V2V Wireless Communication Protocol for Rear-End Collision Avoidance on Highways

Fei Ye, Matthew Adams, Sumit Roy

{fye, mar22, sroy}@u.washington.edu

Department of Electrical Engineering, University of Washington, Seattle, WA

***Abstract*— More than 23% of annual vehicle accidents are rear-end collisions, which provides an important test-case for enhanced collision avoidance approaches based on v2v wireless communications. In this work, we propose and study the impact of a 802.11 based multi-hop MAC protocol that propagates an emergency warning message (EWM) down a platoon of cars on a highway. The design objective is to ensure reception of this message with stringent (low) delay constraints so as to provide drivers with requisite available maneuver time (AMT) to avoid rear-end collision. We provide realistic simulation studies of protocol performance within ns-2 environment for various topology (1 lane and 3 lanes) and background traffic scenarios, as well as different protocol parameter settings, to highlight the potential of this approach for effective collision avoidance or mitigation.**

I. Introduction

Since 1994, the number of fatal vehicle crashes in the United States annually has never fallen below 35,000, and the number of persons killed in traffic accidents each year has consistently exceeded 39,000 [1]. Moreover, 23% of all vehicle crashes (both fatal and nonfatal), or more than 1.5 million crashes per year, are rear-end collisions [2]. In Washington State, for the year 2005, rear-end crashes were the leading type of collision on state highways (32.2%) compared to other major collision types such as fixed object (20.2%) and sideswipes (8%) [3].

The occurrence of a rear-end collision on a highway is a combined result of a lead vehicle's deceleration and a following vehicle's insufficient maneuvering time. Two major causes exist for a following vehicle's insufficient maneuvering time. First, drivers tend to keep shorter time-headway than is recommended in driver's manuals. Second, drivers often have a limited line-of-sight, which makes it difficult to anticipate hazardous conditions beyond the vehicle immediately in front. Therefore, when the driver's Needed Maneuvering Time (NMT) (driver reaction time plus the vehicle's response time) is greater than the Available Maneuvering Time (AMT), a rear-end collision is inevitable. Studies [4] show that the driver's reaction time has a mean of 1.5s and an 85^{th} percentile of 1.9s , which dominates the NMT. Other studies [5] suggests that 60% of the rear-end crashes could potentially be avoided if the driver had an extra 0.5s. In most cases, to avoid a rear-end collision, the driver does not need to know detailed information about the situation beyond the lead vehicle. Simply warning of the potential hazard ahead would be enough.

Existing vehicle safety systems are based on various types of sensors (radar, vision sensors), which have a field-of-vision limited to immediate neighbors around the vehicle of interest. Therefore, these systems are not effective in providing drivers vision beyond the lead vehicle to avoid rear-end collision. Recently, the allocation of 75MHz in the 5.9GHz band for Dedicated Short Range Communication (DSRC) [6] has created ample opportunities for vehicle-to-vehicle (v2v) and vehicle to roadside (V2R) communication, where safety applications and rich media content delivery are enabled using low-cost commodity radios. In this paper, we study Emergency Warning Message (EWM) delivery in v2v multi-hop networks in order to prevent chain rear-end collisions on highways.

