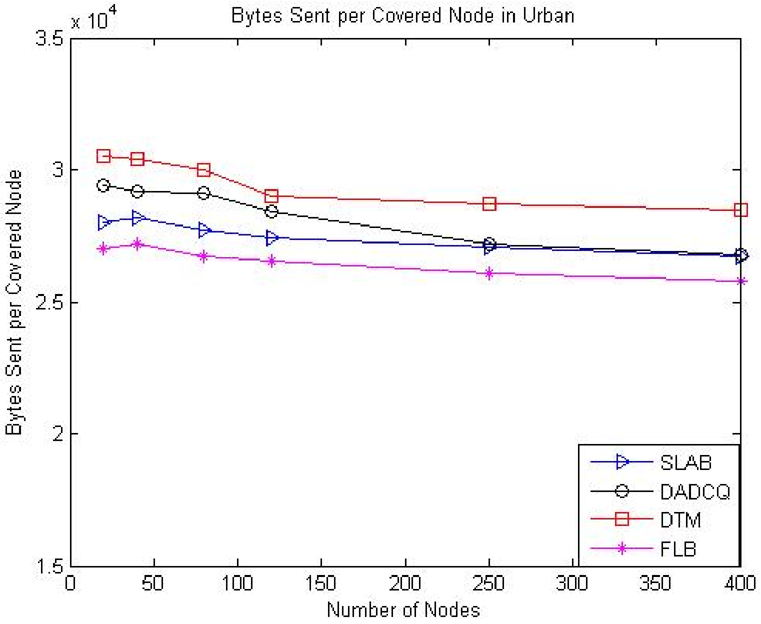


Figure 3.16: Bytes Sent per Covered Node in Urban

CHAPTER 4

BANDWIDTH EFFICIENT FUZZY LOGIC-ASSISTED BROADCAST

In this chapter, we propose a bandwidth efficient fuzzy logic-assisted broadcast (BEFLAB) protocol which aggressively reduces the number of rebroadcasting vehicles while maintaining an acceptable reachability level. The proposed protocol uses fuzzy logic to obtain a set of candidate forwarding vehicles, then based on the distance-to- mean value of each vehicle in this set, the receiving vehicle decides whether to rebroadcast or not. Material in this chapter is published in [26].

4.1 THE PROPOSED BEFLAB SCHEME

In this section we describe the proposed Bandwidth Efficient Fuzzy Logic-Assisted Broadcast (BEFLAB) scheme. Each receiving vehicle identifies a set of potential forwarders and uses a fuzzy logic system, which relies on mobility and coverage factors, to determine a set of candidate forwarding vehicles, and then based on the distance-to-mean value of each vehicle in this set of candidate forwarders, the receiving vehicle decides to rebroadcast or drop the message. Fig. 4.1 shows the proposed broadcast system modules.

4.1.1 Assumptions

We assume all the vehicles are equipped with a Global Positioning System (GPS), so each vehicle is aware of its position and moving velocity information. Each vehicle is able to keep track of its neighboring vehicles using periodic hello messages. These broadcasted hello messages contain position, velocity and vehicle's ID informa-

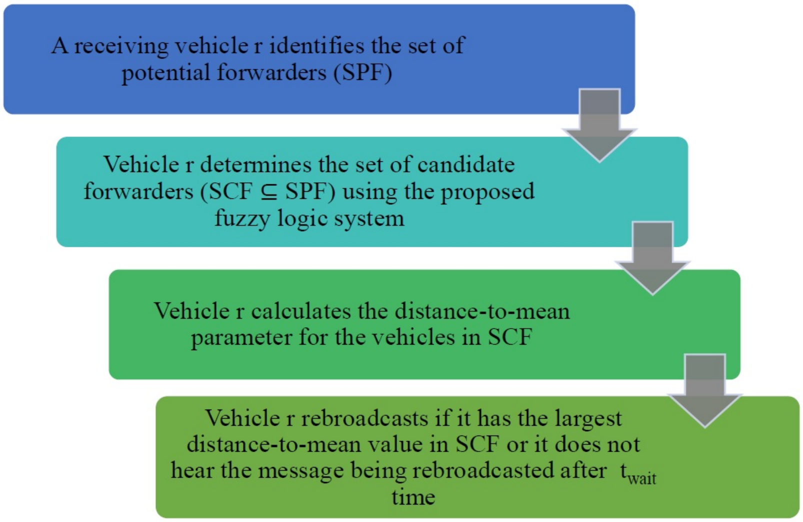


Figure 4.1: BEFLAB System Modules

tion. Based on the received hello messages, vehicles construct and update their own neighbors information tables.

We assume that each vehicle before broadcasting a message, includes the IDs of its neighbors in the header. After receiving the message, the next rebroadcaster vehicle updates this header to include its neighbors' IDs before it transmits.

4.1.2 Proposed Broadcast Protocol

Here is a detailed explanation of the proposed algorithm shown in Fig. 4.2. When Vehicle r receives a warning broadcast message (with unique sequence number) for the first time, using a random assessment delay mechanism [2], it identifies the transmitting neighbors from which the message was received. Since the message transmitting vehicles include their neighbors' IDs in the header of the message, receiving vehicle r knows the set of the transmitters' neighbors. Vehicle r identifies the set of common neighbors between itself and the transmitters and treats it as a set of potential forwarders (SPF). Vehicle r utilizes the proposed fuzzy logic system (Fig. 4.3), which uses mobility and coverage factors as inputs, to determine whether it is qualified to

Algorithm 1 BEFLAB Broadcast Method

```
procedure REBROADCASTING DECISION
    if Vehicle $r$ receives a message with a seq. number which was previously received then
        It drops the message
    else
        It uses a random assessment delay mechanism to find the transmitting neighbors
        It identifies SPF
        It calculates its MF and CF
        It uses fuzzy logic system to determine its rebroadcasting status
        if Vehicle $r$ is not qualified to rebroadcast then
            It drops the message
        else
            It determines SCF and calculates distance-to-mean parameter for the vehicles in SCF
            if Vehicle $r$ has the largest distance-to-mean value in SCF then
                It rebroadcasts
            else
                It waits for $t_{wait}$ time
                if Vehicle $r$ hears the message being forwarded during $t_{wait}$ then
                    It drops the message
                else
                    It rebroadcasts
                end if
            end if
        end if
    end if
end procedure
```

Figure 4.2: BEFLAB System Algorithm

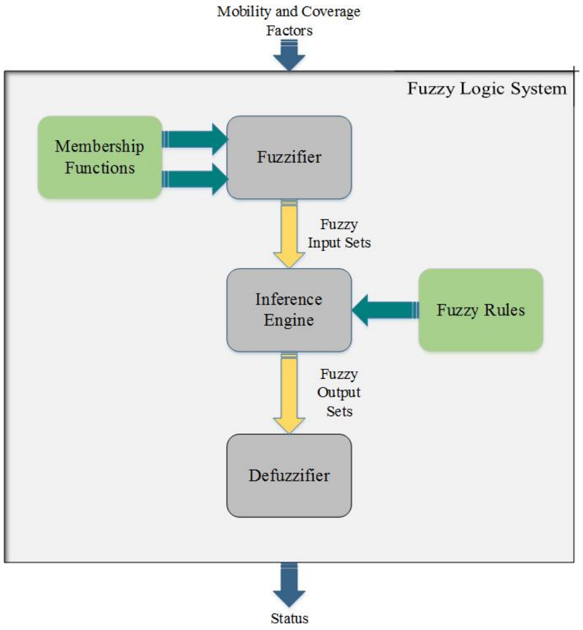


Figure 4.3: Fuzzy Logic System Structure

rebroadcast. Vehicle r calculates its mobility factor (MF) and its coverage factor (CF) using Equations 4.1, 4.2, and 4.3.

$$MF = \frac{v_i - v_{min}}{v_{max} - v_{min}} \tag{4.1}$$

where v_i denotes the velocity of vehicle i and v_{min} and v_{max} are the minimum and maximum velocity among common neighbors set and vehicle r, respectively. A lower mobility factor indicates a lower velocity and vehicles with lower velocity are more qualified to rebroadcast the message.

To obtain the coverage factor (CF), the distance-to-mean method proposed in [20] is used. The distance-to-mean in our method considers distance from the vehicle to spatial mean of the potential forwarder vehicles.The spatial mean of a set of n points (x_i,y_i) is calculated as:

$$(\bar{x}, \bar{y}) = (\frac{1}{n}\sum_{i=1}^{n} x_i, \frac{1}{n}\sum_{i=1}^{n} y_i) \tag{4.2}$$

If the vehicle is positioned at (x,y), then the normalized distance to mean variable,

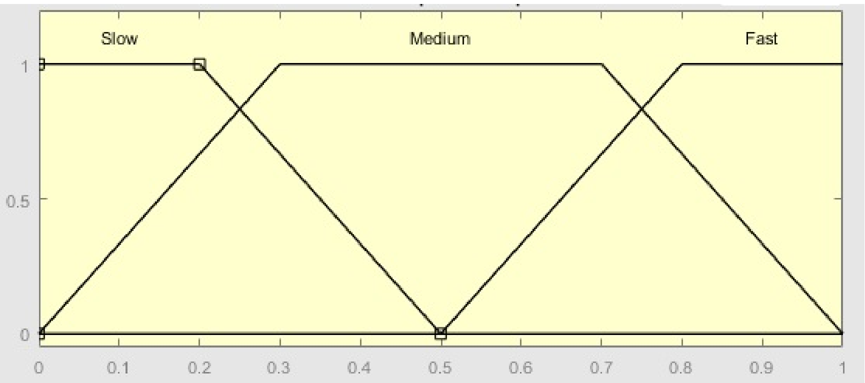


Figure 4.4: Membership Function for Mobility Factor

CF, can be obtained using Equation 4.3.

$$CF = \frac{1}{R}\sqrt{(x-\bar{x})^2 + (y-\bar{y})^2} \tag{4.3}$$

where, R is the transmission radius. When CF is small, it means the potential forwarder vehicles are distributed evenly around the vehicle, indicating that it should favor not rebroadcasting.

The trapezoidal membership functions of mobility, and coverage factors for this proposed broadcast scheme, are defined in Figs. 4.4, and 4.5. Each vehicle uses the mobility membership function to calculate which degree the mobility belongs to $\{slow, medium, fast\}$. Similarly, it calculates the degree of coverage, which is $\{low, medium, high\}$. The Max-Min fuzzy inference method is applied which means the fuzzy operator AND takes the minimum value of the antecedents [37]. Based on fuzzy values of input variables and using If-Then rules (as given in Table. 4.1), the vehicle status as being rebroadcaster or non-rebroadcaster is determined. The output membership function is shown in Fig. 4.6. In this work, we use Center of Gravity (COG), which is the most popular defuzzification technique and widely utilized in actual applications. The correlation between input and output variables is given in Fig. 4.7.

If vehicle r finds its status as non-rebroadcasting, it drops the message. Other-

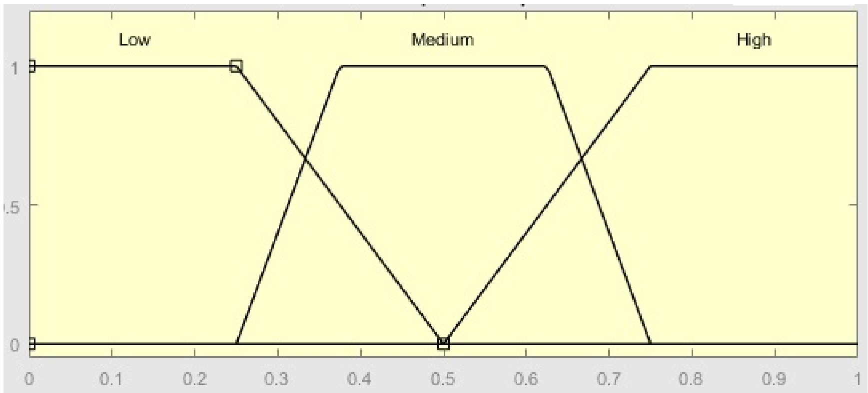


Figure 4.5: Membership Function for coverage Factor

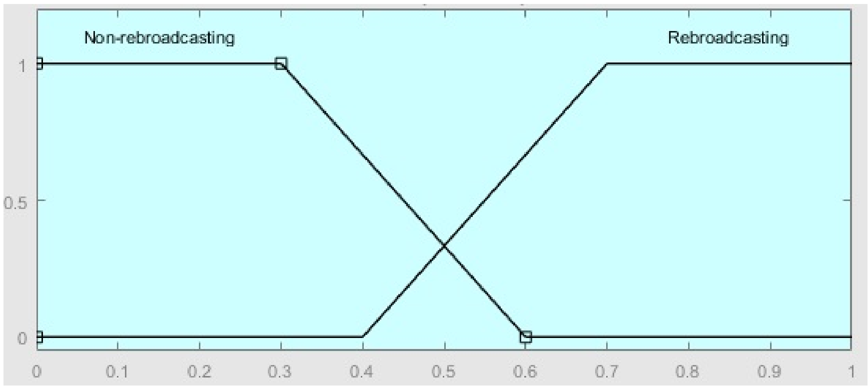


Figure 4.6: Output Membership Function

wise, vehicle r, again using the proposed fuzzy logic system, determines the set of vehicles (in SPF) that are qualified to rebroadcast and treats it as a set of candidate forwarders (SCF). Vehicle r calculates the distance-to-mean of the vehicles in SCF. It rebroadcasts if its distance-to-mean is the largest in the set, or after t_{wait} time it does not hear the message being forwarded by another vehicles. t_{wait} is given by Equation 4.4.

$$t_{wait} = T_{max}(1 - \frac{d_{min}}{R}) \tag{4.4}$$

where d_{min} denotes vehicle r's nearest neighbor distance. In section 4.2, using simulations, we obtain an optimal value for T_{max}.

Table 4.1: Fuzzy Rules

	Mobility	Coverage	Status
Rule 1	slow	low	non-rebroadcasting
Rule 2	slow	medium	rebroadcasting
Rule 3	slow	high	rebroadcasting
Rule 4	medium	low	non-rebroadcasting
Rule 5	medium	medium	rebroadcasting
Rule 6	medium	high	rebroadcasting
Rule 7	fast	low	non-rebroadcasting
Rule 8	fast	medium	non-rebroadcasting
Rule 9	fast	high	rebroadcasting

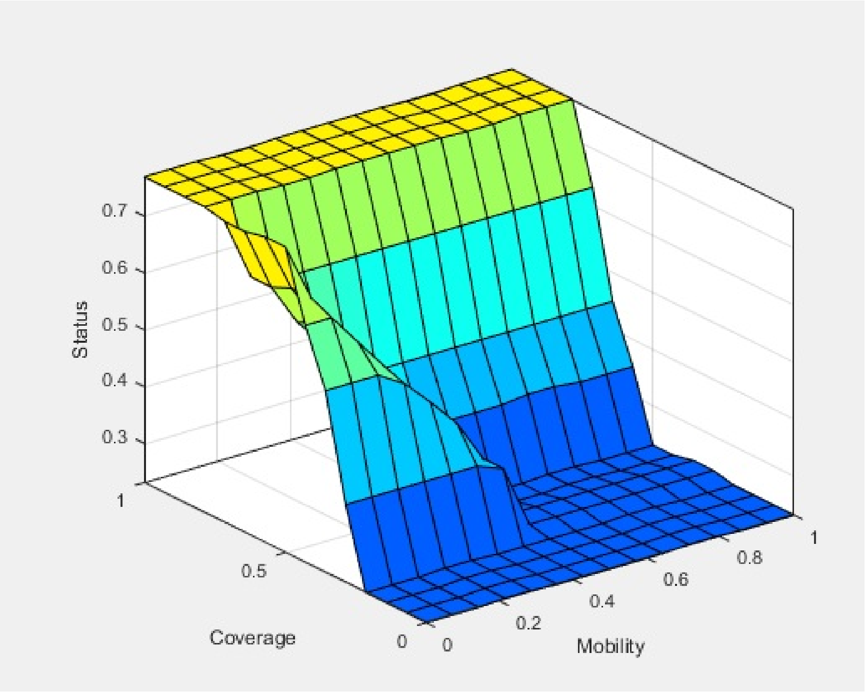


Figure 4.7: Correlation Between the Input Factors and the Output

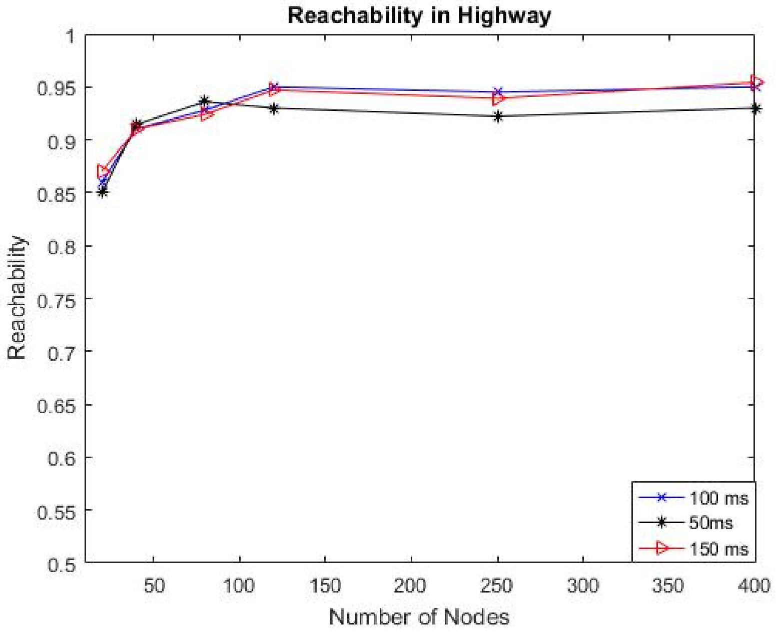


Figure 4.8: Reachability for Different T_{max}

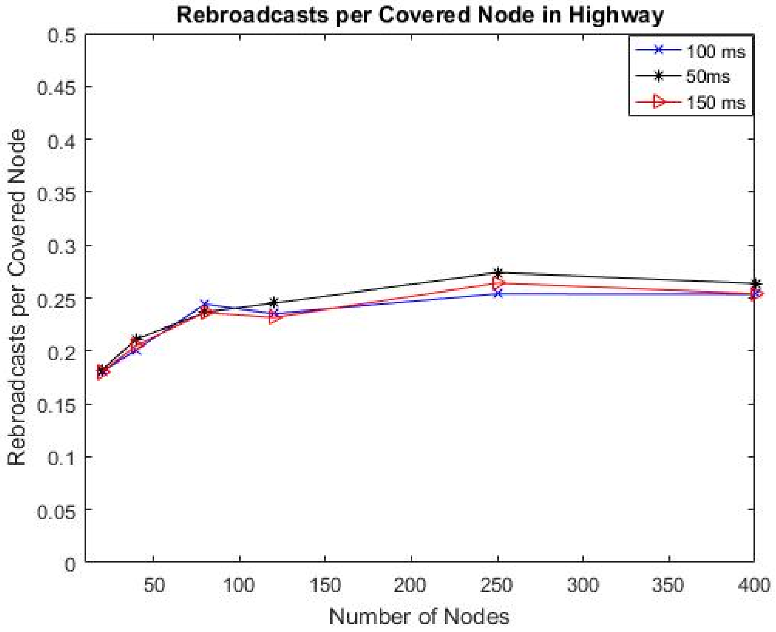


Figure 4.9: Rebroadcasts per Covered Vehicle for Different T_{max}

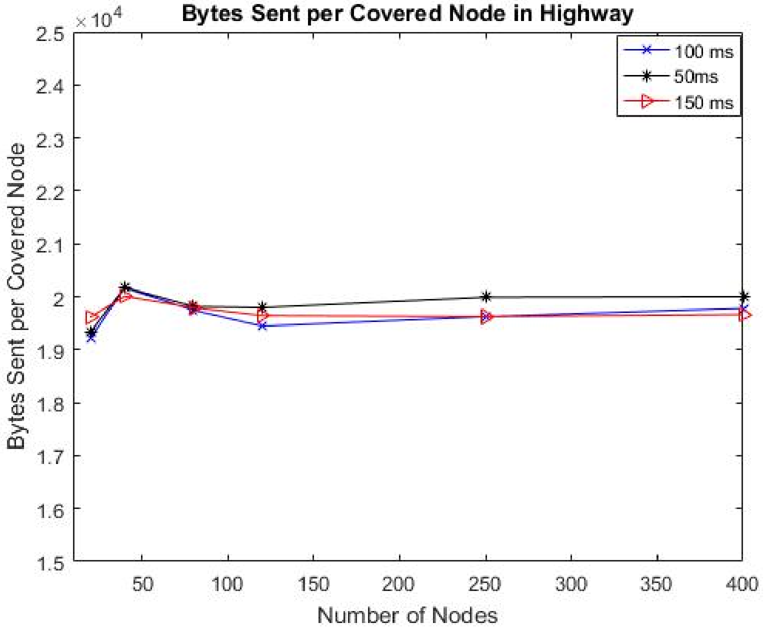


Figure 4.10: Bytes Sent per Covered Vehicle for Different T_{max}

4.2 SIMULATION AND RESULTS

To determine the performance efficiency of our proposed broadcast protocol, we use ns-3.24 [38]. The network simulation is set up to have an active period of 1800 seconds and communication range is considered as 250 meters. The data size of each packet is 500 bytes. Signal propagation is modeled with Nakagami propagation. We use the WAVE model [39], which is the overall system architecture for vehicular communications implemented in ns-3.24 and also use IPv4 layer 3 addressing. Three sets of results are presented for each protocol using the following metrics: reachability, rebroadcasts per covered vehicle, and number of bytes sent per covered vehicle. Reachability is measured as average fraction of vehicles that receive source messages. Messages rebroadcasts per covered vehicle metric is defined as the ratio between number of retransmissions to number of vehicles that receive the message (ignoring overhead from hello messages) is calculated. Finally, bytes sent per covered vehicle is calculated as a ratio of total number of bytes sent to number of vehicles that receive the message (including overhead from hello messages). In order to assess scalability, we run the simulation for low, medium, and high traffic densities.

We run the simulation for three different values of T_{max} in Equation 4.4 as 50,100, and 150 milliseconds, to select the one with the best performance. According to the results shown in Figs. 4.8 - 4.10, we decide to pick the value 100 milliseconds as T_{max}.

4.2.1 Highway Environment

The vehicle's mobility is generated based on ns-3.24 constant speed mobility model and the position allocation is based on ns-3.24 random rectangle position model, which places vehicles uniformly on a straight line (highway road scenario). The performance of our proposed protocol, BEFLAB, is compared with the distance-to-mean broadcast (DTM) protocol [20], Distribution Adaptive Distance with Channel Quality (DADCQ) protocol [22], Statistical Location Assisted Broadcast (SLAB) [23], and Fuzzy Logic-based Broadcast (FLB) [25] protocols. According to Fig. 4.11, BEFLAB ability of successful message delivery in terms of reachability is shown. BEFLAB reaches more than 90% of vehicles in the network for almost all density scenarios. Fig. 4.12 proves that BEFLAB significantly reduces number of retransmission for various numbers of vehicles. Fig. 4.13 demonstrates bandwidth consumption in terms of bytes sent per covered node. It is observed that BEFLAB, for all densities, has the lowest bytes sent in comparison with other protocols.

