A Vehicle-to-Vehicle Communication Protocol for Cooperative Collision Warning

Xue Yang
University of Illinois at Urbana-Champaign
xueyang@uiuc.edu

Jie Liu
Microsoft Research
liuj@microsoft.com

Feng Zhao
Microsoft Research
zhao@microsoft.com

Nitin H. Vaidya
University of Illinois at Urbana-Champaign
nhv@uiuc.edu
*

Abstract

This paper proposes a vehicle-to-vehicle communication protocol for cooperative collision warning. Emerging wireless technologies for vehicle-to-vehicle (V2V) and vehicle-to-roadside (V2R) communications such as DSRC [1] are promising to dramatically reduce the number of fatal roadway accidents by providing early warnings. One major technical challenge addressed in this paper is to achieve low-latency in delivering emergency warnings in various road situations. Based on a careful analysis of application requirements, we design an effective protocol, comprising congestion control policies, service differentiation mechanisms and methods for emergency warning dissemination. Simulation results demonstrate that the proposed protocol achieves low latency in delivering emergency warnings and efficient bandwidth usage in stressful road scenarios.

1. Introduction

Traffic accidents have been taking thousands of lives each year, outnumbering any deadly diseases or natural disasters. Studies [18] show that about *60%* roadway collisions could be avoided if the operator of the vehicle was provided warning at least one-half second prior to a collision.

Human drivers suffer from perception limitations on roadway emergency events, resulting in large delay in propagating emergency warnings, as the following simplified example illustrates. In Figure 1, three vehicles, namely A, B, and C, travel in the same lane. When A suddenly brakes abruptly, both vehicles B and C are endangered, and being further away from A does not make vehicle C any safer than B due to the following two reasons:

- Line-of-sight limitation of brake light: Typically, a driver can only see the brake light from the vehicle directly in front[1]. Thus, very likely vehicle C will not know the emergency at A until B brakes.
- Large processing/forwarding delay for emergency events: Driver reaction time, i.e., from seeing the brake light of A to stepping on the brake for the driver of vehicle B, typically ranges from 0.7 seconds to 1.5 seconds [6], which results in large delay in propagating the emergency warning.

Figure 1. V2V helps to improve road safety

Emerging wireless communication technologies are promising to significantly reduce the delay in propagating emergency warnings. The Dedicated Short Range Communications (DSRC) consortium[2] is defining short to medium range communication services that support public safety in vehicle-to-vehicle (V2V) communication environment[1].

∗ This work was funded in part by Palo Alto Research Center while the first author worked there as a summer intern. The first author is also supported in part by Vodafone-U.S. Foundation Graduate Fellowship.

1 In favorable conditions, a driver may see brake lights further ahead. But we consider typical or worst-case scenarios.

2 IEEE P1609 Working Group is proposing DSRC as IEEE 802.11p standard.

Using V2V communication, in our previous example, vehicle A can send warning messages once an emergency event happens. If vehicles B and C can receive these messages with little delay, the drivers can be alerted immediately. In such cases, C has a good chance of avoiding the accident via prompt reactions, and B benefits from such warnings when visibility is poor or when the driver is not paying enough attention to the surroundings. Thus, the vehicle-to-vehicle communication enables the *cooperative collision warning* among vehicles A, B and C.

Even though V2V communication may be beneficial, wireless communication is typically unreliable. Many factors, for example, channel fading, packet collisions, and communication obstacles, can prevent messages from being correctly delivered in time. In addition, ad hoc networks formed by nearby vehicles are quite different from traditional ad hoc networks due to high mobility of vehicles.

A *Vehicular Collision Warning Communication* (VCWC) protocol is discussed in this paper. Major contributions of this paper include:

- Identifying application requirements for vehicular cooperative collision warning.
- Achieving congestion control for emergency warning messages based on the application requirements.

The rest of this paper is organized as follows. Application challenges are discussed in Section 2. Section 3 presents the related work. Section 4 describes the proposed Vehicular Collision Warning Communication (VCWC) protocol. Performance evaluation using ns-2 simulator is presented in section 5. Finally, the conclusions are drawn in section 6.

2. Application Challenges

Using V2V communication, when a vehicle on the road acts abnormally, e.g., deceleration exceeding a certain threshold, dramatic change of moving direction, major mechanical failure, etc., it becomes an abnormal vehicle (AV). An AV actively generates Emergency Warning Messages (EWMs), which include the geographical location, speed, acceleration and moving direction of the AV, to warn other surrounding vehicles. A receiver of the warning messages can then determine the relevancy to the emergency based on the relative motion between the AV and itself.

2.1. Challenge 1: Stringent delay requirements immediately after the emergency

Over a short period immediately after an emergency event, the faster the warning is delivered to the endangered vehicles, the more likely accidents can be avoided. We define *EWM delivery delay* from an AV A to a vehicle V as the elapsed duration from the time the emergency occurs at A to the time the *first* corresponding EWM message is successfully received by V. Since a vehicle moving at the speed of 80 miles/hour can cross more than one meter in 30 ms, the EWM delivery delay for each affected vehicle should be in the order of milliseconds.

However, the link qualities in V2V communications can be very bad due to multipath fading, shadowing, and Doppler shifts caused by the high mobility of vehicles. In [15], the performance of a wireless LAN in different vehicular traffic and mobility scenarios is assessed, showing that the deterioration in signal quality increases with the relative and average velocities of the vehicles using 802.11b. Besides unreliable wireless links, packet collisions caused by MAC layer can also contribute to the loss of EWMs.