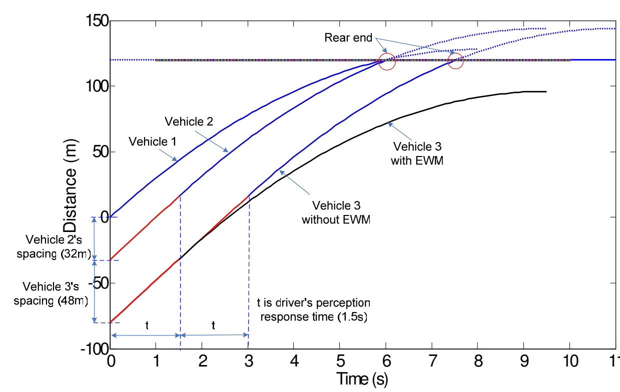


Fig. 1. Chain rear-end collision without EWM

Fig. 1 illustrates a chain rear-end crash involving 3 vehicles on a highway. In this example, all vehicles cruise at an identical speed of 32m/s (72mph) and have the same deceleration of $4m/s^2$. The perception response time of all drivers are also identical (1.5s). Vehicle 2 follows vehicle 1 with an unsafe inter-vehicle spacing of 32m (1s). Vehicle 3 keeps a safe spacing of 48m (1.5s). Additionally, assume that vehicle 1 brakes at time 0 due to an emergency event. Without v2v communication, vehicle 2 and 3 start braking at 1.5s and 3.0s respectively. Vehicle 2 collides with vehicle 1 at the distance of 120m, and gets hit by vehicle 3 later. With a rear-end collision avoidance system, both vehicle 2 and 3 start braking at 1.5s, and vehicle 3 is saved. The observations here are:

- Without v2v communication, the propagation of an emergency message along a platoon is delayed by each driver's perception response time.
- Being further away from vehicle 1 and keeping a relatively large inter-vehicle spacing with vehicle 2 do not

guarantee vehicle 3's safety.

- A rear-end collision avoidance system greatly decreases the propagation delay of an EWM, therefore providing drivers more AMT to avoid collisions.

In this paper, we discuss the challenges in Medium Access Control (MAC) and network layer techniques, and identify the application requirements for a vehicular rear-end collision avoidance warning system. A novel rear-end collision avoidance v2v wireless communication protocol is presented and evaluated by simulation.

II. Challenges in Applying v2v Wireless Network to Collision Avoidance

Though similar, v2v wireless communication networks differ from the well-studied wireless ad hoc network in several ways, particularly related to Medium Access Control (MAC) and routing.

1) The anonymity problem: In a v2v wireless network, the addresses of vehicles on highways are unknown to each other. Although periodic broadcasts from each vehicle may inform direct neighbors about its address, the address-position map will inevitably change frequently due to lane changing, passing, leaving and entering the highway and other relative movements among vehicles. Additionally, in most safety applications, it is the receiver's responsibility to decide the relevance of emergency messages and decide on appropriate actions. Therefore, broadcast and multicast are the proper communication methods for collision avoidance. In fact, through integration with positioning systems, location-based broadcast is the de facto method in most Cooperative Collision Avoidance (CCA) systems.
2) Multihop forwarding: Without any roadside infrastructure, multihop forwarding must be enabled to propagate the EWM along a platoon of vehicles. The ad hoc v2v network is different from traditional ad hoc networks in the following 2 aspects: first, no route setup is performed before forwarding; second, the EWM is sent as a broadcast rather than a unicast transmission.
3) Stringent delay requirement: A rear-end collision occurs when the AMT is less than the NMT. NMT is dominated by the driver's perception response time, which is determined by many factors, and therefore difficult to change. To prevent a rear-end collision, a vehicle must receive the EWM sufficiently prior to the lead vehicle's initiation of deceleration to provide more AMT. The rear-end collision free condition is expressed as:

$$t_{EWM} + T_{NMT} < t^*_{EWM} + T^*_{NMT} + T_{headway} \quad (1)$$

where t_{EWM} denotes the moment that the ith vehicle receives the EWM, T_{NMT} and $T_{headway}$ are the ith vehicle's needed maneuver time and time-headway. * represents the lead vehicle ($(i-1)th$). Assuming identical NMT, the EWM propagation delay from the $(i-1)th$ to the ith vehicle must satisfies:

$$\begin{aligned} T_{delay} &= t_{EWM} - t^*_{EWM} \\ T_{delay} &< T_{headway} \end{aligned} \quad (2)$$

