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

Xue Yang, Jie Liu, Feng Zhao and Nitin H. Vaidya

***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.**

I. INTRODUCTION

Traffic accidents have been taking thousands of lives each year, outnumbering any deadly diseases or natural disasters. Studies [2] 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, as the following simplified example illustrates. In Figure 1, three vehicles, namely A, B, and C, travel in the same lane at the same speed of 80 miles/hour (i.e., 35 meters/second). Assume that at time t_0 the driver of A observes a road hazard and brakes abruptly. The driver of B notices the emergency by observing the brake light of A. In general, human drivers need time, typically in the range of 0.7 seconds to 1.5 seconds [3] to react to an emergency event. Suppose that the driver of B takes 1 second from seeing the brake light of A to stepping on the brake of vehicle B. Then accident is unavoidable if the distance between A and B is less than 35 meters[1]. Suppose that the driver of C cannot directly see the brake light from A. Then, driver C is not aware of the emergency until he/she sees the brake light from B, which is already 1 second after time t_0. Taking into account the reaction delay of driver C, say, 1 second, vehicle C will not begin to decelerate until two seconds after t_0. Consequently, the accident is unavoidable for C if the distance between B and C is less than 35 meters, or the distance between A and C is less than 70 meters.

Fig. 1. V2V helps to improve road safety

To summarize, 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[2].
- Large processing/forwarding delay for emergency events: Driver reaction time typically ranges from 0.7 seconds to 1.5 seconds [3], which results in large delay in propagating the emergency warning.

Above limitations result in large delay in propagating emergency warnings when depending on brake lights and human responses. Environmental conditions such as bad weather or curved roads may further impair human perception in cases of emergency.

Emerging wireless communication technologies are promising to significantly reduce the delay in propagating emergency warnings. The Dedicated Short Range Communications (DSRC) consortium[3] is defining short to medium range communication services that support both public safety and private operations in vehicle-to-roadside (V2R) and vehicle-to-vehicle (V2V) communication environments [1].

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 very 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 for cooperative collision warning among vehicles, wireless

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[1] Here, we assume that all three vehicles have the same deceleration capability.

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

[3] IEEE P1609 Working Group is proposing DSRC as IEEE 802.11p standard.

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. This paper identifies the application requirements for vehicular cooperative collision warning, and proposes a *Vehicular Collision Warning Communication* (VCWC) protocol to satisfy the application needs.

Contributions of this paper include:

- Identifying application requirements for vehicular cooperative collision warning.
- Achieving congestion control by developing rate adjustment algorithms for emergency warning messages based on the application requirements.
- Showing that the proposed protocol can satisfy application requirements without causing too much communication overhead, allowing cooperative collision warning application to share a common channel with other applications.

The rest of this paper is organized as follows. Application challenges for vehicular cooperative collision warning are discussed in Section II. Section III presents the related work. Section IV describes the proposed Vehicular Collision Warning Communication (VCWC) protocol. Performance evaluation using ns-2 simulator is presented in section V. Finally, the conclusions are drawn in section VI.

II. APPLICATION CHALLENGES

Fundamentally, there are two different ways to achieve cooperative collision warning: a *passive* approach and an *active* approach.

- Passive Approach: In the passive approach, all vehicles frequently broadcast their motion information (e.g. location, speed, and acceleration). It is the receiving vehicles' responsibility to determine the potential danger for itself. For example, in Figure 2, by receiving messages from vehicle A, vehicle N_3 may find that the inter-vehicle distance is below a certain threshold. N_3 then warns its driver of potential collision. This requires high-precision vehicle motion information, together with high refresh rate (i.e., the rate at which the messages are sent), to avoid false warning or missed warning.

- Active Approach: In the active approach, 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). Only when an abnormal event occurs, the correspondingly 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. For the example in Figure 2, it is vehicle A's responsibility to warn other vehicles when an abnormal event occurs at A.

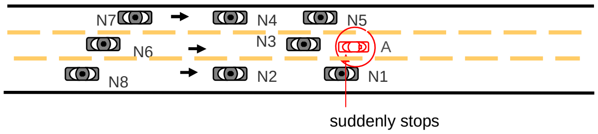

Fig. 2. An example scenario

In both approaches, it is essential for a vehicle to be aware of its own geographical location and its relative position on the road. But the passive approach requires a vehicle to constantly maintain *accurate* knowledge about the motion of *all* nearby vehicles, since all potential dangers are determined based on such knowledge. This requires very high frequency of motion update for *each* vehicle to compensate for poor communication environment and high mobility of the vehicle, which may make the wireless channel saturated all the time, even without any emergency event. The demanded high refresh rate of motion information may further introduce congestion to the vehicle network on crowded roads, which makes the passive approach failed to scale with the traffic density.

On the other hand, in the active approach, a vehicle determines the potential danger based on received warning messages. EWMs are sent only when emergency events actually happen, and are sent by a limited number of vehicles. Therefore, it is possible to provide reliable warnings to surrounding vehicles in time at the low cost of wireless channel bandwidth, through controlling the transmissions of EWMs.

In this paper, we focus on the active approach. Next, we analyze the challenges faced by the application for cooperative collision warning among vehicles.

A. 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 [4], 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. For example, the Signal to Noise Ratio can drop up to 20 dB for a vehicle moving at the speed of 30 miles per hour, comparing with the vehicles moving at much lower speed. 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, it is possible that 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.

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.

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

Furthermore, emergency road situations frequently have chain effects. For example, 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.

Observe that, at the time when an emergency occurs, the emergency warning needs to be delivered to all surrounding vehicles as soon as possible since 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. If radio transmission range is large enough, an approaching vehicle can tolerate a relatively long delivery delay since its distance to the AV is large. The delay relaxation over a longer period makes it possible for the vehicular collision warning communication protocol to satisfy EWM delivery delay requirements and to support a large number of co-existing AVs.