Moreover, in an abnormal situation, all vehicles close to the AV may be potentially endangered and they all should receive the timely emergency warning. But the group of endangered vehicles can change quickly due to high mobility of vehicles. For example, in Figure 2, at the time of emergency event at vehicle A, the nearby vehicles N_1, N_2, N_3, N_4, and N_5 are put in potential danger. Very soon, vehicles N_5 and N_1 may pass A and should no longer be interested in the emergency warning. Meanwhile, vehicles N_6, N_7 and N_8 can get closer and closer to A and should be informed about the abnormal situation.

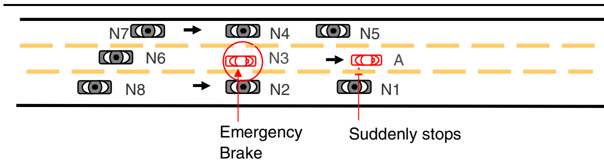


Figure 2. N_3 reacts to the sudden stop of vehicle A with emergency brake

Both the unreliable nature of wireless communication and the fast changing group of affected vehicles create challenges for satisfying the stringent EWM delivery delay constraint in cooperative collision warning.

2.2. Challenge 2: Support of multiple co-existing AVs over a longer period

After an emergency event happens, the AV can stay in the abnormal state for a period of time. For example, if a vehicle stops in the middle of a highway due to mechanical failure, it remains hazardous to any approaching vehicles,

0-7695-2208-4/04 $20.00 © 2004 IEEE

and hence, remains an abnormal vehicle until it is removed off the road.

Furthermore, emergency road situations frequently have chain effects. When a leading vehicle applies an emergency brake, it is probable that vehicles behind it will react by also decelerating suddenly.

We define *co-existing AVs* as all the AVs whose existences overlap in time and whose transmissions may interfere with each other. Due to the fact that an AV can exist for a relatively long period and because of the chain effect of emergency events, many co-existing AVs can be present.

Therefore, in addition to satisfying stringent delivery delay requirements of EWMs at the time of emergency events, the vehicular collision warning communication protocol has to support a large number of co-existing AVs over a more extended period of time.

2.3. Challenge 3: Differentiation of emergency events and elimination of redundant EWMs

Emergency events from AVs following different lanes/trajectories usually have different impact on surrounding vehicles, hence, should be differentiated from each other. As the example in Figure 3 shows, vehicle A is out of control and its trajectory crosses multiple lanes. In such an abnormal situation, N_1 and N_3 may both react with emergency braking and it is important for both N_1 and N_3 to give warnings to their trailing vehicles, respectively. At the same time, since the trajectory of vehicle A does not follow any given lane and it may harm vehicle N_5 in the near future, vehicle A needs to give its own emergency warning as well. In this particular example, three different emergency events are associated with three different moving vehicles.

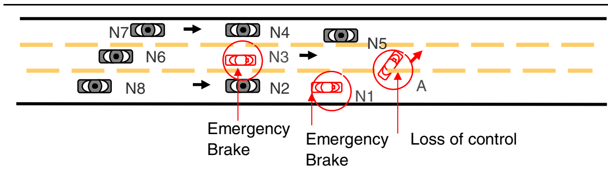


Figure 3. Multiple AVs following different trajectories

On the other hand, multiple AVs may react to a same emergency event and impose similar danger to the approaching vehicles. For example, in Figure 2, vehicle A suddenly stops in the middle of road. In reacting to the sudden stop of A, vehicle N_3 brakes abruptly and stops behind A as well. From the viewpoint of vehicle A, vehicle N_3 shields it from all vehicles behind. In such a case, there is no need for A to continue sending redundant EWMs some time after the emergency for several reasons: first, channel bandwidth would be consumed by unnecessary warning messages; and second, as more senders contend for a common channel, the delays of useful warning messages are likely to increase.

In real life, various reactions from drivers can happen. In the example of Figure 2, EWMs from A is redundant as long as N_3 stays behind it and sends EWMs. Later on, the driver of N_3 may change lane and drive away. When this happens, EWMs from A becomes necessary again if A remains stopped in the middle of the road. Therefore, the design of collision warning communication protocol needs to both take advantage of traffic patterns, and be robust to complicated road situations and driver behaviors.

3. Related Work

Previous research work with regard to V2V communication has focused on three aspects: medium access control, message forwarding, and group management.

In [9], Lee *et. al.* propose a wireless token ring MAC protocol (WTRP) for platoon vehicle communication, in which all participating vehicles form a group and drive cooperatively. A slot-reservation MAC protocol, R-ALOHA, for inter-vehicle communication is discussed in [17]. Several slot reservation MAC protocols [11, 10, 13] are proposed for the Fleetnet Project [7]. Xu *et. al.* discuss a vehicle-to-vehicle Location-Based Broadcast communication protocol, in which each vehicle generates emergency messages at a constant rate [19]. The optimum transmission probability at MAC layer for each message is then identified to reduce the packet collision probability.

Message forwarding can help warning message reach vehicles beyond the radio transmission range. In [14], the authors propose a multi-hop broadcast protocol based on slot-reservation MAC. Considering the scenario that not all vehicles will be equipped with wireless transceivers, emergency message forwarding in sparsely connected ad hoc network consisting of highly mobile vehicles is studied in [3]. Motion properties of vehicles are exploited in [4] to help with message relay. Two protocols to reduced the amount of forwarding messages were proposed in [16].

When an emergency event occurs, there are usually a group of vehicles affected by the abnormal situation. In terms of group management, [12] defines so called “proximity group” based on the location and functional aspects of mobile hosts; [5] defines a “peer space”, in which all traffic participants share a common interest; [2] also discusses group membership management for inter-vehicle communication.