The intuition behind the above has two components. First, a more stringent delay constraint is required to save a careless driver who keeps a small inter-vehicle spacing. Second, the worst case occurs when the driver relies on the lead vehicle's brake light, which results in the maximum delay of T^*_{NMT}. Careful drivers who keep a time-headway in excess of T^*_{NMT} are always safe unless the lead vehicle hits a fixed object. Although transmitting an EWM packet requires less than 1 ms in a clear wireless environment, dramatic delay increase is observed in interference limited situations [8]. Due to multiple lanes, anti-parallel traffic and background ITS traffic, v2v networks are more appropriately considered as dense wireless networks. Traditional wireless networking protocols should thus be enhanced to satisfy the delay constraint.
4) Redundant EWMs: Broadcast packets are not acknowledged. Therefore, periodic broadcasts are used to improve the probability of successful EWM delivery. However, two problems arise. First, a vehicle who has already successfully forwarded an EWM will keep contending with following vehicles for channel access. Second, redundant periodic broadcasts waste bandwidth and suppresses other data traffic. An implicit acknowledgement (ACK) strategy is adopted to eliminate redundant EWMs, in which the reception of an EWM from a subsequent vehicle in the platoon serves as an implicit ACK to vehicles in front. On receiving an implicit ACK, a vehicle immediately stops sending any EWMs related to the same event.

III. Related Work

Based on the challenges described above, existing v2v protocol designs for collision avoidance have focussed on enhancements to both the MAC protocol and routing strategy. A set of slot reservation MAC protocols have been proposed for inter-vehicle communication [14]. Although, R-ALOHA leads to more predictable delays, achieving global synchronization and slot allocation across multiple hops in the absence of a central controller is an unsolved problem. The IEEE 802.11a Distributed Coordination Function (DCF) based MAC protocol is preferred due to the ready availability at low cost of commodity radios. However, several limitations in adopting DCF in v2v communication have been observed in [15]. Although the DCF is the de facto MAC layer in many simulation studies of v2v communication protocol design for safety applications [11], [13], [16], there is not sufficient in-depth understanding of how to satisfy the stringent delay constraint, especially in dense network scenarios.

Due to challenges 1, 2 and 4 noted above, the routing strategy in a v2v network should be broadcast-oriented and use location-based forwarding. Single hop broadcast strategies for safety application are discussed in [9]–[11]. [11] presents a congestion control algorithm to support multiple abnormal vehicles in the same contention area. A multihop broadcast protocol on the basis of slot reservation MAC is proposed in [12]. However, its design metric is the vehicle identification rate (which is a measure of network connectivity) and not delay. An intelligent multihop broadcast strategy with implicit acknowledgement was presented in [13] to achieve low EWM propagation delay.

In this paper, we focus on integrated protocol design and evaluation for rear-end collision avoidance on highways. Based on the discussion in section II, we propose a rear-end collision avoidance protocol which satisfies the stringent delay constraint. Both single lane and multi-lane scenarios are simulated.

IV. REAR-END COLLISION AVOIDANCE COMMUNICATION PROTOCOL

Each vehicle on the highway is assumed to be equipped with a positioning device (e.g. Global Positioning System) and an IEEE 802.11 radio working in ad hoc mode. Vehicles cruising in one lane have identical velocity and knowledge of their lane ID. There are multiple lanes, but we assume no lane changing during the EWM propagation. When an emergency event occurs, the affected vehicle broadcasts an EWM to inform all subsequent peers. The warning message contains the sender's position, lane ID, event ID, event location, event time stamp, and message lifetime. Upon receiving such an EWM, the trailing vehicles inform their drivers of the potential hazard through an audio or visual signal. In such a way, drivers become aware of the emergency situations before they see the braking light of the lead vehicle. We further assume that all vehicles, upon receiving the EWM, start to decelerate after a pre-defined driver's perception response time.