4.2.2 Urban Environment

To get results for the urban environment, we generate vehicle's mobility using Simulation of Urban MObility (SUMO) [40]. In our simulation, the road network uses a 3x3 Manhattan Grid as shown in Fig. 4.14 with an edge length of 1km and an equal distance between any two neighboring intersections. Vehicle movement uses Intelligent Driver Model and vehicle speeds are computed using the car-following model in

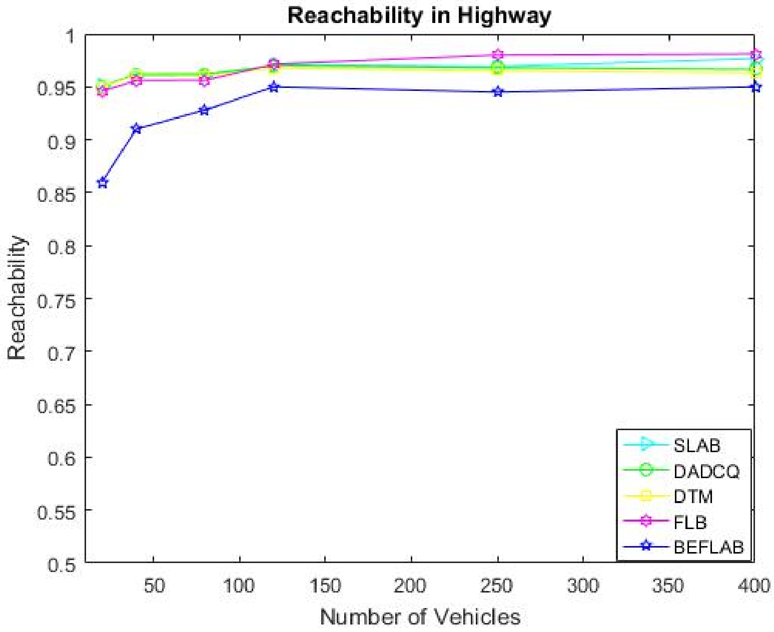


Figure 4.11: Reachability in Highway Environment in Highway

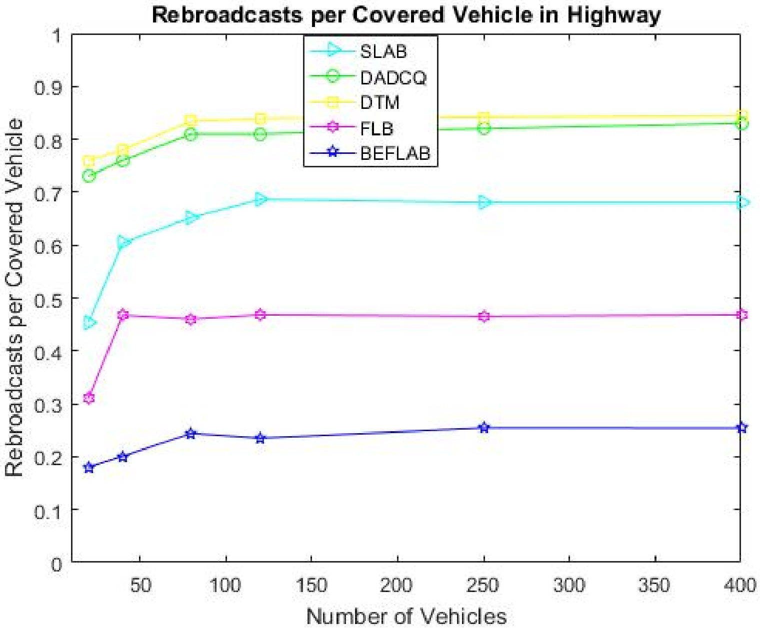


Figure 4.12: Number of Rebroadcasts per Covered Vehicle in Highway

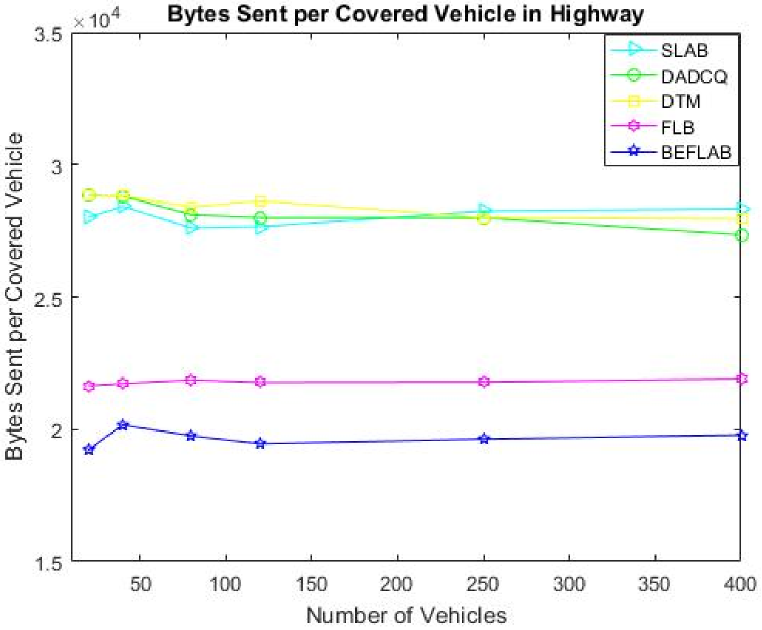


Figure 4.13: Number of Bytes Sent per Covered Vehicle in Highway

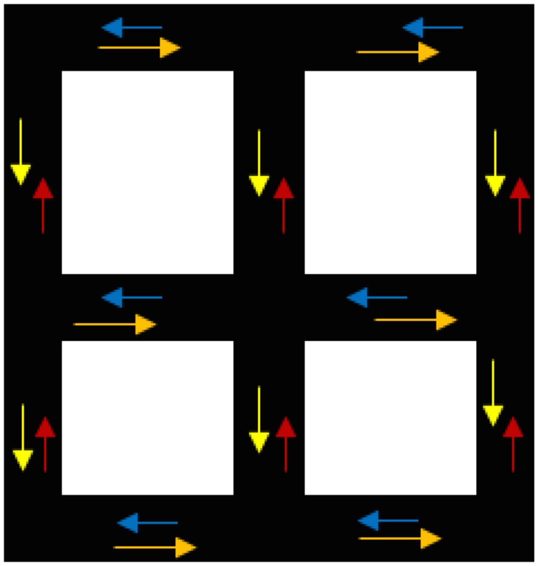


Figure 4.14: 3x3 Manhattan Grid Road

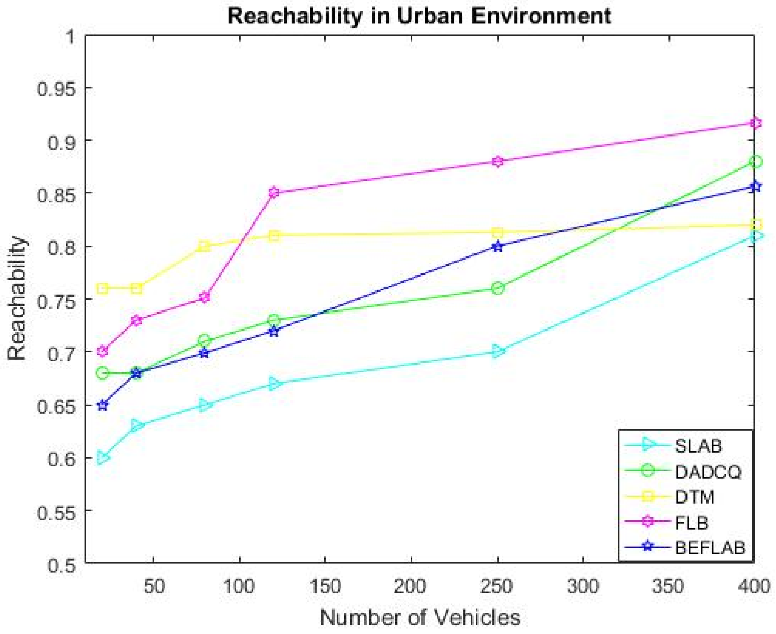


Figure 4.15: Reachability in Urban Environment

which each vehicle speed is adaptive to the leading vehicle speed. Vehicles distribution is a random process and routes are randomly generated. For each traffic scenario, ns-3.24 generates vehicle mobility based on mobility traces created by SUMO. The simulations are run using the parameters as mentioned before. The simulation results for urban environment are shown in Figs. 4.15 - 4.17. Fig. 4.15 proves that BEFLAB can exceed an acceptable percentage of reachability in urban environment. For sparse networks it achieves less level of reachability than FLB, and DTM. As the network density increases BEFLAB can reach more vehicles than SLAB and DTM. From Figs. 4.16 and 4.17, BEFLAB outperforms the other protocols in terms of number of rebroadcasting vehicles and number of bytes sent. It can be attributed to the aggressive behavior of BEFLAB.

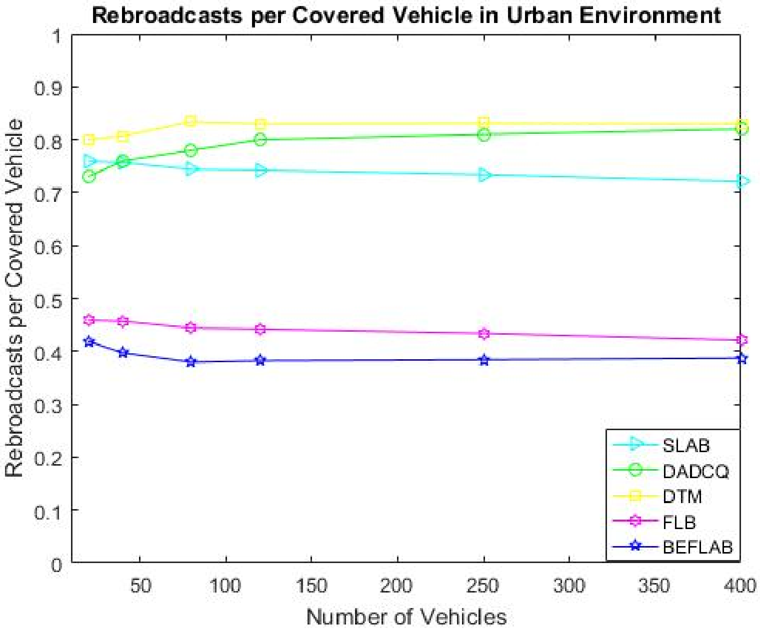


Figure 4.16: Number of Rebroadcasts per Covered Vehicles

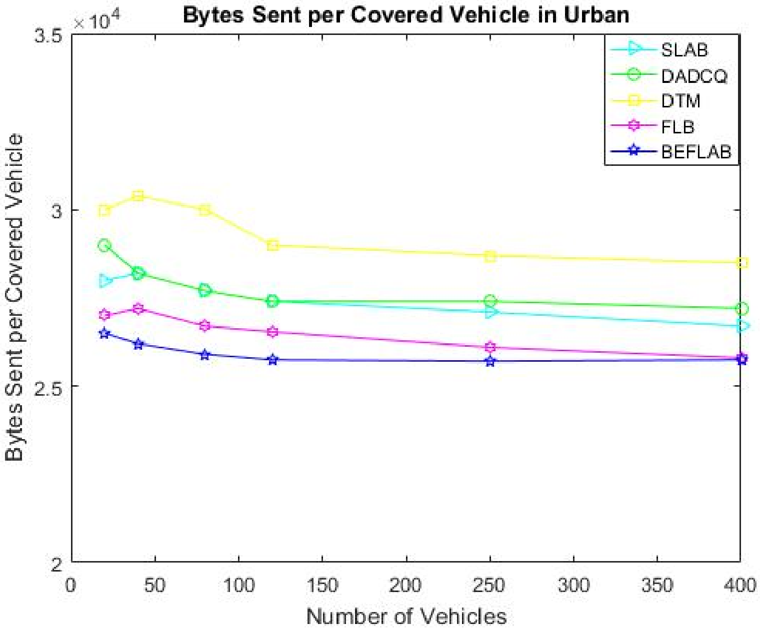


Figure 4.17: Number of Bytes Sent per Covered Vehicles

4.3 SUMMARY

We proposed a bandwidth efficient fuzzy logic-assisted broadcast protocol for vehicular ad hoc networks. In the proposed protocol, each vehicle after receiving a broadcasted warning message, considers its common neighbors with the transmitting vehicles from which the message is successfully received, as the set of potential forwarders (SPF). Relying on mobility and coverage factors, the proposed fuzzy logic-based decision making system determines whether a receiving vehicle is qualified to rebroadcast. If the vehicle is qualified to retransmit, using the fuzzy logic system the status of other vehicles in SPF will be determined and the set of candidate forwarders (SCF) will be obtained. Vehicle r calculates the distance-to-mean parameter for each vehicle in SCF. Vehicle r rebroadcasts if it has the largest distance-to-mean value in the SCF, or it does not hear the message being rebroadcasted after t_{wait} time. The goal of this work is to propose a broadcast scheme that aggressively reduces the number of rebroadcasting vehicles which leads to saving bandwidth. The simulation results confirmed the advantage of the proposed method over DTM, DADCQ, SLAB, and FLB in terms of bandwidth consumption for both highway and urban environments and its comparable reachability performance. Clearly, for dense networks BEFLAB should be the protocol of choice, since it aggressively reduces the number of rebroadcasts while maintaining an acceptable reachability level.

CHAPTER 5

INTELLIGENT HYBRID ADAPTIVE BROADCAST

As shown in Chapters 3 and 4, FLB offers high level of reachability where BEFLAB is more bandwidth efficient. While high reachability is a challenge in sparse networks, bandwidth efficiency is needed in dense networks. The goal of this chapter is to propose an intelligent hybrid adaptive broadcast (IHAB) scheme that combines the strength of FLB and BEFLAB. In order to design a bandwidth efficient VANET broadcast scheme with high level of reachability, each receiving vehicle determines its number of common neighbors with the transmitting neighbors and treat it as the potential transmit density (PDT). If PDT exceeds a threshold, the network is recognized as dense and BEFLAB is the choice of broadcast scheme. Otherwise, the network is sparse and FLB will be used to disseminate the messages. Material in this chapter is published in [27].

5.1 THE PROPOSED IHAB SCHEME

In this section we describe the proposed hybrid adaptive broadcast protocol, in which the potential transmit density is used to select the appropriate broadcast protocol. Fig. 5.1 shows the proposed system modules. Based on the potential transmit density, when the network is sparse, this protocol uses FLB [25], to offer high level of reachability. When the network is dense, the proposed protocol utilities BEFLAB to reduce bandwidth consumption [26].

5.1.1 Assumptions

We assume all the vehicles in the network are equipped with a Global Positioning System (GPS), so each vehicle is aware of its position and its velocity information. Each vehicle keeps track of its neighboring vehicles using periodic hello messages. These broadcasted hello messages contain position, velocity and vehicle's ID information. Based on the received hello messages, vehicles construct and update their own neighbors information tables.

We also assume that each vehicle before broadcasting a message, includes the IDs of its neighbors in the header. After receiving the message, the next forwarder vehicle updates this header to include its neighbors' IDs before it transmits.

5.1.2 Proposed Hybrid Adaptive Protocol

Here is a detailed explanation of the proposed algorithm shown in Fig. 5.2. When vehicle r receives a broadcast warning message with a unique sequence number for the first time, it calculates a delay time t_{delay} based on equation 5.1.

$$t_{delay} = T_{max}\ (1 - \frac{d}{R}) \tag{5.1}$$

where, d is the distance to the closest vehicle from which the message is received and R is the transmission range. If this message is again received before the timer expires, the timer will be reset. When the timer expires with no new received messages, vehicle r determines the transmitting neighbors from which the message is received. Since the message transmitting vehicles include their neighbors' IDs in the header of the message, receiving vehicle r knows the set of the transmitters' neighbors. Vehicle r identifies the number of common neighbors between itself and the transmitting neighbors and considers it as the potential transmit density (PTD). Vehicle r compares PTD to a threshold. If PTD exceeds the threshold, vehicle r determines the network as dense and uses BEFLAB, which is a bandwidth efficient method, to decide whether

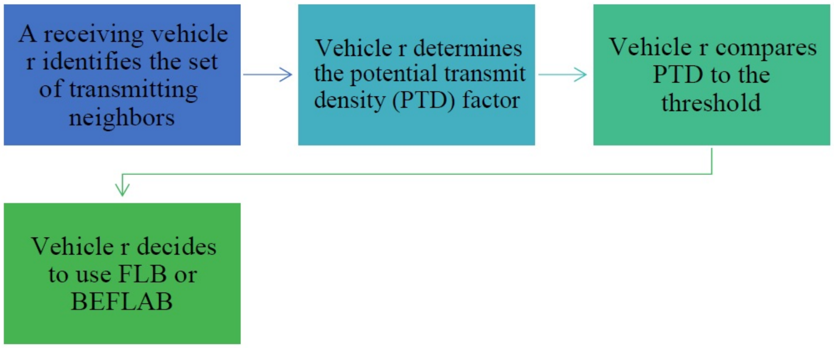


Figure 5.1: Reachability in Highway Environment

to rebroadcast. Otherwise, vehicle r considers the network as sparse and uses FLB method to reach more vehicles. The following is a brief overview of FLB [25] and BEFLAB [26].

FLB: In FLB [25], to decide whether to rebroadcast or not, vehicle r calculates the following factors:

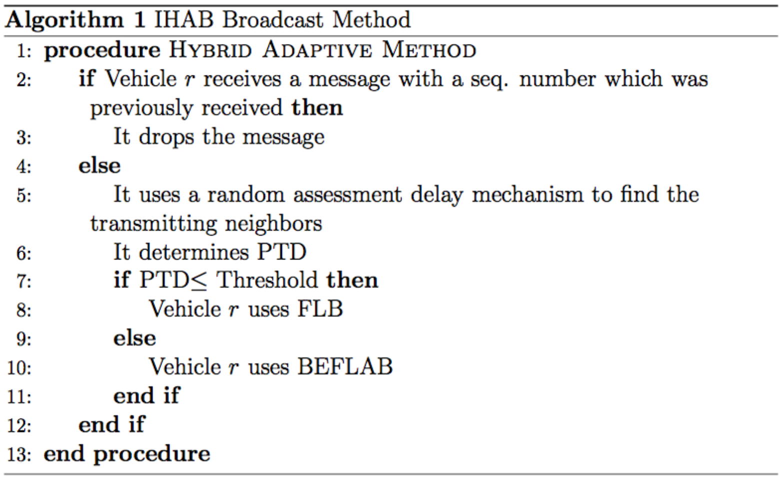
- Coverage
- Connectivity
- Mobility

Using the distance-to-mean parameter proposed in [20], the coverage factor is determined. The distance-to-mean parameter is the distance from the receiving vehicle to the spatial mean of the transmitting neighbors. The spatial mean of a set of n points (x_i,y_i) is calculated as:

$$(\bar{x}, \bar{y}) = (\frac{1}{n}\sum_{i=1}^{n} x_i, \frac{1}{n}\sum_{i=1}^{n} y_i) \tag{5.2}$$

If the vehicle is positioned at (x,y), then the normalized distance to mean variable, M, is given by Equation 5.3.

$$M = \frac{1}{R}\sqrt{(x-\bar{x})^2 + (y-\bar{y})^2} \tag{5.3}$$



Algorithm 1 IHAB Broadcast Method

```
procedure HYBRID ADAPTIVE METHOD
    if Vehicle $r$ receives a message with a seq. number which was previously received then
        It drops the message
    else
        It uses a random assessment delay mechanism to find the transmitting neighbors
        It determines PTD
        if PTD$\leq$ Threshold then
            Vehicle $r$ uses FLB
        else
            Vehicle $r$ uses BEFLAB
        end if
    end if
end procedure
```

Figure 5.2: IHAB System Algorithm

where, R is the transmission radius. When M is small, it means the neighboring transmitters are distributed evenly around the vehicle, indicating that it should favor not rebroadcasting.

In FLB, each vehicle before broadcasting a warning message, includes the IDs of its neighbors in the header. After receiving the message, the next forwarder vehicle updates this header to include its neighbors' IDs before it transmits. In order to determine the connectivity factor, the receiving vehicle uses its number of neighbors, which are not common with the neighbors of its transmitting neighbors. The normalized number of uncommon neighbors (uncommon neighbors divided by the number of 2-hop neighbors) value is introduced as the connectivity factor. Vehicles with more number of uncommon neighbors are more qualified to rebroadcast the warning message.

The definition of the last factor, mobility, is given in Equation 5.4.

$$MobilityFactor = \frac{v_r - v_{min}}{v_{max} - v_{min}} \tag{5.4}$$

where v_r denotes the velocity of the receiving vehicle and v_{min} and v_{max} indicate the minimum and maximum velocity among neighboring transmitter vehicles and the receiving vehicle, respectively. A lower mobility factor indicates a lower velocity. Vehicles with lower velocity are more qualified to rebroadcast the message. These three factors are fed to the proposed fuzzy logic system as input variables, to determine whether the receiving vehicle is qualified to rebroadcast.

$BEFLAB$: In BEFLAB [26], vehicle r identifies the set of potential forwarders, then it determines the set of candidate forwarders using a fuzzy logic system. Vehicle r calculates the distance-to-mean parameter for the vehicles in the set of candidate forwarders. Vehicle r rebroadcasts if it has the largest distance-to-mean value in this set or it does not hear the message being rebroadcasted after a proposed t_{wait} time. BEFLAB aggressively reduces the number of rebroadcasting vehicles while maintaining an acceptable level of reachability.

5.2 SIMULATION AND RESULTS

We evaluate the efficiency of our proposed broadcast protocol using ns-3, a simulation tool based on C++ [38]. The simulations are run using the parameters' values stated in Table 5.1.