In summary, MAC protocols coordinate channel access among different vehicles; multi-hop forwarding mechanisms extend the reachable region for warning messages; and group management protocols define the group of vehicles that share a common interest.

Different from prior work, this paper focuses on congestion control issues related to vehicular cooperative collision warning application. More specifically, based on the application challenges we discussed in Section 2, the proposed Vehicular Collision Warning Communication (VCWC) protocol discusses how to adjust EWM transmission rate so that stringent EWM delivery delay constraints can be met while a large number of co-existing AVs can be supported. The detail of the proposed VCWC protocol is discussed below.

4. Vehicular Collision Warning Communication Protocol

A vehicle can become an abnormal vehicle (AV) due to its own mechanical failure or due to unexpected road hazards. A vehicle can also become an AV by reacting to other AVs nearby. Once an AV resumes it regular movement, the vehicle is said no longer an AV and it returns back to the normal state. In general, the abnormal behavior of a vehicle can be detected using various sensors within the vehicle. Exactly how normal and abnormal status of vehicles are detected is beyond the scope of this paper. We assume that a vehicle controller can automatically monitor the vehicle dynamics and activate the collision warning communication module when it enters an abnormal state. A vehicle that receives the EWMs can verify the relevancy to the emergency event based on its relative motion to the AV, and give audio or visual warnings/advice to the driver.

Each message used in VCWC protocol is intended for a group of receivers, and the group of intended receivers changes fast due to high mobility of vehicles, which necessitate the message transmissions using broadcast instead of unicast. To ensure reliable delivery of emergency warnings over unreliable wireless channel, EWMs need to be repeatedly transmitted.

Conventionally, to achieve network stability, congestion control has been used to adjust the transmission rate based on the channel feedback. If a packet successful goes through, transmission rate is increased; while the rate is decreased if a packet gets lost.

Unlike conventional congestion control, here, there is no channel feedback available for the rate adjustment of EWMs due to the broadcast nature of EWM transmissions. Instead, we identify more application-specific properties to help EWM congestion control, which consists of the EWM transmission rate adjustment algorithm and the state transition mechanism for AVs.

While congestion control policies are the focus of this paper, the proposed VCWC protocol also includes emergency warning dissemination methods that make use of both natural response of human drivers and EWM message forwarding, and a message differentiation mechanism that enables cooperative vehicular collision warning application to share a common channel with other non-safety related applications. Without loss of continuity, the latter two components are largely skipped due to space limitation, however, details for them can be found in [20].

4.1. Assumptions

We first clarify related assumptions we have made for each vehicle participating in the cooperating collision warning.

- Such a vehicle is able to obtain its own geographical location, and determine its relative position on the road (e.g., the road lane it is in). One possibility is that, the vehicle is equipped with a Global Position System (GPS) or Differential Global Position System (DGPS) receiver[3] to obtain its geographical position, and it may be equipped with a digital map to determine which lane it is in.
- Such a vehicle is equipped with at least one wireless transceiver, and the vehicular ad hoc networks are composed of vehicles equipped with wireless transceivers.
- As suggested by DSRC, the transmission range of safety related vehicle-to-vehicle messages is assumed to be 300 meters, and channel contention is resolved using IEEE 802.11 DCF based multi-access control.

4.2. Rate Decreasing Algorithm for EWMs

In VCWC, different kinds of messages are assigned different priority levels, while EWMs have the highest priority. The underlying multi-access control supports priority scheduling such that higher priority traffic can be transmitted in preference to lower priority traffic. Consequently, in considering the EWM congestion control, we can focus on the transmissions of EWMs alone.

The goal of the rate decreasing algorithm is to achieve low EWM delivery delay at the time of an emergency event, while allowing a large number of co-existing AVs.

EWM delivery delay from A to V can be formally defined as the elapsed duration from the time the emergency occurs at A to the time the first corresponding EWM message is successfully received by V. Since an EWM message may encounter some waiting time in the system due to queueing delay, channel access delay, etc., and it may also

3 Currently, commercial DGPS receivers are able to achieve the position resolution in the order of centimeters

suffer from retransmission delay due to poor channel conditions or packet collisions, the EWM delivery delay mainly consists of the waiting time and the retransmission delay.

Formally, the *waiting time* of an EWM message ($Delay_{wait}$) is defined as the duration from the time the EWM is issued by the vehicular collision warning communication module to the time it is transmitted on the wireless channel, as shown in Figure 4.

To account for the message waiting time in the system, let the EWM transmission process from each AV be Poisson and assume there are totally M co-existing AVs. The total arrival rate of EWMs, λ, is the sum of EWM transmission rate from each individual AV. As a simplifying approximation, we also model the channel service process as Poisson since each EWM has the same packet size and there is no feedback between the channel service rate and the EWM transmission rate in our system. With M independent arrival streams from all M AVs, a M/M/1 queueing system can be constructed by merging all arrival streams into one with a total arrival rate of λ. Let the channel service rate be μ. From queueing theory, we know that the system is stable if and only if $\lambda < \mu$ and the average *waiting time* in the system for a message is

$$Delay_{wait} = \frac{1}{\mu - \lambda} + \frac{1}{\mu} \quad (1)$$

if the FCFS (First Come First Serve) service order is applied [8]. Even though contention based MAC protocol is used and the channel in fact serves the backlogged messages from different AVs in a random order, by assuming that each backlogged message is served with equal probability, one can show that the average waiting time remains same when the system is stable [20].

