Vehicle-to-Vehicle Wireless Communication Protocols for Enhancing Highway Traffic Safety

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ABSTRACT

This article presents an overview of highway cooperative collision avoidance (CCA), which is an emerging vehicular safety application using the IEEE- and ASTM-adopted Dedicated Short Range Communication (DSRC) standard. Along with a description of the DSRC architecture, we introduce the concept of CCA and its implementation requirements in the context of a vehicle-to-vehicle wireless network, primarily at the Medium Access Control (MAC) and the routing layer. An overview is then provided to establish that the MAC and routing protocols from traditional Mobile Ad Hoc networks are not directly applicable for CCA and similar safety-critical applications. Specific constraints and future research directions are then identified for packet routing protocols used to support such applications in the DSRC environment. In order to further explain the interactions between CCA and its underlying networking protocols, we present an example of the safety performance of CCA using simulated vehicle crash experiments. The results from these experiments are also used to demonstrate the need for network data prioritization for safety-critical applications such as CCA. Finally, the performance sensitivity of CCA to unreliable wireless channels is discussed based on the experimental results.

INTRODUCTION

Every year in the United States, about six million traffic accidents occur due to automobile crashes. In 2003 alone, these accidents accounted for $230 billion in damaged property, 2,889,000 nonfatal injuries, and 42,643 deaths [1]. While different factors contribute to vehicle crashes, such as vehicle mechanical problems and bad weather, driver behavior is considered to be the leading cause of more than 90 percent of all accidents. The inability of drivers to react in time to emergency situations often creates a potential for chain collisions, in which an initial collision between two vehicles is followed by a series of collisions involving the following vehicles.

In emergency situations, a driver typically relies on the tail brake light of the car immediately ahead to decide his or her own braking action. Under typical road situations, this is not always the best collision avoidance strategy for various reasons. In many cases, the ability to detect an emergency event occurring at some distance ahead is limited by the inability of drivers to see past the vehicle in front of them. If drivers choose to follow the vehicle ahead too closely, as is often the case, then they may not have enough time to apply the brake and stop their vehicle after they see the brake lights of the vehicle ahead illuminate. Driver reaction time (the duration between when an event is observed and when the driver actually applies the brake) typically ranges from 0.75 to 1.5 s [2]. At a speed of 70 mph, this means that between 75 and 150 ft is traveled before any reaction occurs. In dense traffic, the effects of cumulative reaction times, as one vehicle after another reacts to the vehicle ahead braking, can further exacerbate the situation [3]. As a result, a single emergency event can often lead to a string of secondary crashes, creating a multicar chain accident.

Chain collisions can be potentially avoided, or their severity lessened, by reducing the delay between the time of an emergency event and the time at which the vehicles behind are informed about it [3]. One way to provide more time to drivers to react in emergency situations is to develop Intelligent Transportation System applications using emerging wireless communication technology. The primary benefit of such communication will be to allow the emergency information to be propagated among vehicles much quicker than a traditional chain of drivers reacting to the brake lights of vehicles immediately ahead.

Figure 1 details the system architecture proposed by the U.S. Department of Transportation
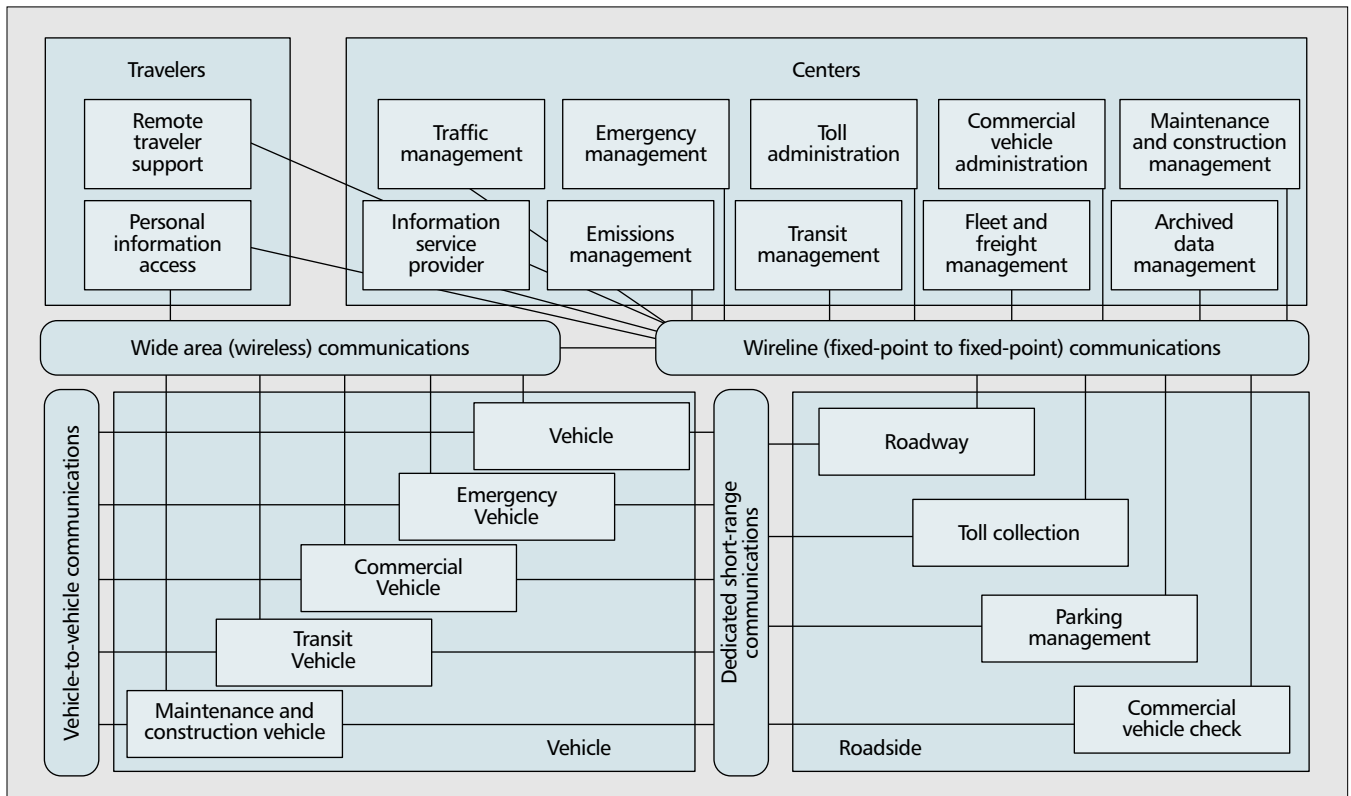
■ Figure 1. *Proposed national ITS architecture (U.S. DOT, 2003).*

