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RESEARCH ARTICLE

Reliable and Scalable Broadcast Scheme for Safety Applications in Vehicular Ad Hoc Network

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Abstract – In vehicular ad hoc networks (VANETs), safety-related applications require fast and reliable message broadcasting techniques for efficient performance. Reducing redundancy and increasing the reliability of message broadcasts are key challenges amid high mobility, rapidly changing topologies, and shorter communication ranges. The broadcasting protocol needs to be scalable for large variations in vehicle densities and road topologies. This paper presents a new broadcast protocol for safety applications in vehicular networks. The discussed scheme is adaptive to current network loads and channel conditions. Compared with other state-of-the-art protocols in its category, it offers better robustness, coverage, and scalability. It achieves these gains by selecting the next relay node adaptively and effectively suppressing redundant transmission of safety messages. Compared to existing work, the presented protocol offers performance improvements in terms of coverage and delay. It offers a 21% improvement in delay compared to the farthest distance-based protocol.

Index Terms – VANET, Ad Hoc Network, Broadcast, Multi-Hop, ITS, Network Protocol.

1. INTRODUCTION

As per the survey [1], the total vehicle population is increasing day by day and will reach 2 billion by 2035. Usage of automobiles at this scale results in high traffic, low efficiency, and road fatalities. Intelligent transportation system (ITS) is an advanced field that aims to reduce road fatalities and offer other services by implementing the Internet of Vehicles (IoV) [2]. In the IoV, every vehicle establishes communication links with other surrounding vehicles and shares crucial information such as position, speed, and sensor outputs to develop cooperative driving that is more efficient and safer. Wireless access in vehicular environments (WAVE) is the technology developed to establish vehicular communication. It is composed of IEEE 802.11p standards that define physical and medium access layers. It is known as dedicated short-range communication (DSRC). Upper layers of WAVE are defined in IEEE 1609.x standards [3], [4].

The practical range of vehicular communication established through WAVE technology is no more than 300 meters in dense traffic scenarios. Within this distance, only a limited number of vehicles will get the alerts, and the driver's reaction time is less in emergencies [5], [6]. The multi-hop alert broadcast is often used to get rid of this problem and spread alerts over a longer distance.

In a multi-hop scenario, the blind broadcasting of alert messages causes an exponential increase in alert re-broadcast. The network gets flooded with excessive redundant alerts, and the performance of the application deteriorates. To eliminate this situation, a restricted broadcast is used in which a limited number of relay vehicles are selected at every hop to convey the message further [7]. The performance of alert dissemination depends on the optimal selection of relay vehicles. A high number of relay nodes does not solve the problem of redundancy, while a low relay count increases failure chances because of failed links or the unavailability of vehicles. The high mobility, shorter communication range, and rapidly changing topologies result in frequent disconnection and varying channel conditions [8]. Broadcast storms occur when broadcasting on high-density networks. Because of the above-cited special characteristics and limitations, reliable and fast alert dissemination is challenging and still an open challenge for researchers [9].

The main objective of the proposed research work is to improve reliability and the rapid delivery of alert messages for vehicular safety applications. In this paper, we propose a multi-hop dissemination protocol called Efficient and Reliable Adaptive Dissemination Protocol (ERAD). ERAD is a smart dissemination protocol that adapts the delay characteristics to actual network conditions. ERAD attempts to improve the delay characteristics and reliability of alert message propagation without increasing overhead. It eliminates the broadcast storm problems by reducing redundant transmission through effective broadcast suppression mechanisms.

Extensive simulations are presented to evaluate the performance of ERAD with different road topologies, vehicle densities, and speeds. Findings are compared with existing protocols. Results demonstrate that ERAD offers high coverage, low delay, and sufficient robustness in extreme network conditions.

The remainder of this paper is organized as follows: In Section 2, we briefly discussed the types of data broadcast methods and past literature related to this work. In Section 3, proposed protocol design and broadcast strategy are described. Section 4 presents the simulation setup and performance analysis. The conclusion and future research direction are presented in Section 5.

2. BACKGROUND AND LITERATURE REVIEW

Due to high-speed vehicles, the topology changes rapidly, and the wireless link is unstable because of interference and short range. In such cases, traditional routing methodologies are not suitable for message routing [10]. Added to this, alert messages are important for all the vehicles in the affected area. Hence, broadcasting based schemes are employed in vehicular communication for alert message dissemination [11].

2.1. Types of Broadcasting Strategies

2.1.1. Single-Hop Broadcast

In this type, the message is only conveyed to immediate neighbor vehicles. The receiving vehicle extracts the conveyed information and acts accordingly. These schemes are used in many cooperative driving safety applications. For example: heading/trailing collision warning, lane change warning, braking warning, etc. [12].