The performance of our proposed protocol, Intelligent Hybrid Adaptive Broadcast (IHAB), is compared with the performance of Fuzzy Logic-based Broadcast (FLB) [25], Bandwidth Efficient Fuzzy Logic-Assisted Broadcast (BEFLAB) [26], Discance-to-Mean (DTM) [20], Distribution-Adaptive Distance with Channel Quality (DADCQ) [22] and Statistical Location Assisted Broadcast (SLAB) [23], and Cross-layer Statistical Broadcast Distance adaptive CW protocols. In order to evaluate scalability, we run the simulation for different traffic densities: low, medium, and high. Three sets of results are presented for each protocol using the following metrics:

- Reachability: Average fraction of vehicles that receive source messages

Table 5.1: The Simulation Parameters

Parameter	**Value**
Number of vehicles	20, 40, 80, 120, 250, 400
Duration	1800 seconds
Packet size	500 bytes
Max speed	30 m/s
Hello message interval	10 seconds
Signal propagation	Nakagami
MAC/PHY protocol	IEEE 802.11p
Transmission range	250 meters
Layer 3 addressing	IPv4

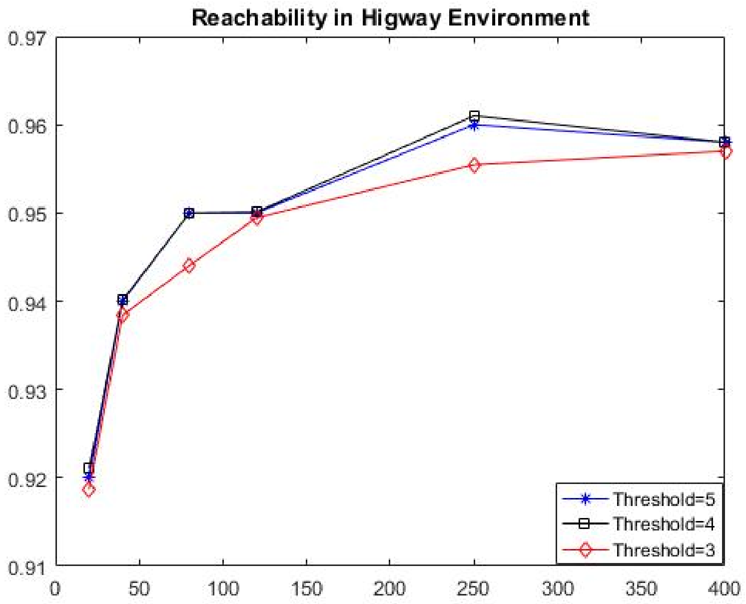


Figure 5.3: Reachability in Highway Environment

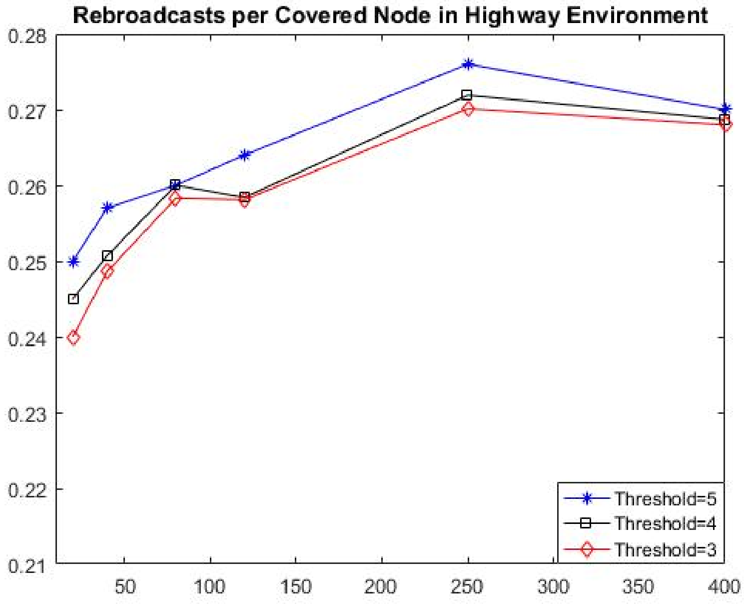


Figure 5.4: Number of Rebroadcasts per Covered Vehicle in Highway

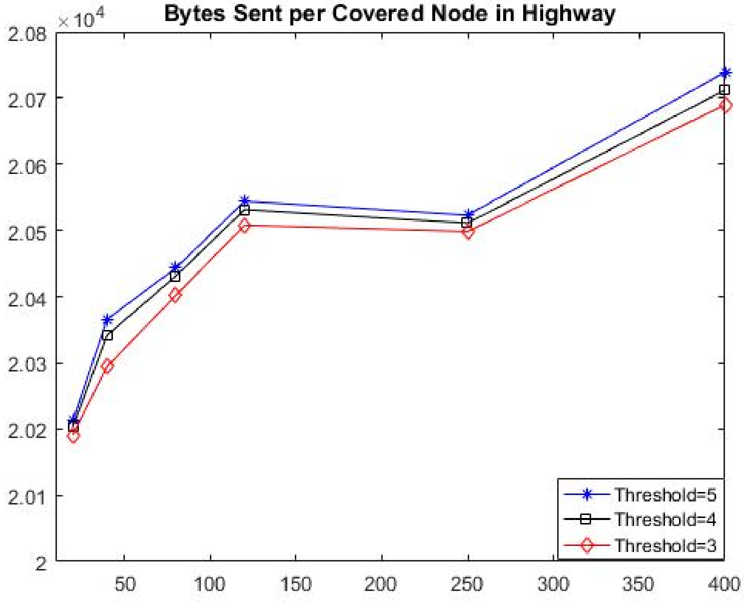


Figure 5.5: Number of Bytes Sent per Covered Vehicle in Highway

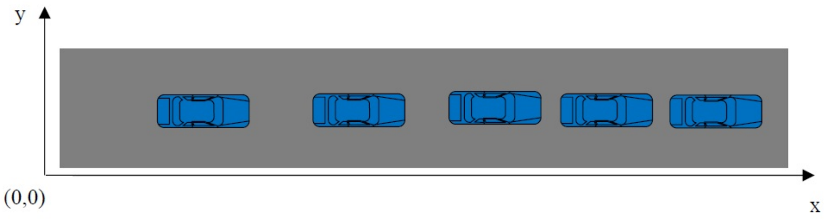


Figure 5.6: Highway Environment

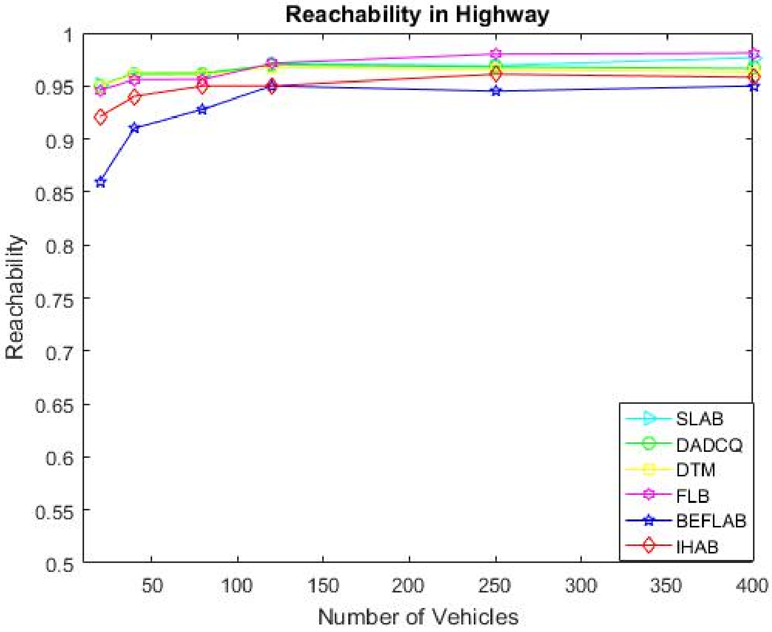


Figure 5.7: Reachability in Highway Environment

- Rebroadcasts per covered node: Number of retransmissions to number of vehicles that receive the message ratio (ignoring overhead from beacons)
- Bytes sent per covered node: Total number of bytes sent to number of vehicles that receive the message ratio (including overhead from beacons)

In order to select the optimal threshold value, based on simulation results from Figs. 5.3 - 5.5, we decide to use a threshold value of 4, which is also consistent with our previous study [18].

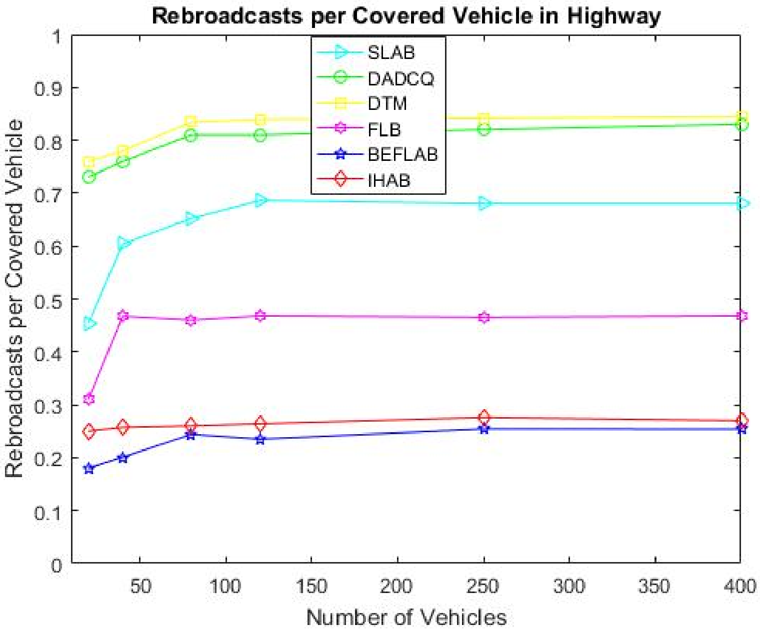


Figure 5.8: Number of Rebroadcasts per Covered Vehicle in Highway

5.2.1 Highway Environment

The vehicle's mobility is generated based on ns-3 constant speed mobility model and the position allocation is based on ns-3 random rectangle position model, which places vehicles uniformly on a straight line (Fig 5.6). We use the WAVE model [39], which is the overall system architecture for vehicular communications implemented in ns-3. The performance of our proposed protocol, IHAB, is compared with the performance of FLB, BEFLAB, DTM, DADCQ, and SLAB protocols. From Fig. 5.7, IHAB has a high level of reachability and reaches more vehicles compared to BEFLAB. Figs. 5.8 and 5.9 prove the efficiency of IHAB in terms of number of rebroadcasts per covered node and number of bytes sent per covered node, respectively compared to FLB and the other protocols with the exception of BEFLAB.

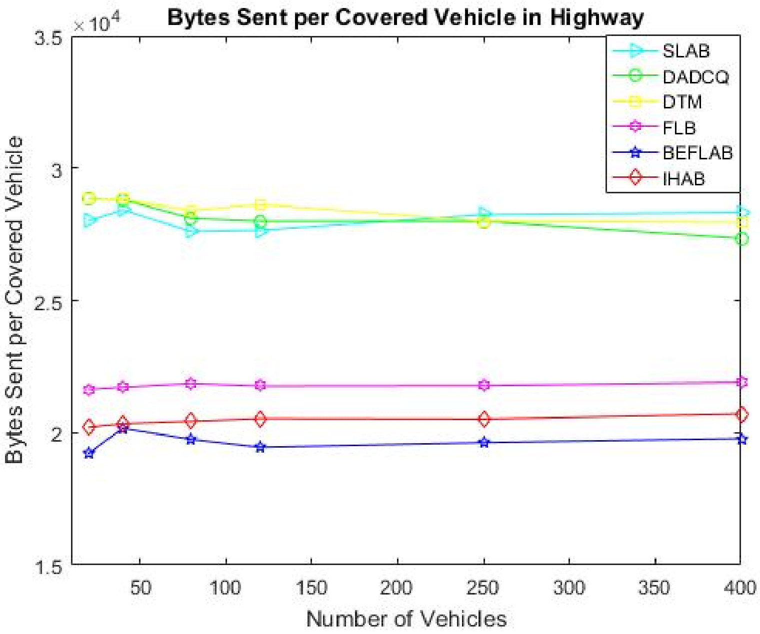


Figure 5.9: Number of Bytes Sent per Covered Vehicle in Highway

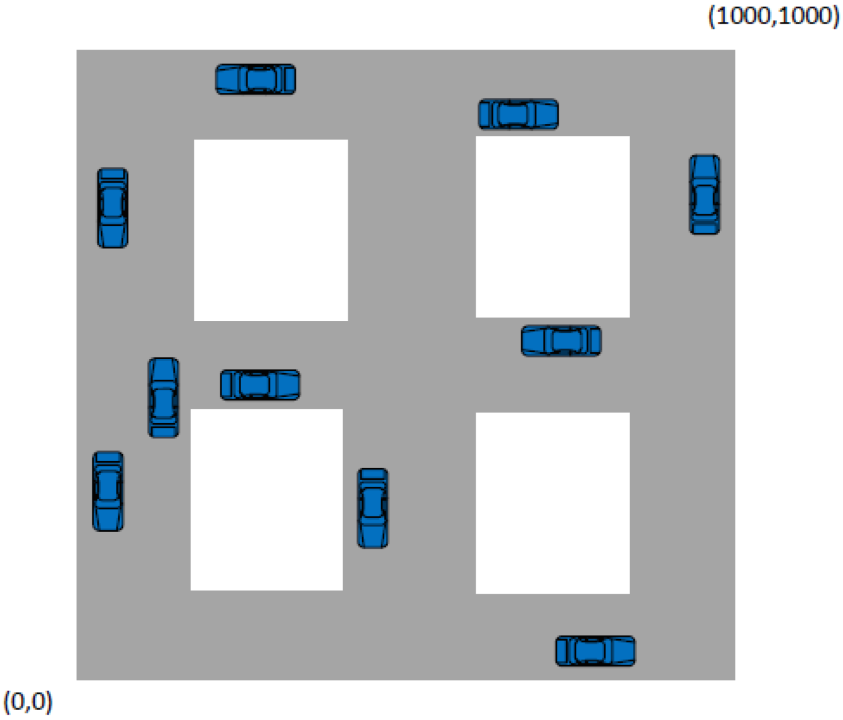


Figure 5.10: 3x3 Manhattan Grid

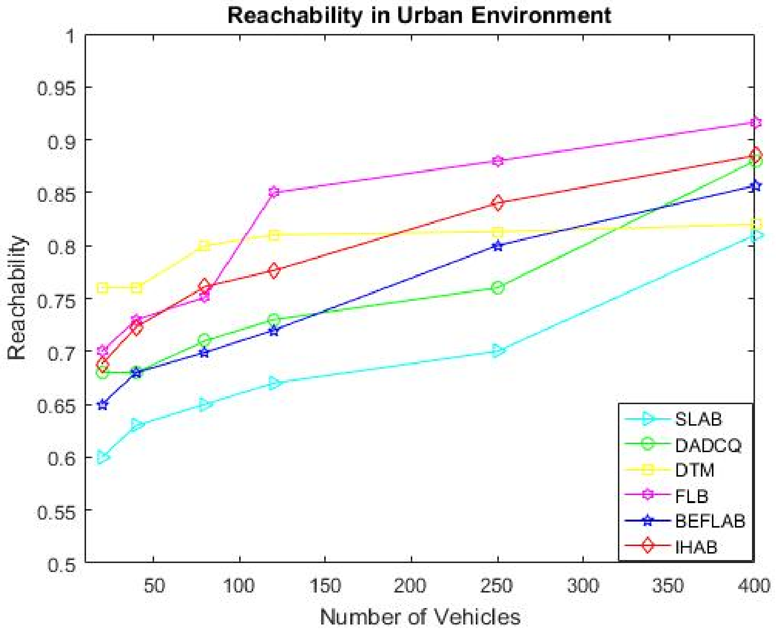


Figure 5.11: Reachability in Urban Environment

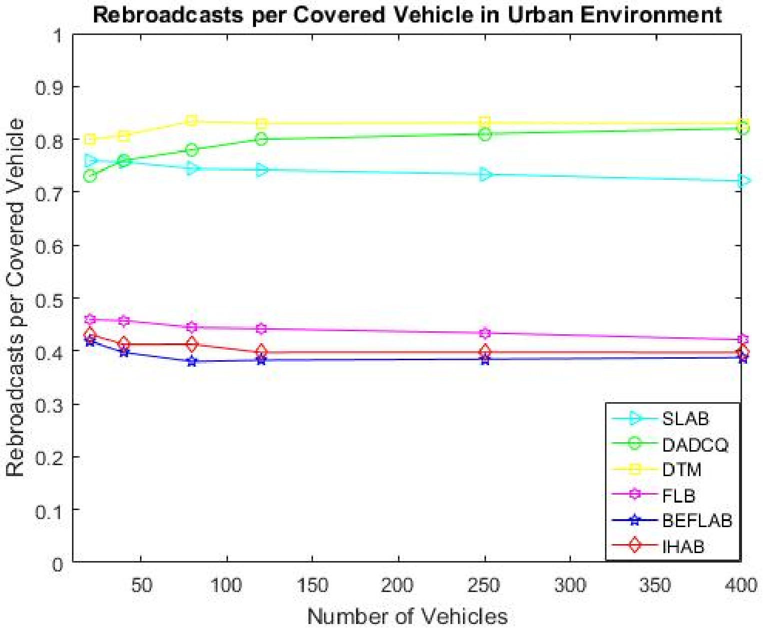


Figure 5.12: Number of Rebroadcasts per Covered Vehicles in Urban

5.2.2 Urban Environment

To get results for the urban environment, we generate vehicle's mobility using Simulation of Urban MObility (SUMO) [40]. In our simulation, the road network uses a 3x3 Manhattan Grid with an edge length of 1km and an equal distance between any two neighboring intersections (Fig 5.10). Vehicle movement uses Intelligent Driver Model and vehicle speeds are computed using the car-following model in which each vehicle's speed is adaptive to the leading vehicle speed. Vehicles distribution is a random process and routes are randomly generated. For each traffic scenario, ns-3 generates vehicle mobility based on mobility traces created by SUMO. The simulations are run using the parameters' values mentioned before. The simulation results for urban environment are shown in Figs. 5.11 - 5.13.

Fig. 5.11 proves that IHAB outperforms BEFLAB in terms of reachability in urban environment. For sparse networks it achieves lower level of reachability than FLB and DTM. As the network density increases IHAB can reach more vehicles than SLAB, DADCQ, DTM, and BEFLAB. Figs. 5.12 and 5.13 show IHAB to be more bandwidth-efficient than FLB and the other protocols with the exception of BEFLAB.

5.3 SUMMARY

In this chapter, we propose an intelligent hybrid adaptive broadcast (IHAB) which combines the strength of our previous proposed broadcast schemes, fuzzy logic-based broadcast (FLB) and bandwidth efficient fuzzy logic-assisted broadcast (BEFLAB). FLB provides reliable message propagation with high level of reachability while BEFLAB offers bandwidth efficiency. In IHAB, when a receiving vehicle receives a broadcast warning message for the first time, it determines the potential transmit density (PTD), which is equal to the number of its common neighbors with the transmitting vehicles. In a dense network (when PTD exceeds a threshold), since bandwidth consumption is a challenge, the receiving vehicle will use BEFLAB method to decide

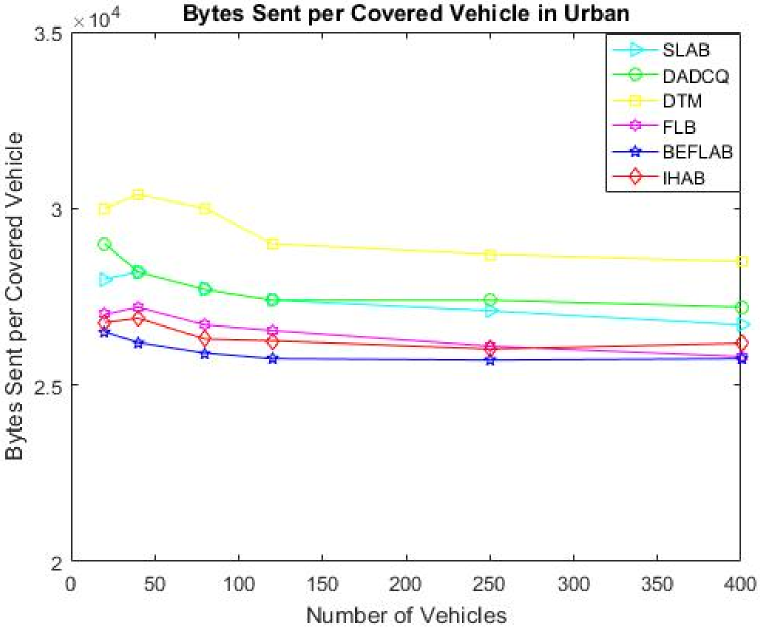


Figure 5.13: Number of Bytes Sent per Covered Vehicles in Urban

whether to rebroadcast. In order to provide high level of reachability, in a sparse network FLB will be used. The proposed protocol performance is compared to FLB, BEFLAB, DTM, DADCQ, and SLAB protocols. The simulation results confirmed IHAB's reachability advantage compared to BEFLAB and its bandwidth efficiency compared to FLB for both highway and urban environments.

CHAPTER 6

CROSS-LAYER STATISTICAL BROADCAST PROTOCOL WITH DENSITY-ADAPTIVE CONTENTION WINDOW

IEEE 802.11p is a modification of the IEEE 802.11 standard to provide Wireless Access in Vehicular Environments (WAVE) [36]. Based on IEEE 802.11p, each vehicle uses the Distributed Coordination Function(DCF), or an Enhanced Distributed Channel Access (EDCA) function to contend for channel access. Each vehicle checks the status of the wireless medium before transmission. If the medium is idle for longer than DCF Inter-Frame Space (DIFS) or Arbitration Inter-Frame Space (AIFS), it can transmit immediately. Otherwise, each vehicle needs to defer until the medium is determined to be idle after a DIFS/AIFS period. After this period, the vehicle generates a random backoff period as an additional deferral time before it transmits. The backoff time is relative to a random integer which is drawn from a uniform distribution over the interval of [0,CW], where CW is the current contention window size. CW is a value determined by aCW_{min} and aCW_{max} depending on the access category. According to the IEEE 802.11p, aCW_{min} is 15, and aCW_{max} is 1023. If multiple neighboring vehicles (which are in the communication range of each other) choose the same backoff time, collisions may happen.

Since in IEEE 802.11p, there is no acknowledgment for broadcast MAC frame, and also there is a different vehicle density for different road types or road segments, the MAC protocol should take these issues into consideration. The solution can be addressed by a CW (contention window) adaptive MAC protocol. This means when the number of transmitting vehicles is large, a proportionally large CW size reduces the number of collisions, while in a low traffic density a small CW size is needed to access the medium.

In this chapter, we propose a cross-layer DTM-based broadcast protocol, in which considering last successful transmission MAC parameters, the new retransmitting vehicle adjusts the new CW size based on local vehicle density information.

6.1 OVERVIEW OF DISTANCE-TO-MEAN BROADCAST METHOD

Fig. 6.2 shows the broadcast module of CSBD, which relies on DTM broadcast method. When a vehicle receives a warning message for the first time, it uses an assessment delay mechanism [2] to find the neighbors who have broadcasted this message. Then to decide whether to rebroadcast or not, it uses the distance-to-mean method proposed in [20], which estimates coverage. The distance-to-mean method considers distance from the vehicle to the spatial mean of the transmitting neighbors from which the message is received. In order to calculate this metric, position information is used. The spatial mean of a set of points (x_i,y_i) is calculated as:

$$(\bar{x}, \bar{y}) = (\frac{1}{n}\sum_{i=1}^{n} x_i, \frac{1}{n}\sum_{i=1}^{n} y_i) \tag{6.1}$$

If the vehicle is positioned at (x,y), then the normalized distance to mean variable, M, is calculated as in Equation 6.2.

$$M = \frac{1}{R}\sqrt{(x-\bar{x})^2 + (y-\bar{y})^2} \tag{6.2}$$

When M is small, it means the neighboring transmitters are distributed evenly around the vehicle, indicating that it should favor not rebroadcasting. Through experiments, [20] proposed a threshold function which is given by Equation 6.3:

$$M_c(N) = 0.95 - 0.74\ exp(-0.11N) \tag{6.3}$$

where N is the neighbor count. A vehicle will decide to rebroadcast the message if M is greater than or equal to M_c. If the same broadcast message is received again, it will be dropped. Fig. 6.3 shows the DTM rebroadcasting decision algorithm.

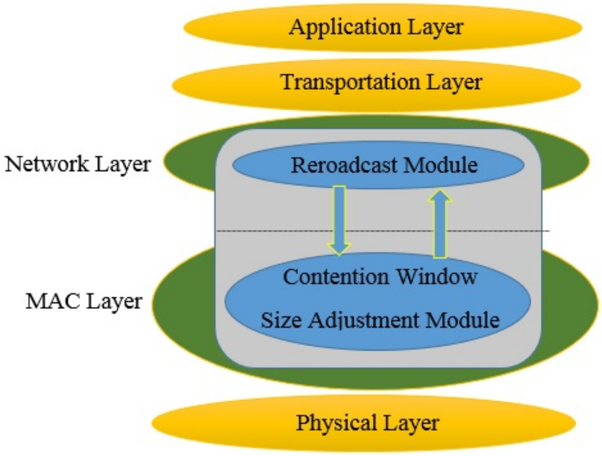


Figure 6.1: CSBD Architecture

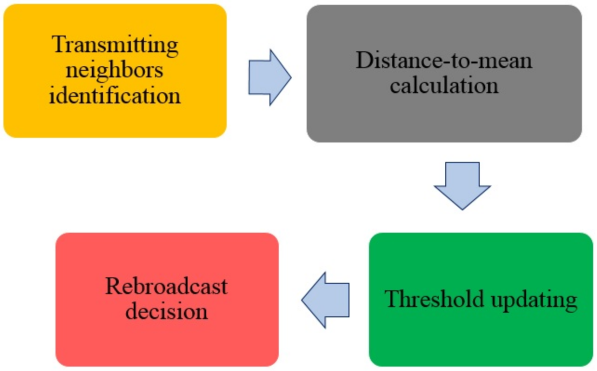


Figure 6.2: Rebroadcast Decision-making Module in CSBD

Algorithm 1 The Distance-to-Mean Broadcast Method

```
procedure Rebroadcasting Decision
    if Received a message with ID which was previously received then
        Drop the packet
    else
        Wait for $t$
        if Received the same packet during $t$ then
            Reset the timer
        end if
        Calculate distance-to-mean value $M$
        Calculate the threshold $M_c(N)$
        if $M \geq M_c(N)$ then
            Qualified to rebroadcast
        end if
    end if
end procedure
```

Figure 6.3: DTM- based Rebroadcasting Decision algorithm

6.2 PROPOSED PROTOCOL

6.2.1 System Model

We assume all the vehicles are equipped with a Global Positioning System (GPS), so each vehicle is aware of its position and moving velocity information. Each vehicle is able to keep track of its neighboring vehicles using periodic hello messages. These broadcasted hello messages contain position, velocity and vehicle's ID information. Based on the received hello messages, vehicles construct and update their own neighbors information table.