(U.S. DOT, 2003) for the development of Intelligent Transportation Systems (ITS) [4]. The architecture is defined around four basic components linked by a communication infrastructure. To date, the majority of development efforts in support of communication capabilities within the ITS architecture have been directed at fixed-point to fixed-point communication and ITS solutions taking advantage of wide area communication networks. More recently, the combined availability of the Global Positioning System (GPS) and deployment of cellular-based communication systems has further fueled the development of vehicle tracking systems and systems providing information to travelers in vehicles through wireless means. Interest in vehicle-to-infrastructure and vehicle-to-vehicle communication capabilities has only recently gained momentum, as such capabilities were in the past either not technically feasible or too costly to implement and operate.

To cater to the emerging wireless communication needs with regard to vehicles, in July 2003 ASTM and IEEE adopted the Dedicated Short Range Communication (DSRC) standard (ASTM E 2213-03) [4]. The aim of this standard is to provide wireless communications capabilities for transportation applications within a 1000 m range at typical highway speeds. It provides seven channels at the 5.9 GHz licensed band for ITS applications, with different channels designated for different applications, including one specifically reserved for vehicle-to-vehicle communications. The ITS safety applications that could leverage the new DSRC standard include any system that can be enhanced by allowing information to flow between vehicles and between vehicles and roadside infrastructure. Examples of such applications include en-route driver information propagation, collision warning and avoidance systems, and adaptive cruise-control systems.

The objective of this article is to demonstrate how DSRC-based wireless communication protocols can be leveraged for the development of a cooperative collision avoidance (CCA) application for enhancing highway traffic safety. We intend to use CCA as an example safety application to allude to the tight communication requirements for ITS safety applications, and to demonstrate example protocol solutions and networking approaches that will be needed to address those requirements.

COOPERATIVE COLLISION AVOIDANCE

The mechanism of CCA is explained using a three-car highway platoon example, as shown in Fig. 2a. In the example, all cars are assumed to cruise initially at a steady speed of 72 mph (32 m/s), and with an intercar spacing (or headway) of 1 s (32 m). Figure 2b illustrates the platoon dynamics after the front car (car 0) initiates an emergency deceleration (at 4 m/s2) as a result of an emergency event. As shown in the figure, the driver in car 1 starts to decelerate when he sees the tail brake light of car 0, and the driver in car 2 does so when he sees the brake light of car 1. With an assumed driver's reaction time of 1.5 s, car 0 gets hit by car 1 at a distance of 120 m, and subsequently, car 1 is hit by car 2. The conclusion from this example is that if drivers react
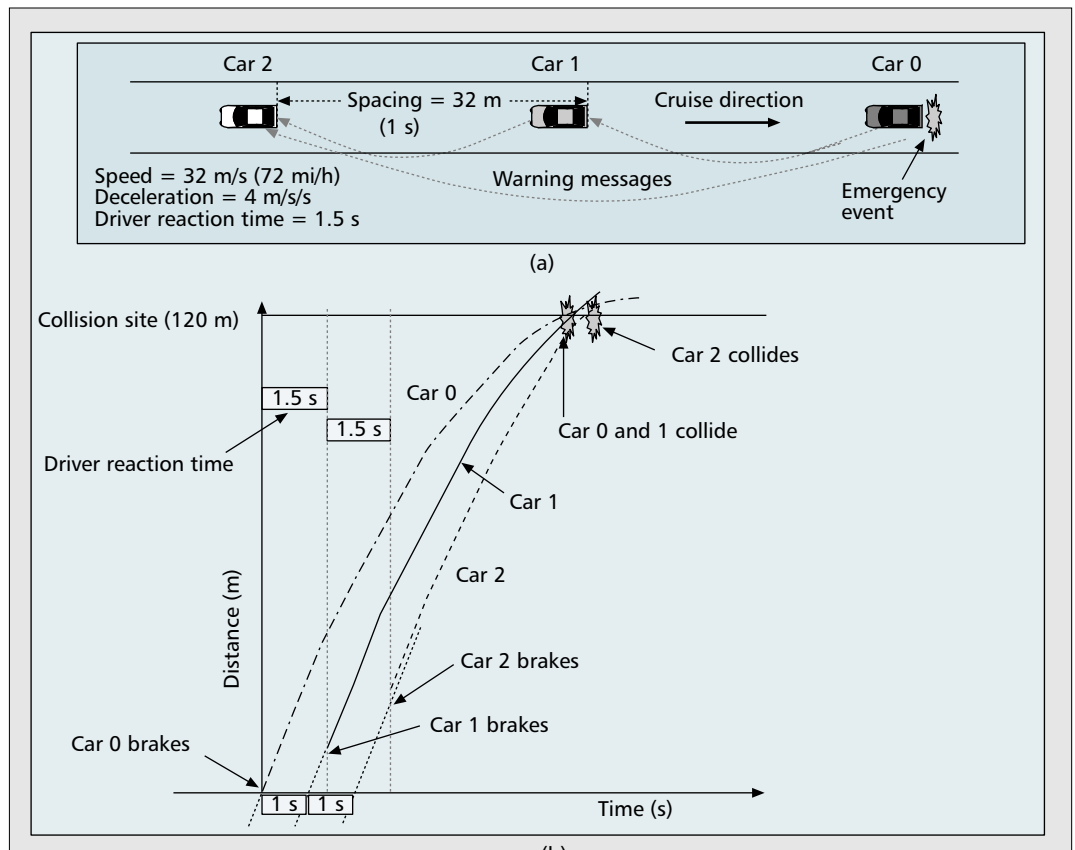
Figure 2. *Model for chain car collisions: a) a three-car highway platoon; b) chain car collisions when drivers react only on the tail light of the car ahead.*