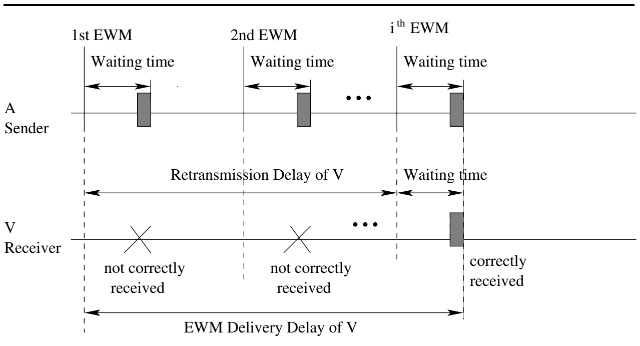


Figure 4. Waiting Time and Retransmission Delay

Supposing that the i^{th} transmitted EWM message from an AV A is the first EWM correctly received by a receiver vehicle V, then the EWM *retransmission delay* ($Delay_{retransmission}$) from A to V is defined as the elapsed duration from the time when the first EWM is generated to the time when the i^{th} EWM is generated by the AV A, as illustrated in Figure 4.

Let p be the probability for an EWM message being correctly received by a vehicle, λ_0 be the initial EWM transmission rate and $f(\lambda_0, k)$ be the EWM transmission rate after the k^{th} transmitted EWM for an AV. Then, the average *retransmission delay* from the AV can be represented as

$$Delay_{retransmission} = \sum_{i=2}^{\infty} (1-p)^{i-1} * p * \left(\sum_{j=1}^{i-1} \frac{1}{f(\lambda_0, j)} \right) \quad (2)$$

By definition, EWM delivery delay ($Delay$) can be represented as:

$$Delay = Delay_{wait} + Delay_{retransmission} \quad (3)$$

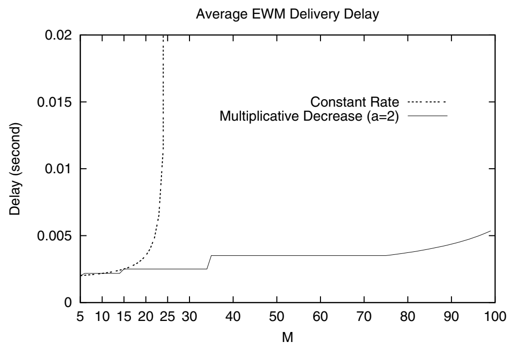
The initial EWM transmission rate λ_0 is usually required to be high so that the EWM delivery delay can be possibly small. However, if the rate remains high or is decreased too slowly, the total arrival rate of EWMs in the system may increase rapidly with the occurrence of new AVs, resulting in a heavily loaded network and large waiting time. On the other hand, if the EWM transmission rate is decreased too quickly, the retransmission delay may become large, dominating the EWM delivery delay.

Both the multiplicative rate decreasing and the additive rate decreasing algorithms are examined for VCWC. Our results showed that, given the EWM transmission rate range ($[\lambda_{min}, \lambda_o]$) constrained by the application[4], both of them can achieve similar results with properly chosen parameters. In this paper, we only report on the multiplicative rate decreasing algorithm for brevity. Specifically, starting with the initial rate of λ_0, the EWM transmission rate of an AV is decreased by a factor of a after every L transmitted EWMs, until the minimum rate λ_{min} is reached. That is,

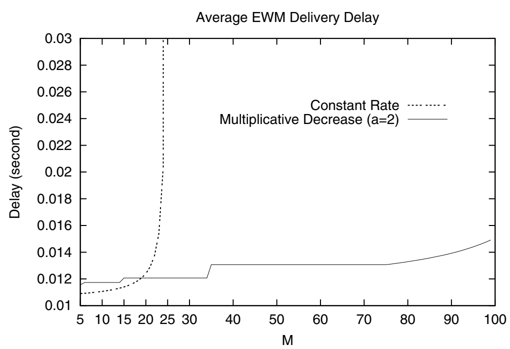
$$f(\lambda_0, k) = max\left(\lambda_{min}, \frac{\lambda_0}{a^{\lfloor \frac{k}{L} \rfloor}}\right) \quad (4)$$

To show the benefits of multiplicative rate decreasing algorithm (using $a = 2$) over the constant rate algorithm that transmits EWMs at an invariant rate λ_0 (i.e., a special case with $a = 1$), the corresponding EWM deliver delays are de-

4 For an approaching vehicle entering the transmission range of an AV, its maximum delay in receiving the emergency warning primarily depends on λ_{min}. Therefore, the value of λ_{min} is determined based on the radio transmission range, maximum speed, deceleration capability of vehicles and channel conditions.



(a) p = 0.9



(b) p = 0.5

Figure 5. EWM Delivery Delay vs. M

rived based on equations 1, 2 and 3, and shown in Figure 5[5].

As we can see, the network becomes unstable when M approaches 25 using the constant rate algorithm, while nearly 100 co-existing AVs can be supported before the EWM delivery delay begins to soar using the multiplicative rate decreasing algorithm with $a = 2$. To emphasize the importance of supporting a large number of co-existing AVs, consider a dense vehicular network with 5 lanes and 15 meter inter-vehicle distance in each lane on average. With a radio transmission range of 300 meters, there are 100 vehicles per transmission range. Since a vehicle can become an AV by reacting to unexpected abnormal road situations, *and* by reacting to other AVs due to the chain effect of emergency events, it is not uncommon that more than 25 AVs may appear at the same time.

When M is very small, the waiting time is negligible and EWM delivery delay is mainly determined by the retransmission delay. Figures 5 (a) and (b) present the delay for a good channel condition (i.e., p = 0.9) and a bad channel condition (i.e. p = 0.5), respectively. Both figures show that the used multiplicative rate decreasing algorithm leads to very little degradation of retransmission delay (i.e., delay when M is small), which is within 1 ms of that using the constant rate algorithm.