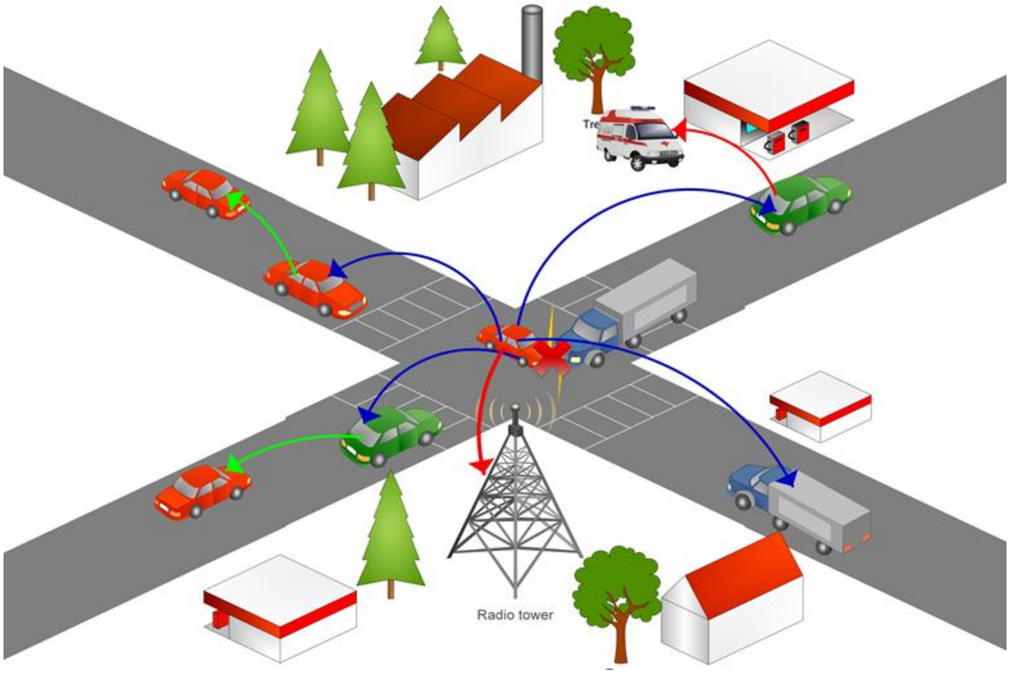

Figure 1 VANET Architecture

2.1.2. Multi-Hop Broadcast

It is observed that a single-hop message covers only a few vehicles, and the driver of the receiving vehicle has little time to react on alert. For transmitting alerts beyond the transmission range of sending vehicles, multi-hop message broadcast strategies are used. Re-broadcasting of an alert message from every vehicle results in network flooding and a broadcast storm problem. To eliminate excessive redundancy, selective rebroadcasting strategies are practiced in multi-hop alert dissemination [13]. Figure 1 represents the VANET architecture in a pure vehicle-to-vehicle (V2V) scenario. It represents the case of single-hop and multi-hop message exchanges. The message lifetime is decided by the area of interest or the number of hops, depending on the application requirements [14].

2.2. Related Work

Due to the needs of the application and the limited range of vehicle communication, emergency alert messages must be sent through the network using a multi-hop broadcasting method. Plain broadcasting (flooding) causes excessive redundancy and bandwidth waste. It creates broadcast storm problems in dense vehicular traffic [15], [16], and [17].

Multi-hop rebroadcasting of the alert by the limited number of forwarders reduces broadcast storm and has the potential to scale well for diversified vehicular traffic [18].

An inter-vehicle separation-based rebroadcasting node selection scheme is widely studied in the literature. This section provides a brief review of state-of-art distant-dependent broadcast protocols. A comparative assessment of the reviewed protocol is provided in Table 1.

Kim et al. [19] present a range-based relay selection protocol called RBRS. RBRS is a native distance-based broadcast, in which broadcast delay is inversely proportional to inter-vehicle distance. It favors boundary nodes for rebroadcasting the message, while other inner circle nodes defer their scheduled transmission on overhearing the message. The slotted p-persistence scheme presented in [20] is a distance-based protocol that assigns a higher probability to nodes located toward the boundary. The probability-based relay selection method reduces the chances of failure by using multiple relays in the network. When there are multiple nodes having higher probability exist, concurrent transmission occurs.

Viriyasitavat et al. [21] discuss urban vehicular broadcast (UV-CAST) protocol. The protocol is suitable for dense and sparse networks. For message delivery in sparse connectivity, boundary vehicles use the store-carry-forward (SCF) mechanism. But it comes at the cost of increased delay and overhead.

Cross-Layer Broadcast Protocol (CLBP) is presented in [22], which is a multi-criteria-based forwarding scheme. To avoid frame collisions, it incorporates request-to-send (RTS) and clear-to-send (CTS) mechanisms. The extra overhead and delay caused by RTS and CTS frames do not quantify CLBP in fast alert dissemination applications.