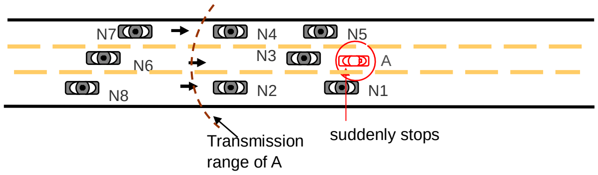

Fig. 3. Approaching Vehicles

For example, in Figure 3, N_3 is quite close to A when the emergency happens. To give enough time for N_3 to completely stop before crashing into A, the delivery delay of the emergency warning has to be as small as possible (e.g. in the order of a few milliseconds). On the other hand, N_6 enters the transmission range of A some time later. 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.

C. 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. For example, in Figure 4, if A suddenly stops, N_3 must react with an abrupt deceleration. On the other hand, if N_5 in another lane suddenly stops, N_3 can keep on moving as long as its trajectory does not interfere with N_5's.

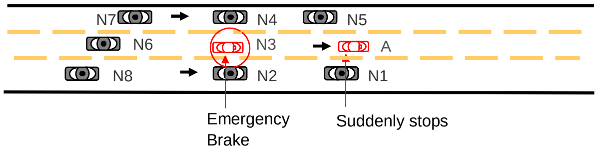

Fig. 4. N_3 reacts to sudden stop of vehicle A with emergency brake

Another slightly complicated example is shown in Figure 5. 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. Furthermore, 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.

On the other hand, as we discussed in Section II-B, an emergency road situation frequently has chain effects. If multiple AVs reacting to an emergency event occupy the same lane and impose similar danger to the approaching vehicles, such as vehicles N_3 and A stopped in the middle of a road in Figure 4, from the viewpoint of vehicle A, vehicle N_3 shields it from all vehicles behind. In such a case, there is no

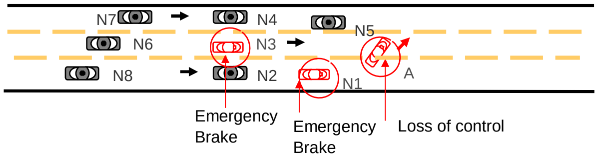

Fig. 5. Multiple AVs following different trajectories

need for A to continue sending redundant EWMs 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.

Even though emergency events can be differentiated based on moving trajectories of vehicles, abnormal vehicles may not follow any predictable trajectory in the cases of emergency. Moreover, various reactions from drivers can be expected in real life. In the example of Figure 4, 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.

III. RELATED WORK

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

In [5], 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. Since the members of the platoon change infrequently, a token ring protocol can be used to provide bounded latency and reserved bandwidth for each vehicle. However, for the application using cooperative collision warning to improve road safety, non-platoon scenarios appear more often. The relative position among vehicles and the group of affected vehicles when emergency occurs change fast, which limits the applicability of WTRP. A slot-reservation MAC protocol, R-ALOHA, for inter-vehicle communication is discussed in [6].

The Fleetnet Project [7] aims at developing ad hoc networks for inter-vehicle communications and for data exchange between moving vehicles and fixed roadside gateways. UMTS Terrestrial Radio Access with Time Division Duplexing (UTRA-TDD), which supports communication range of more than 1 km, is adopted by Fleetnet as the radio interface. Supported by such large communication range, [8], [9], [10] propose the slot reservation MAC protocols.

Xu *et. al.* discuss a vehicle-to-vehicle Location-Based Broadcast communication protocol, in which each vehicle generates emergency messages at a constant rate [11]. The optimum transmission probability at MAC layer for each message is then identified to reduce the packet collision probability and the channel occupancy of emergency messages, given the constant sending rate of emergency messages.

Message forwarding can help warning message reach vehicles beyond the radio transmission range or vehicles within the communication dead angle. In [12], the authors discuss the importance of message forwarding in non-platoon inter-vehicle communication and proposes 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 [13]. To quickly spread messages, receivers that are far away from the sender can forward the message faster. Motion properties of vehicles are exploited in [14] to help with message relay. Two protocols to reduced the amount of forwarding messages were proposed in [15]. One protocol makes use of the relative position information among vehicles to eliminate redundant message forwarding. Another protocol inserts random waiting time before each forwarding, and a vehicle determines if its message forwarding can be dropped or not when the waiting time expires.

When an emergency event occurs, there are usually a group of vehicles affected by the abnormal situation. In terms of group management, [16] defines so called “proximity group” based on the location and functional aspects of mobile hosts; [17] defines a “peer space”, in which all traffic participants share a common interest; [18] 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 II, 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. It also discusses how to exploit the natural chain effect of emergency events to eliminate redundant EWM messages, while ensuring continuous coverage of EWMs for each endangered region. The detail of the proposed VCWC protocol is discussed below.

IV. VEHICULAR COLLISION WARNING COMMUNICATION PROTOCOL

The goal of vehicular collision warning communication is to provide emergency warnings to *all potentially endangered* vehicles so that they can respond to emergency events as early as possible to avoid possible accidents.

When a vehicle on the road acts abnormally, e.g., deceleration exceeding a certain threshold, dramatic change of moving direction, etc., it becomes an AV. A vehicle can become an 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. For example, a vehicle decelerating abruptly in response to an AV ahead becomes an AV itself. In general, the abnormal behavior of a vehicle can be detected using various sensors within the vehicle. Once an AV resumes it regular movement, the vehicle is said no longer an AV and it returns back to the normal state. 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 an EWM message can verify the relevancy to the emergency event and give audio or visual warnings/advice to the driver. Since EWMs sent by an AV include the geographical location, speed, acceleration and moving direction of the AV, relevancy to the emergency event can be determined by a vehicle based on its relative motion to the AV upon receiving EWMs. To avoid all potential accidents, the emergency warning sent by each individual AV is required to be delivered to the surrounding vehicles, where a emergency warning from an AV A is said to be delivered to a vehicle V if any of EWMs sent by A is received by V. Whenever multiple AVs impose similar danger to the surroundings, we endeavor to eliminate redundant EWMs among them.

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.