only on visual information, all three cars in the platoon end up in a chain collision.

For the same platoon, the effects of CCA with wireless communication are illustrated in Fig. 3. In this case, upon meeting the emergency event, car 0 starts sending wireless collision warning messages (W-CWM) to all cars behind it. As shown in Fig. 2a, these messages are forwarded in a multihop manner in order to ensure a complete coverage within the platoon. Upon reception of a W-CWM, a driver reacts by decelerating, even if the brake light on the car ahead is not already lit.

As shown in Fig. 3, car 1 still collides with car 0. However, car 2 can avoid a collision if it receives the W-CWM with sufficiently small delivery latency. For instance, as shown by the solid line for car 2, with a delivery latency of 0.1 s from car 0 to car 2, car 2 manages to stop without a collision at a distance of 115 m from the site of the emergency event. However, for a delivery latency of 0.4 s (shown by the dotted line for car 2), car 2 cannot avoid the collision as the driver is not given enough time to start decelerating well in advance.

Two conclusions can be made form the above scenario. First, using a high-speed wireless communication network, it is possible to design CCA systems that can improve highway safety by avoiding chain collisions. Second, reliable and fast warning message delivery is a crucial requirement for such CCA systems to be able to leverage the underlying networking infrastructure.

STATE OF THE CURRENT RESEARCH

Protocol research for vehicle-to-vehicle communication can be broadly categorized in the areas of Medium Access Control (MAC) and data forwarding across moving vehicles. IEEE 802.11a is considered to be the de facto MAC protocol for DSRC-based communication. Although 802.11a provides a means for rapid application development, in dynamic vehicular environments the protocol suffers from a number of performance limitations as reported in [5]. The first limitation is a hop-unfairness problem due to which the effective data throughput of a multihop flow over 802.11 MAC can be severely limited due to 802.11's self-competition between adjacent nodes in the same flow. The second limitation is a lack of MAC protocol stability, and its subsequent performance inefficiency in highly mobile vehicular environments. Although a number of improvements, including better fairness, quality of service, and the support for differentiated services have been proposed in the literature [5], the basic nondeterministic nature of 802.11 is still an issue for its applicability to dynamic DSRC applications.

A set of Time Division Multiple Access (TDMA)-based slotted MAC protocols have been proposed for avoiding the inherent randomness and delay unpredictability of 802.11 [6]. A slot reservation MAC protocol (R-ALOHA) for intervehicle communication was proposed in [7]. Several other slot reservation MAC protocols [8] were proposed for the Fleetnet project
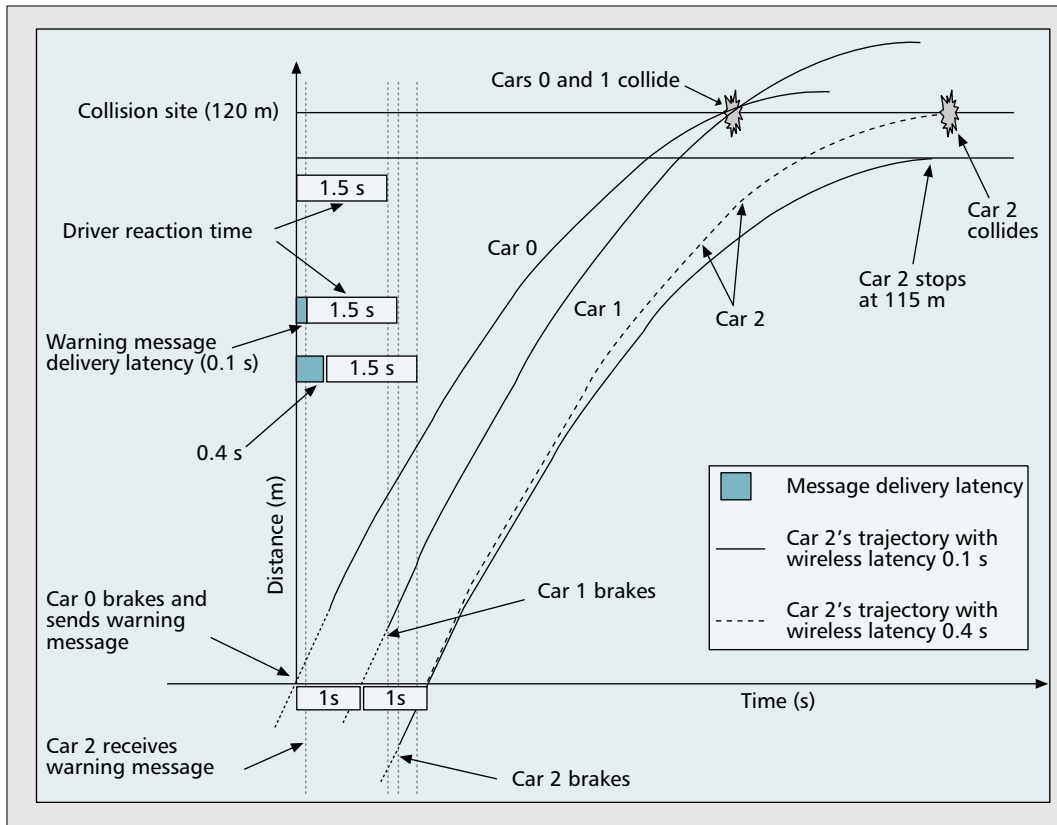
■ Figure 3. *Cooperative collision avoidance (CCA) using vehicle-to-vehicle wireless communication.*