The Real-time adaptive dissemination protocol (RTAD) is presented in [23], which counts the number of received messages to estimate coverage and reliability of alert dissemination. It only forwards the message if any additional coverage is provided by it.

In [24], SEAD: A simple and efficient adaptive data dissemination protocol is presented. To select relay vehicles, it employs a hybrid delay and probability-based strategy. To forward received alert messages, all vehicles are given a distance-dependent delay. On expiration of the delay timer, every vehicle again calculates its broadcast probability, which is dependent on the surrounding density and direction of propagation. Added randomness through probabilistic forwarding makes the protocol superior to a simple delay-based protocol. But a similar surrounding density causes the local synchronization problem. More vehicles are present in a single slot with the same local density, resulting in concurrent transmission and packet collision problems.

In [25], a bi-directional stable communication (BDSC)-based relay node selection method is proposed. Here, the protocol first verifies the bidirectional link stability between neighbor nodes. A stability rank is assigned to every link, and the best link is used to relay the message in the network. In this work, the author presented that every vehicle has a different transmission range, and a single range value raises stability issues for alert dissemination.

Oliveira et al. [26] present an adaptive data dissemination protocol (AddP). It selects the optimum relay node by utilizing local density and distance for alert message dissemination. The concept of message aggregation is presented to reduce channel load by decreasing the number of messages.

In Zhang et al. [27], an adaptive link quality-based safety message (ALQSM) forwarding scheme is proposed. The probability of physical connectivity is calculated first. Based on the probabilities, different scores and priorities are assigned to all single-hop candidates.

An efficient data dissemination protocol (EDDP) is presented in [28], which detects vehicle speed to indirectly estimate traffic condition and adaptively increases the delay time as per high or low traffic conditions.

Table 1 Alert Broadcast Approaches

Protocol	Scheme	Objective	Scenario	Limitation	Simulator
RBRS	Delay-based	Broadcast-storm	Highway	High delay	NS-2
S1PD	Delay-based	Broadcast-storm	Highway	High delay	OPNET
UV-CAST	Delay-based	Disconnected n/w	Grid	High delay and overhead	NS-2
CLBP	RTS-CTS	Reliability	1-way road	Require handshake	NS-2
RTAD	Counter	Broadcast-storm	Urban	High delay	NS-2

SEAD	Hybrid	Redundancy	Highway	Not scalable to Urban	NS-3
BDSC	Stable connection	Reliability	Highway	High overhead	NS-2
AddP	Density based	Broadcast-storm	Urban + Highway	Need of 2-hop information	OMNET++
ALQSM	Stable link	Reliability	Highway + Grid	non-adaptive operation	OMNET++
EDDP	Traffic adaptive	Broadcast-storm	Urban	Less reliable due to beacon-less	OMNET++

2.3. Discussion and Research Gap

As presented in Section 2.2, a lot of work has employed the distance-based forwarding node methods. In a limited test environment with moderate vehicle density, it provides acceptable performance with less delay and lower computational requirements. But when extreme network conditions exist, such as high-speed variations, poor channel conditions, and high vehicle density, failure and delay increase excessively [29].

We observe that a lot of work employs greedy forwarding by electing the farthest node as the next forwarder. All the nodes located at the boundary of the communication range will have a lower signal-to-noise ratio (SNR) [30]. For links with low SNR, multipath fading and the shadow effect make connectivity unstable. Greedy forwarding-based protocols have acceptable performance in limited traffic conditions and communication scenarios. Such a protocol does not scale well for realistic traffic conditions with varying node densities.

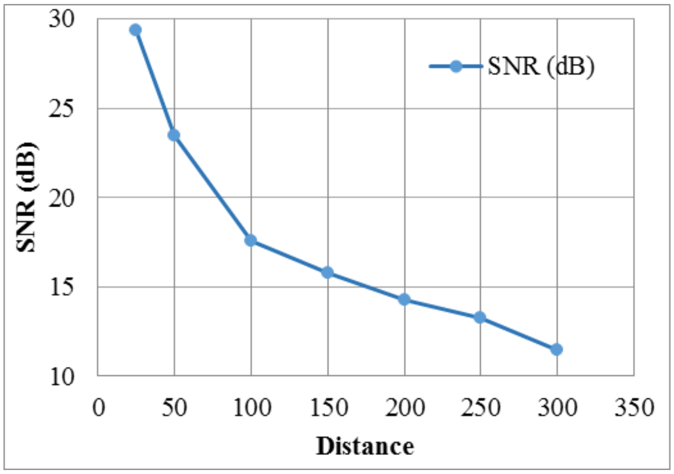

Figure 2 SNR Degradation vs. Distance

As discussed earlier, the effective range of vehicular communication is around 300 m. Simulation-based findings suggest the SNR degrades as inter-vehicle separation increases, as shown in Figure 2. The packet delivery ratio (PDR) in a vehicular network will depend on the minimum received power (Pr), background noise, and efficient broadcast scheduling that reduces concurrent packet transmission [31]. Figure 3 shows PDR vs. inter-vehicle distance statistics for a communication range of 300 m, a data rate of 6 Mbps, and a packet size of 200 bytes.