The proposed VCWC protocol primarily includes the following components:

1) A message differentiation mechanism that enables cooperative vehicular collision warning application to share a common channel with other non-safety related applications.
2) Congestion control policies, which consist of the following two sub-components:
    - An EWM transmission rate decreasing algorithm to satisfy EWM delivery delay requirements and support a large number of co-existing AVs.
    - A state transition mechanism for AVs, which may increase or decrease the EWM transmission rate based on the state of the AV, to eliminate redundant EWMs as well as ensure continuous coverage of EWMs for each endangered region.
3) Emergency warning dissemination methods that make use of both natural response of human drivers and EWM message forwarding.

A. Assumptions

Before describing the details for each component of VCWC, we first clarify 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 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.
- The vehicle-to-vehicle communication channel may be shared by multiple applications, as suggested by DSRC. Therefore, we assume that a common channel is shared by non-time-sensitive messages (e.g. road traffic collection) and time-sensitive safety related collision warning messages.
- As suggested by DSRC, the transmission range of safety related vehicle-to-vehicle messages is assumed to be 300 meters.
- All vehicles sharing the common channel use IEEE 802.11 contention based multi-access control. Further interactions between MAC and the proposed protocol are discussed in Section IV-B.

The proposed protocol does not require all vehicles are equipped with wireless transceivers. Even a small percentage of equipped vehicles can bring benefits to all vehicles on the road.

B. Message Differentiation

The proposed VCWC protocol uses EWM messages to keep the vehicles close to the AV alert when emergency events occur. When a vehicle receives EWMs, it may choose to forward the emergency warning, thus, generating Forwarded EWM Messages (We will further elaborate on EWM forwarding in Section IV-F.).

Compared with Forwarded EWM Messages, EWMs have more stringent delivery delay requirement in providing timely vehicular collision warning. At the same time, non-time-sensitive messages from other applications can also contend for the same channel. Corresponding to their different delay requirements, three classes of messages are defined, where class 1 messages have the highest priority to be transmitted and class 3 messages have the lowest priority:

- Class 1: Emergency Warning Messages (EWMs);
- Class 2: Forwarded EWM Messages;
- Class 3: Non-time-sensitive messages.

One necessary condition for the support of priority division is that underlying MAC protocol should provide service differentiation among different classes of messages. As an extension to IEEE 802.11, 802.11e EDCF (Enhanced Distributed Coordinated Function) [19] provides such a function.

In 802.11, a vehicle wanting to access the channel has to wait the channel to be idle for an "interframe space" (IFS) duration. After that, a backoff procedure is invoked and a backoff counter is randomly chosen from the range of [0, CW] (CW represents the *contention window* size). This backoff counter corresponds to the number of *idle slots* the sender has to wait before accessing the channel. The contention window size, CW, has a minimum value CW_{min} and is exponentially increased by a factor of 2 each time a packet collision happens, until it reaches the maximum value, denoted by CW_{max}. In wireless networks, a packet collision is usually detected through the acknowledgment from the receiver. Since there is no collision detection for broadcast messages, the effective contention window size for broadcast messages is CW_{min}.

In 802.11e EDCF [19], different levels of channel access priorities can be provided through different choices of IFS and contention window sizes. In particular, messages with higher priority can enjoy the channel access privilege over lower priority messages by using a smaller IFS or a smaller contention window.

802.11e EDCF provides probabilistic channel access preference to higher priority messages. Further study in [20] reveals that, in some situations, priority reversal may happen and higher priority messages may lose channel access to messages with lower priorities using schemes like 802.11e EDCF. Considering that EWMs have very stringent delivery delay requirement, mechanisms that either uses out-of-band busy tone signal [20] or in-band black burst [21] can be employed to ensure the channel access privilege of EWM messages.

Through message differentiation, not only higher priority messages can access channel faster than lower priority messages, but also collisions between higher and lower priority messages are avoided to a large extent, which together contribute to the fast delivery of safety related EWMs and Forwarded EWM Messages used by the proposed VCWC protocol.

C. Congestion Control of EWMs

As EWMs are defined as class 1 messages with the highest priority and can typically access channel before other messages with lower priorities do, for the present, let us ignore the channel contention between EWMs and class 2, 3 messages, focusing on the transmissions of EWMs alone.

To ensure reliable delivery of emergency warnings over unreliable wireless channel, EWMs need to be repeatedly transmitted at a certain rate. Conventionally, to achieve network stability, congestion control has been used to force transport connection to obey "conservation of packets" principle, namely, a new packet is not put into the network until an old packet leaves [22]. Particularly, the transmission rate is adjusted 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.

In vehicular collision warning communication, the transmission rate of EWM also needs to be adjusted to achieve low latency for the delivery of emergency warnings in various situations. An EWM message encounters some *waiting time* in the system due to queueing delay, channel access delay, etc.. After an EWM is transmitted, it may not be received correctly by an intended receiver due to poor channel condition or packet collisions. As the emergency warning cannot be delivered until another EWM is transmitted, the inter-transmission duration of EWMs contributes to the *retransmission delay* for the delivery of a emergency warning. An EWM delivery delay is determined by both the waiting time and the retransmission delay. If EWM transmission rate is chosen to be inappropriately high, with the presence of multiple co-existing AVs, the network may be heavily loaded and the waiting time in the system may be large. On the other hand, if EWM transmission rate is chosen to be very low, the retransmission delay will be large, which dominates the EWM delivery delay.

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 controlling channel congestion.

1) Decrease of EWM Transmission Rate: Observe that, even though the number of co-existing AVs (i.e., their existences overlap in time and their transmissions interfere with each other) can be large, the number of *new* AVs that occur within a very short period of time (say, less than 100 milliseconds) is typically small. Furthermore, at the time when an emergency event occurs, it is desirable to deliver the emergency warning to all nearby vehicles as soon as possible. As time goes by, however, the EWM delivery delay to approaching vehicles can be relaxed to some extent as we discussed in Section II-B. Hence, it is possible to satisfy the EWM delivery delay requirements and to support a large number of co-existing AVs at the same time by gradually decreasing the EWM transmission rate. In addition, by decreasing EWM transmission rate over time, the AVs associated with the most recent emergency events implicitly gain priority in utilizing the channel.