Overall, comparing with the constant rate algorithm, the multiplicative rate decreasing algorithm with $a = 2$ extends the supported number of co-existing AVs significantly, while causing very little delay degradation when the network load is low. A larger a can support even more co-existing AVs, but leads to further increased delay when the network load is low. As most practical scenarios have less than 100 co-existing AVs, the proposed VCWC protocol employs the multiplicative rate decreasing algorithm with $a = 2$.

4.3. State Transitions of AVs

The objective of the state transition mechanism is to ensure EWM coverage for the endangered regions and to eliminate redundant EWMs, while incurring little control overhead.

Each AV may be in one of three states, *initial AV*, *non-flagger AV* and *flagger AV*. When an emergency event occurs to a vehicle, the vehicle becomes an AV and enters the *initial AV* state, transmitting EWMs following the rate decreasing algorithm described in Section 4.2. An *initial AV* can become a *non-flagger AV*, refraining from sending EWMs contingent on some conditions to eliminate redundant EWMs. In some road situations, it is necessary for a *non-flagger AV* to become a *flagger AV*, resuming EWM transmissions at the minimum required rate.

Transition from *initial AV* state to *non-flagger AV* state: An AV in the *initial AV* state can further reduce its EWM transmission rate down to zero, becoming a *non-flagger AV*, if the following two conditions are *both* satisfied:

1. At least T_{alert} duration has elapsed since the time when the vehicle became an initial AV. As EWMs have been repeatedly transmitted over T_{alert} duration, by then, the vehicles having been close to the AV should have received the emergency warning with high probability.
2. EWMs from one of the "followers" of the initial AV are being overheard; here, we define vehicle X as a "follower" of vehicle Y, if X is located behind Y in the same lane and any vehicle endangered by Y may also be endangered by X.

5 To obtain the numerical results, we have assumed that the channel service rate μ is about 2500 EWMs per second, λ_0 is 100 messages/sec, λ_{min} is 10 messages/sec and one new AV occurs every 10 ms. The value of L is set to 5. More discussions with regard to the choices of these parameters can be found in [20].

In the example shown in Figure 6(a), abnormal vehicle A malfunctions and stops. Upon receiving the EWMs from vehicle A, the trailing vehicle N_3 reacts and stops as well. As N_3 responds with abrupt action, it also becomes an AV and begins to send EWM messages. Since A and N_3 impose similar danger to any vehicle approaching this region, using above state transition rule, A enters the *non-flagger AV* state when it receives EWMs from N_3, *and* T_{alert} duration has elapsed since the initial occurrence of the emergency event at vehicle A. On the other hand, without overhearing any EWMs from other AVs behind, N_3 is not eligible to be a non-flagger. Hence, it remains as an *initial AV* and keeps on sending EWM messages. With EWMs from N_3, approaching vehicles can get sufficient warning to enable their drivers to respond appropriately.

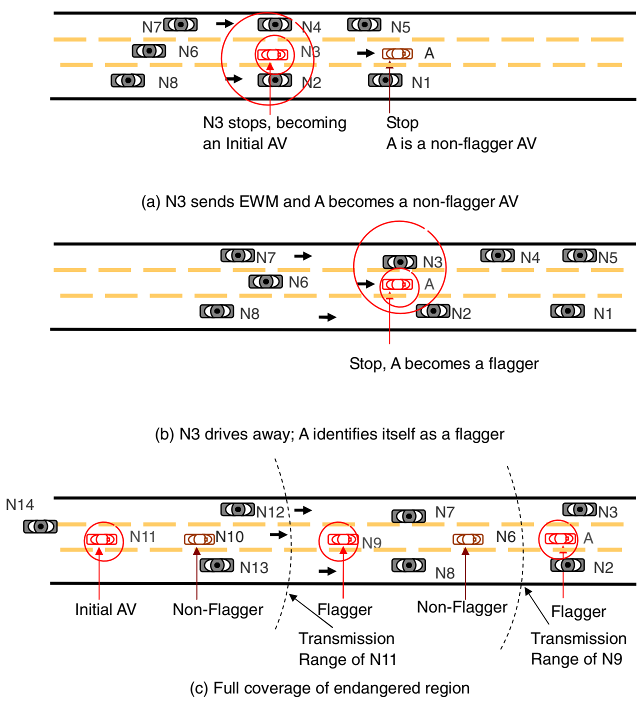


Figure 6. Example for *non-flagger AVs* and *flagger AVs*

Transitions between *non-flagger AV* state and *flagger AV* state: An AV in the *non-flagger AV* state sets a timer for a Flagger Timeout (FT) duration. If it does not receive any EWMs from its followers when the FT timer expires, the *non-flagger AV* changes its state to *flagger AV*. Otherwise, it simply resets the FT timer and repeats above procedures. If a *flagger AV* receives EWMs from one of its followers, it will relinquish its flagger responsibility, becoming *a non-flagger AV*.

A *flagger AV* transmits EWMs at the minimum rate λ_{min} since a vehicle can only become a *flagger AV some time* after the emergency. Observe that, at the time when an emergency occurs, the emergency warning needs to be delivered to all surrounding vehicles as soon as possible because the endangered vehicles can be very close to the AV. After a while, however, the nearby vehicles should have received the emergency warnings with high probability. What matters then is to give emergency warnings to approaching vehicles that just enter the transmission range of the AV. Therefore, the value of λ_{min} is mainly determined by the radio transmission range, maximum speed, deceleration capability of vehicles and channel conditions. If radio transmission range is large enough, an approaching vehicle can tolerate a relatively long delivery delay. For example, in Figure 6(a), N_6 enters the transmission range of A some time after the emergency event. If we assume that the transmission range is 300 meters, as suggested by DSRC [1], then one or two second delay in receiving the emergency warning for N_6 should not cause much negative impact.