6.2.2 Contention Window Size Adjustment

Motivation

According to IEEE 802.11p MAC specification, the back off time is calculated by:

$$backoff = SlotTime * Rand() \tag{6.4}$$

where Rand() is a number randomly drawn from a uniform distribution over the interval [0,CW], where CW is the contention window size defined as:

$$CW = 2^n - 1; n \in \{4, 5, 6, ..., 10\} \tag{6.5}$$

The contention window size is initialized to aCW_{min} which is equal to 15 and based on Equation 8.10 it is obvious that the set of available values for CW is defined as $15, 31, 63, 127, 255, 511, 1023$. However, since at the MAC layer there is no reception acknowledgment and retransmission of broadcast frames, the contention window size does not change. In a high density network, there is a high probability to have a high data traffic load, so a small contention window will potentially increase the chances for collision. This will negatively affect the network data dissemination. In addition, when the number of vehicles in the network is small, a large contention window may increase end-to-end delay. So due to these issues, we propose a contention window size adjustment algorithm, which adapts to local density.

Proposed Method

We assume that each vehicle, before broadcasting a packet, includes the number of its neighbors and its current contention window in the header. When a vehicle r, receives a broadcast message and decides to rebroadcast, it checks its transmitting neighbors from which the message is successfully received to select vehicle t, which has the smallest contention window CW_t^s and checks vehicle t's number of neighbors (N_t). Since vehicle r successfully received the message from vehicle t, we can adjust vehicle r contention window (CW_r) based on contention window of vehicle t and the number of neighbors of vehicle t and vehicle r, N_t and N_r, respectively. In the neighboring set, if two or more transmitting vehicles have the same value of CW_t^s , vehicle r selects the one with the largest number of neighbors. We consider two cases: case 1 ($N_r \geq N_t$) and case 2 ($N_r < N_t$).

$\underline{Case1\ (N_r \geq N_t)}$: Define a density-dependent factor, DF as:

$$DF = \begin{cases} \lfloor \frac{N_r}{N_t} \rfloor & \text{for } \frac{N_r}{N_t} \leq 1.5, \quad (6.6) \\ \lceil \frac{N_r}{N_t} \rceil & \text{for } \frac{N_r}{N_t} > 1.5. \quad (6.7) \end{cases}$$

where $\lfloor . \rfloor$ and $\lceil . \rceil$ denote the floor and ceiling functions, respectively, while the value 1.5 is the result of experiments. From Equations. 6 and 7, DF is greater than or equal to 1. Vehicle r will adjust its contention window, CW_r, based on the calculated value of DF and contention window of vehicle t, CW_t^s as follows:

$$CW_r = \begin{cases} CW_t^s & \text{if DF=1}, \quad (6.8) \\ ((CW_t^s + 1) * 2) - 1 & \text{if DF>1}. \quad (6.9) \end{cases}$$

Equation 9 shows how to reach a higher contention window level which is given in Equation 8.10 and defined by IEEE 802.11 standard . Note that for DF>1, CW_r can be increased to a maximum of 1023.

<u>$Case2$ ($N_r < N_t$)</u>: Define an inverse density-dependent factor, IDF as:

$$IDF = \lfloor \frac{N_t}{N_r} \rfloor \tag{6.10}$$

where $\lfloor . \rfloor$ denotes the floor function. Similarly, IDF is greater than or equal to 1.Vehicle r will adjust its contention window, CW_r, based on the calculated value of DF and contention window of vehicle t, CW_t^s as follows:

$$CW_r = \begin{cases} CW_t^s & \text{if IDF=1}, \quad (6.11) \\ ((CW_t^s + 1)/2) - 1 & \text{if IDF>1}. \quad (6.12) \end{cases}$$

Based on defined possible contention window size values in Equation 8.10, Equation 12 shows how to decrease the level of CW. Note that for IDF>1, CW_r can be decreased to a minimum of 15.

After contention window size adjustment and updating the packet header and rebroadcasting the packet, vehicle r waits for a t_{wait} time which is described in Equation 8.4.

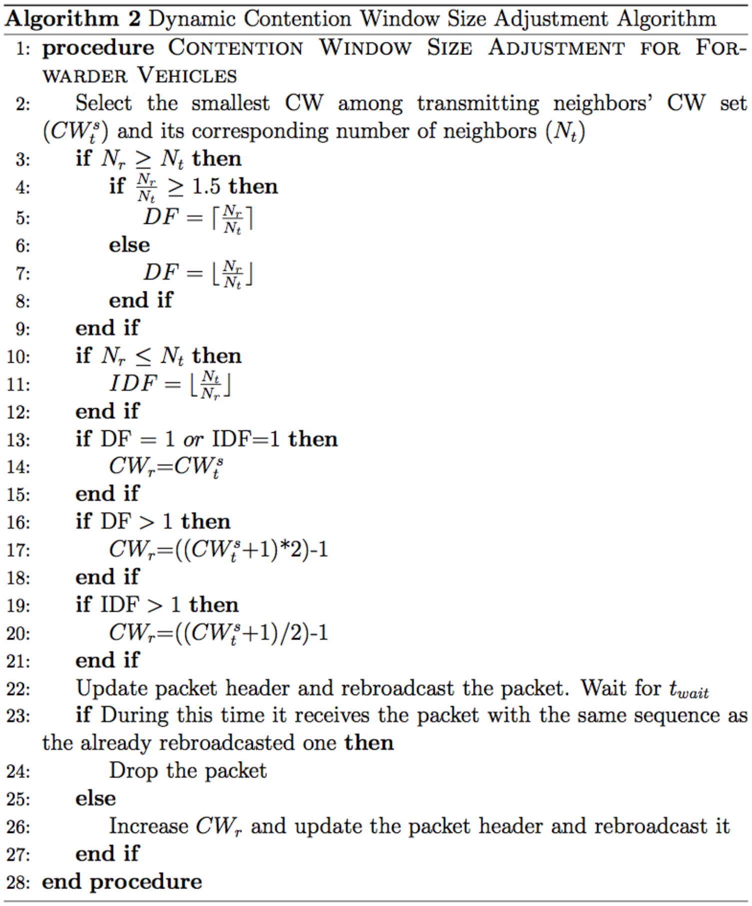
$$t_{wait} = T_{max}(1 - \frac{d_{min}}{R}) \tag{6.13}$$

where d_{min} denotes vehicle r's nearest neighbor distance and R is the communication range. If during this time it hears the message from other forwarders in the communication range, it can consider it as a sort of acknowledgment of successful transmission. In this case the vehicle drops the message. If during t_{wait}, it does not receive the transmitted message from its neighbors, it means that its broadcast was not successful, so it will increase the contention window size as stated in Equation 9 and rebroadcasts the message again and sets the timer. This dynamic contention window size adjustment algorithm is shown in Fig 6.4.

6.3 PERFORMANCE EVALUATION

In this section we present our simulation analysis for the proposed cross-layer statistical broadcast protocol, which we described in the previous section. To determine the efficiency of our proposed broadcast protocol, we use the network simulator tool, ns-3.24 [38]. We use the overall architecture for vehicular communication systems, WAVE model [39], which is implemented in ns-3. Table 6.1 states the simulation parameters that we use. We assume that all traffic data has the same priority and all transmitters have the same value of Arbitration inter-Frame Space (AIFS). We evaluate the performance based on three sets of results: reachability, number of rebroadcasts per covered vehicle, and number of bytes sent per covered vehicle.

Reachability represents the average normalized portion of vehicles that successfully receive the broadcast source messages. The second metric, number of messages rebroadcast per covered vehicle, is the ratio of number of retransmissions to the number of vehicles that receive the message (ignoring the overhead from hello messages).



Algorithm 2 Dynamic Contention Window Size Adjustment Algorithm

```
procedure CONTENTION WINDOW SIZE ADJUSTMENT FOR FORWARDER VEHICLES
    Select the smallest CW among transmitting neighbors' CW set ($CW_t^s$) and its corresponding number of neighbors ($N_t$)
    if $N_r \geq N_t$ then
        if $\frac{N_r}{N_t} \geq 1.5$ then
            $DF = \lceil \frac{N_r}{N_t} \rceil$
        else
            $DF = \lfloor \frac{N_r}{N_t} \rfloor$
        end if
    end if
    if $N_r \leq N_t$ then
        $IDF = \lfloor \frac{N_t}{N_r} \rfloor$
    end if
    if DF = 1 or IDF=1 then
        $CW_r$=$CW_t^s$
    end if
    if DF > 1 then
        $CW_r$=(($CW_t^s$+1)*2)-1
    end if
    if IDF > 1 then
        $CW_r$=(($CW_t^s$+1)/2)-1
    end if
    Update packet header and rebroadcast the packet. Wait for $t_{wait}$
    if During this time it receives the packet with the same sequence as the already rebroadcasted one then
        Drop the packet
    else
        Increase $CW_r$ and update the packet header and rebroadcast it
    end if
end procedure
```

Figure 6.4: Dynamic Contention Window Size Adjustment Algorithm

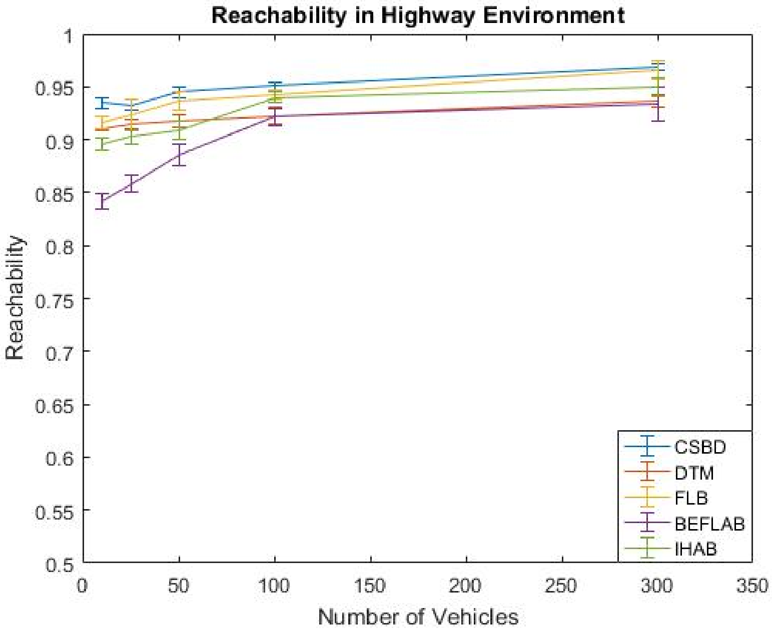


Figure 6.5: Reachability in Highway Environment

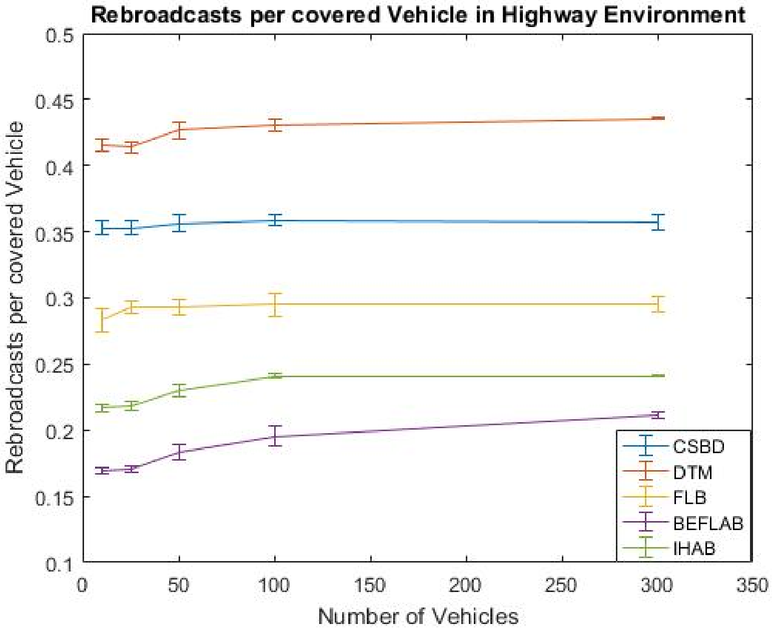


Figure 6.6: Number of Rebroadcasts per Covered Vehicles

Table 6.1: The Simulation Parameters

Parameter	**Value**
Number of vehicles	10, 25, 50, 100, 300
Duration	1200 seconds
Max speed (Highway)	25 m/s
Max speed (Urban)	14 m/s
T_{max}	100 ms
Hello message period	1 second
Hello message size	64 bytes
Warning message period	20 seconds
Warning message size	512 bytes
Signal propagation model	Nakagami
MAC/PHY protocol	IEEE 802.11p
Transmission range	250 meters
Layer 3 addressing	IPv4

Finally, the number of bytes sent per covered vehicle is calculated as a ratio of total number of bytes sent to number of vehicles that receive the message (including overhead from hello messages). In order to assess scalability, we run the simulation for low, medium, and high traffic densities. For each scenario, we run the simulation 7 times and the results are based on the average of the 7 runs. We also show the 95% confidence intervals in error bars.

6.3.1 Highway Environment

We use ns-3.24 constant speed mobility model to generate the vehicles' mobility. We also use ns-3.24 random rectangle position model to uniformly allocate vehicles' position on a straight line (highway environment). The performance of our proposed

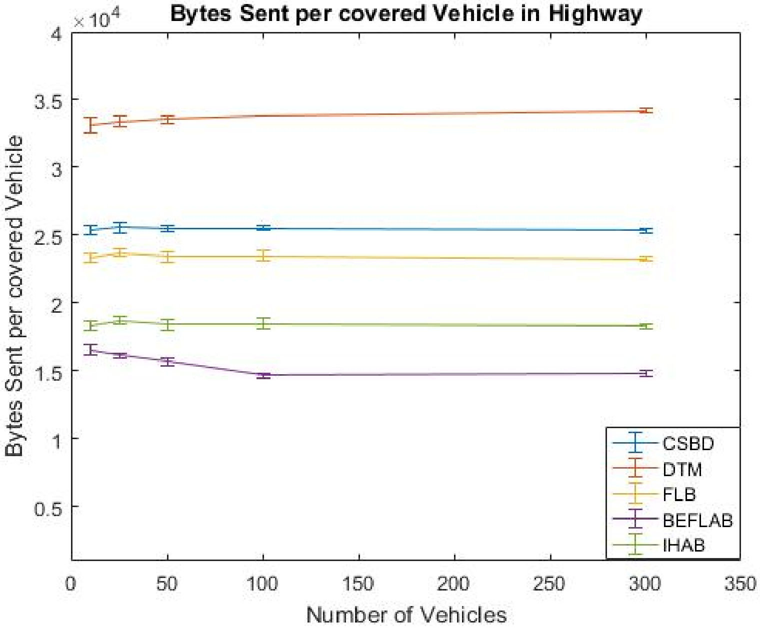


Figure 6.7: Number of Bytes Sent per Covered Vehicles

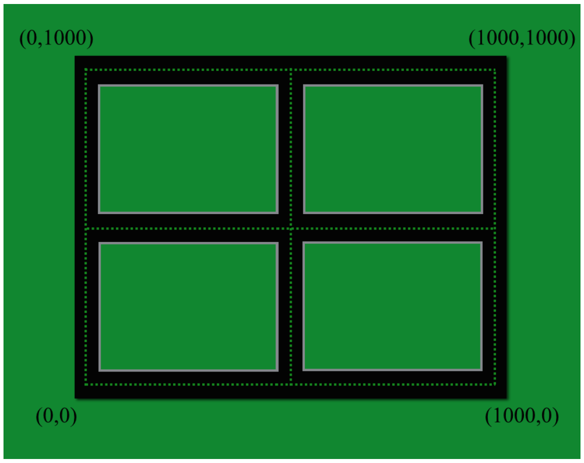


Figure 6.8: 3x3 Manhattan Grid

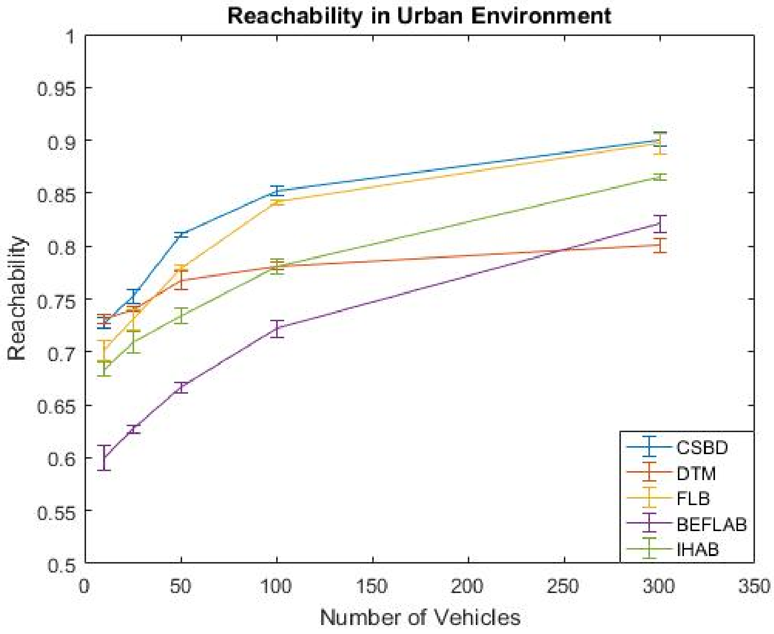


Figure 6.9: Reachability in Urban Environment

protocol, CSBD, is compared to that of DTM [20], FLB [25], BEFLAB [26] and IHAB [27] protocols. Fig. 6.5 proves the success of CSBD in message delivery in terms of reachability which is close to 93% when the network has a fewer number of vehicles and increases up to 96% when the network begins to be dense. From Fig. 6.6, we observe that in CSBD there is a significant decrease in number of retransmissions for various numbers of vehicles compared to DTM. It can be seen from the graphs that with an increased number of vehicles, the number of rebroadcasts reaches a plateau. This proves the scalability of CSBD to control the number of rebroadcasting vehicles for dense network scenarios. However, this comes at the cost of higher average number of retransmissions. This should be expected as FLB, BEFLAB, and IHAB are more aggressive in suppressing more vehicles from rebroadcasting. Fig. 6.7 shows bandwidth usage in terms of average number of bytes sent per covered vehicle. It clearly shows that for all densities, CSBD consumes less bandwidth than DTM, and, as expected, more than FLB, BEFLAB, and IHAB.

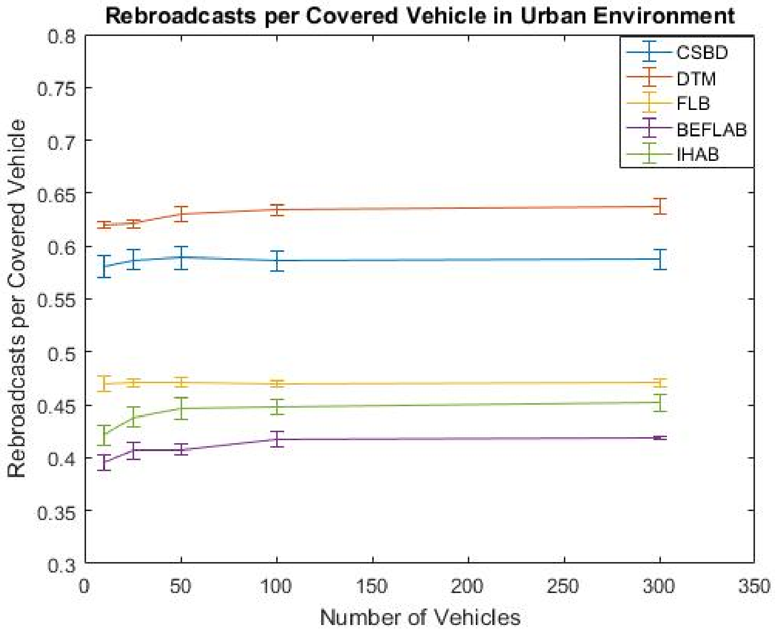


Figure 6.10: Number of Rebroadcasts per Covered Vehicles

6.3.2 Urban Environment

To get results from urban environment, we simulate scenarios of different vehicle traffic densities using ns-3.24 and Simulation of Urban MObility (SUMO) [40]. In our simulation, the road network uses a 3x3 Manhattan Grid with an edge length of 1km and a distance of 500m between any two neighboring intersections. The simulation results for urban environment are shown in Figs. 6.9, 6.10, and 6.11. As we see from Fig. 6.9, compared with the other protocols, CSBD provides the highest reachability in all scenarios particularly, in low density networks.

Similar to the simulation results for the highway scenario, Figs. 6.10, and 6.11 confirm that CSBD still offers relatively closer bandwidth performance compared to the other protocols.

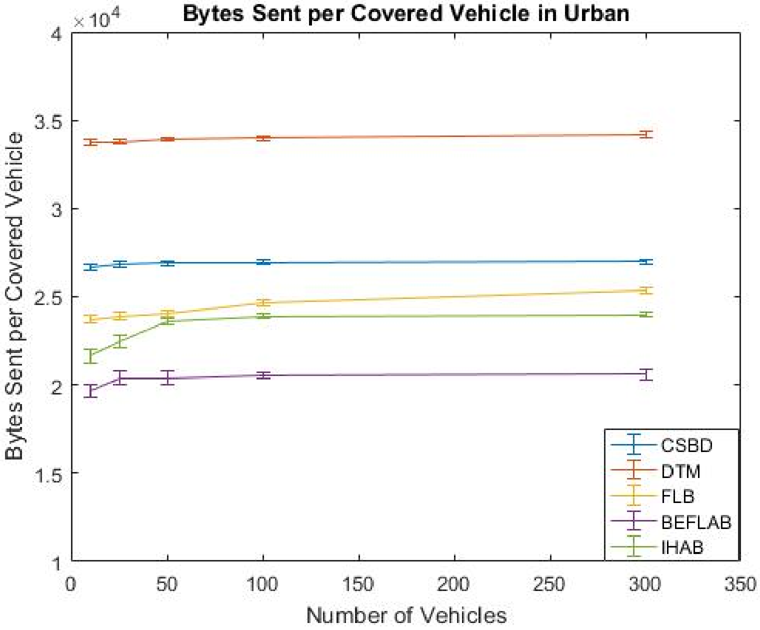


Figure 6.11: Number of Bytes Sent per Covered Vehicles

6.4 SUMMARY

We proposed a reachability enhanced cross-layer statistical broadcast method for vehicular ad hoc networks. In the proposed protocol, each vehicle, after receiving a new broadcast message, decides whether to rebroadcast the message or not. The rebroadcasting decision is made by comparing the vehicle's distance to the spatial mean of its transmitting neighbors to a created decision threshold. If the vehicle makes the decision of retransmitting, then it computes a density-dependent factor to decide to keep, increase, or decrease the base value (the smallest contention window size of the transmitting neighbors) in order to adapt the contention window size in the MAC layer. The simulation results confirmed the advantage of the proposed method (CSBD) compared to the other protocols in terms of reachability. However, this was accompanied by a slight disadvantage in bandwidth efficiency. This should be expected due to the aggressive rebroadcast suppression behavior of FLB, BEFLAB, and IHAB. CSBD reached more vehicles in the network meeting high levels of reachability in both highway and urban environments. It can be considered as one of the main effective protocols in sparse networks.

CHAPTER 7

VOLUNTEER DILEMMA INSPIRED BROADCAST

In this chapter, we propose an efficient receiver-oriented broadcast scheme in which the receiving vehicles' probability of forwarding is modeled by a symmetric volunteer dilemma game. Utilizing fuzzy logic techniques and considering information from the network layer about local density and probability of transmission, we adjust contention window size at the MAC layer.

