Cooperative Collision Warning Using Dedicated Short Range Wireless Communications

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ABSTRACT

The emergence of the 802.11a-based Dedicated Short Range Communications (DSRC) standard and advances in mobile ad hoc networking create ample opportunity for supporting delay-critical vehicular safety applications in a secure, resource-efficient, and reliable manner. In this paper, we focus on the suitability of DSRC for a class of vehicular safety applications called Cooperative Collision Warning (CCW), where vehicles periodically broadcast short messages for the purposes of driver situational awareness and warning. First, we present latency and success probability results of Forward Collision Warning (FCW) applications over DSRC. Second, we explore two design issues that are highly relevant to CCW applications, namely performance trends with distance and potential avenues for broadcast enhancements. Simulation results reveal interesting insights and trade-offs related to application-perceived latency and packet success probability performance. For instance, we conjecture the existence of an optimal broadcast rate that minimizes our novel latency measure for safety applications, and we characterize it for plausible scenarios.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless Communication*;; C.2.5 [**Computer-Communication Networks**]: Local and Wide Area Networks

General Terms

Performance,Standardization,Measurement

Keywords

DSRC, IEEE 802.11p, vehicular communications, safety, broadcast rate, transmission range, metrics, simulation

1. INTRODUCTION

The rapid evolution of wireless data communication technologies witnessed recently creates ample opportunity to utilize these technologies in support of vehicular applications. For instance, cellular-based systems, such as $OnStar^{TM}$, are already being used for tasks like automated reporting of traffic accidents. Similarly, wireless local-area network (WLAN) systems, such as *Dedicated Short Range Communications (DSRC)* [1], are being studied as inter-vehicle communications platforms for applications like collision avoidance, automated highway systems [7], and passenger teleconferencing. Among the opportunities being explored, special emphasis is given to the development of *safety* applications (e.g. collision avoidance, road hazard notification) versus *non-safety* applications (e.g. trip planning, infotainment), for obvious reasons. In this paper, we study the suitability of DSRC as a platform for a class of safety applications known as *Cooperative Collision Warning (CCW)*.

Dedicated Short Range Communications (DSRC) [1] is a proposed variant of IEEE 802.11a [3], designed to operate within a frequency band (5.9 GHz) licensed solely for the purposes of vehicular communications, and is being optimized for operation within high-speed vehicular environments. It is currently undergoing joint development by government and industry partners for adoption as the de-facto standard for communications-based vehicular safety and non-safety applications. In general, the DSRC physical layer is adapted from the IEEE 802.11a standard using OFDM modulation, and the DSRC medium access control layer is adapted, in part, from the original IEEE 802.11 and IEEE 802.11e (QoS) [20] standards.

State-of-the-art vehicle safety systems are based on various types of sensors, e.g. radars, lidars, and vision sensors. However, sensor-based systems give rise to the following drawbacks: i) the limited range and field-of-view (FOV) limit sensing to nearest vehicles that are immediately around the vehicle of interest, and ii) the cost associated with these possibly sophisticated sensors limits their applicability only to luxury vehicles. Therefore, there is strong interest in the automotive community to investigate the key role communication-based safety systems could play in either complimenting or replacing some of the sensing-based systems due to their versatility (ability to support a wide variety of applications) and competitive cost.

Cooperative Collision Warning (CCW) is an important class of safety applications that target the prevention of vehicular collisions using *vehicle-to-vehicle (V2V)* communications. The ultimate goal of CCW is to realize the concept of "360 degrees driver situation awareness" [9, 8, 19], whereby vehicles alert drivers of impending threats without expensive equipment. CCW applications are generally characterized by the periodic broadcast of short messages bearing status information (e.g. location, velocity, control settings) that neighboring vehicles can use, for instance, to warn the driver of an impending collision. Example CCW applications include *Forward Collision Warning (FCW)*, *Lane Change Assistance (LCA)*, and *Electronic Emergency Brake Light (EEBL)*. In FCW, a vehicle uses the messages it receives and knowledge of its own status to compute the likelihood of a collision with the vehicle directly in front of it. In LCA, a vehicle computes the likelihood that vehicles in adjacent lanes are going to enter into its path unsafely. In EEBL, a vehicle uses control status information in the messages it receives to determine if one or more leading vehicles are braking. In each of these instances, and for CCW in general, status messages must be transmitted quickly and reliably in order to match the reliability of state-of-the-art sensor-based warning and driver assistance systems, yet, with less cost.

The problem of supporting low-latency, single-hop broadcast applications over vehicular ad hoc networks has received recent attention in the literature [10, 11, 13, 12, 14, 15]. Perhaps the most relevant to our research are [12] and [13]. In [12], the authors study the impact of the rapid repetition of broadcast messages on the reception failure probability of random access protocols using analysis and simulation. In [13], the authors quantify the channel access time and probability of reception under deterministic and statistical channel models. Both studies consider generic broadcast applications which provide limited insights about the performance (e.g. latency) perceived by safety applications.