Continuing our example in Figure 6: at this point of time, N_3 is an *initial AV* and A is a *non-flagger AV* (Figure 6 (a)). After a while, N_3 finds a traffic gap on the next lane and drives away. As vehicle A can no longer hear EWMs from N_3, A changes its state to *a flagger AV* after its FT timer expires, and begins to send EWMs again, as shown in Figure 6 (b).

The situation involving several reacting AVs is illustrated in Figure 6 (c). The last AV in a "piled up" lane, vehicle N_{11} in this example, always remains as an *initial AV* and sends EWMs (as it is not eligible to be a *non-flagger AV* without receiving EWMs from a follower). Additionally, vehicle N_9 identifies itself as a flagger as it cannot hear EWMs from N_{11}. Similarly, vehicle A also identifies itself as a flagger since it is out of the transmission range of N_{11} and N_9.

Because an AV starts to generate its own EWMs if no EWMs from its followers are overheard when its FT timer expires, the longest time period during which no EWMs are transmitted to a vehicle since it enters the transmission range of an AV is $2FT$[6]. By choosing an appropriate value for FT based on the radio transmission range, maximum speed, deceleration capability of vehicles, channel conditions and the value of λ_{min}, we can ensure that, with very high probability, all approaching vehicles can receive emergency warning in time to react to potential danger ahead.

Implementing above state transition mechanism does not incur any additional control messages beyond the EWMs already being sent, and the mechanism is robust to dynamic

6 The reason for $2FT$ is that, in the worst-case scenario, an AV does not receive any EWMs during current FT duration and the last EWM the AV received was transmitted immediately after the previous FT timer started.

0-7695-2208-4/04 $20.00 © 2004 **IEEE**

road scenarios and wireless link variations. If the channel is good, there will be only one AV sending EWMs per transmission range; if the channel condition is poor, EWMs from existing flaggers may get lost and more flaggers than necessary can appear from time to time. But clearly, the correctness of the above algorithm is not affected, which ensures that a vehicle entering the transmission range of an AV will always be covered by EWMs transmitted by *flagger AVs* or *initial AVs*.

Since EWMs sent by an AV include the geographical location, speed, acceleration and moving direction of the AV, an AV can determine whether another AV is a follower or not based on the relative motions between them upon receiving EWMs. How to exactly define those rules using motion properties is beyond the scope of this paper. However, it may be noted that, sometimes it is difficult to clearly determine whether two AVs impose similar danger to surroundings or not due to complicated road situations. Thus, to ensure the correctness of the protocol, rather conservative rules should be applied. Consequently, in the middle of emergency events, many co-existing AVs may be present. As we discussed previously, the proposed VCWC protocol is able to support many co-existing AVs using the rate decreasing algorithm.

5. Performance Evaluation

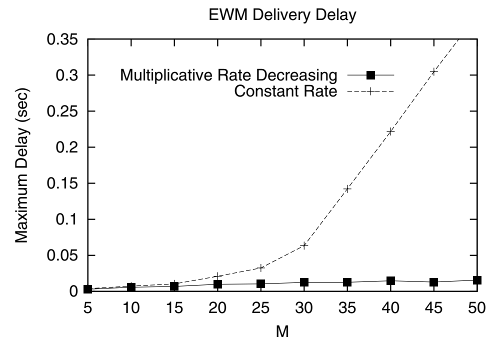
The proposed VCWC protocol is implemented using ns-2 network simulator. The channel physical characteristics follow the specification of 802.11b, with channel bit rate of 11 Mbps. The radio transmission range is set to 300 meters, as suggested by DSRC [1].

The underlying MAC protocol is based on IEEE 802.11 DCF, with the added functions of service differentiation. In our implementation, whenever an AV has a backlogged EWM, it raises an out-of-band busy tone signal, which can be sensed by vehicles located within two hop distance. Vehicles with lower priority messages defer their channel access whenever the busy tone signal is sensed.

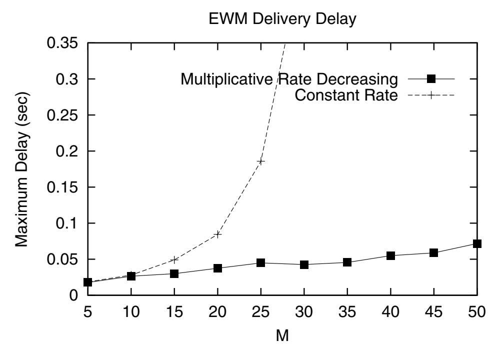
From empirical data, we set the minimum EWM transmission rate λ_{min} to 10 messages/sec, the flagger timeout duration FT to 0.5 seconds and the minimum EWM transmission duration T_{alert} for an *initial AV* to 450 milliseconds in the simulations. Using simulation results, we also identified in [20] that the combination of $L = 5$ and $\lambda_0 = 100$ messages/sec is a proper choice for the multiplicative rate decreasing algorithm.

5.1. EWM Delivery Delay

As we discussed in Section 3, prior related work has focused on different issues from this paper, which makes direct performance comparison difficult. Below, the simulation results for EWM delivery delay achieved by the multiplicative rate decreasing algorithm used by the proposed VCWC protocol, compared with the constant rate algorithm that transmits EWMs at the rate of λ_0, are presented.