7.1 VOLUNTEER DILEMMA GAME FOR VANET BROADCAST

Volunteer dilemma is a classic paradigm in the public goods game, in which each participant in the set of players must choose whether to become a volunteer and pay a cost (C) and grant the benefit (B) to all N players ($B>C$), or whether to wait for others to contribute and hope to reap the benefit without paying the cost (free riding).

In our proposed broadcast model, vehicles are considered as players. When each vehicle receives a broadcast message it has two options: become a volunteer and retransmit the message or decline to volunteer and remain silent. Since each rebroadcasting volunteer vehicle would cover the vehicles in its transmission range (R), the benefit for all N vehicles can be considered as:

$$B_i = R_i = R, i = 1, 2, ..., N. \tag{7.1}$$

We also consider the cost of being a volunteer for vehicle i (C) to be the difference between the transmission range and its distance-to-mean value (dtm), which

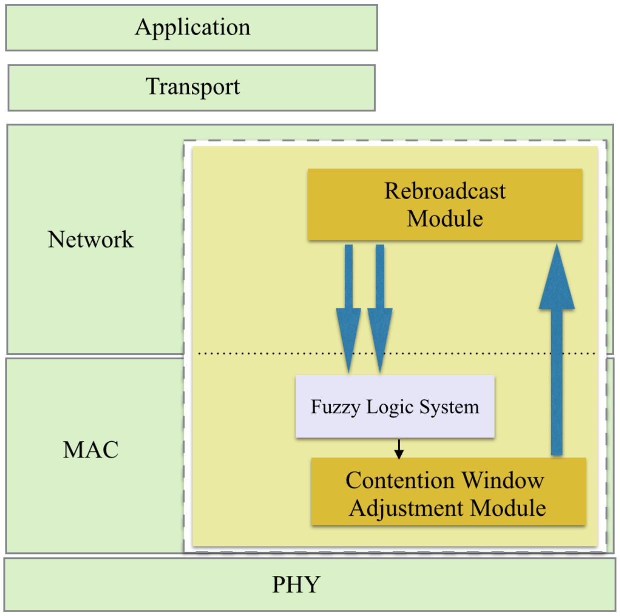


Figure 7.1: VDIB Architecture

represents the distance that will be covered redundantly.

$$C_i = R - dtm_i, i = 1, 2, ..., N. \tag{7.2}$$

$$dtm_i = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2} \tag{7.3}$$

where $(\bar{x}, \bar{y})$ is the spatial mean of the N vehicles (players), which is calculated as in Equation 7.4:

$$(\bar{x}, \bar{y}) = (\frac{1}{N}\sum_{j=1}^{N} x_j, \frac{1}{N}\sum_{i=j}^{N} y_j) \tag{7.4}$$

First, let us start with the general case, the asymmetric scenario, where the cost and benefit are different for each player. Assume the probability of remaining silent (defection) for vehicle i is α_i, then the expected utility (E_i) is:

$$E_i = \alpha_i B_i(1 - \prod_{j \neq i} \alpha_j) + (1 - \alpha_i)(B_i - C_i) \tag{7.5}$$

where N is number of participating vehicles in the game and B_i and C_i denote the benefit and cost of being a volunteer for vehicle i, respectively. So:

$$E_i = \alpha_i R(1 - \prod_{j \neq i} \alpha_j) + (1 - \alpha_i)(dtm_i) \tag{7.6}$$

After getting a partial differential with respect to α_i and considering the equation equal to zero, we get:

$$\frac{R - dtm_i}{R} = (\prod_{j \neq i} \alpha_j), i = 1, 2, ..., N. \tag{7.7}$$

To get the solution of Equation 7.7, we determine the product of cost to benefit ratio of all playing vehicles, which is stated in Equation 7.8.

$$\prod_{j}^{N} \frac{R - dtm_j}{R} = (\prod_{j} \alpha_j)^{N-1} \tag{7.8}$$

Then, solving for α_i, we get Equation 7.9:

$$\alpha_i = (\frac{1}{\prod_{j \neq i} \alpha_j}).(\prod_{j}^{N} \frac{R - dtm_j}{R})^{\frac{1}{N-1}} \tag{7.9}$$

Finally, considering Equation 7.7, the derived result for α_i is:

$$\alpha_i = \frac{R}{R - dtm_i} (\prod_{j}^{N} \frac{R - dtm_j}{R})^{\frac{1}{N-1}} \tag{7.10}$$

If $0<\alpha_i<1$ for i=1,2,...,N, there is a mixed Nash-equilibrium.

However, in Equation 7.10, if C_i is different for different vehicles ($i = 1, 2, ..., N$) , then $\alpha_i > 1$, since $\frac{R}{R-dtm_i} > 1$ (where $\frac{R}{R-dtm_i} = \frac{B}{C_i}$).

Therefore, we consider the special case, when each vehicle has to pay the same cost to become a volunteer, while the benefit that they receive is similar (symmetric volunteer dilemma). This cost is considered:

$$C_i = C = R - dtm_{ave}, i = 1, 2, ..., N \tag{7.11}$$

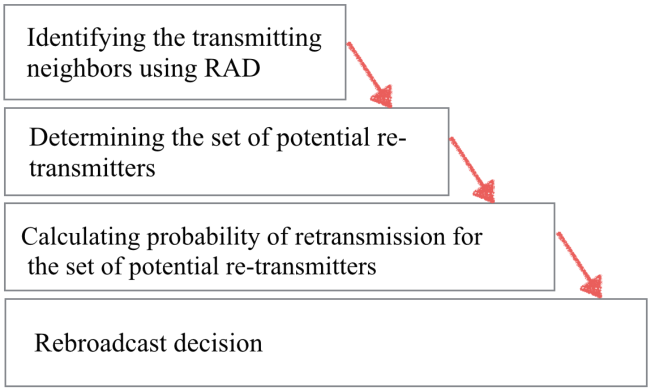


Figure 7.2: Rebroadcast Decision-making Module

where dtm_{ave} is the participants' average distance-to-mean value:

$$dtm_{ave} = \frac{1}{N} \sum_{i=1}^{N} dtm_i \tag{7.12}$$

According to Equation 7.10, in this case the probability of defection for vehicle i is:

$$\alpha_i = \frac{R - dtm_{ave}}{R} \tag{7.13}$$

which satisfies Nash-equilibrium $(0 < \alpha_i < 1)$.

Finally, the probability that the message will be forwarded can be determined as:

$$P = 1 - (\prod_{i}^{N} \alpha_i) = 1 - (\frac{R - dtm_{ave}}{R})^{\frac{N}{N-1}} \tag{7.14}$$

In subsection 7.2.2, the details of the proposed broadcast scheme are explained.

7.2 PROPOSED METHOD

In this section we describe the proposed game theory-based broadcast protocol, in which the receiving vehicle decides whether to rebroadcast according to the estimated probability of transmission. If the vehicle finds itself qualified to rebroadcast the message, it will adjust the contention window based on a fuzzy logic system which takes the information of similarity of density (subsection 7.2.3), and probability of

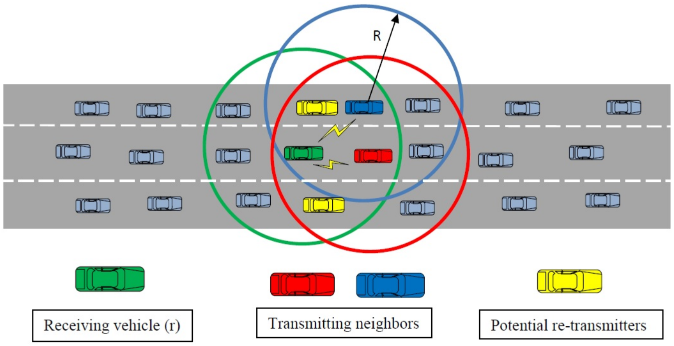


Figure 7.3: Potential Re-transmitting Vehicles in VDIB

transmission into consideration. Fig. 7.1 shows the network architecture of VDIB scheme.

7.2.1 Assumptions

In this scheme, we assume that each vehicle in the network is equipped with an On Board Unit (OBU) wireless transceiver/receiver and a Global Positioning System (GPS). Vehicles establish and periodically update their own neighbors' information tables based on the received beacon messages. These broadcasted beacon messages include information about position, and the vehicle's ID.

We also assume that each vehicle, before broadcasting a message, includes the IDs of its neighbors in the header.

7.2.2 Rebroadcast Procedure in the Network Layer

Fig. 7.2 shows VDIB rebroadcast decision-making process. To design a broadcast protocol, when vehicle r receives a new safety warning broadcast message (with a unique sequence number), the game will be started. Vehicle r uses a distance-based random assessment delay mechanism [41] to identify its transmitting neighbors from which the message has been received. As mentioned before, each transmitting vehicle includes its neighbors' ID list in the header of the message. Therefore, vehicle r is able to determine the neighbor(s) of its transmitting neighbors. Vehicle r identifies the mutual neighbors of vehicle r and its transmitting neighbors. This set of mutual neighbors are assumed to have received the message, and are therefore potential forwarders. We call them the set of potential re-transmitters (Fig. 7.3). Note that vehicle r has position information for the vehicles in this set and can therefore calculate their dtm_{avg}. This is needed for vehicle r to calculate their probability of transmission (Equation 7.14). The number of players in the game are the number of vehicles in the set of potential re-transmitters. Based on the symmetric volunteer dilemma game, vehicle r calculates the probability of transmission for the set of potential re-transmitters including itself as in Equation 7.15:

$$P_{set} = 1 - (\frac{C}{B})^{\frac{N}{N-1}} \tag{7.15}$$

where C and B ($B > C$) denote the cost and benefit of vehicles in the set of potential re-transmitters, respectively. There is cost associated with message rebroadcast and because of that each player in the game would rather have other participants retransmit the message. We consider the cost $R - dtm_{ave}$, where dtm_{ave} is the average distance of playing vehicles (potential forwarders) to their spatial mean values (including vehicle r) and R is the communication range. The ratio of cost to benefit will be:

$$\frac{C}{B} = 1 - \frac{dtm_{ave}}{R} \tag{7.16}$$

Vehicle i that rebroadcasts the message will have the payoff $U = B - C$, in which B is the benefit value generated (R) and C is the cost of getting benefit from rebroadcasting ($R - dtm_{ave}$). So, the utility function for each vehicle is:

$$U = B - C = dtm_{ave} \tag{7.17}$$

Vehicle r uses P_{set} (from Equation 7.15), as a threshold and compares this threshold to its normalized distance-to-mean value ($\frac{dtm_r}{R}$). If $\frac{dtm_r}{R}$ is equal to or greater than the threshold, VEHICLE R starts to adjust the contention window size based on P_{set} and proposed local density factor (to be discussed in subsection 7.2.3) and rebroadcasts the message. If $\frac{dtm_r}{R}$ is less than the threshold, vehicle r waits for a t_{wait} time (defined in Equation 7.18). If during this time it hears the message, it means that at least one of its neighbors has rebroadcast the message and in this case vehicle r drops the message. Otherwise, it rebroadcasts the message.

$$t_{wait} = T_{max}(1 - \frac{d_{min}}{R}) \tag{7.18}$$

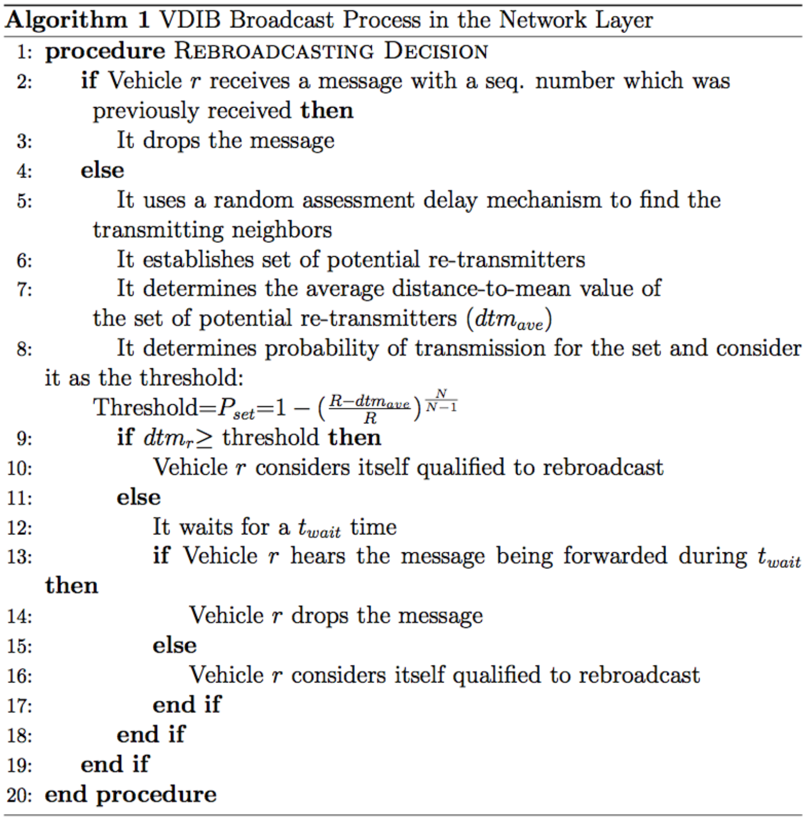
where d_{min} denotes the distance between vehicle r and its nearest neighbor. Based on our simulation results presented in [26], we use the value of 100 ms for T_{max}. The summarized algorithm of rebroadcast process is shown in Fig. 7.4.

7.2.3 Dynamic Contention Window Size Adjustment in the MAC Layer

Fuzzy Logic Module

In this section, we briefly describe the fuzzy logic decision-making system, since we use this technique to adjust CW size in the MAC layer of our proposed scheme. Lotfi Zade introduced the Fuzzy Logic (FL) system in 1965. Fuzzy logic is mainly a multivalued logic technique, in which intermediate values are interpreted as typical assessments such as low/high, slow/fast, true/false. Fuzzy logic techniques are broadly utilized to improve the decision-making process in VANET due to FL techniques' ability to keep track of the rapid changes in VANET environments. Some of the areas that fuzzy logic has been applied to are:

- Routing algorithms
- Broadcast protocols
- Cluster head selection methods



Algorithm 1 VDIB Broadcast Process in the Network Layer

```
procedure REBROADCASTING DECISION
    if Vehicle $r$ receives a message with a seq. number which was previously received then
        It drops the message
    else
        It uses a random assessment delay mechanism to find the transmitting neighbors
        It establishes set of potential re-transmitters
        It determines the average distance-to-mean value of the set of potential re-transmitters ($dtm_{ave}$)
        It determines probability of transmission for the set and consider it as the threshold:
        Threshold=$P_{set}$=$1-(\frac{R-dtm_{ave}}{R})^{\frac{N}{N-1}}$
        if $dtm_r \geq$ threshold then
            Vehicle $r$ considers itself qualified to rebroadcast
        else
            It waits for a $t_{wait}$ time
            if Vehicle $r$ hears the message being forwarded during $t_{wait}$ then
                Vehicle $r$ drops the message
            else
                Vehicle $r$ considers itself qualified to rebroadcast
            end if
        end if
    end if
end procedure
```

Figure 7.4: VDIB Broadcast Algorithm in the Network Layer

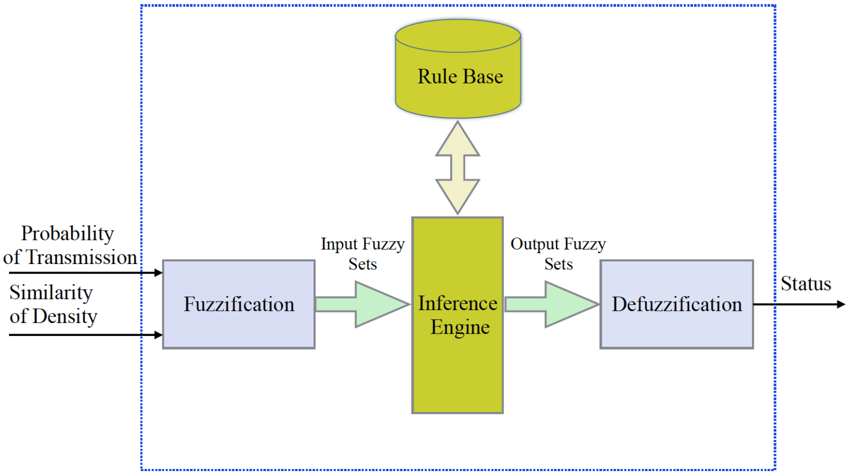


Figure 7.5: Fuzzy Logic-based *CW* Adjustment Module

- Localization techniques

The basic components of each fuzzy logic system are fuzzifier, inference engine, and defuzzifier. As the first process in the fuzzy logic system, fuzzifier converts the crisp input values, which are the probability of transmission and similarity of density, to fuzzy sets which are sets of membership functions. The knowledge based inference engine is implemented by the fuzzy logic rule-based processor to obtain the solution (the status to decrease, keep, or increase the CW) based on IF-THEN sets of rules.

Finally, The defuzzifier is used to alter the decision to the crisp output. The conventional defuzzification techniques are: Center of gravity method, Mean of Maximum method, and Height method. In our proposed scheme, we use the center of gravity method. Fig. 7.5 shows the proposed fuzzy logic-based CW adjustment module.

Fuzzy Logic-based CW Adjustment

According to the IEEE 802.11p, aCW_{min} is 15, and aCW_{max} is 1023. If multiple neighboring vehicles (which are in the transmission range of each other) choose the same backoff time, collisions happen. With increased number of transmitting vehicles, the network experiences collisions more frequently. This means that when the number of transmitting vehicles is large, a relatively large CW size can reduce the number of collisions, while in a low traffic density a small CW size can efficiently access the medium.

We assume that each vehicle before broadcasting a message, includes its current contention window size in addition to the list of its neighbors' IDs in the header. When vehicle r receives a broadcast message and decides to rebroadcast, it checks its transmitting neighbors from which the message is successfully received to select vehicle t, which has the smallest contention window CW_t^s, and counts the neighbors of vehicle t (N_t). The CW size of vehicle t will be used by the fuzzy logic system to adjust the CW size of vehicle r to increase its chance of successful transmission. The fuzzy logic system has two inputs (Fig. 7.5): probability of transmission of the set of potential re-transmitters, P_{set} (Equation 7.15), and similarity of density (SD) factor (Equation 7.19). A larger value of P_{set} implies that more potential re-transmitters are likely to retransmit. In this case, the CW size needs to be increased to reduce the number of potential collisions. On the other hand, the CW size needs to be decreased if P_{set} is small to reduce latency. The second input of the fuzzy logic system, SD factor, is given in Equation 7.19.

$$SD = \frac{N_r - N_t}{max\{N_r, N_t\}} \tag{7.19}$$

It is obvious that the value of SD is in (-1,1) interval. When N_r is greater than N_t, SD will have a positive value and for N_r less than N_t, SD will be negative. For the situation that $\mid N_r - N_t \mid$ is large, the similarity of density is low, so vehicle r needs to decrease or increase the contention window for negative and positive values, respectively. Fig. 7.7 shows the membership functions of the fuzzy input parameters and Table. 7.1 states the fuzzy IF-THEN rules.

The triangular membership functions of probability of transmission, similarity of density, and status are defined in Fig. 7.7. Vehicle r uses the probability of transmission membership function to calculate which degree the set of potential re-transmitters' probability of transmission belongs to $\{low, medium, high\}$. Similarly, it calculates the similarity of the density's degree, which is:

$\{negative - low, medium, positive - low\}$.

The Max-Min fuzzy inference method is applied which means the fuzzy operator AND takes the minimum value of the antecedents [37]. Based on fuzzy values of the input variables and using If-Then rules (as given in Table. 7.1), the adjustment status for vehicle r is determined as *decrease*, *keep*, or *increase*. The correlation between input and output parameters is shown in Fig. 7.8.

Vehicle r will adjust its contention window size, CW_r , based on the determined status and contention window size of vehicle t, CW_t^s. If the status is keep, then:

$$CW_r = CW_t^s \tag{7.20}$$

If the status is increase, vehicle r uses Equation 7.21 to increase the contention window size.

$$CW_r = ((CW_t^s + 1) * 2) - 1 \tag{7.21}$$

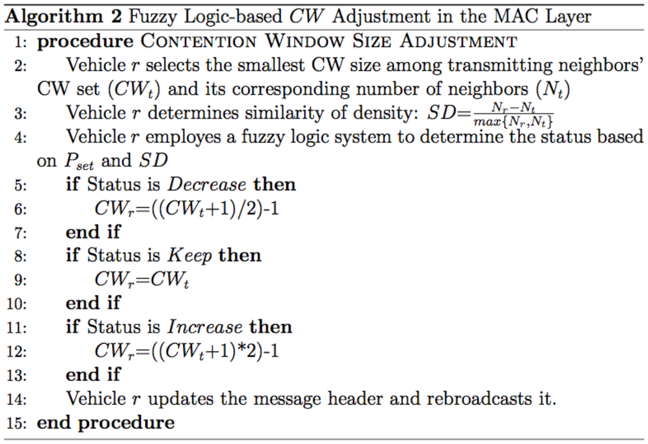
If the status is decrease, vehicle r uses Equation 7.22 to decrease the contention window size.

$$CW_r = ((CW_t^s + 1)/2) - 1 \tag{7.22}$$

Fig. 7.6 shows the algorithm of the fuzzy logic-based CW adjustment method.

7.3 PERFORMANCE EVALUATION

To determine the performance of our proposed broadcast protocol, we use ns-3.24 [38]. The network simulation is set up to have an active period of 1800 seconds and the



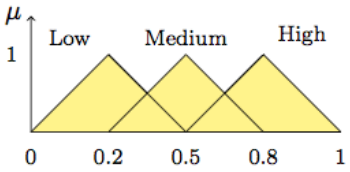
Algorithm 2 Fuzzy Logic-based CW Adjustment in the MAC Layer

```
procedure CONTENTION WINDOW SIZE ADJUSTMENT
    Vehicle $r$ selects the smallest CW size among transmitting neighbors' CW set ($CW_t$) and its corresponding number of neighbors ($N_t$)
    Vehicle $r$ determines similarity of density: $SD=\frac{N_r-N_t}{max\{N_r,N_t\}}$
    Vehicle $r$ employs a fuzzy logic system to determine the status based on $P_{set}$ and $SD$
    if Status is Decrease then
        $CW_r$=(($CW_t$+1)/2)-1
    end if
    if Status is Keep then
        $CW_r$=$CW_t$
    end if
    if Status is Increase then
        $CW_r$=(($CW_t$+1)*2)-1
    end if
    Vehicle $r$ updates the message header and rebroadcasts it.
end procedure
```

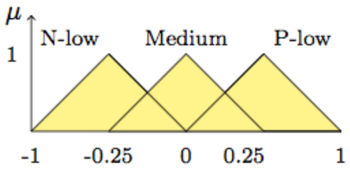
Figure 7.6: Fuzzy Logic-based CW Adjustment Algorithm

Table 7.1: Fuzzy Rules for CW Adjustment

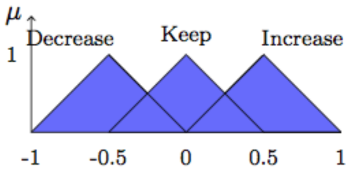
Probability of Transmission	Similarity of Density	Status
Low	Negative-low	Decrease
Low	Medium	Decrease
Low	Positive-low	Keep
Medium	Negative-low	Decrease
Medium	Medium	Keep
Medium	Positive-low	Increase
High	Negative-low	Keep
High	Medium	Keep
High	Positive-low	Increase



a) Probability of Transmission



b) Similarity of Density



c) Status

Figure 7.7: Fuzzy Membership Functions of *CW* Adjustment System

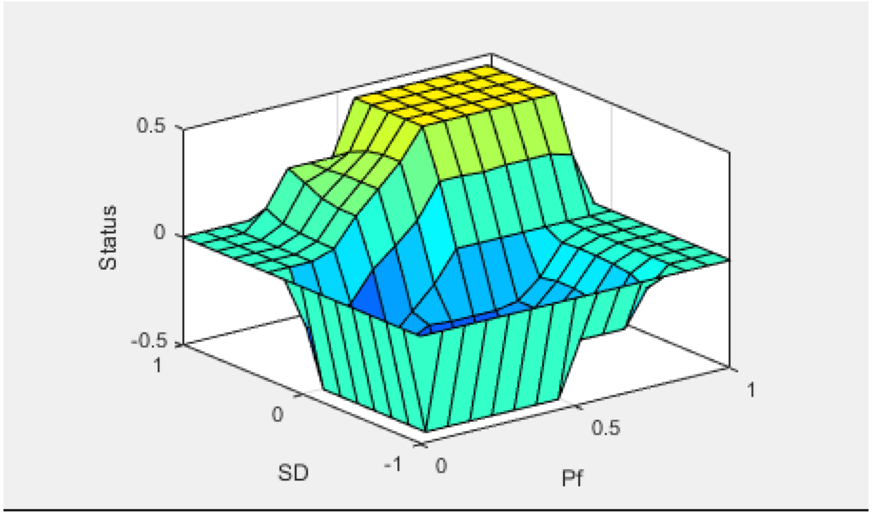


Figure 7.8: Correlation of *CW* Adjustment System Parameters

Table 7.2: The Simulation Parameters

Parameter	**Value**
Number of vehicles	20, 40, 80, 120, 250, 400
Duration	1800 seconds
Packet size	500 bytes
Signal propagation	Nakagami
MAC/PHY protocol	IEEE 802.11p
Transmission range	250 meters
Layer 3 addressing	IPv4

communication range is considered to be 250 meters. The data size of each packet is 500 bytes. Signal propagation is modeled with Nakagami propagation. We use the WAVE model [39], which is the overall system architecture for vehicular communications implemented in ns-3 . We also use IPv4 layer 3 addressing. The simulation parameters are also stated in Table 7.2. Based on our previous study [18], and also based on the simulation results of [27], we come up with an optimal threshold value of 4. Three sets of results are presented for each protocol using the following metrics: reachability, rebroadcasts per covered vehicle, and number of bytes sent per covered vehicle. Reachability is measured as the average fraction of vehicles that receive source messages. Messages rebroadcast per covered vehicle metrics, defined as the ratio of the number of retransmissions to the number of vehicles that receive the message (ignoring the overhead from hello messages), is calculated. Finally, bytes sent per covered vehicle are calculated as a ratio of total number of bytes sent to the number of vehicles that receive the message (including overhead from hello messages). In order to assess scalability, we run the simulation for low, medium, and high traffic densities.