The rate decreasing algorithm is discussed in detail in Section IV-D.

2) State Transitions of AVs: Each AV may in be one of the 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 IV-D. An *initial AV* can become a *non-flagger AV*, refraining from sending EWMs contingent on some conditions to eliminate redundant EWMs. While *non-flagger AVs* rely on EWMs from other AVs to warn the approaching vehicles, the state of a vehicle often changes due to dynamic road situations. In some cases, it is necessary for a *non-flagger AV* to become a *flagger AV*, resuming EWM transmissions at the minimum required rate.

State transitions of AVs are elaborated in Section IV-E.

D. Rate Decreasing Algorithm for EWMs

The rate decreasing algorithm helps to achieve low EWM delivery delay at the time of an emergency event, with the presence of a large number of co-existing AVs. The key issue is to determine how the EWM transmission rate should be decreased over time.

An EWM message may encounter some waiting time in the system due to queueing delay, channel access delay, etc., and it may also suffer from retransmission delay due to poor channel conditions or packet collisions. 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. 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 6.

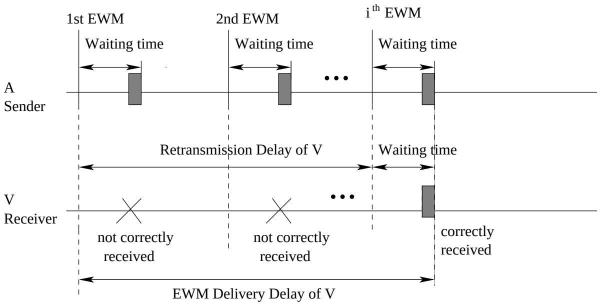

Fig. 6. Waiting Time and Retransmission Delay

By definition, EWM delivery delay from A to V is the elapsed duration from the time the emergency occurs at A to the time the first corresponding EWM message is successfully received by V, hence, EWM delivery delay ($Delay$) can be represented as

$$Delay = Delay_{wait} + Delay_{retransmission} \tag{1}$$

If EWM transmission rate 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. In other words, the faster each AV decreases its EWM transmission rate, the more co-existing AVs can be supported before the network becomes unstable. On the other hand, if EWM transmission rate is decreased too quickly, the retransmission delay may become large, dominating the EWM delivery delay.

A multiplicative rate decreasing algorithm is used by the proposed VCWC protocol[4]. Specifically, an AV in the *initial AV* state starts to transmit EWMs at a high rate λ_0, and EWM transmission rate is decreased over time until the minimum rate λ_{min} is reached[5]. Let the EWM transmission rate of an AV after the k^{th} transmitted EWM be $f(\lambda_0, k)$, then

$$f(\lambda_0, k) = max\left(\lambda_{min}, \frac{\lambda_0}{a^{\lfloor \frac{k}{L} \rfloor}}\right) \tag{2}$$

In other words, the EWM transmission rate is decreased by a factor of a after every L transmitted EWMs.

In order to determine an appropriate value for parameter a, we derived simplified analysis, which is presented in the Appendix, to calculate how the EWM delivery delay changes with the number of co-existing AVs using various choices of a. The results show that $a = 2$ is adequate in achieving low EWM delivery delay for a wide range of co-existing AVs. Simulation results in Section V also suggests that this choice of a is acceptable in achieving low EWM delivery delay and supporting a large number of co-existing AVs.

The benefits of using multiplicative rate decreasing algorithm with $a = 2$, as opposed to using a constant rate algorithm that transmits EWMs at the rate λ_0 (i.e., a special case with $a = 1$), are illustrated in Figure 7 based on the analysis[6].

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 chain effects of emergency events, it is not uncommon that more than 25 co-existing AVs may appear.

When M is very small, the waiting time is negligible and EWM delivery delay is mainly determined by the retransmission delay. From EWM delivery delays associated with small values of M shown in Figure 7, we can see that degradation of the retransmission delay is insignificant. Let p represent the probability for an EWM message being correctly

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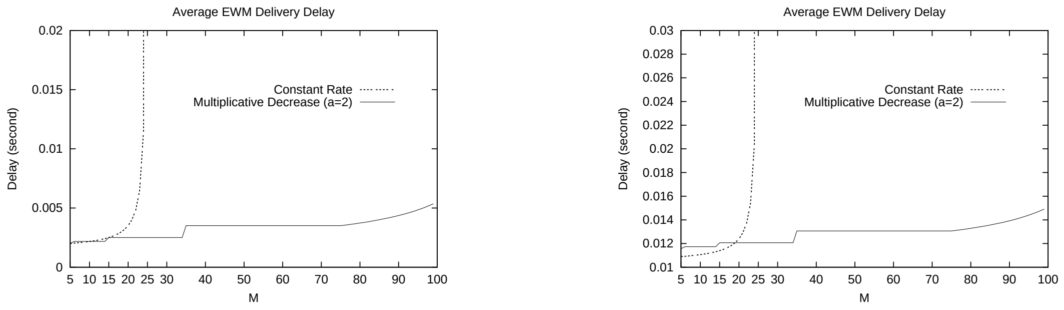
[4] We also examined the additive rate decreasing algorithm. Our results showed that, constrained by the initial EWM transmission rate λ_0 and the minimum rate λ_{min}, both of them can achieve similar results with properly chosen parameters. In this paper, we only report on the multiplicative rate decreasing algorithm for brevity.

[5] 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.

[6] To obtain the numerical results, we have assumed that the wireless channel can serve about 2500 EWMs per second, λ_{min} is 10 messages/sec and one new AV occurs every 10 ms. The value of λ_0 is set to 100 messages/sec and L is set to 5. Later in Section V, the choices of these parameters will be further discussed.