(a) EWM Delivery Delay vs. M ($p = 0.9$)



(b) EWM Delivery Delay vs. M ($p = 0.5$)

Figure 7. EWM Delivery Delay Comparison Between Multiplicative Rate Decreasing & Constant Rate Algorithm

The simulated scenario includes a road segment of 300 meters, with 5 lanes and 10 vehicles distributed on each lane. There are totally 50 vehicles and all of them are within each other's transmission range. The total number of co-existing AVs (M) varies from 5 to 50, where the occurrence rate of new AVs is 5 every 0.1 second. Each AV continuously sends EWMs until the end of the simulation. EWM warning from each AV is required to be delivered to all vehicles within the transmission range (it is upto each individual vehicle that receives the EWM warning to decide whether the EWM warning is relevant or not). The maximum EWM delivery delay among all AV-receiver pairs is measured. Figure 7 (a) shows the maximum EWM delivery delay when channel condition is relatively good (p = 0.9), while Figure 7 (b) presents the results with a poor channel condition (p = 0.5).

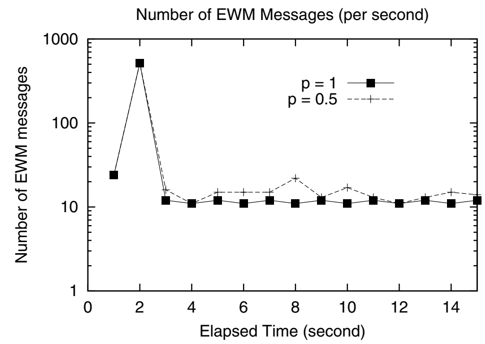
With 5 co-existing AVs, the network offered load resulting from EWM transmissions is low, implying a low message waiting time in the system. In addition, the degradation of retransmission delay using the proposed rate decreasing algorithm is quite insignificant, as we discussed in Section 4.2. Hence, both the multiplicative rate decreasing algorithm and the constant rate algorithm achieve low EWM delivery delay when M is small, as shown in Figures 7 (a) and (b). With the increase of co-existing AVs, however, the offered load using the constant rate algorithm increases rapidly, leading to fast growing message waiting time. Beyond 25 co-existing AVs, the total EWM arrival rate exceeds channel service rate, the system becomes unstable and the message waiting time increases dramatically. On the other hand, the rate decreasing algorithm controls the EWM transmission rate over time. When new AVs join, existing AVs have reduced their EWM transmission rates, leading to moderately increased network load. Consequently, with the increase of co-existing AVs, EWM delivery delay only increases slightly using the rate decreasing algorithm.

Similar results based on the analytical derivation have been presented in Figure 5. We can see that the simulation results in Figure 7 agree with our analytical results in Figure 5 on the general trend.

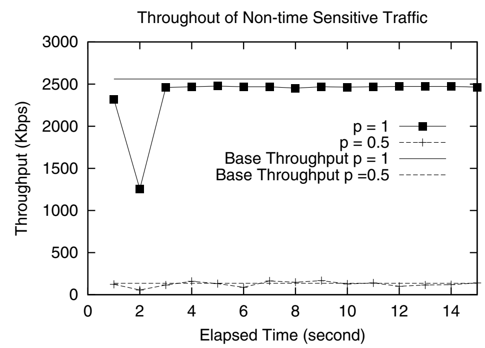
It is possible to decrease the EWM transmission rate used by the constant rate algorithm so that EWM delivery delay increases more slowly with the increase of co-existing AVs. However, due to the increased retransmission delay, it unnecessarily increases the EWM delivery delay when there are only a smaller number of co-existing AVs.

5.2. Elimination of Redundant EWMs

To show the effects of redundant EWM elimination, it is assumed that all AVs impose similar danger to the approaching vehicles. One 600 meter long road lane segment is simulated, and 60 vehicles equipped with wireless transceivers are evenly distributed on the road. Emergency event happens to the leading vehicle as soon as a simulation starts. To simulate the worst-case scenario, we let each trailing vehicle that received EWMs from the leading vehicle react with abrupt deceleration, and eventually stop in the lane. Thus, all trailing vehicles within the transmission range of the leading vehicle become AVs once they begin their reactions. Driver reaction time is randomly chosen over the range from 0.7 seconds to 1.5 seconds. Throughout the simulations, there exist two source stations that have constantly backlogged non-time-sensitive messages with packet size of 512 bytes.



(a) Number of EWMs (Per Second)



(b) Throughput of Non-time Sensitive Traffic (Per Second)

Figure 8. Elimination of Redundant EWMs

Figure 8(a) illustrates how the total number of EWMs from all AVs changes over time for two channel conditions ($p = 1$ and $p = 0.5$), where the number of EWMs is measured over each second. For example, the point at time 1 s in Figure 8(a) represents the total number of EWMs sent from time 0 s to 1 s.

At time 0 s, the leading vehicle becomes an AV, and starts to send EWMs. As the driver reaction time ranges from 0.7 seconds to 1.5 seconds, the number of EWMs surges from 1 s to 2 s when all the trailing vehicles located within the transmission range of the leading vehicle become AVs. Each AV transmits EWMs for at least T_{alert} (450 ms) duration, and then is qualified as a *non-flagger AV* if EWMs from a follower are overheard. As evident in Figure 8(a), redundant EWMs are effectively eliminated as the amount of EWMs drops significantly from time 2 s to 3 s. In the end, with perfect channel condition, only one AV remains transmitting EWMs at the rate of 10 messages/sec. When channel condition is bad, say $p = 0.5$, slightly more

EWMs may be transmitted from time to time, as shown in Figure 8(a).