The proposed work overcomes a few limitations examined in the reviewed work. It primarily focuses on reducing message dissemination failures and improving delay performance through the adaptive selection of next forwarding nodes. The adaptive relay node selection process prioritizes reliable relay nodes against the farthest-distance nodes to increase reliability. The next section describes the proposed modifications that exhibit good performance under lossy wireless communication.

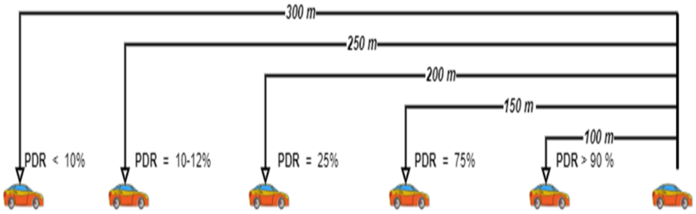

Figure 3 PDR Vs Distance

3. ERAD: EFFICIENT AND RELIABLE ADAPTIVE DISSEMINATION PROTOCOL

This section presents a scalable and robust multi-hop dissemination protocol called ERAD—an efficient and reliable adaptive dissemination protocol. ERAD is designed by keeping in mind the high mobility of vehicles, the large variation in vehicle density, and the unreliable channel characteristics present in vehicular communication. The protocol is used to disseminate the alert message over longer distances during emergencies.

Delay performance and coverage of any multi-hop dissemination protocol are governed by the rate of failure of relaying, channel availability, and rate of redundancy in the network. ERAD uses instantaneous SNR and inter-vehicle separation to select the next forwarding node for the alert dissemination process. For a proper illustration of ERAD functioning, Section 3.1 presents the considered assumptions, Section 3.2 represents message formats, and the protocol flow, algorithm, and detailed operation of the protocol are explained in Section 3.3.

3.1. Assumptions

We assume all vehicles are equipped with 802.11p-based communication capabilities, GPS for position detection, and sufficient sensors to detect emergency events. We also assume that the vehicle provides a user interface to the driver for alert intimation. The presented work considers the periodic exchange of beacon messages to convey crucial information such as vehicle ID, position, and speed to immediate neighbors.

3.2. Message formats

Beacon and alert messages are the two types of messages used in protocol work. (i) Beacon messages are periodic messages exchanged between vehicles to share the most recent vehicle states. It includes information such as vehicle ID, message ID, and location information. When a vehicle detects an emergency, it generates and transmits alert messages to notify other vehicles in the area of the emergency. Alert messages follow multi-hop communication over a larger distance beyond the scope of single-hop transmission.

Table 2(a) Alert Message Format

Field	Description
S_{id}	Originator ID
F_{id}	Forwarder ID
M_{id}	Message ID
$S_{x,y}$	Originator location
$F_{x,y}$	Forwarder location
H	Hops

Table 2(b) Beacon Message Format

Field	Description
V_{id}	Vehicle ID
M_{id}	Message ID
$V_{x,y}$	Senders location

Table-2(a-b) shows the detailed parameters of beacon and alert messages.

3.3. Message Dissemination Process

ERAD is a multi-hop message dissemination protocol that provides fast and reliable alert message dissemination. ERAD employs an adaptive relay node selection scheme based on SNR and distance to implement efficient redundancy suppression and reliable alert dissemination. Instantaneous SNR values at every receiving vehicle represent current channel conditions and the surrounding environment. Using the SNR value in the determination of delay time along with distance slightly reduces the one hop distance but increases reliability by reducing failures in communication because of bad channel conditions. The delay time is the amount of time that each forwarder will wait before forwarding the alert. Efficient selection of delay time reduces overall message propagation delay, and SNR-based selection criteria reduce failure in packet reception because of poor SINR, propagation conditions, and random shadow and fading effects. The protocol uses the slotted contention window-based relay section method. The total number of slots is computed by using the maximum transmission range and the minimum vehicle separation.

```
Require: Beacon exchange and maintain neighbor table $T_{kb}$
while Alert message received do
  if Message is new then
      Calculate $SNR_i$
    if $SNR_i >= SNR_{th}$ then
      Calculate $d_i$ and Get $cw$
      Calculate $Delay$ and Initialize $Timer$
        if Timer expired then
            Broadcast the alert
        else if Received again then
            defer scheduled broadcast
        end if
    else if $SNR_i < SNR_{th}$ then
            Do not contend for broadcast
    end if
  else if Message is repeated then
            Do not broadcast
  end if
```

Algorithm 1 Alert Message Broadcast

Algorithm 1 describes the mechanism of alert message broadcast and redundancy suppression.