A. MAC Enhancement

The MAC layer is based on standard IEEE802.11 DCF. To satisfy the stringent EWM propagation delay constraint, the following enhancement is proposed: whenever an EWM is generated, it is inserted to the head of the queue, but behind any former EWMs. Equivalently, a virtual queue is created for EWMs, which has absolute priority over regular queues (for data). In DCF, to decrease collision probability, each transmission failure leads to doubled Contention Window (CW) size in the next backoff up to a maximum value. However, the probability of successful channel access rapidly decreases as the backoff stage increases. This may lead to unacceptable delay for some EWMs. To provide EWM higher probability of channel access, a fixed CW size is used for EWM; i.e. the binary exponential back-off is disabled. Furthermore, an EWM has no retry limitation. We note that the IEEE802.11e Enhanced Distributed Channel Access (EDCA) [7] also provide QoS support by use of different contention parameters (i.e. Arbitration Inter-Frame Space, different CW_{min} and CW_{max}) for different traffic classes. However, this only provides QoS

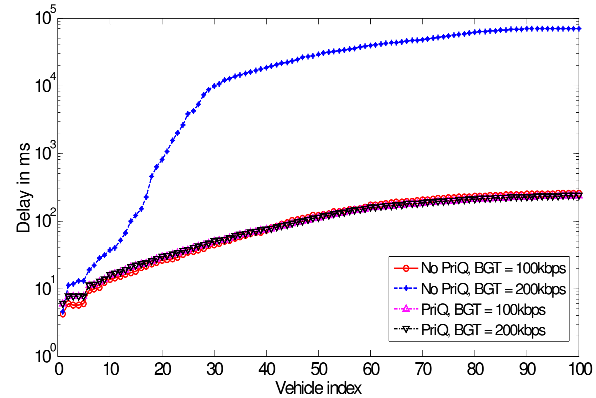


Fig. 2. The EWM propagation delay in single lane scenario with/without priority queue

(e.g.) guarantees in a statistical sense and is not an appropriate approach for collision avoidance.

B. Multihop Broadcast

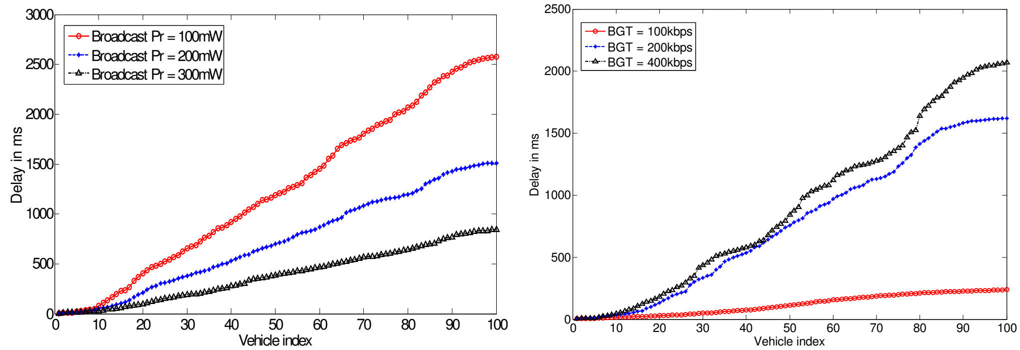
Due to the anonymity problem, EWMs are sent as broadcasts. Upon receiving an EWM, a vehicle accepts this warning message only if it comes from vehicles in front with the same lane ID, the event ID is new, and the message has not exceeded its lifetime. The vehicle immediately informs its driver and broadcasts a new EWM. Since group communication is not acknowledged in DCF, a sender should periodically broadcast until an implicit ACK is received. The implicit ACk is defined as an EWM with the same event ID from a subsequent vehicle in the same lane. This mechanism greatly reduces the redundancy. An EWM propagation stops when this message expires.