The amount of channel bandwidth consumed by EWM messages can be revealed from the throughput loss of non-time-sensitive traffic. The throughput obtained by the non-time-sensitive traffic, which is also measured over each second, is shown in Figure 8(b). The curves marked as "base throughput" show the throughput obtained by non-time-sensitive traffic when there is no emergency event. Evidently, messages related to vehicular collision warning only consume significant channel bandwidth during a short period after the emergency event. Starting from time $3\ s$, non-time-sensitive traffic suffers very little throughput loss. When channel condition is bad, say $p = 0.5$, the relative throughput loss is even smaller comparing with $p = 1$ because the base throughput itself is very low with poor channel condition.

From above simulation results, we conclude that the proposed VCWC protocol can satisfy emergency warning delivery requirements and support a large number of co-existing AVs at the low cost of channel bandwidth.

6. Conclusion

This paper proposes a Vehicular Collision Warning Communication (VCWC) protocol to improve road safety. In particular, it defines congestion control policies for emergency warning messages so that a low emergency warning message delivery delay can be achieved and a large number of co-existing abnormal vehicles can be supported. It also introduces a method to eliminate redundant emergency warning messages, exploiting the natural chain effect of emergency events.

References

[1] Dedicated Short Range Communications (DSRC) Home. http://www.leearmstrong.com/DSRC/DSRCHomeset.htm.

[2] L. Briesemeister. *Group Membership and Communication in Highly Mobile Ad Hoc Networks*. PhD thesis, Technical University of Berlin, Germany, Nov 2001.

[3] L. Briesemeister and G. Hommel. Role-Based Multicast in Highly Mobile but Sparsely Connected Ad Hoc Networks. In *First Annual Workshop on Mobile Ad Hoc Networking & Computing (Mobihoc)*, August 2000.

[4] Z. D. Chen, H. Kung, and D. Vlah. Ad Hoc Relay Wireless Networks over Moving Vehicles on Highways. In *Proc. ACM Mobihoc'01*, 2001.

[5] I. Chisalita and N. Shahmehri. A Peer-to-Peer Approach to Vehicular Communication for the Support of Traffic Safety Applications. In *5th IEEE Conference on Intelligent Transportation Systems, Singapore*, pages 336–341, Sep. 2002.

[6] M. Green. "How Long Does It Take to Stop?" Methodological Analysis of Driver Perception-Brake Times. *Transportation Human Factors*, 2(3):195–216, 2000.

[7] H. Hartenstein, B. Bochow, A. Ebner, M. Lott, M. Radimirsch, and D. Vollmer. Position-Aware Ad Hoc Wireless Networks for Inter-Vehicle Communications: the Fleetnet Project. In *Proc. ACM Mobihoc'01*, 2001.

[8] L. Kleinrock. *Queuing Systems Volume I: Theory*. John Wiley & Sons, 1975.

[9] D. Lee, R. Attias, A. Puri, R. Sengupta, S. Tripakis, and P. Varaiya. A Wireless Token Ring Protocol For Ad-Hoc Networks. In *IEEE Aerospace Conference Proceedings*, March 2002.

[10] M. Lott, R. Halfmann, and M. Meincke. A Frequency Agile Air-Interface for Inter-Vehicle Communication. In *Proc. ICT 2003*, 2003.

[11] M. Lott, R. Halfmann, E. Schulz, and M. Radimirsch. Medium access and radio resource management for ad hoc networks based on UTRA TDD. In *Proc. ACM MobiHOC'01*, 2001.

[12] R. Meier, M.-O. Killijian, R. Cunningham, and V. Cahill. Towards Proximity Group Communication. In *Advanced Topic Workshop, Middleware for Mobile Computing, Heidelberg, Germany*, Nov. 2001.

[13] M. Meincke, M. Lott, and K. Jobmann. Reservation Conflicts in a Novel Air Interface for Ad Hoc Networks based on UTRA TDD. In *IEEE VTC 2003 Fall*, 2003.

[14] L. B. Michael and M. Nakagawa. Non-Platoon Inter-Vehicle Communication Using Multiple Hops. *IEICE Trans. Commun*, E82-B(10), October 1999.

[15] J. P. Singh, N. Bambos, B. Srinivasan, and D. Clawin. Wireless LAN Performance Under Varied Stress Conditions in Vehicular Traffic Scenarios. In *IEEE VTC 2002 Fall*, volume 2, pages 743–747, 2002.

[16] M.-T. Sun, W.-C. Feng, T.-H. Lai, K. Yamada, and H. Okada. GPS-Based Message Broadcast for Adaptive Inter-Vehicle Communications. In *IEEE VTC 2000*, 2000.

[17] R. Verdone. Multi-hop R-Aloha for inter-vehicle communication at millimeter waves. *IEEE Transaction on Vehicular Technology*, 46(4):992–1005, November 1997.

[18] C. D. Wang and J. P. Thompson. Apparatus and method for motion detection and tracking of objects in a region for collision avoidance utilizing a real-time adaptive probabilistic neural network, 1997. US.Patent No. 5,613,039.

[19] Q. Xu, R. Sengupta, and D. Jiang. Design and Analysis of Highway Safety Communication Protocol in 5.9 GHz Dedicated Short Range Communication Spectrum. In *IEEE VTC 2003 Spring*, 2003.

[20] X. Yang, J. Liu, F. Zhao, and N. H. Vaidya. A Vehicle-to-Vehicle Communication Protocol for Cooperative Collision Warning. Technical report, University of Illinois at Urbana-Champaign, Dec 2003.