Figure 5 illustrates the steps involved in the functioning of the protocol. The first receiving node verifies if the message is new by message-id. For every new message, the receiving node implements SNR-based quality checking and contends for broadcast candidates depending on its position. The repeated message indicates that another node with a shorter delay has already broadcast the message; hence, the node drops the idea of broadcasting it. Every node calculates the size of the contention window (CW) for broadcast scheduling using Equation 1.

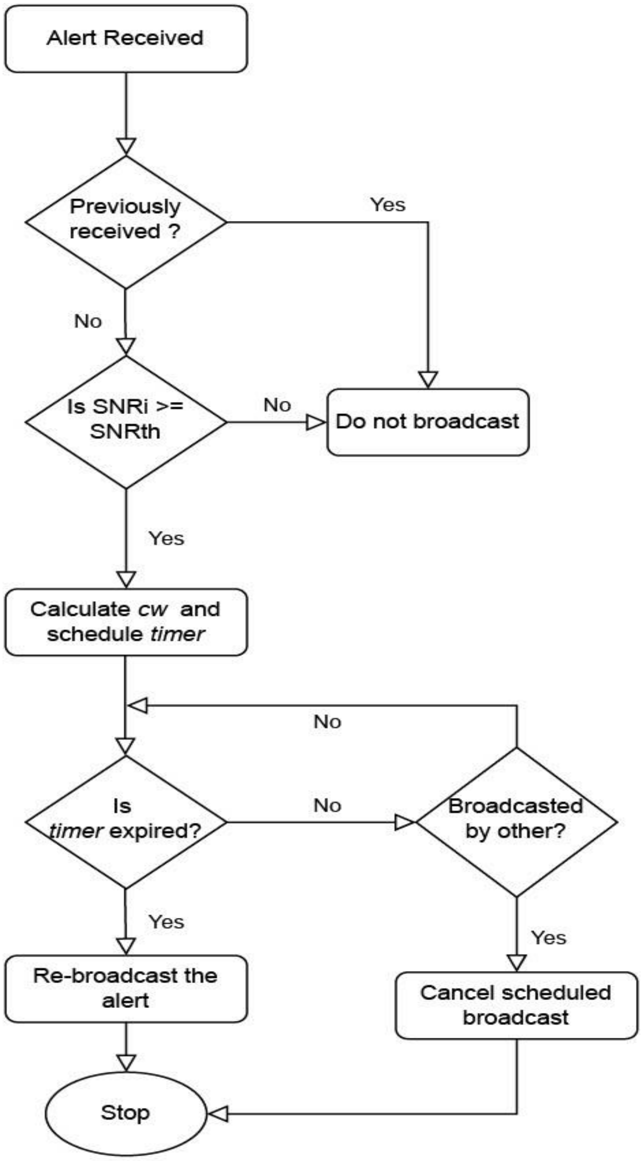

Figure 5 Re-Broadcast Procedures at Every Node

$$cw = \alpha\left(\frac{Dmax}{k}\right) \qquad (1)$$

Here, D_{max} is the maximum transmission range of the node, and k is the vehicle length plus the minimum distance between two vehicles. The multiplying factor α is added to accommodate node density-based adaptation in contention-window size. Adaptive variation in CW provides less delay at moderate vehicle densities and reduces the probability of concurrent transmission by employing a larger CW at high vehicle densities. Signal-to-noise (SNR)-based screening and maximum CW are calculated as per Equation 2.

$$cwm = cw.\beta^{\left(\frac{\mathrm{SNR_i - SNR_{th}}}{\mathrm{w}}\right)} \qquad (2)$$

Once the maximum size of the contention window is found, vehicles based on their respective positions calculate their slot as shown in Equation 3.

$$Si = \left(1 - \frac{di}{Dmax}\right) * cwm \qquad (3)$$

4. EVALUATION

Extensive simulations are conducted for the proposed work. Network Simulator 3 (NS3) is used for network simulation, while Simulation of Urban Mobility (SUMO) is used to generate mobility traces on a real road network [32], [33]. NS3 and SUMO are both open-source software widely used in research and academia. Vehicle mobility traces with realistic road topology, vehicle density, and speed are generated by the use of SUMO. This NS3-compatible vehicular trace file is called in NS3 to add WAVE-based wireless communication capabilities. Network functionalities and applications are installed on all moving traces of vehicles and communication statistics are recorded.

Different mobility patterns and vehicle densities are considered when evaluating ERAD performance. For comparison, two existing protocols, flooding and slotted 1-persistent broadcast, are recreated in the same environment. In the flooding strategy, every vehicle, irrespective of its location and requirements, broadcasts all received packets for the first time. S1PD is a representative delay-based protocol used for reference. In S1PD, every potential relay candidate elects one slot depending on its separation from the sender. Slots are converted to delay, prioritizing the farthest vehicle to rebroadcast the received packet.