(a) p = 0.9

(b) p = 0.5

Fig. 7. EWM Delivery Delay vs. M

received by a vehicle. Figures 7 (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 retransmission delay using the rate decreasing algorithm with $a = 2$ 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. As most practical scenarios have less than 100 co-existing AVs, the proposed VCWC protocol employs the multiplicative rate decreasing algorithm with $a = 2$.

E. 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. The state transition diagram is illustrated in Figure 8, and the various state transitions are explained in the rest of this section.

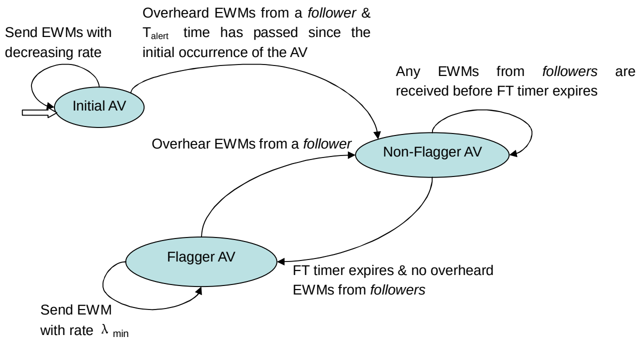


Fig. 8. State transition diagram

Recall that each AV may be in one of the three states, *initial AV*, *non-flagger AV* and *flagger AV*. In the *initial AV* state, an AV starts to transmit EWMs at rate λ_0 and the rate is decreased over time using the rate decreasing algorithm discussed above; in the *flagger AV* state, an AV repeats EWMs at the minimum rate λ_{min}; and in the *non-flagger AV* state, an AV does not send any EWMs.

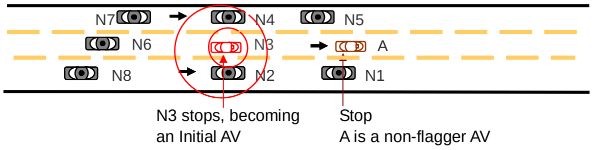
Transition from *initial AV* state to *non-flagger AV* state: An AV in the *initial AV* state can further reduce its EWM transmission rate down to zero, becoming a *non-flagger AV*, contingent on the following two conditions:

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.

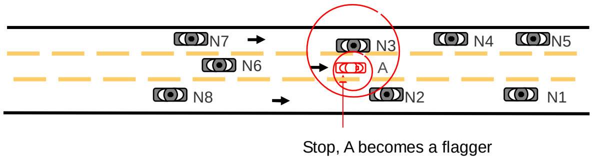
2) EWMs from one of the "followers" of the initial AV are being overheard; here, we define vehicle X as a "follower" of vehicle Y, if X is located behind Y in the same lane and any vehicle endangered by Y may also be endangered by X.

Reducing the EWM transmission rate of an AV to zero serves the purpose of eliminating redundant warning messages. One such example occurs when many AVs reacting to an emergency stop in the middle of a highway lane. As shown in the example in Figure 9 (a), vehicle A malfunctions and stops. The trailing vehicle N_3 reacts and also stops. As A and N_3 impose similar danger to any vehicle approaching this region, using the 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. Therefore, 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.

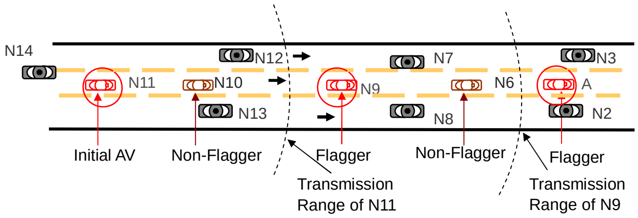
Transitions between *non flagger AV* state and *flagger AV* state: An AV in the *non-flagger AV* state sets a timer for a Flagger Timeout (FT) duration. If it does not receive any EWMs from its followers when the FT timer expires, the *non-flagger AV* changes its state to *flagger AV*, transmitting EWMs at the minimum rate λ_{min}. Otherwise, it simply resets the FT



(a) N3 sends EWM and A becomes a non-flagger AV



(b) N3 drives away; A identifies itself as a flagger



(c) Full coverage of endangered region

Fig. 9. Example for *non-flagger AVs* and *flagger AVs*

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*.

Continuing our example in Figure 9: at this point of time, N_3 is an *initial AV* and A is a *non-flagger AV* (Figure 9 (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 9 (b).

The situation involving several reacting AVs is illustrated in Figure 9 (c). The last AV in a “piled up” lane, vehicle N_{11} in this example, is an *initial AV* and sends EWMs since there is no AVs behind. 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.

The *last* AV in a “piled up” lane 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), and an AV starts to generate its own EWMs if no EWMs from its followers are overheard when its FT timer expires. Therefore, the longest time period during which no EWMs are transmitted to a vehicle since it enters the transmission range of an AV is $2FT$[7]. By choosing an appropriate value for FT based on the radio transmission range, maximum speed of vehicles, deceleration capability of vehicles and channel conditions, 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 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.

Summary of the state transition mechanism: As illustrated in Figure 8, when an emergency event initially occurs, the associated vehicle enters *initial AV* state and repeatedly sends EWMs following the rate decreasing algorithm described in Section IV-D. An AV changes from an *initial AV* to a *non-flagger AV*, contingent on two conditions: first, T_{alert} time duration has elapsed since the initial occurrence of the AV; second, EWMs from one of the followers are overheard. A *non-flagger AV* changes to a *flagger AV* if no EWM from its followers is overheard when FT timer expires. Due to dynamic road situations and variation of channel conditions, an AV may transit between the states of *non-flagger AV* and *flagger AV*.

F. *Emergency Warning Dissemination*

Emergency warning dissemination helps to deliver emergency warnings to the affected vehicles located in the communication dead angle or beyond the radio transmission range. Even though it is beneficial to disseminate emergency warnings, it is also necessary to limit the dissemination range because disseminating emergency warnings indiscriminately would have no significant benefit in terms of ensuring driving safety and could disturb the normal traffic flow.