7.3.1 Simulation Results

To evaluate the performance of our proposed scheme, we obtain simulation results for both highway and urban environments. Also the confidence interval of the results are shown.

Highway Environment

The vehicle's mobility is generated based on ns-3.24 constant speed mobility model and the position allocation is based on ns-3 random rectangle position model, which places vehicles uniformly on a straight line (highway road scenario). The performance of our proposed protocol, VDIB, is compared with the distance-to-mean broadcast (DTM) [20], Distribution Adaptive Distance with Channel Quality (DADCQ) [22], Statistical Location Assisted Broadcast (SLAB) [23], Fuzzy Logic-based Broadcast (FLB) [25], bandwidth efficient intelligent broadcast (BEFLAB) [26] and intelligent hybrid adaptive broadcast (IHAB) [27] protocols. Fig. 7.9 shows VDIB protocol's ability of successful message delivery in terms of reachability. VDIB reaches more than 94% of vehicles in the sparse network and up to 98% in the dense network scenarios. Based on Fig. 7.10 we observe that VDIB produces less number of retransmissions compared to SLAB, DADCQ, DTM, and FLB. Since BEFLAB and IHAB are very aggressive in suppressing retransmissions, they outperform VDIB in terms of the number of rebroadcasts per covered vehicle. Fig. 7.11 presents the number of bytes sent per covered vehicle. While VDIB has the lowest number of bytes sent compared to DTM, SLAB, DADCQ, and FLB protocols, it loses to BEFLAB. VDIB has similar performance as IHAB in sparse networks and slightly better performance than IHAB in dense networks. This is due to the different size of beacon messages of the two protocols as IHAB's beacon messages include velocity information.

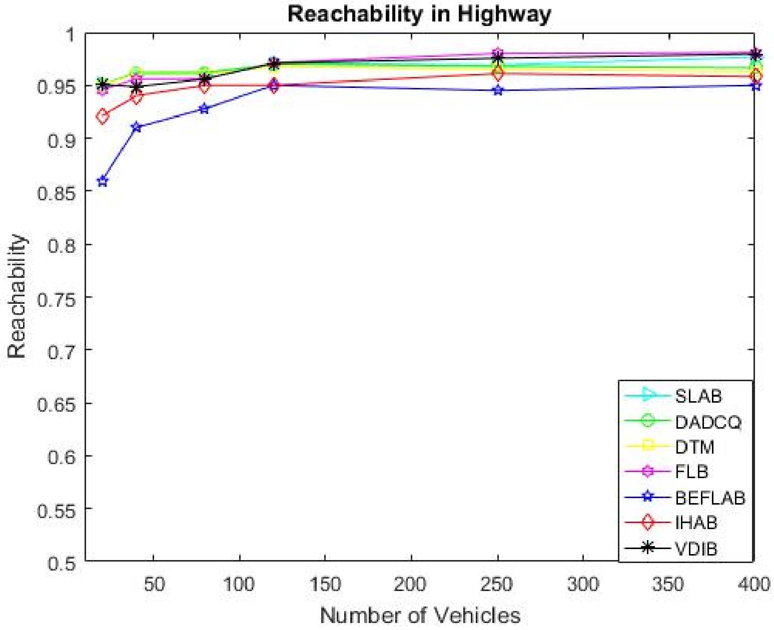


Figure 7.9: Reachability in Highway environment

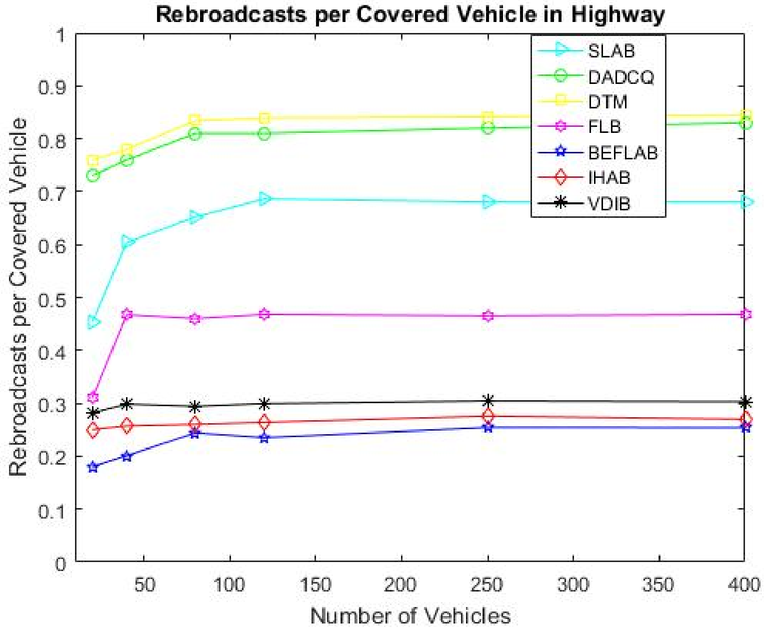


Figure 7.10: Rebroadcasts per covered vehicle in Highway environment

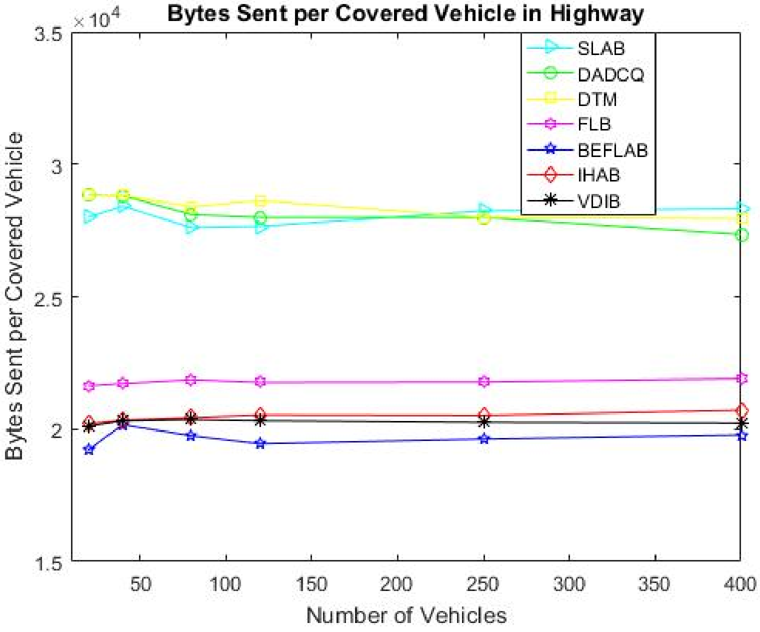


Figure 7.11: Bytes sent per covered vehicle in Highway environment

Urban Environment

To get results for the urban environment, we generate vehicles' mobility using Simulation of Urban MObility (SUMO) [40]. In our simulation, the road network uses a 3x3 Manhattan Grid with an edge length of 1km and an equal distance between any two neighboring intersections. Vehicle movement uses Intelligent Driver Model and vehicle speeds are computed using the car-following model in which each vehicle speed is adaptive to the leading vehicle speed. Vehicle distribution is a random process and routes are randomly generated. For each traffic scenario, ns-3 generates vehicle mobility based on mobility traces created by SUMO. The simulations are run using the parameters as mentioned before. Figs. 7.12 - 7.14 show the simulation results in urban environment. Based on Fig.7.12, VDIB has a reachability percentage around 70% in sparse networks, which is close to FLB, and IHAB, and outperforms DADCQ, SLAB, and BEFLAB. In sparse networks, DTM has a better performance in terms of reachability. With an increased number of vehicles in the network, VDIB reaches

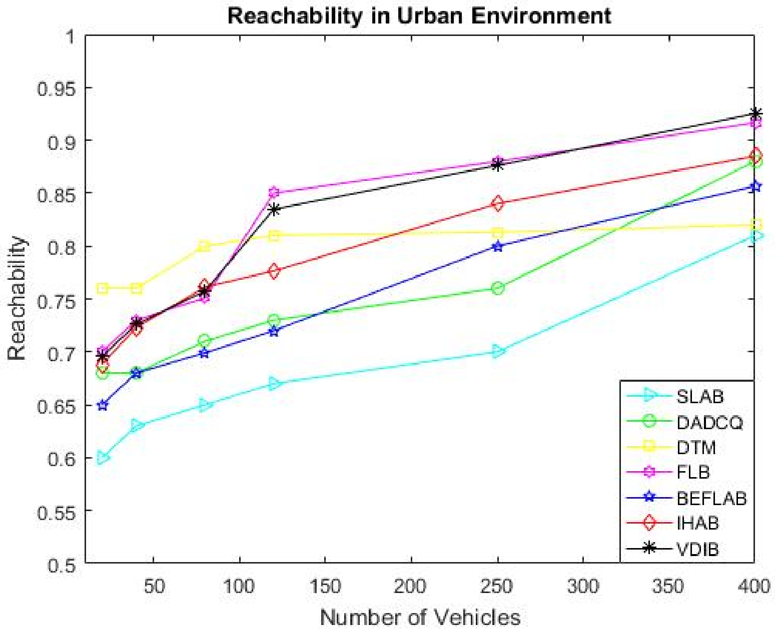


Figure 7.12: Reachability in Urban environment

almost the same fraction of vehicles that FLB reaches, while they both outperform DTM, DADCQ, SLAB, BEFLAB, and IHAB. Fig. 7.13 and Fig. 7.14 show that the performance of VDIB in terms of bandwidth consumption is very close to BEFLAB's and IHAB's, while there is a big improvement compared to DTM, DADCQ, and SLAB. VDIB has a close but still better bandwidth performance than FLB which can be attributed to its more restrict process to select the forwarding vehicles.

Confidence Interval

We compute the confidence interval for the proposed scheme performance metrics shown in Figs 7.15 - 7.20 with 95% confidence intervals represented in error bars. As observed the obtained confidence intervals are very decrease with all density scenarios.

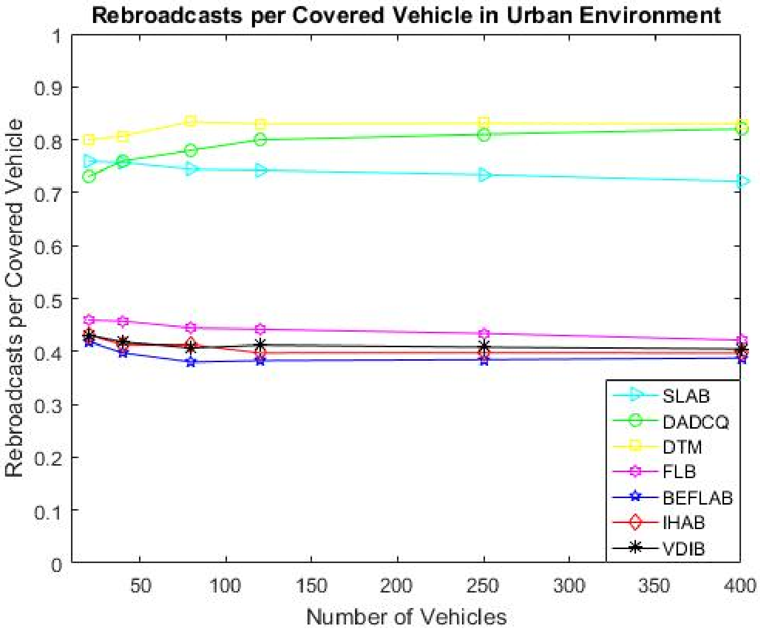


Figure 7.13: Rebroadcasts per covered vehicle in Urban environment

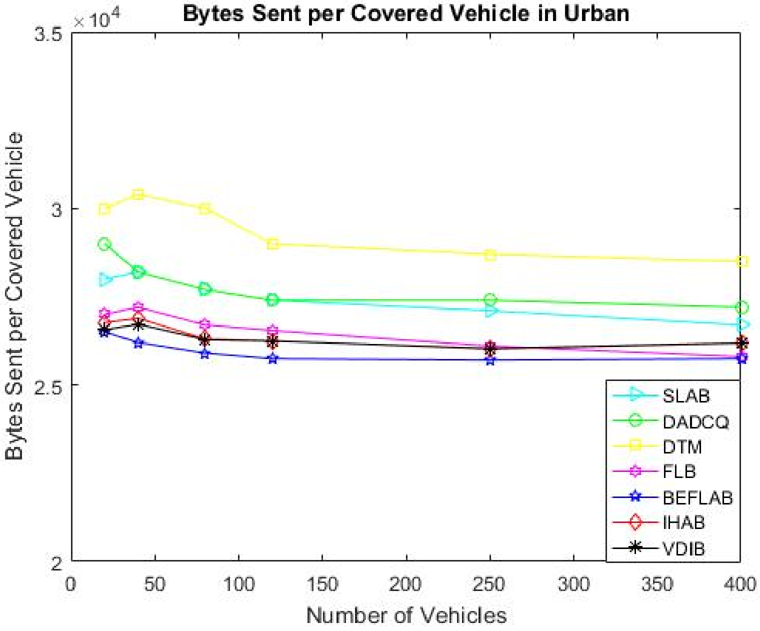


Figure 7.14: Bytes sent per covered vehicle in Urban environment

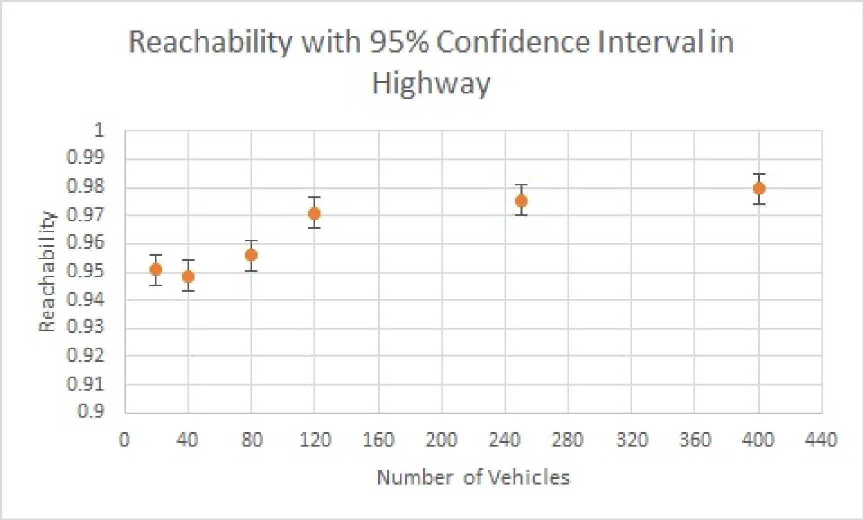


Figure 7.15: Reachability in Highway with 95% Confidence Interval

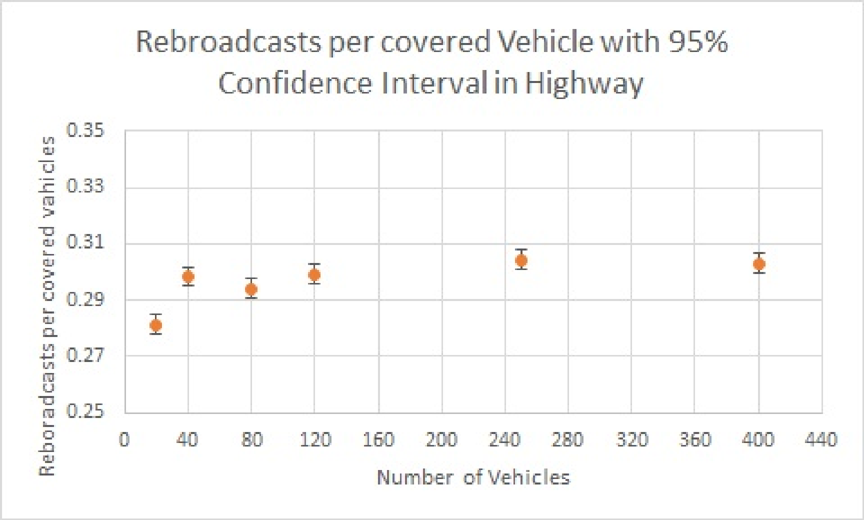


Figure 7.16: Number of Rebroadcasts per covered vehicles in Highway with 95% Confidence Interval

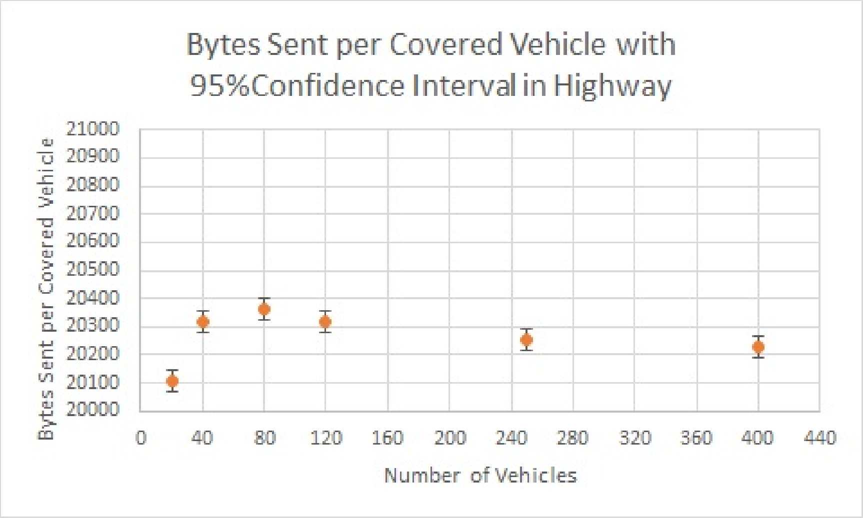


Figure 7.17: Bytes sent per covered vehicle in Highway with 95% Confidence Interval

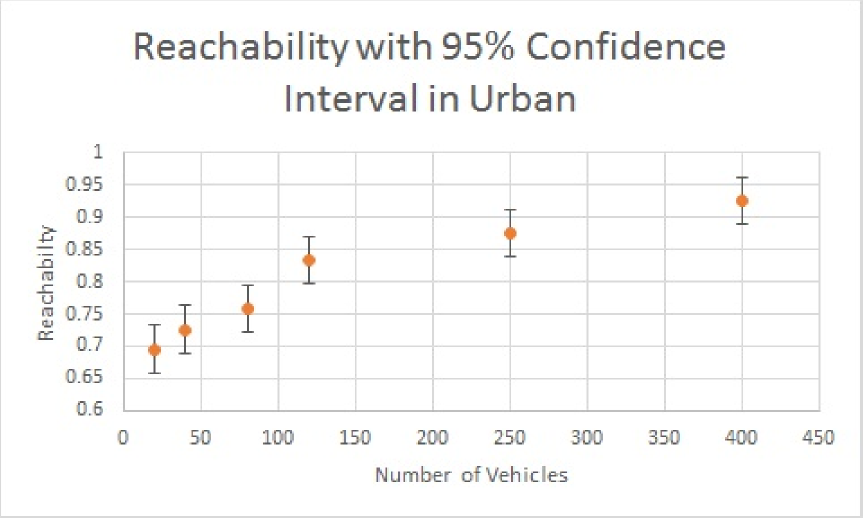


Figure 7.18: Reachability in Urban with 95% Confidence Interval

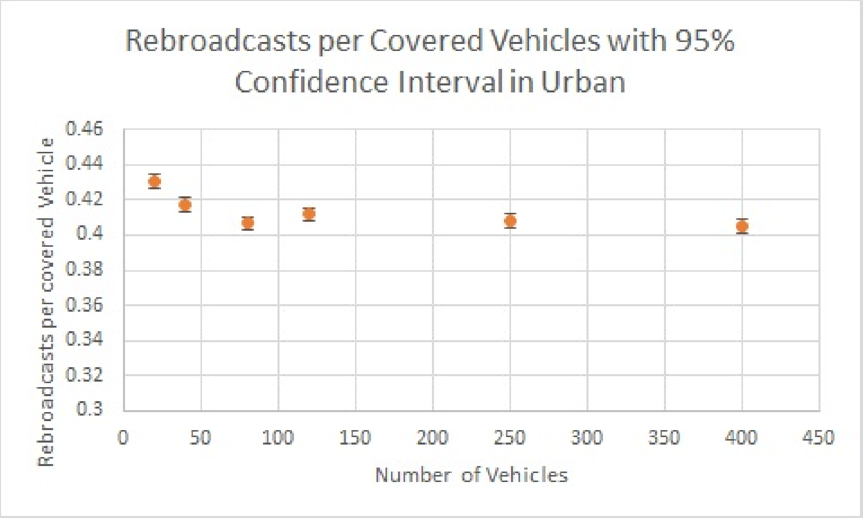


Figure 7.19: Number of Rebroadcasts per covered vehicle in Urban with 95% Confidence Interval

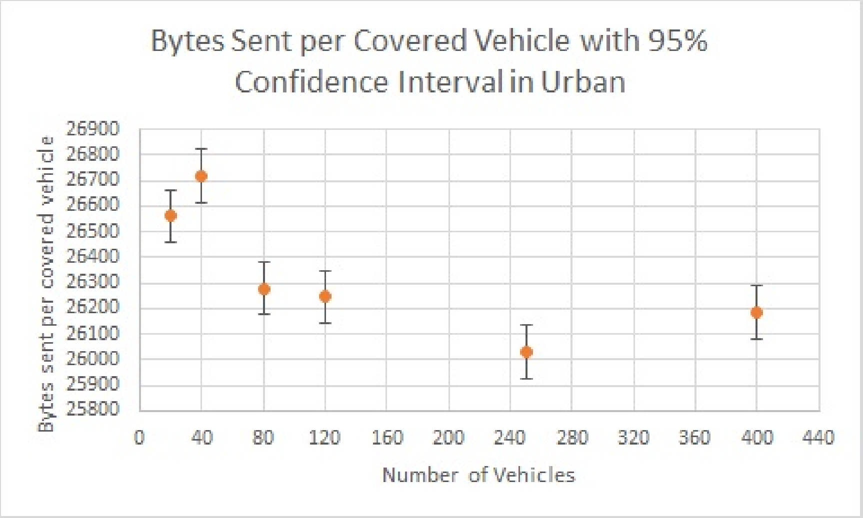


Figure 7.20: Bytes sent per covered vehicle in Urban with 95% Confidence Interval

7.4 SUMMARY

In this chapter, we modeled a cross-layer VANET broadcast scheme using a game-theoretical environment and fuzzy logic approach. In this work, each playing vehicle predicted the probability of forwarding for the set of players depending on the number of players, and also cost and benefit. This proposed Volunteer Dilemma Game Inspired Broadcast Scheme utilized information from the network layer to adjust the contention window size in the MAC layer based on a fuzzy logic decision-making system. The proposed scheme is designed to save bandwidth by suppressing more vehicles from rebroadcasting while at the same time tries to achieve high reachability. The simulation results indicated the advantage of the proposed method over DTM, DADCQ, SLAB, FLB, BEFLAB, and IHAB in both highway and urban environments. VDIB outperforms DTM, DADCQ, and SLAB in terms of reachability and bandwidth utilization. Compared to FLB, VDIB produces less number of retransmissions and bytes sent, while FLB slightly performs better in terms of reachability. VDIB outperforms BEFLAB and IHAB in terms of reachability, while due to BEFLAB and IHAB's aggressive retransmission suppression behavior, they have better performance in terms of bandwidth consumption.