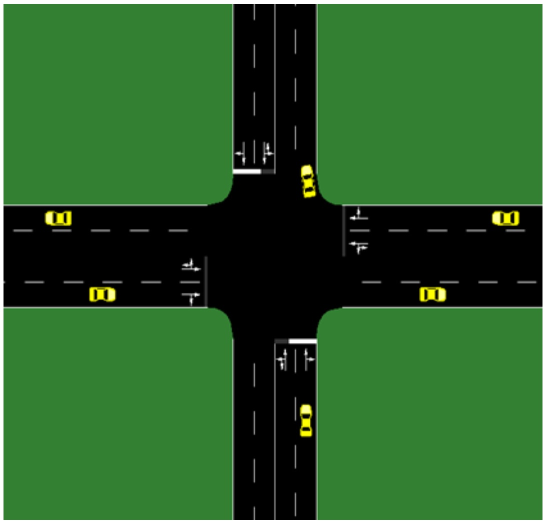

Figure 6 Vehicular Movements

4.1. Test-Bed Scenario

2 × 2 km 4-lane grid road network imported from OpenStreetMap into SUMO. SUMO generates road networks and vehicles' mobility over them. The figure 6 shows the imported road network and its corresponding vehicle traffic. Physical and MAC layer parameters are configured in NS3 to implement wireless connectivity among vehicles. The default transmission range is ~ 300 m; and the data rate for beacon and alert messages is 6 Mbps. Vehicle densities are varied from 200 to 600, and speeds are varied from 50 to 100 km/h. A list of all simulation parameters is provided in Table 3.

Figure 7 shows the pictorial representation of the safety application scenario. A crash site is in the middle of the highway. To avoid randomness because of vehicle insertion and exit, measurement statistics were calculated over an area of interest (AoI) of 1 km around the center point.

Table 3 Simulation Parameters

Parameters	**Value**
Area	2 ×2 km
Simulation time	100 sec
Vehicle density	200 – 600
Vehicle Speed	50-70-100 km/h
Tx Range	300 m
Packet size	200 bytes
Data rate	6 Mbps
MAC & Physical layer	802.11p
Propagation	2-ray ground

4.2. Performance Metrics

Three key performance metrics—coverage, delay, and hop count—are measured to evaluate the overall performance of the ERAD protocol.

4.2.1. Coverage

It represents the overall reachability of the alert message within the considered network. Reliability and dependability of safety message dissemination are ensured by high coverage. The coverage percentage is calculated by dividing the percentage of Alert receiving vehicles by the total number of vehicles.

$$Coverage\ (\%) = \frac{Number\ of\ vehicles\ who\ received\ alert}{Total\ number\ of\ vehicles}$$

4.2.2. Delay

It represents the average time an alert message takes to reach all vehicles located within the boundaries of the area of interest. Safety message broadcasting is a time-sensitive task, and a large delay reduces the applicability of the protocol for the envisioned application. Measuring the average time, an alert message takes to reach a boundary gives the delay metric.

$$Delay\ (mean) = \frac{1}{N_{recev}} \sum_{v=1}^{N_{recev}} \text{Recev\_time} - \text{Genr\_time}$$

4.2.3. Hop-Count

It is the measurement of the average number of rebroadcasts a message requires to reach the boundary of measurement. Every time a message is rebroadcast, a hop count variable is incremented to reveal the per-message hop count.

$$Hop_{count} = \frac{1}{N_{recev}} \sum_{v=1}^{N_{recev}} \text{Required\_broadcast}$$