[9]. The common idea across all these protocols is to dynamically allocate transmission time slots to individual vehicles within a group of vehicles. This requires accurate time synchronization using onboard GPS receivers. Although GPS receivers are becoming more and more common in vehicles, TDMA-based protocols face the following implementation difficulties. First, in the absence of a centralized scheduling entity, distributed slot synchronization and allocation across multiple hops is known to be a difficult spatial TDMA problem. Moreover, high vehicular mobility makes MAC coordination much more difficult than the traditional distributed slot allocation scenarios. Considering these difficulties, it is fair to conclude that further research will be needed before TDMA protocols can be applied to intervehicle DSRC applications. As an interim, 802.11a with appropriate performance optimizations is still likely to be the preferred MAC protocol for emerging DSRC applications.

While the traditional Mobile Ad Hoc Network (MANET) routing protocols such as Ad Hoc Distance Vector (AODV) may seem to be appropriate for DSRC applications, the main limitation is that they require an explicit route-establishment phase before the data transmission begins. The low delivery-latency requirement for the ITS safety applications (less than 200 ms [3]) prohibits such a route-establishment phase. Also, for several ITS safety applications, the classical definition of routing cannot be applied for packets from source to sink, because the identities of the prospective receivers are a priori unknown. Considering these two factors, we conclude that the MANET-style packet-forwarding protocols may be applicable only for relatively large delay-tolerant data applications such as in-vehicle Internet services. But they will not be adequate for low-latency vehicle safety applications such as CCA or cooperative cruise control.

Based on the above analysis it can be concluded that, for vehicular safety applications, the routing protocols should preferably be broadcast oriented and they should rely on packet forwarding based on geographic, directional, and other relevant temporal contexts of the source and the destination vehicles. To explain this further, consider an example scenario in which a packet broadcast by a vehicle traveling on a freeway is received by a vehicle moving in the opposite direction. In this case, if the packet contains data relevant only to the CCA application, it will not be forwarded any further since the context of the received packet indicates that the data is of no use for vehicles traveling in the direction opposite to the source vehicle. Packet-forwarding protocols for such applications can be designed based on constraints such as geographical location, as originally proposed for mobile networks in [10]. This idea has been adapted for vehicular networks in several protocols [11], in which selective forwarding of a packet is performed based on the packet's information content and the receiver's geographic location. Note that specific context and constraint parameters will have to be designed in an application-specific manner, and the parameters may differ significantly based on the nature of the respective target applications.

```
/* a WCWM message arrives at a vehicle */
If (Direction of Arrival  == Front){
    Start vehicle deceleration;
    Start originating WCWM msg. periodically;
}
```

■ **Pseudo code 1.** *Message interpretation logic
for an intermediate vehicle executing NB.*

```
/* a vehicle emergency event is detected */
do
    periodic broadcast of WCWM with this event_id;
until
    receive the same packet with DOA = Back;
```

■ **Pseudo code 2.** *Message generation logic by an
event-detecting vehicle executing I-BIA.*

```
/* a W-CWM message arrives at a vehicle */
If (Direction of Arrival  == BACK)
    Ignore message;
Else{ /* message came from the front */
    If (this message was received before)
        Ignore message;
    Else{ /* first time reception of this message */
        Start vehicle deceleration;
        Wait for a random duration for receiving any
        packet from behind, for the same event;
        if (such a packet was received)
            /* information about the event has already
               been propagated beyond this car */
            no further action is needed;
        Else{ /* message generation is needed */
            do
                periodic broadcast of W-CWM with
                appropriate event_id;
            until
                receive the same packet
                with DOA = Back;
        }
    }
}
```

■ **Pseudo code 3.** *Message interpretation logic
for an intermediate vehicle executing I-BIA.*

COMMUNICATION PROTOCOLS FOR COOPERATIVE COLLISION AVOIDANCE

In this section we present a class of example context-aware packet forwarding protocols to demonstrate their effectiveness in designing a CCA application for intraplatoon scenarios, where all vehicles within a platoon are assumed to be equipped with DSRC devices.

DIRECTION-AWARE BROADCAST FORWARDING

For the CCA application defined in Section 2, when a vehicle meets an emergency situation, it needs to send a W-CWM to all cars behind within its platoon. Since the identities of those prospective receivers may not be known a priori, classical unicast and multicast routing will not work. In the present approach, the vehicle in an emergency situation broadcasts a W-CWM first, and then all its recipients selectively forward the message based on its direction-of-arrival. This mechanism ensures that the W-CWM will be eventually delivered to all the vehicles within the platoon. The following design targets have been identified for this CCA system:
• Minimize the number of vehicles involved in intraplatoon chain collisions
• Prioritize data from safety-related ITS applications over low-priority ITS applications
• Limit vehicle collisions in the presence of radio channel errors

Upon detecting an emergency event, a W-CWM is broadcast by the detecting vehicle. The message contains an *origin_vehicle_id* (of the event detecting vehicle) and an *event_id* (unique within the detecting vehicle), which are used for uniquely identifying the emergency event. An *msg_seq_no* is also added so that the tuple {*origin_vehicle_id*, *msg_seq_no*} can uniquely identify a message across the platoon. A *message_type* field identifies the associated ITS application, which is CCA in this particular case.