V. PERFORMANCE EVALUATION OF REAR-END COLLISION AVOIDANCE

The proposed rear-end collision avoidance protocol is implemented in the ns2 network simulator with proper modifications. The performance is evaluated in a single lane scenario and a 3-lane scenario with 100 vehicles in each lane. We assume low visibility on the roadway (i.e. rain, fog) such that each vehicle can only see one vehicle ahead. The first vehicle is forced to execute an emergency brake, which triggers an EWM message broadcast. In the 3-lane scenario, one EWM is generated and propagated in the central lane. Vehicles are not allowed to change lanes. Basic parameters used in our simulation are summarized in Table I. In the following evaluation, several key parameters such as queue types, broadcast power, and background traffic are discussed.

A. Performance in Single Lane Scenario

In the single lane scenario, 100 vehicles were placed in a platoon with fixed time-headway (1 s), which is less than the driver's perception response time (1.5 s). Under the assumption that drivers can only see one vehicle ahead, all the vehicles will eventually rear-end. By default, each vehicle has 400kbps unicast background data traffic, 200 mW EWM broadcast



(a) EWM propagation delay under different broadcast power

(b) EWM propagation delay under different background traffic

Fig. 3. The EWM propagation delay in single lane scenario under different broadcast power and background traffic (with priority queue).

power, 200mW unicast power, and a priority queue for EWMs. First, we compare the results with and without a priority queue in Fig. 2. Without priority queuing, the accumulated delay does not remarkably increase when background traffic is light (100 kbps). But in the case of 200 kbps background traffic, there is a large queuing delay for EWM, and the total delay increase dramatically to 70 seconds, which clearly does not meet the strict delay constraint for collision avoidance. Therefore, priority queueing is needed for vehicle safety applications.

According to Fig. 3(a) and Fig. 3(b), the EWM propagation delay in single lane scenario is extremely low regardless of the parameter settings as long as priority queuing is adopted. The accumulated EWM propagation delay for the whole platoon is always less than 2.5 s, and the per vehicle latency is almost identical, and less than 30 ms. Therefore, all vehicles are saved.

B. Performance in 3-lane scenario

In the 3-lane scenario, vehicles have a fixed reaction time (1.5 s) and uniformly distributed inter-vehicle spacing from 20 m to 45 m. Without v2v communication, statistically 70 rear-end crashes will occur. By default, each vehicle has 100kbps unicast background data traffic, 200mW EWM broadcast power, 100mW unicast power, and priority queuing. The 3-lane scenario is a much denser vehicular wireless network, thus larger accumulated delay than that in the single lane scenario is observed (Fig. 4). Both EWM broadcast power and the amount of background traffic impact the EWM propagation delay, however, the former dominates. Very few vehicles are endangered, even in the case of small EWM broadcast power (e.g. red line with circle mark in Fig. 4(a)). To understand this, we plot the per vehicle EWM propagation delay and time-headway for every single simulation run. Fig.5 is a typical plot with 100 mW EWM broadcast power, 100 mW unicast power, and 100 kbps background traffic per vehicle. According to our assumption, if the per vehicle EWM propagation delay exceeds its time-headway (i.e. the 38th vehicle in Fig.5), a rear-end collision occurs. It shows that the proposed rear-end collision avoidance protocol successfully prevents collisions for more than 99% of vehicles in 3-lane scenario under the worst case assumption that each vehicle has a limited vision of only the immediate vehicle ahead.

VI. Conclusion

In this paper, we have discussed the importance and challenges of using v2v wireless communication for vehicle safety applications. A stringent EWM delay constraint is identified as the key metric for protocol design. An integrated rear-end avoidance protocol is presented, which is based on 802.11 MAC and multihop broadcast. Simulation results from both single lane and multiple lane scenarios demonstrate that the EWM propagation delay in the proposed protocol satisfies the stringent delay requirements. With appropriate EWM broadcast power, more than 99% of vehicles are free of rear-end collisions, even in the dense multiple lane scenario plus the worst case visibility assumption.