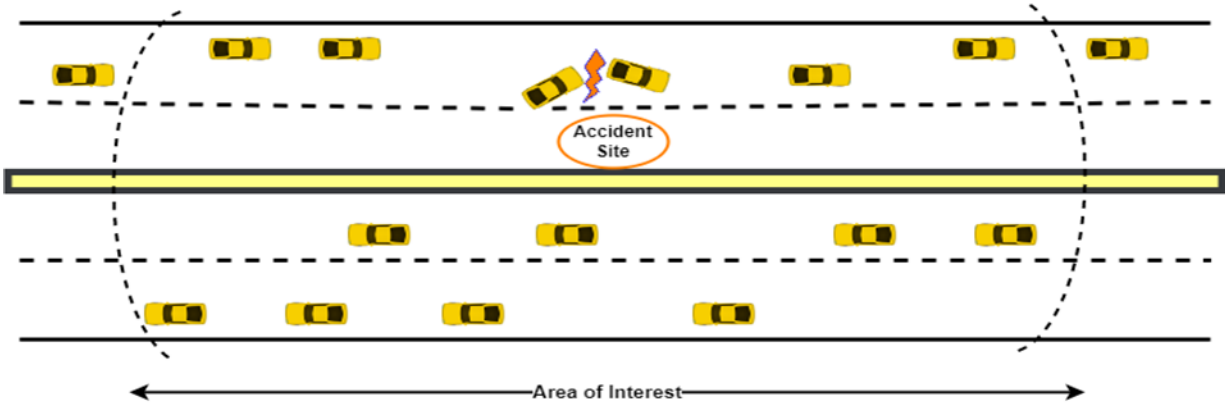

Figure 7 Application Scenario

4.3. Results

This section provides a comparative analysis of the proposed work. The results are compared with native flooding and S1PD protocols. Figure 8 shows the net coverage of alert messages in the considered network. It represents coverage statistics with different node densities in the network. It shows that the ERAD protocol provides higher coverage compared to S1PD. In the flooding protocol, every node will retransmit the alert, so coverage is higher in flooding but at the cost of excessive broadcasting of alert messages. ERAD provides comparable coverage with reduced traffic. Figure 9 shows coverage against vehicle speeds. In comparison to S1PD and flooding, ERAD is clearly more stable at varying vehicle speeds.

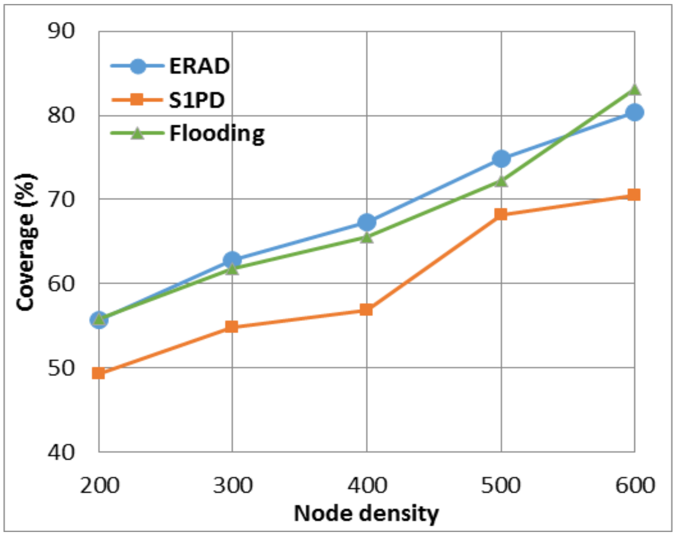

Figure 8 Coverage Vs Node Density

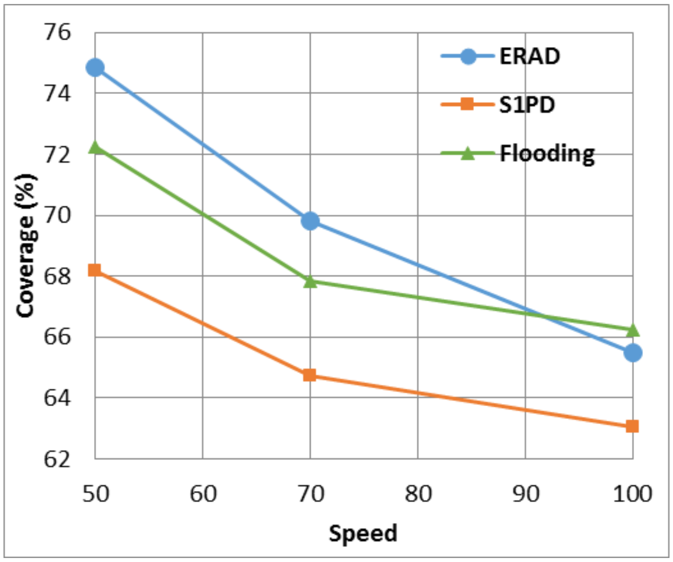

Figure 9 Coverage Vs Speed

Figure 10 shows the average delay versus node density plot. Safety alert message transmission is a time-sensitive task. So a good protocol must provide a minimal delay in broadcasting the message on the network. It is evident that, due to the adaptiveness employed in broadcast delay, ERAD offers the best delay performance compared to the S1PD protocol. At a node density of 400, there is a 21% delay improvement compared to S1PD.