Upon receiving emergency warning from an AV ahead, the drivers of the trailing vehicles may decelerate abruptly

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[7] 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.

if they determine that their vehicles are in danger. If the deceleration exceeds the threshold for detecting abnormal status of vehicles, the trailing vehicles themselves also become abnormal vehicles, generating EWMs of their own. Hence, abrupt reactions from the endangered drivers lead to a natural way of disseminating the emergency warnings.

From another perspective, abrupt reactions from the trailing vehicles of an AV cause new emergency events and can further endanger unprepared vehicles behind them. For example, in Figure 10, vehicles N_9 and N_{10} are out of the transmission range of vehicle A. Suppose A suddenly brakes and begins to send EWMs. If vehicle N_6 reacts with abrupt deceleration upon receiving the emergency warning from A, and vehicles N_9 and N_{10} are totally unprepared for such response from N_6, vehicles N_9 and N_{10} are put in danger by the abrupt reaction from N_6. On the other hand, if EWMs originated from vehicle A can be forwarded to N_9 and N_{10}, and if delay associated with message forwarding is small, then vehicles N_9, N_{10} can be aware of the emergency event occurred at vehicle A early and be prepared for the possible abrupt reaction from N_6.

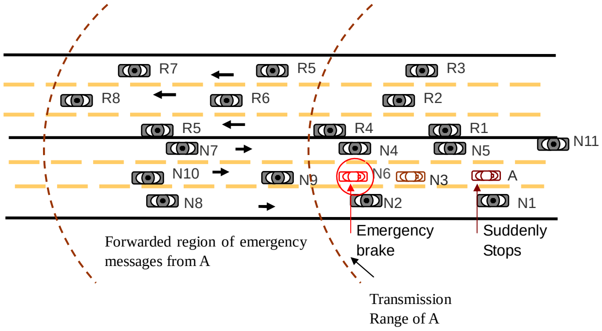

Fig. 10. EWM message forwarding

Therefore, two forms of emergency warning dissemination are undertaken in the proposed VCWC protocol. The first one relies on the natural responses of drivers. When the driver of a vehicle endangered by an AV decides to take an abrupt reaction, the vehicle becomes a new AV, generating its own EWMs. The second form of emergency warning dissemination relies on Forwarded EWM Messages. That is, EWMs originated from each individual AV are forwarded up to a certain distance. For example, in Figure 10, abnormal vehicle A initiates EWMs upon emergency. All vehicles that receive EWMs from vehicle A, including N_3 and N_6, may forward EWMs from A regardless of their drivers' reactions toward the emergency event occurred at vehicle A. At the same time, if some vehicles, say N_3 and N_6, react abruptly, then they become abnormal vehicles (AVs) and generate their own EWMs as well.

Various message forwarding methods, e.g., the methods discussed in [13], [14] and [15], can be applied here to enable efficient forwarding of EWMs. The contribution of this paper with regard to emergency warning dissemination lies in the following observation. Assume that an AV can only cause hazards to vehicles located no more than S distance away (equivalently, a rational driver will *react abruptly* only if the vehicle is no more than distance S away from an AV). In addition, the maximum travel distance of a vehicle during driver reaction time is assumed to be D. Then it is sufficient to forward EWMs from each individual AV to vehicles that are no more than distance $S+D$ away from the AV by taking advantage of the judgment of the drivers. The reason is that, for a vehicle that is less than $S+D$ but more than S away from the AV, it normally will decelerate *gradually* upon receiving the forwarded emergency warning. As one of the results, its trailing vehicles will also be slowed down, hence, be prepared for the emergency event ahead implicitly.

Further dissemination of emergency warning stops if no new reacting AV appears. Since all vehicles affected by the existing AVs have been informed and no abruptly reacting vehicles appear to cause new hazards, there is no benefit to disseminate the emergency warning any further.

Being categorized as class 2 messages, Forwarded EWM Messages have higher priority in accessing channel than class 3 non-time-sensitive messages from other applications. At the same time, Forwarded EWM Messages yield channel access to more time-critical class 1 EWM messages. Later, we use simulation results to show that, the proposed VCWC protocol not only provides fast delivery of EWMs, but also enables the timely delivery of Forward EWM Messages despite of the presence of aggressive non-time-sensitive low priority messages.

In summary, the goal of VCWC protocol is to provide emergency warnings to all potentially endangered vehicles so that they can respond to emergency events as early as possible to avoid possible accidents. The correctness of the protocol in fulfilling the goal is supported by the following factors:

- Even in very stressful scenarios with many co-existing AVs, VCWC protocol can still support low EWM delivery delays at the time of emergency using the multiplicative rate decreasing algorithm.
- Each AV repeats EWMs for at least T_{alert} duration, which, with very high probability, ensures that all its surrounding vehicles receive the emergency warning at the time of emergency.
- To warn any approaching vehicle in the future, among AVs imposing similar danger to the surroundings, the *flagger AVs* and *initial AVs* ensure that all the endangered regions are covered with EWMs in various road situations. On the other hand, AVs creating different dangers are responsible for sending their own EWMs. Therefore, any vehicle approaching a dangerous region will get the corresponding emergency warning.
- With unreliable wireless communication, more flaggers than necessary may appear. This only results in more transmitted EWMs and has no impact on the correctness of the protocol.
- All vehicles affected by an emergency event will receive the emergency warning in time through emergency warn-

ing dissemination.

V. PERFORMANCE EVALUATION

The proposed VCWC protocol is implemented using ns-2 network simulator [23]. 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 the 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 (class 1 message), 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. To give channel access priority to class 2 messages over class 3 messages, a smaller minimum contention window size (size 7) is applied to class 2 messages, while class 3 non-time-sensitive messages use minimum contention window size of 31.