Naïve Broadcast — Naïve broadcast (NB) forwarding serves as a baseline packet-routing mechanism for the target CCA application. After detecting an emergency event, the detecting vehicle starts sending W-CWM messages periodically at regular intervals [4]. Upon receiving a W-CWM message, a vehicle executes the logic as shown in pseudo code 1 to decide whether to decelerate and start generating its own W-CWM messages. According to the NB logic, a vehicle ignores a message if it comes from behind with respect to its direction of movement. However, if it comes from the front, it infers that there is an emergency event in the front and, in that case, the vehicle immediately starts deceleration and starts broadcasting periodic W-CWM messages of its own.

Executing the NB logic will ensure that all vehicles within the platoon will eventually receive a warning message and will decelerate to avoid collisions with vehicles ahead. Note that no explicit mechanism has been provided to stop W-CWM propagation. The warning message propagation for an event will stop only when the message arrives at the last car of the platoon, where there is no more receiver vehicle behind it.

Intelligent Broadcast with Implicit Acknowledgment — The primary limitation of NB is its excessive message forwarding, which escalates message collisions for 802.11 MAC. High MAC collisions reduce the message-delivery rate, and also increase the delivery latency, because successful delivery after message drops will have to rely on the periodic retransmissions from the event-detecting vehicle. To avoid these, we introduce an *implicit acknowledgment*-based message generation and transmission strategy, intelligent broadcast with implicit acknowledgment (I-BIA), that can improve the system performance by reducing the number of messages that are injected within a platoon for a given vehicle emergency event.

As shown in pseudo code 2, after starting the periodic broadcast, if an event-detecting vehicle

receives the same message from behind, it infers that at least one vehicle in the back has received that message and will be responsible for propagating it along the rest of the platoon. In that case, the event-detecting vehicle stops the broadcast so as to avoid transmitting unnecessary messages. An intermediate vehicle applies similar implicit acknowledgment logic (as shown in pseudo code 3) in its action upon receiving a W-CWM message. As in NB, a receiver vehicle acts on a message only if it is received from the front. The vehicle also checks if the message has been received before. If multiple cars in a platoon are within the wireless transmission range of a single transmitter vehicle, then it is possible for a vehicle to receive a message more than once, forwarded by different vehicles in the front. In case of such multiple receptions, a vehicle acts only upon the first reception.

Upon receiving a packet for the first time, the vehicle starts deceleration, and it also attempts to find out if the information about the specific event has been propagated beyond this vehicle to the back of the platoon. This is achieved by waiting (for a time of random duration) to see if the vehicle receives another W-CWM message from the back, with the same *event_id*. If it does receive one, this means that at least one vehicle behind this one has already started sending messages for this event to inform the rest of the platoon. In that case the current vehicle simply takes no further action.

However, if the vehicle does not receive any message with the same *event_id* within that random period, then it assumes the responsibility of propagating information of this emergency event to the back of the platoon. At this point, the vehicle starts generating W-CWM messages with the proper event_id, and uses the same implicit acknowledgment technique outlined in pseudo code 3 for limiting the total number of generated messages.

## SAFETY PERFORMANCE OF COOPERATIVE COLLISION AVOIDANCE

An ns-2-based hybrid simulation system [12] for joint evaluation of ITS applications, wireless network protocols, and vehicle-following logic with drivers' behavior has been used for demonstrating the performance of CCA with the presented packet-forwarding protocols. The representative performance in this section corresponds to CCA for a one-lane intraplatoon scenario, as described in Fig. 2. Vehicle emergency situations are created by forcing the vehicle at the front of a platoon (of 50 cars) to rapidly decelerate (8 m/s^2), which triggers a CCA process by initiating a wireless collision-warning message. This high deceleration rate models a vehicle hitting a fixed object and stopping within a very short distance. The parameters used for modeling the vehicle dynamics and the network operation are listed in Table 1. All results correspond to a scenario in which a single emergency event at the platoon front causes chain collisions of vehicles.

| Vehicle Related Parameters	
Platoon Size	50 vehicles
Vehicle Speed	70 m/hr (32 m/s)
Inter-vehicle Spacing	[0.3 – 0.9] s ≡ [9.6 – 28.8] m
Vehicle Length	4 m
Emergency Deceleration	8 m/s^2
Regular Deceleration	4.9 m/s^2
Drivers' Reaction Time	[0.75 – 1.5] s
Network Related Parameters	
MAC Protocol	IEEE 802.11 with custom link-layer priority for ITS safety applications
Radio model	Two ray ground
Routing Protocol	Direction-aware broadcast forwarding
W-CWM Message Size	64 bytes
W-CWM Period	100 ms
I-BIA Random Wait Time	[0 – 10] ms
Background ITS Traffic	[80 – 800] kb/s/vehicle

Table 1. *Baseline experimental parameters.*

Effects of Intelligent Broadcast — The number of vehicles crashed as a percentage of the platoon (of 50 vehicles) is plotted in Fig. 4a, for intervehicle spacing ranging from 0.3 s (9.6 m) to 0.9 s (28.8 m). With the CCA system turned off, if the vehicles decelerate based only on the tail brake light of the front cars, then for this entire range of vehicle spacing, all cars in the platoon will collide in a chain collision. However, as shown in Fig. 4a, by turning the CCA system on, with NB as the direction-aware forwarding protocol, it is possible to bring the platoon collision down to 48 percent, when the vehicle spacing is nearly 1 s. As expected, with increased vehicle spacing, the CCA system is able to save more vehicles from the chain crash. The performance of the CCA can further be improved by applying the I-BIA forwarding. At vehicle spacing of 0.9 s, the percentage platoon collision is reduced from 48 percent with NB to 20 percent with I-BIA. In absolute terms, this amounts to saving 14 more vehicles from crashing, as compared to the NB.