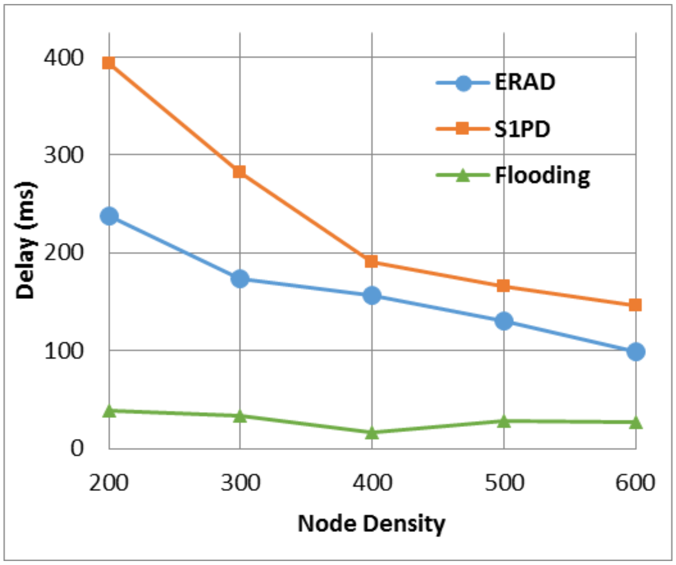

Figure 10 Delay Vs Node Density

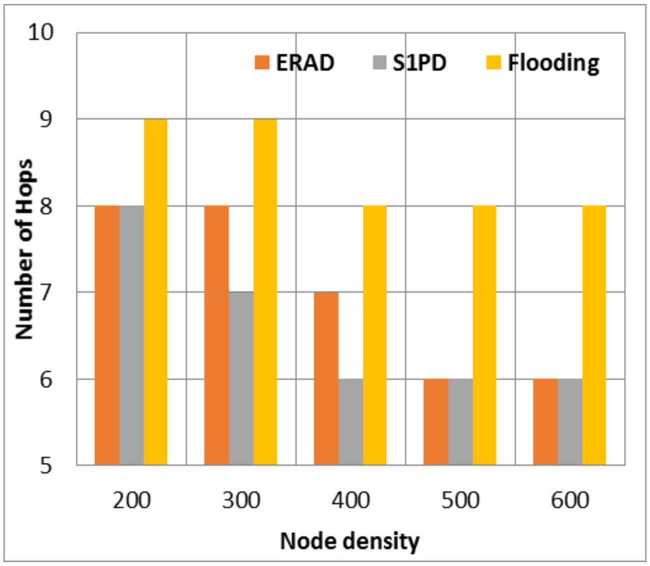

Figure 11 Hops Vs Node Density

Figure 11 shows the plot of hops versus node density. It represents the average number of hops an alert message will require to reach the measurement point. S1PD is the farthest distance protocol and requires less number of hops compare to ERAD. But as node density increases, ERAD performs comparably to S1PD. In a flooding-based broadcast, an alert message will need a high number of hops to reach its destination.

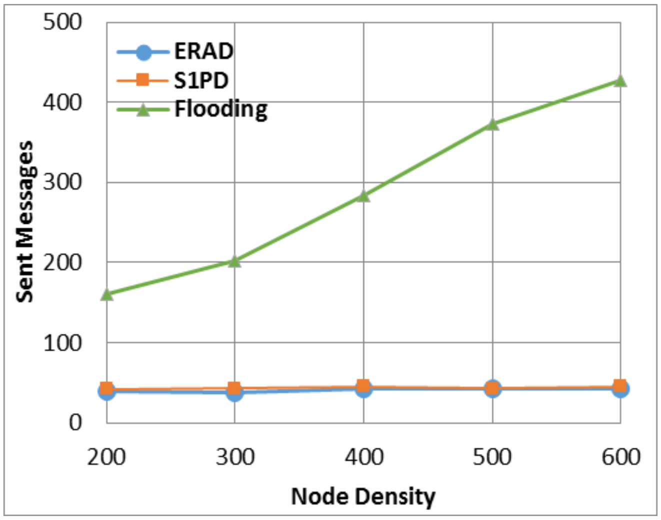

Figure 12 Sent Messages Vs Node Density

Figure 12 depicts the total number of alert messages sent. In the event of flooding, all receiving nodes, regardless of requirements, broadcast the alerts. So, the exponential rise in sent messages is visible in the chart. This will result in broadcast storm problems and failures in the network due to excessive packet collisions. ERAD and S1PD are consuming less bandwidth by sending very few alert messages for acceptable network coverage.

The findings confirm that the proposed work provides improvements in delay performance because of an adaptive and reliable next broadcast node selection process. The attempts to delay improvements do not adversely affect the coverage and redundancy of the networks.

5. CONCLUSION

Multi-hop broadcasting by its nature results in congestion in networks and performance degradation starts with increased vehicle densities. High-speed vehicles, topological variations, and short communication ranges are challenges that affect the performance of safety message broadcasts in vehicular networks. ERAD uses a stable and efficient next relay node selection method that increases the reliability of message broadcast, and improves delay performance. Simulation results confirm that ERAD offers higher coverage and a lower delay compared to the S1PD protocol. By efficiently suppressing redundant broadcasts, ERAD eliminates the issue of broadcast storm problems. ERAD is more stable and reliable and provides rapid alert dissemination in the network. These features make it a suitable candidate for implementing various applications of the Internet of Vehicles (IoV). In future work, message priority-based queuing can be added to widen the application scope to include non-safety applications as well.

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