Assuming that a rational driver will react abruptly only if the vehicle is no more than 300 meters away from an AV and the maximum vehicle travel distance during driver reaction time is less than 300 meters (i.e., $S = 300$ meters and $D \leq 300$ meters in Section IV-F), each EWM is forwarded up to 600 meters. To reduce the amount of Forwarded EWM Messages, methods similar to the ones introduced in [15] are used. That is, a certain forwarding region is defined based on the relative positions of vehicles to the AV. Only vehicles located within the forwarding region will generate Forwarded EWM Messages. Before sending a Forwarded EWM Message, a vehicle waits for a random duration. If the same message from other vehicles are overheard before the waiting time expires, the vehicle drops the forwarding.

From empirical data [24], 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.

A. Parameters for the Rate Decreasing Algorithm

EWM delivery delay is the most important metric in the context of vehicular collision warning communication, and the multiplicative rate decreasing algorithm in the proposed VCWC protocol plays an important role in providing low EWM delivery delay. In the multiplicative rate decreasing algorithm, an AV sends EWMs at the initial rate of λ_0, and the rate is halved after every L transmitted EWMs until it reaches λ_{min}. We first use simulations to identify appropriate choices for λ_0 and L.

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 simulation starts with 5 AVs, and then 5 more vehicles become AVs every 0.1 second, leading to 50 AVs eventually. In addition, each AV continuously sends EWMs until the end of the simulation. Recall that EWM delivery delay from an AV to a vehicle is defined as the elapsed duration from the time the emergency event occurs at the AV to the time a corresponding EWM message is firstly successfully received by the vehicle. One common receiving vehicle is used to measure the EWM delivery delay for all AVs, where the maximum EWM delivery delay among all AVs is presented.

For various channel conditions[8], Figure 11 (a) shows how the maximum EWM delivery delay changes with L when λ_0 is fixed at 100 messages/sec, and Figure 11 (b) shows the maximum EWM delivery delay vs. λ_0 when L is fixed at 5.

Simulation results in Figure 11 show that the combination of $L = 5$ and $\lambda_0 = 100$ messages/sec performs well in terms of providing low EWM delivery delay in such a stressful scenario. Despite of the presence of 50 co-existing AVs, all emergency warnings can be delivered within a few milliseconds when channel condition is relatively good, and the maximum EWM delivery delay is less than 70 milliseconds even with a poor channel condition ($p = 0.5$).

Smaller values of L result in faster decrease of EWM transmission rate, which in turn, contributes to larger retransmission delay when channel condition is bad. On the other hand, EWM transmission rate is decreased more slowly using larger values of L, and the average waiting time in the system becomes large with 50 co-existing AVs, dominating the EWM delivery delay. Similarly, higher values of λ_0 leads to increased waiting time, while lower values of λ_0 leads to an increased retransmission delay.

B. EWM Delivery Delay

As we discussed in Section III, prior related work has focused on different issues from this paper, which makes direct performance comparison difficult. Below, to show the benefits of the multiplicative rate decreasing algorithm used by the proposed VCWC protocol, we show the obtained EWM delivery delay in comparison with the constant rate algorithm that transmits EWM at the rate λ_0, where λ_0 used by both algorithms is 100 message/sec and L used by the multiplicative rate decreasing algorithm is 5 as we identified in Figure 11.

Simulation scenarios are similar to the one used in Section V-A, but the total number of co-existing AVs (M) varies from 5 to 50. Figure 12 (a) shows the results when channel condition is relatively good (p = 0.9), while Figure 12 (b) shows 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 IV-D. 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 12 (a) and (b).

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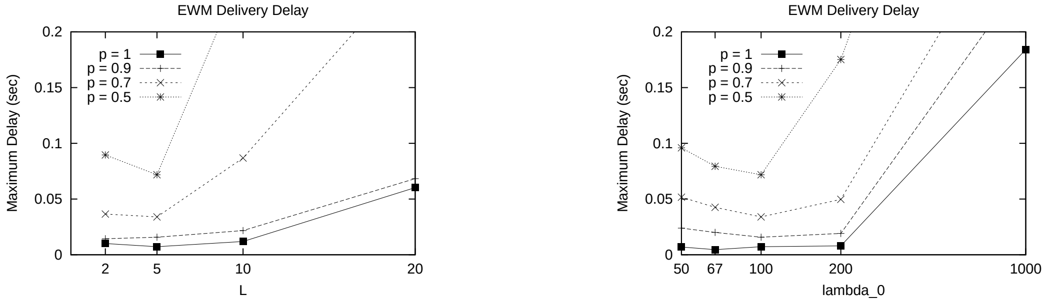
[8] Recall that p represents the probability for an EWM message being correctly received by a vehicle.



(a) EWM Delivery Delay vs. L (λ_0 = 100 messages/sec)

(b) EWM Delivery Delay vs. λ_0 (L = 5)

Fig. 11. EWM Delivery Delay with M = 50

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.

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.

C. *Properties of the Proposed VCWC Protocol*

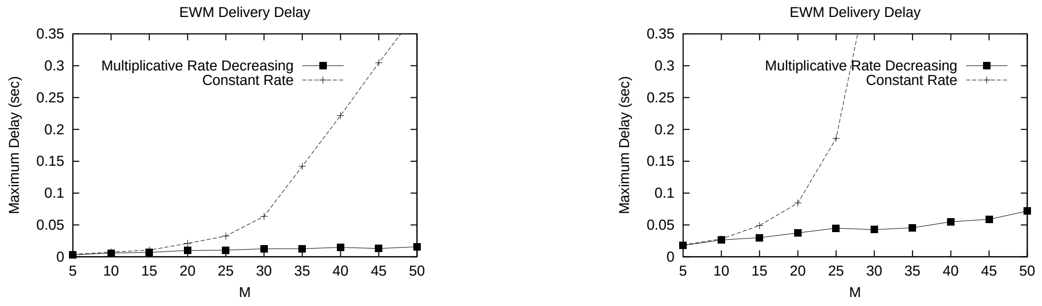
To show various properties of the proposed VCWC protocol, we simulate one road lane segment that is 600 meter long. EWMs from an AV are forwarded to vehicles that are no more than 600 meters away from the AV. V_n vehicles equipped with wireless transceivers are assumed to be evenly distributed on the road. A small value of V_n indicate a sparse vehicle network, while large values of V_n indicate dense vehicle networks. In order to forward EWMs, at least two vehicles per transmission range are required (i.e., $V_n = 4$). 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.