The message-delivery latency with the I-BIA protocol is presented in the top graph of Fig. 5. Latency is defined as the time duration between when the emergency event occurs at the platoon front and when a corresponding W-CWM message is delivered to a vehicle. Relative stop distances between consecutive vehicles are reported in the middle graph of Fig. 5. Since the vehicle length is assumed to be 4 m, any relative stop
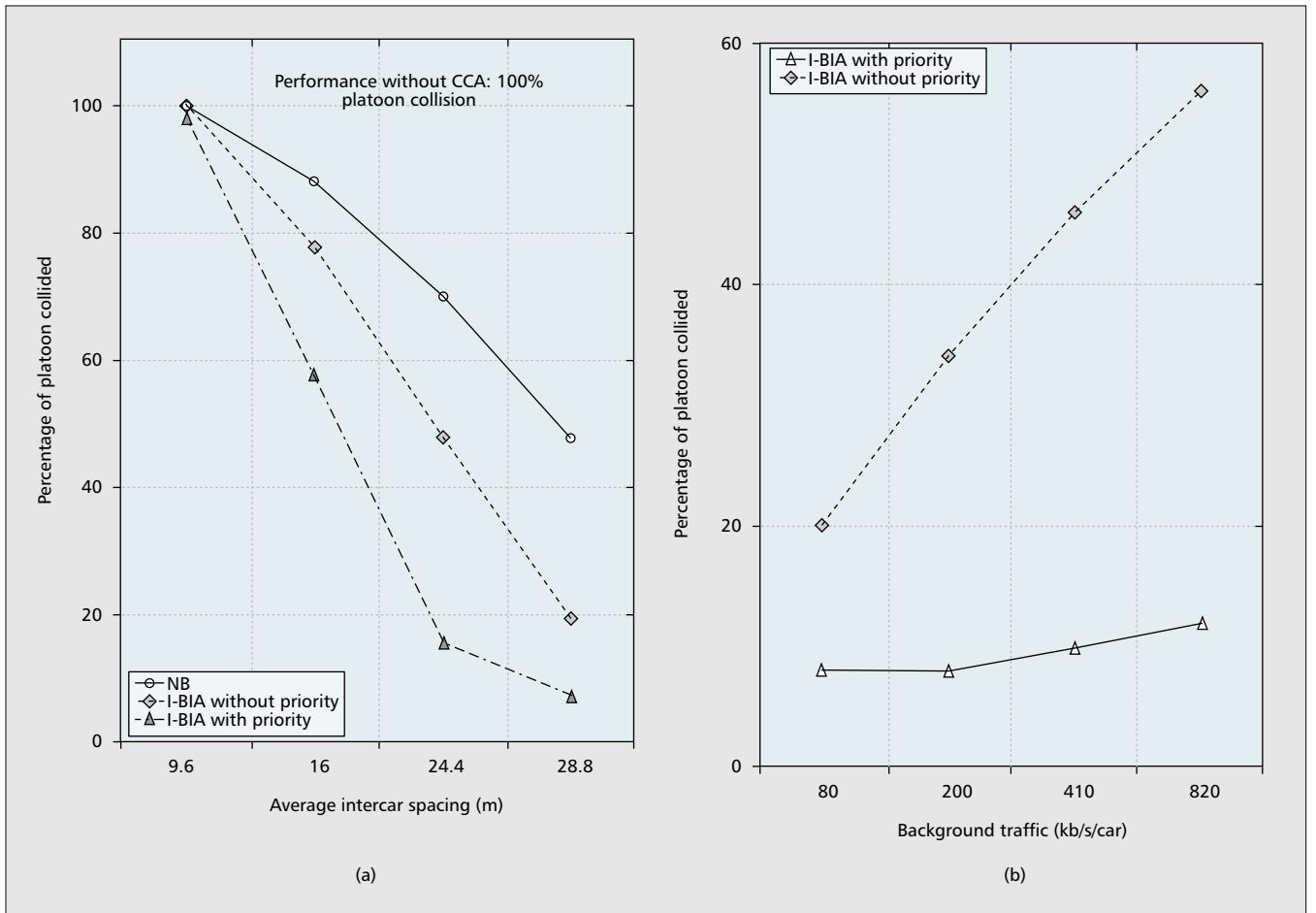
