An Infrastructure-less Framework for Preventing Rear-End Collisions by Vehicular Sensor Networks

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***Abstract*—We consider *vehicular sensor networks (VSNs)* consisting of a large number of sensor nodes deployed on vehicles to facilitate vehicular applications. We try to apply such VSNs to preventing rear-end collisions that are common accidents due to sharp stops. An infrastructure-less framework is proposed, which only relies on vehicles' onboard sensors to prevent such accidents. The proposed framework consists of a distributed warning protocol and a location-based backoff scheme. Vehicle-to-vehicle communications is used to form *warning groups*, where a warning group is a set of vehicles that drive along the same lane and every pair of adjacent cars is within a certain distance. Only single-hop transmissions are needed to join and leave a group, thus keeping the group maintenance overhead low. When a sudden brake event is detected in a warning group, the location-based backoff scheme can quickly propagate warning messages among its group members. Simulation results show that the proposed approach outperforms existing schemes.**

Keywords: Collision Prevention, IEEE 802.11p, Traffic Safety, Vehicular Sensor Network.

I. INTRODUCTION

Recent advances in vehicular communication technologies and embedding sensing MEMS make *vehicular sensor networks (VSNs)* possible. Such systems have the advantages of both *vehicular ad hoc networks (VANETs)* and *wireless sensor networks (WSNs)*. This leads to many applications, such as traffic safety [1] and vehicle security [5]. VSNs consist of many sensor nodes deployed on roads or vehicles, which cooperate through *vehicle-to-vehicle (V2V)*, *vehicle-to-roadside (V2R)*, and *vehicle-to-infrastructure (V2I)* communications.

This work focuses on preventing rear-end collisions among vehicles by V2V communications. References [4], [7] rely on roadside infrastructures to achieve this goal, but this is sometimes not feasible in suburban and rural areas. Brake-warning based on vehicular networks has been studied in [1], [2], [11]. Reference [1] deals with frontal collisions due to improper overtaking. Reference [11] presents an intelligent V2V broadcast with implicit acknowledgment for highway safety. In comparison, our design consists of a distributed warning protocol and a location-based backoff scheme to further reduce the number of warning messages. Reference [2] also uses V2V communications to avoid rear-end collisions on highways. However, the scheme relies on obtaining lane IDs through infrastructure roadside units. In addition, too many vehicles may be warned unnecessarily, causing high message overheads. Contrarily, our infrastructure-less framework avoids chained vehicle collision due to emergency brake with efficient and quick message exchange.

II. PROBLEM DEFINITION

We consider vehicles on the roads that form VSNs via V2V communications. Each vehicle is equipped with a GPS receiver and a distance sensor (such as a magnetic sensor [1] or a laser range finder [9]) in its front end. GPS can provide a vehicle's absolute position and velocity. The distance sensor is directional and can detect the distance of a vehicle to the one in its front. This also implies the possibility of estimating the velocity of the vehicle in its front. We assume that IEEE 802.11p [3] is used with the WAVE (Wireless Access in Vehicular Environments) mode to support V2V communications. Periodical beacons containing vehicles' IDs and positions are transmitted by each vehicle to their neighbors. Note that although the distance between two vehicles can be estimated by GPS outputs, message exchange between these two vehicles is needed. In our model, employing distance sensors can obtain the same result and is communication-free.

The *rear-end collision avoidance problem* is defined as follow. Each radio interface has a fixed transmission range R. Each vehicle i has to keep a safety distance of d_i^s from the vehicle in front of it. According to the "two-second" rule [6], we set $d_i^s = s_i \times \delta$, where s_i is the current speed of i and $\delta = 0.55$. We will form dynamic *warning groups* for vehicles on the road, where a warning group is a sequence of vehicles in the same lane such that each vehicle does not keep a safety distance from the vehicle in its front except the first one.

Our goal is to design an efficient protocol for vehicles to join/leave their warning groups. In addition, when any vehicle i of a group takes an emergency brake, a warning message should be sent immediately to those vehicles behind i in the same group. Such warning messages have the highest priority and may be delivered through multi-hop forwarding. Therefore, drivers can become aware of such events even before they actually see the braking signals.

III. THE PROPOSED FRAMEWORK

We propose an infrastructure-less framework. A distributed warning protocol is proposed in Section III-A. To quickly propagate emergent braking events, a location-based backoff scheme is presented in Section III-B.

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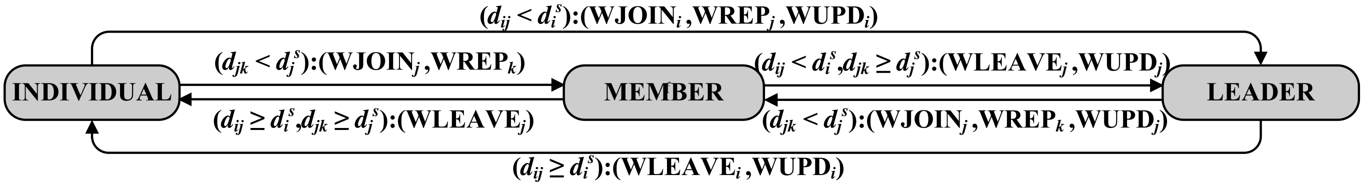


Fig. 1: State transition diagram of vehicle j, where j is immediately in front of vehicle i and behind vehicle k.