The Forwarded EWM Message delivery delay for a vehicle is measured as the elapsed duration from the time the emergency event occurs at the AV where EWMs originate to the time the first Forwarded EWM Message is successfully received by the vehicle. Figure 13(a) presents the maximum Forwarded EWM Message delivery delay over all vehicles that are out of the transmission range of the leading vehicle. It can be seen that the Forwarded EWM Message delivery delay largely depends on the density of vehicles equipped with wireless transceivers. The less the density, the larger the delay. When the vehicle network is reasonably dense, the delivery delay for the Forwarded EWM Messages is less than 100 ms in various channel conditions, despite of the existence of aggressive non-time-sensitive traffic, which demonstrates that the message differentiation mechanism defined in VCWC protocol can indeed support service differentiation and satisfy the vehicular collision warning requirements.

To show the effects of redundant EWM elimination, it is assumed that all AVs impose similar danger to the approaching vehicles. Figure 13(b) 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 13(b) 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 because 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 13(b), 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 13(b).

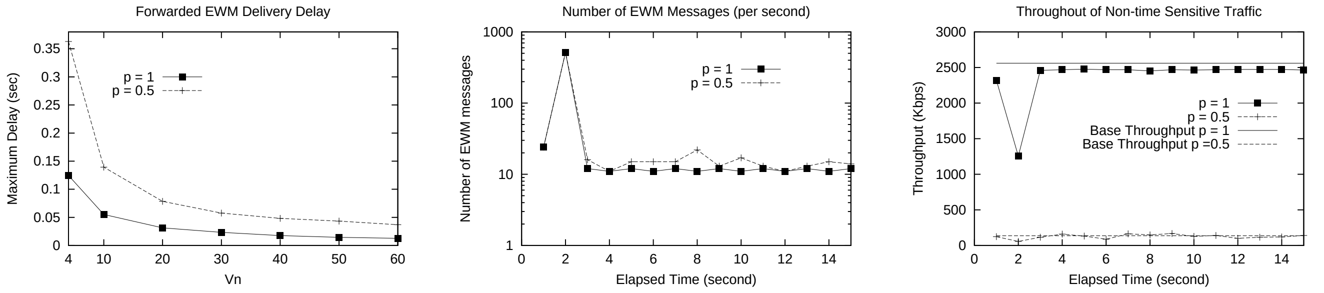
The throughput obtained by the non-time-sensitive traffic,



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

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

Fig. 12. EWM Delivery Delay Comparison Between Multiplicative Rate Decreasing & Constant Rate Algorithm



(a) Forwarded EWM Message Delivery Delay

(b) Number of EWMs (Per Second)

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

Fig. 13. Properties of VCWC Protocol

which is also measured over each second, is shown in Figure 13(c). 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.

VI. 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 introduces a method to eliminate redundant emergency warning messages, exploiting the natural chain effect of emergency events. It also enables the cooperative collision warning application to share a common channel with other applications using service differentiation mechanisms.

APPENDIX

In the rate decreasing algorithm described in Section IV-D, an *initial AV* starts to transmit EWMs at a rate of λ_0, and decreases the EWM transmission rate by a factor of a after every L transmitted EWMs until it reaches the minimum rate λ_{min}. Below, simplified analysis is presented to determine a suitable value for a. Simulation results in Section V suggest that this choice of a is acceptable in achieving low EWM delivery delay and supporting a large number of co-existing AVs.

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

$$Delay_{retransmission} = \sum_{i=2}^{\infty} (1-p)^{i-1} * p * \left(\sum_{j=1}^{i-1} \frac{1}{f(\lambda_0, j)} \right) \qquad (3)$$

To account for the message waiting time in the system, let the EWM arrival 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 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

$$Delay_{wait} = \frac{1}{\mu - \lambda} + \frac{1}{\mu} \tag{4}$$

if the FCFS (First Come First Serve) service order is applied [25]. 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 as follows.

Proof: Let R represent the residue service time on the channel and $E[N]$ represent the average number of packets waiting in the system, then the average waiting time for an arrived packet P_θ is

$$Delay_{wait} = R + \frac{1}{\mu} + \frac{E[N]}{2} * \frac{1}{\mu} + \frac{\lambda Delay_{wait}}{2} * \frac{1}{\mu}$$

where the second item accounts for the channel service time for P_θ itself, the third item accounts for the fact that, on average, there are $E[N]$ packets in the system by the time P_θ arrives. Since each packet is served with equal probability, on average, half of them will be served before P_θ. The last item accounts for the fact that during the waiting time of P_θ, $\lambda Delay_{wait}$ new packets would arrive. Again, because of the random service order, half of the new arrived packets will be served before P_θ. By little's law, we have $E[N] = \lambda Delay_{wait}$. Therefore, $Delay_{wait} = R + \frac{1}{\mu} + E[N] * \frac{1}{\mu}$, which is exactly the average waiting time representation for FCFS service order.

■

Finally, we can calculate the EWM delivery delay ($Delay$) by adding $Delay_{wait}$ and $Delay_{retransmission}$ together, as equation 1 shows. In obtaining the numerical results in Figure 7, we have assumed that channel service rate μ is 2500 messages/sec, which roughly equals to the channel service rate in our simulations. λ_{min} is set to 10 messages/sec, λ_0 is set to 100 messages/sec and L is set to 5 (the choices for these parameters are justified in Section V). The total EWM arrival rate λ for the constant rate algorithm is simply $\lambda_0 M$, where M is total number of co-existing AVs. For the rate decreasing algorithm, the total EWM arrival rate depends on how fast the EWM transmission rate decreases and how fast the new AVs occur. Using the multiplicative rate decreasing algorithm with $a = 2$, we have assumed a very stressful scenario, in which one new AV occurs every 10 ms, to obtain the numerical results of Figure 7.

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