CHAPTER 8

TRANSMISSION RANGE ADAPTIVE BROADCAST FOR VANET

To be able to improve reachability in sparse networks, the transmission range adaptation is one of the possible strategies. However, increasing transmission range might have other effects, for example, increased transmission range potentially increases the interference, which can cause packet loss. So it is beneficial to increase the transmission range when the density of vehicles is low as the increase in interference level would be small. Alternatively, to reduce interference, the transmission range can be reduced when the density of vehicles is found to be very high. In this chapter, we use Point Pattern Analysis technique to estimate spatial distribution of vehicles and adaptively assign the transmission range for different distribution scenarios. This work is motivated by the observation that the majority of proposed broadcast schemes use a static transmission range for vehicle to vehicle communication and also the authors of [42] and [43] consider only the vehicle density to adjust the transmission power and they do not take spatial distribution of vehicles into account. In this work, we propose a smart receiver-oriented broadcast scheme which dynamically adapts transmission range not only based on vehicles density, but also considering the spatial distribution of vehicles to increase reachability, specially in sparse network scenarios. Transmission range adaptation of rebroadcasting vehicles is performed based on Nearest Neighbor Distance method which is one of the Point Pattern Analysis (PPA) techniques. In order to prevent packet collision, we also use a fuzzy logic technique to adjust the contention window size at the MAC layer, based on the spatial distribution and network density. To identify the set of potential forwarders in our proposed rebroadcast mechanism, we utilize the bloom filter technique which reduces the re-

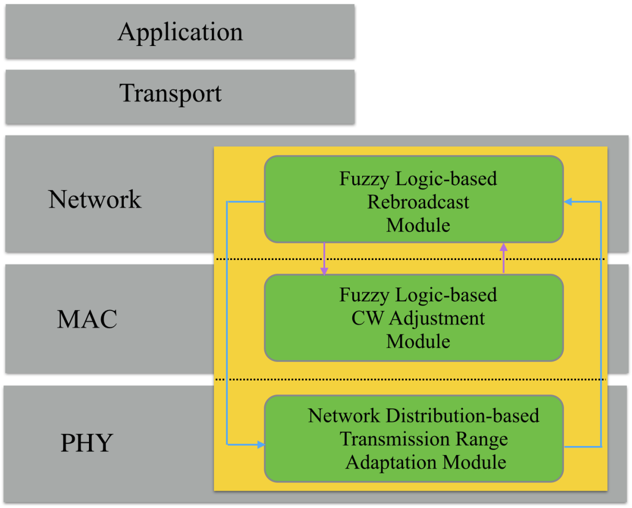


Figure 8.1: TRAB's Architecture

sulted the overhead resulting from the inclusion of the neighbors' IDs in the header of broadcast messages.

8.1 PROPOSED PROTOCOL

In this chapter, we propose a bloom filter-assisted smart broadcast scheme in which based on the spatial distribution of vehicles in the network, the transmission range will be adapted. Also, at the MAC layer, considering the distribution and density information, the contention window size will be adjusted by a fuzzy logic system. Fig. 8.1 shows the cross-layered architecture of our proposed broadcast scheme.

8.1.1 Assumptions

We assume that all the vehicles are equipped with a Global Positioning System (GPS), so each vehicle is aware of its position and moving velocity information. Each vehicle is able to keep track of its neighboring vehicles using periodic hello messages. These broadcast hello messages contain position, velocity and ID information. Based on the received hello messages, vehicles construct and update their own neighbors information tables.

In addition, each vehicle is going to include in the header the IDs of its neighboring vehicles. Since this may introduce high overhead, we propose to use the bloom filter technique to mitigate this overhead, as explained in the following subsection.

8.1.2 Bloom Filter

In this work, we use a bloom filter to mitigate overhead. A bloom filter is a space and time efficient data structure which is used to check whether an element is present in a set [44]. This probabilistic data structure shows that the element either definitely is not a member of the set or might be a member of the set. As shown in Fig. 8.2, each bloom filter is made up of two basic parts: an $m - bit$ array and k hash functions $h_1(.)$, $h_2(.)$... $h_k(.)$. Each hash function is used to map an element to an index value within the range $[1, m]$.

In order to insert an element a into a bloom filter, first the hash functions are applied on a, which generates k indexes. Then, all the array's bits at the location of these generated indexes will be set to 1.

To search for an element b in a bloom filter array, the first step is again applying the hash functions to produce k indexes. If all the bits that are located at these indexes have been set to 1, then element b can be considered a member of the set.

Here, the only type of error that can be named is false positive, which reports a non-member element b as a member of the set.

In our proposed rebroadcast system, each broadcasting vehicle inserts its neighbors IDs into a bloom filter which will then be added to the header. Then, each receiving vehicle checks whether its neighbors belong to the array of received broadcast message and determines the common neighbors with the transmitting neighbor. subsection 8.1.3 provides the details of the proposed rebroadcast system.

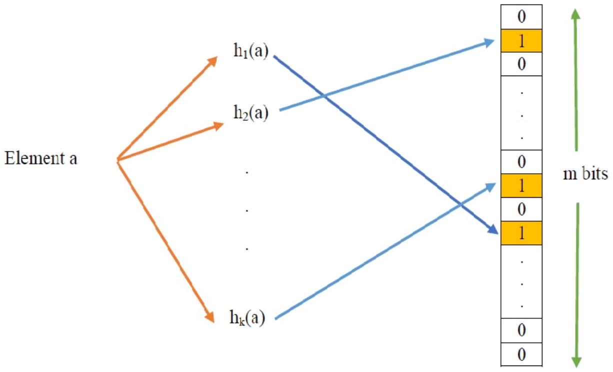


Figure 8.2: A basic bloom filter with m bits and k hash functions

8.1.3 Rebroadcast System

When Vehicle r receives a new broadcast warning message with a unique sequence number, it uses the random assessment delay mechanism proposed in [2] to identify the transmitting neighbors from which the message has been successfully received. In order to identify a set of potential forwarders (SPF), vehicle r determines if the ID of its neighbors belong to the bloom filters of these transmitting neighbors.

Given that false negative of a bloom filter is 0, the uncommon neighbors between vehicle r and its transmitting neighbors are predicted correctly. Then we can estimate the common neighbors between them by eliminating the uncommon neighbors from vehicle r's set of neighbors. Vehicle r treats this predicted set of common neighbors as the set of potential forwarders.

Vehicle r utilizes a fuzzy logic system to determine whether it is qualified to rebroadcast. This proposed fuzzy logic system is fed with mobility and coverage factors as inputs. Vehicle r calculates the mobility factor (MF) using Equation 8.1.

$$MF = \frac{v_i - v_{min}}{v_{max} - v_{min}} \tag{8.1}$$

where v_i denotes the velocity of vehicle i and v_{min} and v_{max} are the minimum velocity and maximum velocity of the potential forwarders including vehicle r. A lower mobility factor indicates a lower velocity and vehicles with lower velocity are more qualified to rebroadcast the message.

To obtain the coverage factor (CF), the distance-to-mean method proposed in [20] is used. The distance-to-mean method determines the distance from the vehicle to the spatial mean of the potential forwarders. The spatial mean of a set of n points, (x_i,y_i), is calculated as:

$$(\bar{x}, \bar{y}) = (\frac{1}{n} \sum_{i=1}^{n} x_i, \frac{1}{n} \sum_{i=1}^{n} y_i) \tag{8.2}$$

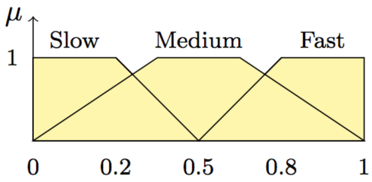
If the vehicle is positioned at (x,y), then the normalized distance to mean variable, CF, can be obtained using Equation 8.3.

$$CF = \frac{1}{TR}\sqrt{(x - \bar{x})^2 + (y - \bar{y})^2} \tag{8.3}$$

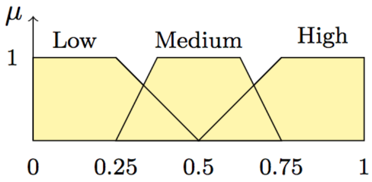
where TR is vehicle r's current transmission range. When CF is small, it means the potential forwarding vehicles are distributed evenly around the vehicle, indicating that it should not rebroadcast.

As shown in Fig. 8.3, we use the trapezoidal membership functions for mobility and coverage factors, and also for the membership functions of the output. Each receiving vehicle uses the mobility membership function to calculate which degree the mobility belongs to $\{slow, medium, fast\}$. Similarly, it calculates the degree of coverage, which is $\{low, medium, high\}$. The Max-Min fuzzy inference method is applied which means the fuzzy operator AND takes the minimum value of the antecedents [37]. Based on fuzzy values of input variables and using If-Then rules (as given in Table. 8.1), the vehicle status as rebroadcasting or non-rebroadcasting is determined. In this work, we use the most popular defuzzification technique, Center of Gravity (COG), which is widely used in actual applications.

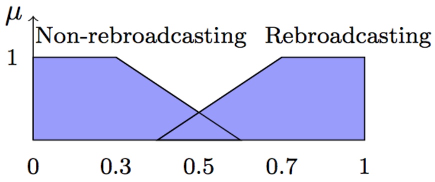
If vehicle r finds its status as non-rebroadcasting, it drops the message. Otherwise, vehicle r, again using the proposed fuzzy logic system, determines the set of



a) Mobility Factor



b) Coverage Factor



c) Status

Figure 8.3: Membership Functions of Rebroadcast System

Table 8.1: Fuzzy Rules

Mobility	Coverage	Status
slow	low	non-rebroadcasting
slow	medium	rebroadcasting
slow	high	rebroadcasting
medium	low	non-rebroadcasting
medium	medium	rebroadcasting
medium	high	rebroadcasting
fast	low	non-rebroadcasting
fast	medium	non-rebroadcasting
fast	high	rebroadcasting

```
Algorithm 1 TRAB Broadcast Method
procedure REBROADCAST SYSTEM
    if Vehicle $r$ receives a message with a seq. number which was previously received then
        It drops the message
    else
        It uses a random assessment delay mechanism to find the transmitting neighbors
        It identifies SPF using bloom filter technique
        It calculates its MF and CF
        It uses fuzzy logic system to determine its rebroadcasting status
        if Vehicle $r$ is not qualified to rebroadcast then
            It waits for $t_{wait}$ time
            if Vehicle $r$ hears the message being forwarded during $t_{wait}$ then
                It drops the message
            else
                It considers itself as a rebroadcasting vehicle
            end if
        end if
    end if
end procedure
```

Figure 8.4: Rebroadcast Algorithm

vehicles (in SPF) that are qualified to rebroadcast and treats it as a set of candidate forwarders (SCF). Vehicle r calculates the distance-to-mean of the vehicles in SCF. It rebroadcasts if its distance-to-mean is the largest in the set, or after t_{wait} time it does not hear the message being forwarded by other vehicles. t_{wait} is given by Equation 8.4.

$$t_{wait} = T_{max}(1 - \frac{d_{min}}{TR}) \tag{8.4}$$

where d_{min} denotes vehicle r's nearest neighbor distance. Based on simulation results shown in [26], we use the optimal value, 100 ms, for T_{max}. In Fig. 8.4, the algorithm of the rebroadcast process in the network layer is shown.

8.1.4 Transmission Range Adaptation

Point Pattern Analysis

Point Pattern Analysis (PPA) is the arrangement evaluation of a set of points on a surface, which reports the actual spatial or time-related location of points. In a numerical data set, Complete Spatial Randomness (CSR) refers to the spatial model of a random process or a Poisson distribution. Nearest neighbor distance and quadrat techniques are specifically introduced for pattern analysis of point data.

In this work, we use the Nearest Neighbor Distance analysis to estimate the spatial distribution of vehicles in the network.

In the nearest neighbor distance analysis method, as one of the PPA models, the distance of each point (here vehicles) to its nearest neighbor is determined and the average nearest neighbor distance for all vehicles is calculated. Nearest Neighbor Index (NNI) is a unit-less statistical metric that determines the distribution. NNI is defined as the ratio of the observed average distance to the expected average distance of CSR (Equation. 8.5).

$$NNI = \frac{\bar{D_o}}{\bar{D_E}} \tag{8.5}$$

where $\bar{D_o}$ is the observed mean distance between each vehicle and its nearest neighbor:

$$\bar{D_o} = \frac{\sum_{i=1}^{n} d_i}{n} \tag{8.6}$$

and $\bar{D_E}$ is the expected mean distance for the vehicles given a uniform random pattern:

$$\bar{D_E} = 0.5\sqrt{\frac{A}{n}} \tag{8.7}$$

Generally, for uniform patterns, the value of NNI is expected to be around 1. Also, clustered patterns are considered to have an NNI close to 0. Finally, NNI of sparse patterns is expected to have a value greater than 2 (Fig. 8.5).

Transmission Range Adaptation Algorithm

In this work, each rebroadcasting vehicle estimates the distribution of vehicles on the road using the nearest neighbor distance method. Based on the algorithm shown in Fig. 8.6, when a receiving vehicle decides to rebroadcast the message, it uses the calculated NNI to dynamically adjust the transmission range.

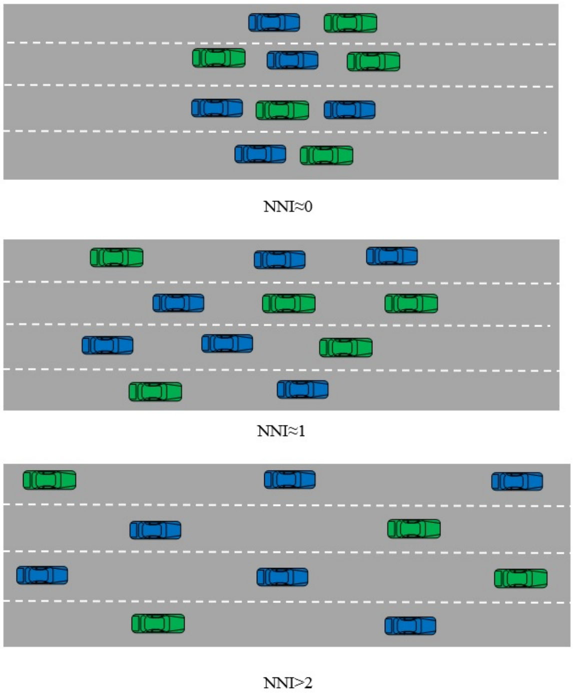
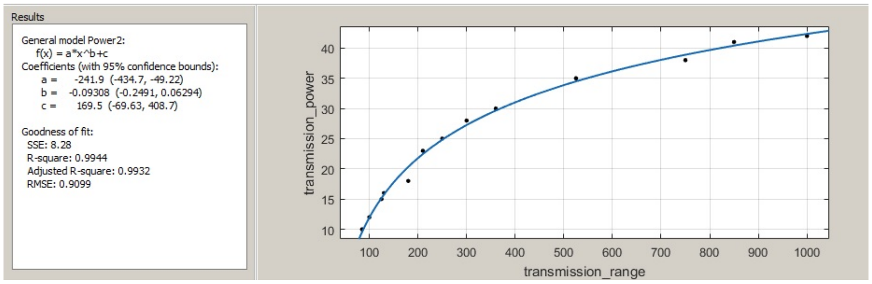


Figure 8.5: NNI Value for Different Spatial Distribution of vehicles

Algorithm 2 Transmission Range Adaptation

```
procedure TRANSMISSION RANGE ADAPTATION
    Calculate NNI
    if $NNI \geq 2$ then
        $TR \leftarrow TR_{max}$
    else
        $TR \leftarrow 0.25 * TR_{max} * (1 + NNI)$
    end if
    Calculate the proper Transmission Power
end procedure
```

Figure 8.6: Transmission Range Adaptation Algorithm



```
General model Power2:
    f(x) = a*x^b+c
Coefficients (with 95% confidence bounds):
      a =     -241.9  (-434.7, -49.22)
      b =   -0.09308  (-0.2491, 0.06294)
      c =      169.5  (-69.63, 408.7)

Goodness of fit:
  SSE: 8.28
  R-square: 0.9944
  Adjusted R-square: 0.9932
  RMSE: 0.9099
```

Figure 8.7: Transmission Power Function

To obtain the proper transmission power as a function of transmission range, as Fig. 8.7 shows, we use ns-3 simulation experimentation for an environment with the Nakagami propagation model. Then, using MATLAB Curve Fitting Tool, we define a function with 95% confidence bounds when the root mean squared error (RMSE) equals 0.9, given by Equation 8.8.

$$P_{tr} = -241.9(TR)^{-0.93} + 169.5 \tag{8.8}$$

where P_{tr} and TR are the transmission power and transmission range, respectively.

8.1.5 Contention Window Size Adjustment

According to IEEE 802.11p MAC specification, the back off time is calculated by:

$$backoff = SlotTime * Rand() \tag{8.9}$$

where Rand() is a number randomly drawn from a uniform distribution over the interval of [0,CW]. CW can be defined as:

$$CW = 2^n - 1; n \in \{4, 5, 6, ..., 10\} \tag{8.10}$$

The initialized contention window size is considered aCW_{min} which is equal to 15. However, since at the MAC layer there is neither reception acknowledgment nor retransmission of broadcast frames, the contention window size dose not change. In a dense network, there is a high probability to have a high data traffic load, so a small contention window causes a high probability of collision. This issue inefficiently affects the network data dissemination. In addition, when the number of vehicles in the network is small, a large contention window could increase end-to-end delay. So due to these issues, we propose a contention window size adjustment algorithm which considers both the local density and distribution information.

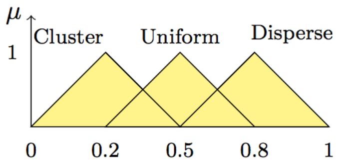
We assume that each vehicle before broadcasting a message, includes its current contention window size and its number of neighbors in the header. When vehicle r, receives a new warning broadcast message and decides to rebroadcast, it checks its transmitting neighbors from which the message is successfully received to select vehicle t, that has the smallest contention window CW_t^s and checks vehicle t's number of neighbors (N_t). In the neighboring set, if two or more transmitting vehicles have the same value of CW_t^s , vehicle r selects the one that has the largest number of neighbors. Since vehicle r successfully received the message from vehicle t, vehicle r considers CW_t^s the base value to adjust its contention window (CW_r). We propose a fuzzy logic-based contention window size adjustment system, which uses the information of spatial distribution and similarity of density to decide to keep, decrease, or increase the base value as CW_r. As the first metric, spatial distribution, the normalized value of NNI is used.

$$NNI_{normalized} = \frac{NNI}{NNI_{max}} \tag{8.11}$$

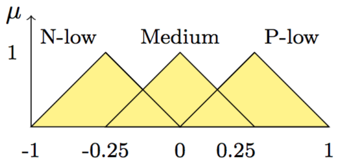
where in our proposed network with maximum transmission range of 1000 meters, NNI_{max} can be defined as:

$$NNI_{max} = 1.2\sqrt{n} \tag{8.12}$$

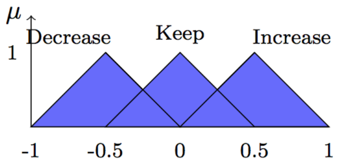
As the second input of the fuzzy system, we introduce the $similarity\ of\ density$



a) Spatial Distribution



b) Similarity of Density



c) Status

Figure 8.8: Fuzzy Membership Functions of CW Adjustment

(SD) metric, described in Equation 8.13:

$$SD = \frac{N_r - N_t}{max\{N_r, N_t\}} \tag{8.13}$$

It is obvious that the value of SD will be in the interval [-1,1]. When N_r is greater than N_t, SD will have a positive value and for N_r less than N_t, SD will be negative. The larger $\mid N_r - N_t \mid$, the smaller similarity of density. In this case, if SD has a negative value ($negative - low$), the contention window size will be decreased, and if it has a positive value ($positive - low$) the contention window size will be decreased. Fig. 8.8 shows the membership functions of the fuzzy input parameters and Table. 8.2 states the fuzzy IF-THEN rules.

Table 8.2: Fuzzy Rules of *CW* Adjustment System

Spatial Distribution	Similarity of Density	Status
Cluster	Negative-low	Keep
Cluster	Medium	Increase
Cluster	Positive-low	Increase
Random	Negative-low	Decrease
Random	Medium	Keep
Random	Positive-low	Increase
Disperse	Negative-low	Decrease
Disperse	Medium	Decrease
Disperse	Positive-low	Increase

Table 8.3: The Simulation Parameters

Parameter	**Value**
Number of vehicles	10, 25, 50, 100, 300
Duration	1200 seconds (20 minutes)
Max speed (Highway)	25 m/s
Max speed (Urban)	14 m/s
T_{max}	100 ms
Hello message period	1 second
Hello message size	64 bytes
Warning message period	20 seconds
Warning message size	512 bytes
Signal propagation model	Nakagami
MAC/PHY protocol	IEEE 802.11p
Transmission range	250 meters
Layer 3 addressing	IPv4

8.2 PERFORMANCE EVALUATION

In this section, we evaluate the efficiency of our proposed broadcast scheme and discuss the results. We use ns-3, which is one the most reliable and scalable network simulators, with the stated parameters in Table 8.3.

We present the results based on four different metrics:

- Reachability
- Rebroadcasts per covered vehicle
- Bytes sent per covered vehicle
- Per hop delay

We define reachability as the average ratio of vehicles in the network which successfully receive the source message. As the second metric, number of rebroadcasts per covered vehicle represents the ratio of the number of retransmissions to the total number of vehicles when we ignore the overhead from beaconing. To get the bytes sent per covered vehicle, we consider the ratio of the total number of bytes sent to the number of vehicles that receive the message, including overhead from beaconing. Finally, we define the per hop delay as the ratio of end-to-end delay (the time difference between generating the message and delivering it to the last covered vehicle) to the number of hops (between the source and last covered vehicles). This per hop delay is a metric which reflects the complexity of the algorithm. We also run the simulation in different scenarios of traffic density (low, medium, and high) to determine the scalability.