A. Distributed Warning Protocol

Our scheme consists of a mutual-warning mechanism and a self-warning mechanism. We first discuss the mutual-warning part. Assume that vehicle i is immediately behind vehicle j in the same lane. Let d_{ij} be the distance between i and j. Recall the safety distance d_i^s. If $d_{ij} \geq d_i^s$, no action is needed; otherwise, we will put i and j into one warning group. When i detects this situation, it will broadcast a WJOIN message with its current location and ID. Based on i's position, j can determine that it is immediately in front of i. Then j will reply a WREP message with the ID of its group leader and add i into its 1-hop warning list. If there is no vehicle in front of j or j has kept in safety distance from the vehicle in front of it, j will form a new group and serve as the group leader; otherwise, the group leader is the first vehicle in the chain of vehicles not keeping in safety distances with each other. On the other hand, if later on the safety condition $d_{ij} \geq d_i^s$ holds, i will send a WLEAVE message to j to leave j's group. In response, j will remove i from its 1-hop warning list. Note that WJOIN, WREP, and WLEAVE are local (1-hop) broadcasts, so the control overhead should be quite low.

Let i immediately follow j and j immediately follow k in the same lane. We summarize the states of j as follows:

- $INDIVIDUAL$: i keeps in safety distance from j and so does j from k.
- $LEADER$: j keeps in safety distance from k, but i does not keep in safety distance from j.
- $MEMBER$: j does not keep in safety distance from k.

Whenever j transits to the LEADER state, it broadcasts a WUPD message to its group members. Whenever j is in the LEADER/MEMBER state and performs an emergency brake, it immediately broadcasts a WARN message to the group members behind it. A vehicle only accepts a WUPD/WARN message from a vehicle in front of it in the same warning group. Both WUPD and WARN need to be rebroadcast (see Section III-B). Fig. 1 shows the state transition diagram of j, where the label on each transition edge is formatted as (event):(action). For instance, $(d_{jk} < d_j^s)$:(WJOIN$_j$, WREP$_k$) represents that as $d_{jk} < d_j^s$ is detected, j broadcasts a WJOIN message and then k replies a WREP message. Note that due to GPS errors, some neighboring vehicles in different lanes may incorrectly reply WREP messages to a WJOIN message. A vehicle may thus belong to multiple warning groups at the same time, and a warning group may include vehicles in neighboring lanes. However, this only causes our system to warn extra vehicles, but would not cause problems.

Next, we discuss the self-warning mechanism when i is too close to j, which is in front of i. We define a driver's *Needed Maneuvering Time (NMT)* to be the sum of needed reaction time η (from seeing a braking signal to taking an emergency brake) and emergency braking time. This value must be less than the *Available Maneuvering Time (AMT)*. Suppose that j takes an emergency brake at the maximum braking acceleration a_j. Then, after time interval Δt, j will move a distance of $B_j(\Delta t) = s_j \times \Delta t + \frac{1}{2} \times a_j \times \Delta t^2$, where s_j is the current speed of j. Also, $B_j(\frac{s_j}{a_j})$ is the total moving distance before j fully stops. To ensure a sufficient AMT when j takes an emergency brake, d_{ij} must satisfy the following condition for any time interval Δt before i fully stops:

$$B_j(\Delta t)+d_{ij} > \begin{cases} s_i \times \Delta t & , \ 0 < \Delta t \leq \eta \\ s_i \times \eta + B_i(\Delta t - \eta) & , \ \eta < \Delta t \leq \eta + \frac{s_i}{a_i} \end{cases} .$$

According to [8], η is about 1.5 second in average, which is a major part of NMT. The upper part in the above inequality is the distance before i starts to brake, while the lower is that after i starts to brake. If the condition is violated for any Δt, the onboard unit of i will warn its driver to keep a longer distance from j.