Figure 4. *Effectiveness of CCA using wireless messaging: a) prioritized messaging; b) priority with varying background traffic.*
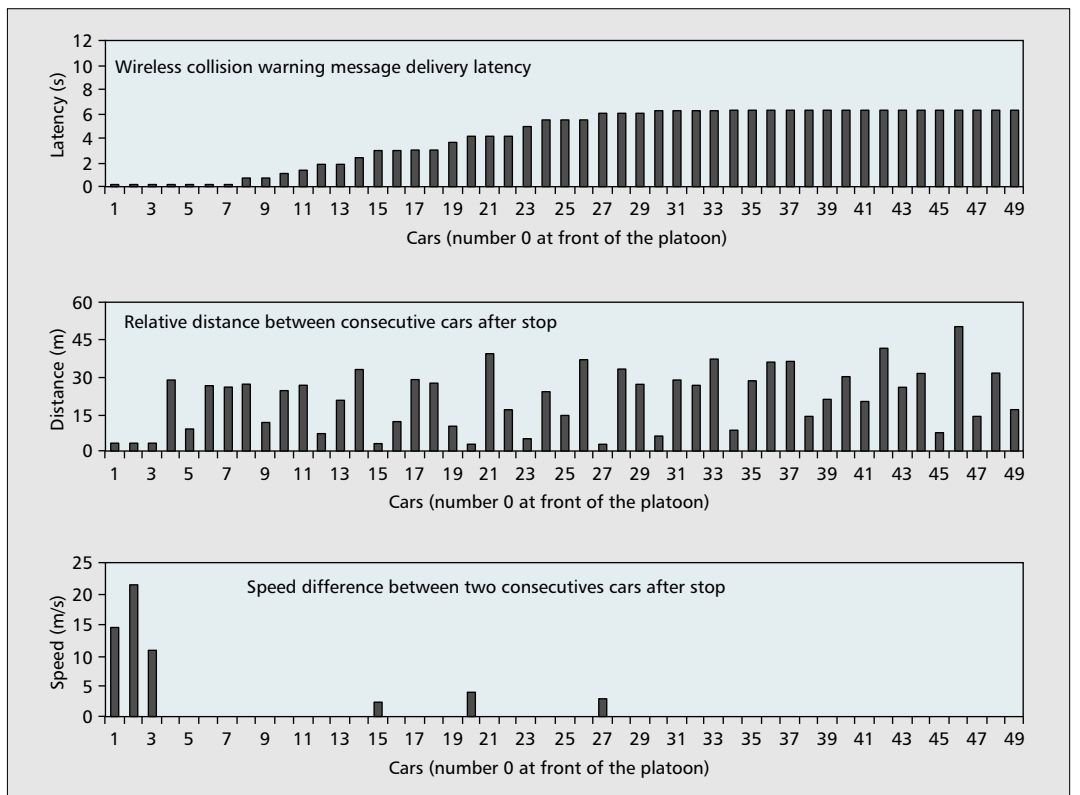
Figure 5. *Message delivery latency and vehicle safety details for I-BIA (vehicle spacing 28.8 m).*
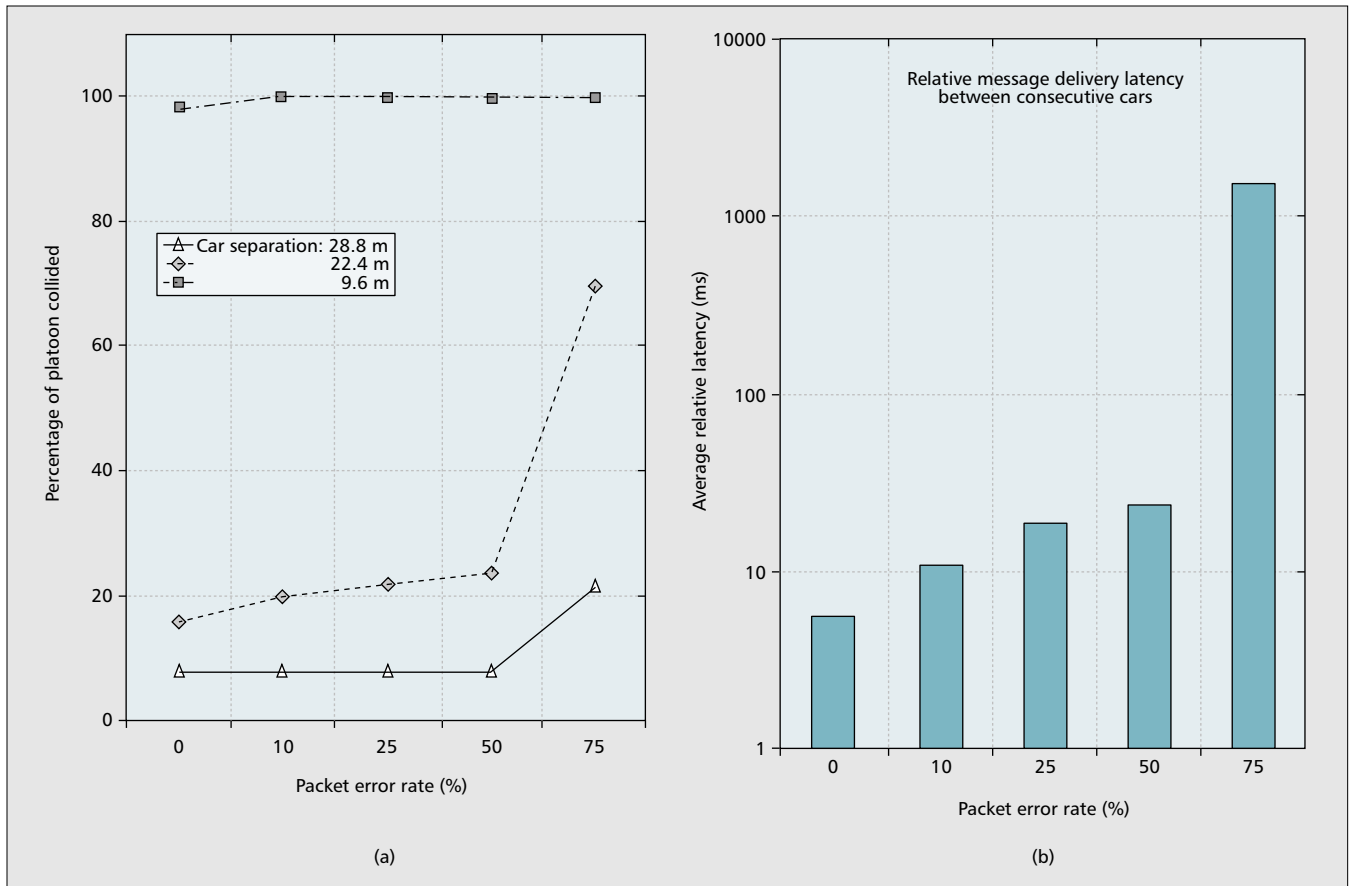
■ Figure 6. *Vehicle collision performance and relative network latency in the presence of packet errors: a) CCA performance with packet errors; b) relative delivery latency between vehicles.*