8.2.1 Simulation Results

To analyze the performance of our proposed broadcast scheme and compare with the other protocols, we get the simulation results for both highway and urban en-

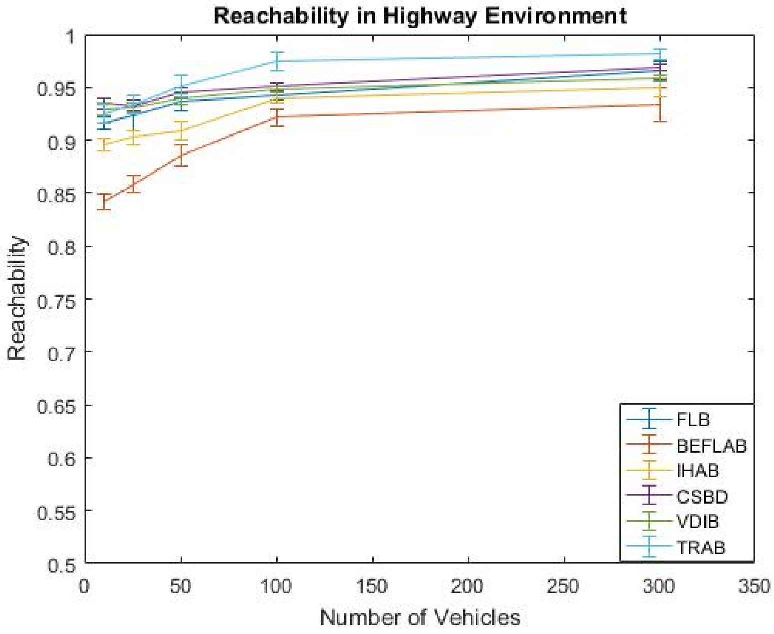


Figure 8.9: Reachability in Highway

vironments. Also, the 95% confidence intervals of results are indicated by the error bars.

Highway Environment

In order to simulate a highway environment, we use the ns-3 random rectangle position model to uniformly place the vehicles on a straight line. Then, using the ns-3 constant speed mobility model, we generate the vehicles' mobility. As the overall system architecture for vehicular communications, we employ WAVE model [39].

We compare the performance of the proposed scheme, TRAB, with FLB, BEFLAB, IHAB, CSBD, and VDIB. As stated in Table 8.3, we run the simulations for various numbers of vehicles in the network. Fig. 8.9 shows that TRAB is the successful scheme to deliver the message in terms of reachability compared to the other schemes. The reachability of TRAB is close to 93% when the network is sparse and increases up to 98% when the network begins to be dense. This is because the scheme can adapt the transmission range and contention window size.

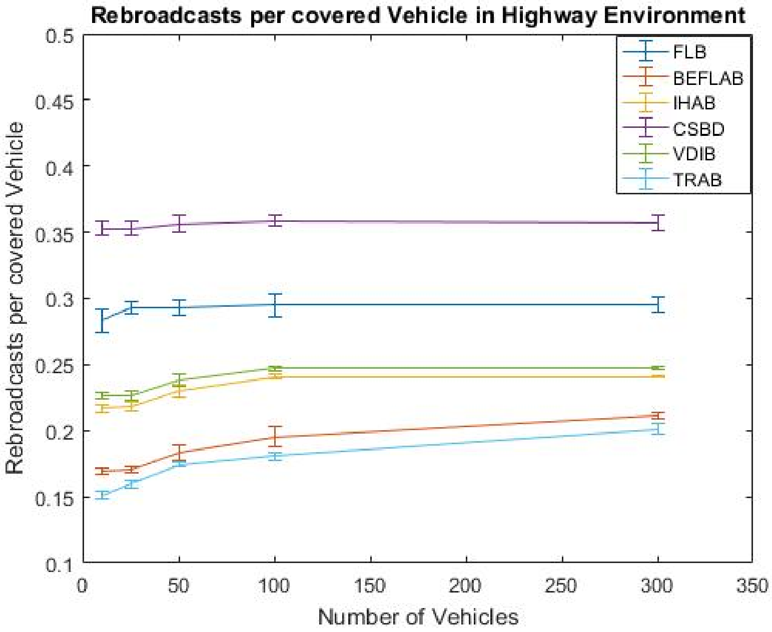


Figure 8.10: Rebroadcasts per covered Vehicle in Highway

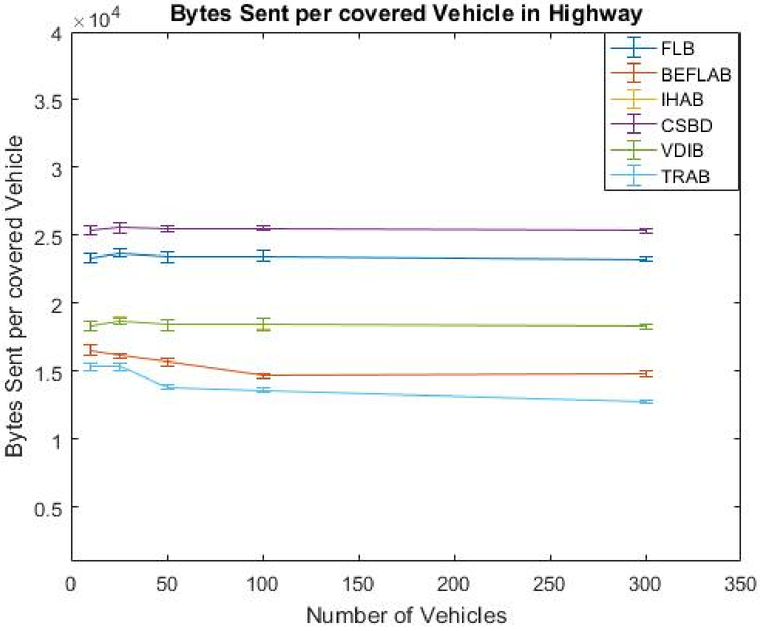


Figure 8.11: Bytes Sent per Covered Highway

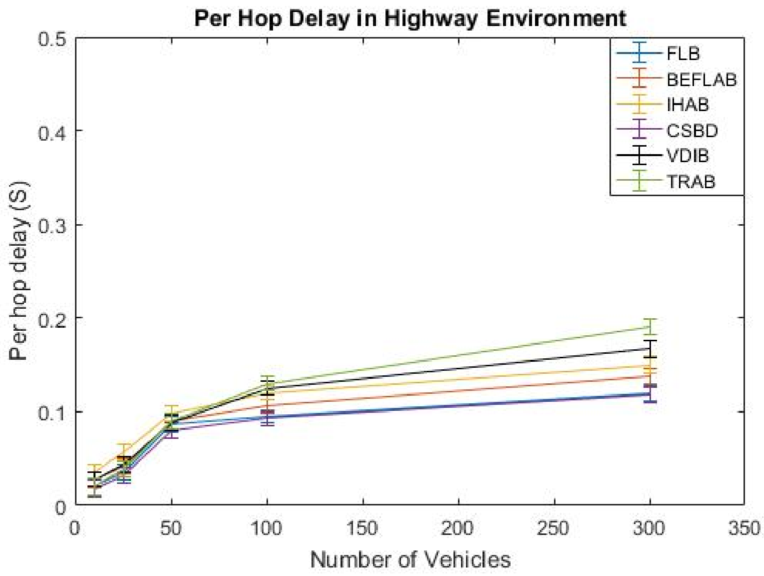


Figure 8.12: Per Hop Delay in Highway

From Figs. 8.10, and 8.11, we observe that with an increased number of vehicles, the number of rebroadcasts and the bytes sent per vehicle reach a plateau. This proves that propose algorithm is scalable to control the bandwidth usage in dense network scenarios. Also, it can be seen from Figs. 8.10, and 8.11, that TRAB outperforms the other protocols in terms of bandwidth consumption. It significantly reduces the number of retransmissions and also the number of bytes in all traffic density scenarios, because of the following reasons. The first reason is that TRAB is aggressive in determining the forwarding vehicles. Also, its adaptive transmission range reduces the number of redundant transmission hops, specially in sparse networks.

Fig. 8.12 indicates the per hop delay of TRAB, FLB, BEFLAB, IHAB, CSBD, and VDIB. As can be seen from Fig. 8.12, TRAB experienced the highest value of per hop delay compared to the other protocols. This comes as no surprise due to the computation complexity of TRAB. However, this should not be an issue as vehicles are expected to have high processing capabilities.

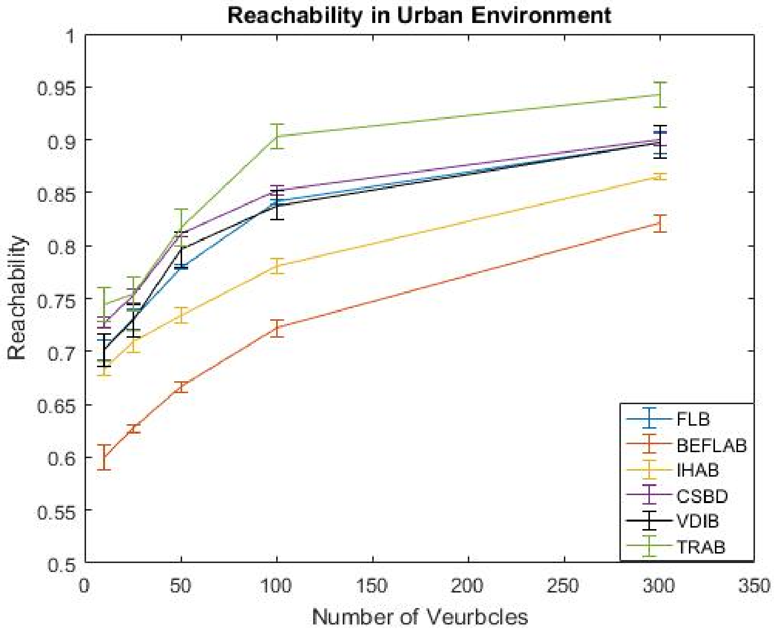


Figure 8.13: Reachability in Urban

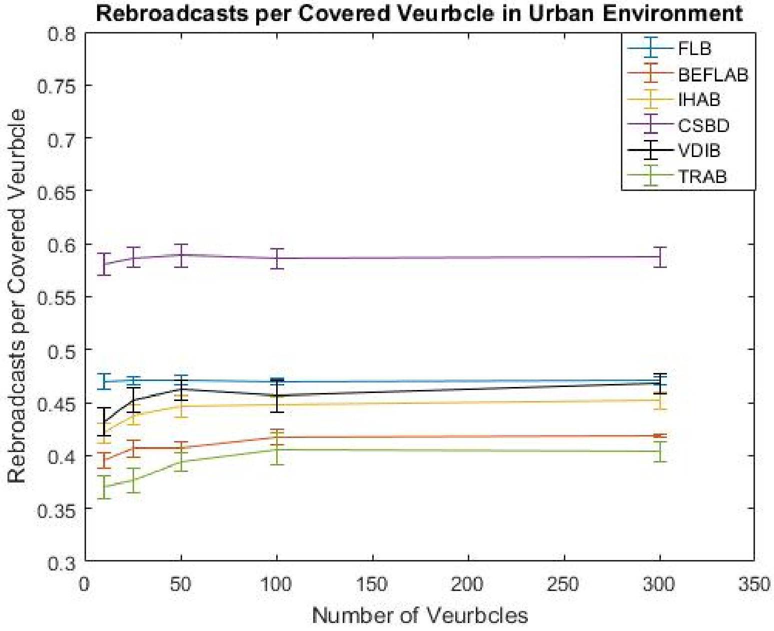


Figure 8.14: Rebroadcasts per covered Vehicle in Urban

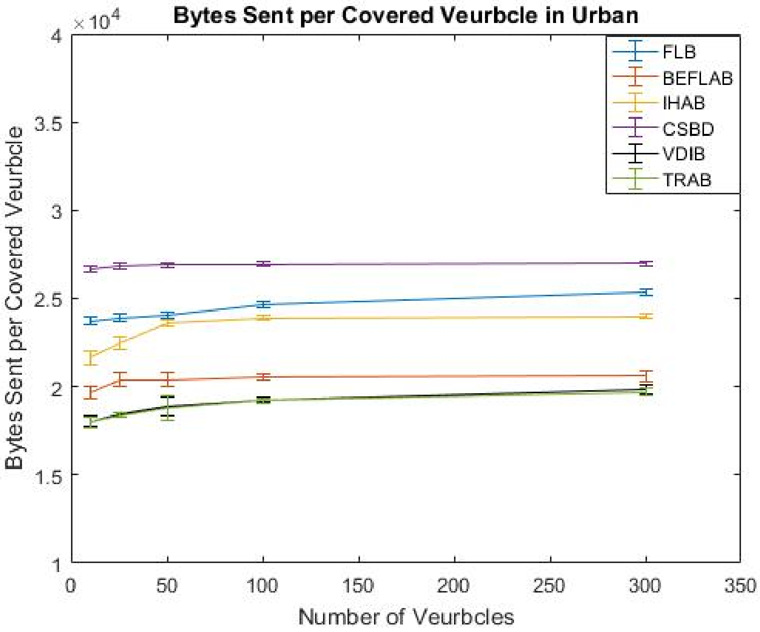


Figure 8.15: Bytes Sent per Covered Vehicle in Urban

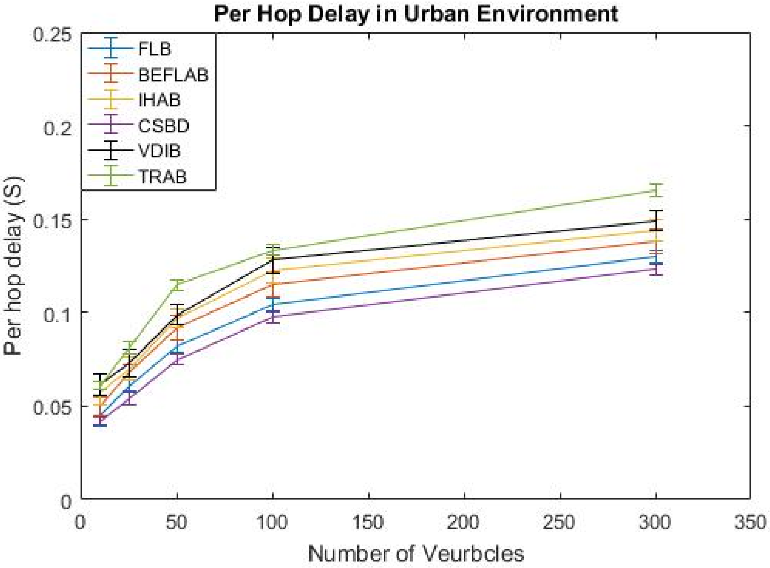


Figure 8.16: Per Hop Delay in Urban

Urban Environment

We consider a 3x3 Manhattan grid road as urban environment, which has an edge length of 1Km and an equal distance of 0.5 Km between neighboring intersections. We also employ Simulation of Urban MObility (SUMO) [40] to generate mobility of vehicles and utilize the car-following model, in which each vehicle adjusts its velocity based on the velocity of the leading vehicle. Using ”randomTrips.py” in SUMO, we randomly generate the distribution of vehicles and routes. Finally, in order to generate node mobility, we use Ns2MobilityHelper class to import the generated mobility traces into ns-3.

The simulation results for urban environment are shown in Figs. 8.13 - 8.16. Based on Fig. 8.13, it is clear that TRAB enhances the reachability for various numbers of vehicles. In average, the reachability of TRAB is almost 75% when the network has a few number of vehicles, and it increases up to 94% when the network has 300 vehicles. As we mentioned for the highway environment, this reachability enhancement is resulted because of the transmission range adaptation and the contention window size adjustment.

From Figs. 8.14, and 8.15, similar to the simulation results for the highway, we can see that TRAB has the best performance in reducing the number of retransmissions and bytes sent. The aggressive behavior of TRAB in determining the forwarding vehicles and suppressing the redundant transmissions by an adaptive transmission range result in an efficient bandwidth usage performance in terms of the number of rebroadcasts per vehicle and the number of bytes per vehicle. Finally, Fig. 8.16 compares the per hop delay of TRAB with that of the other protocols. From Fig. 8.16, it is clear that per hop delay of TRAB is the highest one. This is typically because of the computation complexity of TRAB.

8.3 SUMMARY

In this chapter, we proposed an intelligent receiver-oriented broadcast scheme for VANET. Based on fuzzy logic technique, each receiving vehicle determines whether to rebroadcast or remain silent. Bloom filter method is used to mitigate the overhead due to inclusion of vehicles neighbor IDs in the header of broadcast message. Then, each forwarding vehicle adjusts its transmission range and the contention window size, which are PHY-layer and the MAC layer related parameters, respectively. The forwarding vehicle adapts the transmission range based on the estimated spatial distribution of vehicles, calculated using the nearest neighbor distance method. Also, using a fuzzy logic system, the forwarding vehicle adjusts the contention window size based on the spatial distribution and similarity of density factor. Simulation results confirmed the ability of this scheme to enhance reachability, and to utilize bandwidth more efficiently at the cost of relatively high per hop delay. Wile the reachability enhancement can be attributed to the adaptive transmission range and adjustable size of the contention window, TRAB's efficient bandwidth consumption performance comes as a result of its aggressive behavior in suppressing the number of rebroadcasts. Although the computation complexity of TRAB is the highest, this should not be an issue as vehicles are expected to have high processing capabilities.

CHAPTER 9

CONCLUSIONS AND FUTURE WORK

9.1 CONCLUSION

Intelligent Transportation Systems (ITSs) play a significant role in saving lives and making transportation more reliable. Vehicular Ad-hoc Networks (VANETs) is one of the promising technologies to improve roads' safety. VANET is a subclass of Mobile Ad hoc Networks (MANETs), in which the nodes are vehicles. Since VANET can potentially have a larger number of nodes, scalability is an issue that needs to be addressed when designing VANET protocols.

Efficient data dissemination is needed in VANETs to support both safety and non-safety applications. Safety related data includes periodic beaconing, and emergency warning alarms, such as traffic and road condition warnings. Non-safety data is data generated by applications such as multimedia and commercial communications. Since multi-hop broadcast is one of the main approaches to disseminate data in VANET, it is necessary to come up with a reliable multi-hop broadcast communication scheme. Flooding is the simplest wireless broadcast method, in which each node rebroadcasts when it receives a message. This blind, thoughtless broadcast method causes growing number of retransmissions, which yields extreme overhead (broadcast storm) and packet loss. Therefore, it is a critical issue to design a reliable multi-hop broadcast protocol to satisfy reachability and bandwidth consumption requirements. In a dense network where vehicles are very close to each other, smaller number of vehicles are required to rebroadcast to avoid broadcast storm while at the same time meet the reachability requirement. If the network is sparse, more vehicles need to retransmit to provide high reachability. So, it is obvious that there is a tradeoff between reachability and bandwidth consumption.

This work has been undertaken to design reliable smart receiver-based multi-hop broadcast schemes for VANET. We introduced the fuzzy logic-based broadcast (FLB) protocol. In FLB, relying on coverage, connectivity, and mobility factors calculated by a receiving vehicle, the fuzzy logic system determines if the vehicle is qualified to rebroadcast or not. Simulation results showed that FLB performs well in terms of reachability in both highway and urban environments.

We proposed a bandwidth efficient fuzzy logic-assisted broadcast (BEFLAB) scheme, in which the number of rebroadcasts are aggressively suppressed. In BEFLAB, each receiving vehicle uses a fuzzy logic system which relies on mobility and coverage factors and determines the set of candidate forwarders. Then, the receiving vehicle decides to rebroadcast or drop the message based on the distance-to-mean parameter of each vehicle in the set of candidate forwarders. Simulation results showed that BEFLAB significantly saves the bandwidth while maintaining an acceptable reachability level.

In order to design a bandwidth efficient VANET broadcast scheme with a high level of reachability, we proposed an intelligent hybrid adaptive broadcast (IHAB) protocol. While high reachability is a challenge in sparse networks, bandwidth efficiency is needed in dense networks. IHAB combines the strength of FLB and BEFLAB, where FLB offers high level of reachability and BEFLAB is more bandwidth efficient. In IHAB, each receiving vehicle determines its number of common neighbors with the transmitting neighbors and treats it as the potential transmit density (PDT). If PDT exceeds a threshold (dense network) the receiving vehicle will use the BEFLAB method to decide whether to rebroadcast, otherwise (sparse network) FLB will be used. The simulation results confirmed IHAB's reachability advantage compared to BEFLAB and its bandwidth efficiency compared to FLB for both highway and urban environments.

Since in sparse networks, reachability is the main concern, we proposed a cross-layer statistical broadcast protocol with density-adaptive contention window (CSBD). CSBD utilizes cross-layer information to enhance the reachability of broadcast while maintaining relatively good bandwidth performance in VANET. When a vehicle receives a broadcast message it uses the distance-to-mean (DTM) method to calculate the spatial mean of the transmitting neighbors from which it has received the message, and then calculates its distance to this spatial mean. This distance will be compared with a given threshold to decide to rebroadcast or to remain silent. If the vehicle makes the decision of retransmitting, then it computes a density-dependent factor to decide to keep, increase, or decrease the base value (the smallest contention window size of the transmitting neighbors) in order to adapt the contention window size at the MAC layer. Based on our simulation results, CSBD reached more vehicles in the network meeting high levels of reachability in both highway and urban environments. It can be considered as one of the main effective protocols in sparse networks.

We proposed an efficient receiver-oriented broadcast scheme in which the receiving vehicles' probability of forwarding is modeled by a symmetric volunteer dilemma game. In this volunteer dilemma inspired broadcast (VDIB) scheme, vehicles that receive the broadcast message are players. At least one of the players should pay a cost and be a volunteer to rebroadcast the message, then all will benefit from this volunteering. Utilizing fuzzy logic techniques and considering information from the network layer about local density and probability of transmission, the contention window size at the MAC layer is adjusted. Simulation results indicated that VDIB is an efficient scheme in terms of reachability and bandwidth consumption for varying number of vehicles in both highway and urban environments.

We proposed a transmission range adaptive broadcast (TRAB) scheme based on fuzzy logic technique. Also, a bloom filter method is used to mitigate the overhead

Table 9.1: Proposed Broadcast Schemes Effectiveness

Protocol	Reachability	Number of Rebroadcasts	Bandwidth Usage
FLB	✓		
BEFLAB		✓	✓
IHAB		✓	✓
CSBD	✓		
VDIB	✓	✓	✓
TRAB	✓	✓	✓

resulting from the inclusion of the neighbors' IDs. Each receiving vehicle determines whether to rebroadcast or drop the message. Then, each forwarding vehicle adjusts its transmission range and the contention window size, which are PHY-layer and the MAC layer related parameters, respectively. The transmission range is adapted based on the estimated spatial distribution of vehicles, calculated using the nearest neighbor distance method. Also, utilizing a fuzzy logic system, the forwarding vehicle adjusts the contention window size based on the spatial distribution and similarity of density factor. Simulation results confirmed the ability of this scheme to enhance reachability, and to utilize bandwidth more efficiently at the cost of relatively high processing delay. Although the computation complexity of TRAB is the highest among the proposed broadcast protocols, this should not be an issue as vehicles are expected to have high processing capabilities.

The efficiency of the proposed broadcast schemes are summarized in Table 9.1.

9.2 FUTURE WORK

Several potential research topics and extensions can enhance the work presented in this dissertation. The following is a listing of some of them:

- Adaptive beaconing. Periodic hello messages are needed to activate safety applications. They are required to exchange neighbors' information and enable awareness of nearby vehicles. As mentioned in our work, in dense networks the main challenge is bandwidth efficiency. Therefore, beaconing interval adaptation would help to save bandwidth as in a dense network topology changes slowly.

- Channel condition consideration. Due to the impact of wireless channel condition, channel quality parameters (i.e SNR, SINR) could be taken into account in rebroadcast decision making process. It is obvious that considering channel quality condition would increase the reachability and reliability.
- Interference-aware transmission range adaptation. Increased transmission range may potentially increase the interference, which can lead to packet loss. So, in this work we relied on the fact that it is beneficial to increase the transmission range when the density is low as the increase in interference level would be small. Alternatively, to reduce interference, we reduce the transmission range when the density is very high. As a potential research work, measured level of interference can be considered as one of the factors into the transmission range adaptation algorithm.

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