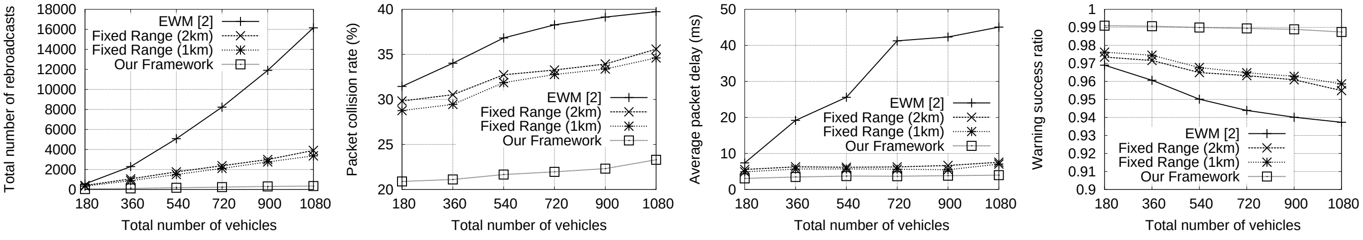
B. Location-based Backoff Scheme

To reduce the number of WUPD and WARN messages, we design a location-based backoff scheme. It facilitates farther receivers from the sender to rebroadcast at earlier time. Each WARN message contains the sender's position, group leader ID, and a sequence number. When vehicle j receives a WARN message, j first checks whether the message is sent from j's warning group (according to the group leader ID) and the sender is in front of j. If so, j will calculate the distance d_j^w between itself and the sender. A larger value of d_j^w will give a smaller backoff timer BT_j, as defined below:

$$BT_j = \begin{cases} [0, 2^{\tau+1}-1] & \frac{\rho-1}{\rho}R < d_j^w \leq R \\ [2^{\tau+1}, 2^{\tau+2}-1] & \frac{\rho-2}{\rho}R < d_j^w \leq \frac{\rho-1}{\rho}R \\ \vdots & \\ [2^{\tau+\rho-1}, 2^{\tau+\rho}-1] & 0 < d_j^w \leq \frac{1}{\rho}R \end{cases} ,$$

where $\rho = \lceil \frac{R}{d_j^s} \rceil$, R is the transmission range, and τ is a small integer. Thus, this gives farther receivers higher priorities to rebroadcast.

On the other hand, an implicit inhibition strategy is adopted to eliminate redundant WARNs. Specifically, the reception of a WARN from a vehicle in the back of j in the same group serves as an implicit message to prevent j from competing again. On receiving such a rebroadcast, j will remove the message in its waiting queue. Furthermore, to improve reliability,



(a) (b) (c) (d)

Fig. 2: Comparisons of (a) total number of rebroadcasts, (b) packet collision rate, (c) average packet delay, and (d) warning success ratio.

a vehicle which already sent the WARN message will try to overhear any rebroadcasting from any vehicle behind it. If it can not overhear any such rebroadcasting, it will rebroadcast again with a new sequence number. We recommend that such rebroadcasting be executed at most once. Note that WUPD messages are rebroadcast similarly.

IV. PERFORMANCE EVALUATION

We simulate the proposed framework by QualNet 4.5 [10] with some modifications. The two-ray ground radio model and IEEE 802.11p MAC protocol are adopted. A 10-km six-lane highway (three lanes per direction) with 180, 360, 540, 720, 900, and 1080 vehicles is simulated. 20% of vehicles are randomly chosen to take emergency brakes. The broadcast power is set to 32 mW. The normal speed and emergency deceleration speed are set to 25 m/s and 8 m/s^2, respectively. We set $R = 300$ m, $\eta = 1.5$ s, and $\tau = 1$. We compare our scheme against a simple Fixed Warning Range (FWR) method that warns vehicles in 1 km or 2 km behind the vehicle taking an emergency brake and the Emergency Warning Message (EWM) method [2] that warns vehicles in the same lane behind the vehicle taking an emergency brake. The main performance indices are the total number of rebroadcasts, packet collision rate, average packet delay, and warning success ratio. Each simulation is repeated 100 times and then we take the average value.

Fig. 2(a) illustrates the total numbers of rebroadcasts under different numbers of vehicles. We can observe that our scheme has the lowest number of rebroadcasts. More importantly, while the number of rebroadcasts of EWM increases exponentially as the number of vehicles increases, that of ours only increases linearly. This is because our scheme only warns the vehicles without following safety distances so that its total number of rebroadcasts is proportional to the warning group size instead of the total number of vehicles. On the contrary, EWM will warn too many unnecessary vehicles in the same lane about emergency brake so that its total number of rebroadcasts dramatically increases with the total number of vehicles. Note that with less than 180 vehicles, the network connectivity becomes very low and all schemes perform about the same.

Fig. 2(b) and Fig. 2(c) show the packet collision rates and average packet delays under different numbers of vehicles, respectively. It can be observed that our scheme still outperforms FWR and EWM. The reason is similar to what is discussed earlier. In addition, our location-based backoff scheme can further reduce these indices because we prioritize WARN messages.

Fig. 2(d) shows that the above advantages will lead to the highest warning success ratio for our scheme. In particular, our location-based backoff scheme significantly improves the warning success ratio because re-broadcasters are assigned with different contention windows based on their locations and our overhearing mechanism does help increase the reliability of warning messages.

From these results, we conclude that the proposed approach can achieve the best performance, leading to more efficient use of wireless bandwidth. On the other word, adopting our scheme in vehicular networks can both avoid transmissions of emergency messages wasting bandwidth due to unnecessary rebroadcasts and prevent emergency messages from transmission collisions caused by serious packet contention.

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