VII. Acknowledgements

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TABLE I

Simulation Parameters

Parameter	Value
Number of lanes	1 or 3
Platoon size	100 vehicles
Vehicle Velocity	25m/s
Time-headway	uniform distribution in [0.8s - 1.8s]
Inter-vehicle spacing	uniform distribution in [20m - 45m]
Deceleration	5m/s/s
Driver's perception response time	1.5s
Channel data rate	2Mbps
EWM size	128 Bytes
CW_{min}	15
CW_{max}	1023
Fixed CW for EWM	15
EWM lifetime	30s
EWM broadcast period	50ms
EWM process time	0s

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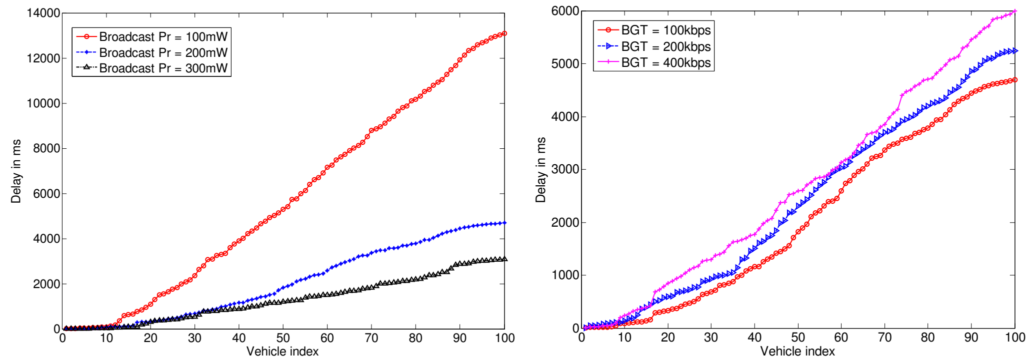

(a) The EWM propagation delay under different broadcast power

(b) The EWM propagation delay under different background traffic

Fig. 4. The EWM propagation delay in 3-lane scenario (with priority queue).

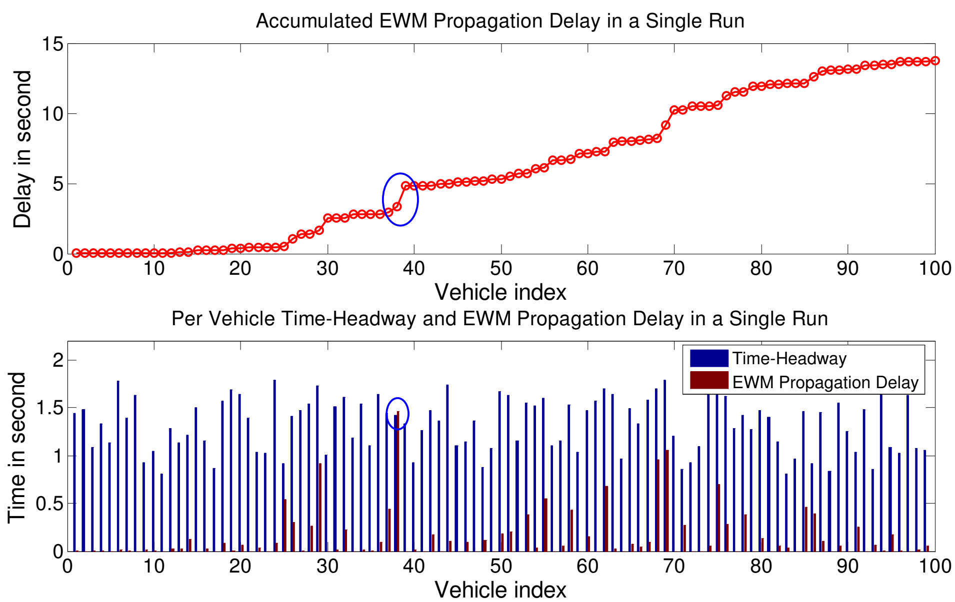

Fig. 5. Per vehicle EWM delay and time-headway.

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