distance of 4 m or less corresponds to a collision. For vehicles avoiding a collision, the given relative distance thus indicates the margin of safety provided by CCA with the involved DSRC protocols. The bottom graph in Fig. 5 further reports the severity of vehicle collisions in terms of the relative speed between two consecutive cars, when they stop. Any relative speed greater than zero indicates a collision, and its magnitude indicates the severity of the collision.

Effects of Prioritized Communication for CCA Traffic — Performance of the CCA has also been evaluated with a link-layer priority structure, in which safety-critical CCA data packets are given higher priority compared to the background data traffic generated by non-CCA ITS applications [4]. This has been accomplished by providing two link-layer queues: one for CCA traffic and the other for background non-CCA traffic. A CCA-first pre-emptive scheduling has been implemented so that the MAC layer will not transmit any background traffic until the queue for the CCA traffic is found to be empty.

Performance of I-BIA with link-layer priority for CCA is shown in the third graph of Fig. 4a. It can be observed that with 80 kb/s/vehicle background traffic, the link-layer priority does not improve the crash performance when the vehicle spacing is small (0.3 s or 9.6 m). However, as the vehicle spacing increases, the benefits of prioritized delivery becomes more pro-

nounced. But for very large vehicle spacing (greater than 0.9 s or 28.8 m), the gap between the two scenarios again shrinks. Even though the message delivery latency for nonpriority cases is large in this particular case, the vehicles have enough time to stop without colliding due to their large physical spacing. It should be noted that even though the difference in the percentage of collisions is not too large, it does make a significant difference in terms of the number of vehicles that are saved. For example, for a vehicle spacing of 0.9 s (28.8 m), the priority model saves six additional cars over the nonpriority approach. This underlines the need and effectiveness for priority-based data networking in ITS safety-critical applications such as CCA.

As shown in Fig. 4b, without priority for CCA messages, the vehicle crash performance degrades almost linearly with increasing background traffic. However, with priority turned on, the number of additional vehicles involved in the chain crash does not increase significantly. Without priority, for an order of magnitude increase in the background load (from 80kb/s/vehicle to 800 kb/s/vehicle), the number of cars crashed in the platoon increases from 10 to 28. With priority turned on, the number of crashed vehicles increases only from four to six.

Effects of Channel Error — Crash performance in noisy channel conditions is reported in Fig. 6a. Packet errors in this experiment were

caused by independent bit errors. The effects of fading and burst errors have not been considered. Observe that with very small vehicle spacing (i.e., 0.3s), the channel condition makes very little difference since almost the entire platoon crashes in this situation. With higher vehicle spacing, the crash performance does not change significantly until up to 50 percent of the W-CWM messages become corrupted due to channel errors. Beyond that point, packet loss affects the CCA operation, as a result of which more vehicles in the platoon collide.

To understand the insensitivity of vehicle crash rates up to 50 percent packet loss, relative packet-delivery latencies between consecutive vehicles have been measured for a wide range of packet error rates. High relative latency may indicate that a vehicle in the platoon received the W-CWM message a long time after the vehicle in front of it received the message. In such a situation, the lack of reaction time is likely to lead the car behind to crash.

The numbers in Fig. 6b demonstrate that for packet error rates up to 50 percent, the relative latencies do not increase significantly. This is primarily due to the fact that a given W-CWM message is broadcast in the platoon by multiple vehicles. Due to this transmission redundancy, even when a certain number of transmissions for that packet are corrupted (up to 50 percent), the message manages to go across the platoon with an average relative latency of 23 ms, which is fairly low compared to the drivers' reaction time of more than 750 ms. That is why the vehicle crash rate does not go up significantly.

However, for very large packet error rates (beyond 50 percent), the built-in redundancy of I-BIA becomes exhausted and the average relative message delivery latency shoots up to more than 1600 ms, which is way more than the average drivers' reaction time of 1100 ms. This explains the drastic degradation of CCA performance, as shown in Fig. 6a, for packet error rates beyond 50 percent. Finally, note that the simulations in this work were conducted with a simplistic two-ray-ground propagation model. More work is needed to capture the effects of mobility, channel fading, and multipath on the networking as well as the integrated vehicle collision performance.

CONCLUDING REMARKS

In this article we have presented an overview of vehicle cooperative collision avoidance (CCA) application using the emerging Dedicated Short-Range Communication (DSRC) infrastructure for intervehicle wireless networking. The concept of CCA has been introduced with an overview, and its implementation issues have been analyzed in light of specific requirements from the MAC and routing-layer protocols of the underlying wireless networks. Specific constraints and future research directions have then been identified for packet-routing protocols to support an effective CCA system within the DSRC environment. To explain the interactions between CCA and its underlying networking protocols, we have presented example safety performance of CCA from simulated intraplatoon vehicle crash experiments. The results from these experiments were also used to demonstrate the need for network data prioritization for safety-critical applications such as CCA. Finally, the performance sensitivity of CCA to unreliable wireless channels has been discussed using these experimental results.

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