In this paper, we present a detailed analysis of FCW over DSRC under realistic and stressful conditions, using novel performance metrics that give key insights into the impact of interference and successive packet losses on the performance of FCW, and CCW applications in general. The basis for this analysis is a large-scale VANET simulation environment that includes, among other things, detailed cooperative collision warning application models, realistic multi-lane vehicular traffic models, and DSRC radio models. We also present a study of broadcast enhancement techniques for CCW applications that reveal interesting trade-offs inherent to the latency perceived by periodic broadcast safety applications.

This paper is organized as follows: Section 2 presents an overview of the DSRC standard. Section 3 describes the simulation testbed and scenarios used in the analysis. The performance of FCW over DSRC is quantified and analyzed in Section 4. This is followed by a discussion of DSRC performance trends with distance and broadcast enhancements in Section 5. Finally, conclusions are drawn in Section 6.

2. DEDICATED SHORT RANGE COMMUNICATIONS (DSRC)

In this section, we present background information on the DSRC standard and the motivation for its development.

DSRC [1] is a multi-channel wireless standard, currently under development, that is based on the IEEE 802.11a PHY and the IEEE 802.11 MAC. It is targeted to operate over a 75 MHz licensed spectrum in the 5.9 GHz band allocated by the FCC in 1999 for the support of low-latency vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [4]. Next, we present DSRC in more detail, including why it is being developed in lieu of existing 802.11 standards.

The motivation for the development of DSRC (versus 802.11) is based largely on the need for a more tightly controlled spectrum for maximized reliability. Clearly, communications-based V2V/V2I safety systems should not operate in an unlicensed band (either at 2.4 GHz or 5 GHz). The proliferation of hand-held and hands-free (e.g. Bluetooth) devices that occupy these bands, along with the projected increase in WiFi hot spots and wireless mesh extensions, could cause intolerable and uncontrollable levels of interference that could hamper the reliability and effectiveness of low-latency vehicular safety applications. This, in turn, makes a strong case for investigating DSRC as a potential candidate for supporting low-latency vehicular safety applications to reduce collisions and save lives on the road. Even with a licensed band, cooperative spectrum management must ensure reliable and fair access to all applications, including priority scheduling of traffic between different application classes (e.g. safety over non-safety) as well as within a given class (e.g. safety messages with different priority levels). Unlike 802.11, multi-channel coordination is a fundamental capability of DSRC. Although IEEE 802.11 PHY supports multiple channels, MAC operation over the multiple channels is left optional to individual vendors and is not supported by the standard.

As pointed out earlier, DSRC is similar to IEEE 802.11a, except for the major differences summarized below:

- *Operating Frequency Band:* DSRC is targeted to operate in a 75 MHz licensed spectrum around 5.9 GHz, as opposed to IEEE 802.11a which is allowed to utilize only the unlicensed portions in the 5 GHz band.

- *Application Environment:* DSRC is meant for outdoor high-speed vehicle (up to 120 mph) applications, as opposed to IEEE 802.11a originally designed for indoor WLAN (walking speed) applications. Thus, all PHY parameters are optimized for the indoor low-mobility propagation environment. This brings new challenges for wireless channel propagation with respect to multi-path delay spread and Doppler effects caused by high mobility, as illustrated in [15].

- *MAC Layer:* The DSRC band plan consists of seven channels which include one control channel (Ch. 178) to support high-priority safety messages and six service channels to support non-safety applications. Prioritizing safety over non-safety applications is an open problem that started to receive attention in the literature and is closely related to the problem of multi-channel coordination. Aside from these differences, the DSRC MAC follows the original IEEE 802.11 MAC [3] and its extensions (e.g. IEEE 802.11e QoS).

- *Physical Layer:* The bandwidth of each DSRC channel is 10 MHz, as opposed to the 20 MHz IEEE 802.11a channel bandwidth. Clearly, this has direct impact on the maximum data rate DSRC can support (27 Mbps), as well as timing parameters (e.g. guard interval of 1.6 μsec) and frequency parameters (e.g. sub-carrier frequency spacing of 156.25 KHz). Aside from these and some differences in the transmit power limit, the DSRC PHY follows exactly the same frame structure, 64 sub-carrier OFDM-based modulation scheme, and training sequences specified by IEEE 802.11a PHY. Thus, the impact of the drastically different vehicular environment on the DSRC PHY performance needs thorough investigation.

The DSRC standard is still under development. The first major draft of the standard was developed by ASTM, which is now being evaluated by the following IEEE working groups: i) IEEE 802.11 TGp (a.k.a. wireless access for vehicular environment (WAVE)) with focus on PHY/MAC design [2], ii) IEEE 1609.4 with focus on multi-channel coordination [5], and iii) IEEE 1609.3 with focus on network layer protocols and services [6].

3. LARGE-SCALE VANET SIMULATION

In this section, we describe the VANET simulation testbed used for our performance evaluation. We outline the simulation parameters and modeling assumptions underlying vehicular mobility patterns, CCW applications, and DSRC PHY/MAC simulation.

3.1 Freeway Mobility Scenarios

In an attempt to reflect realistic mobility patterns in vehicular network simulations, the developed simulator accommodates two types of vehicle mobility scenarios, namely city scenarios [15] and freeway scenarios. In this paper, we focus on a simple eight-lane straight freeway stretch of length 1 mile with 4 lanes in each direction and no entries/exits, as shown in Figure 1. The lane width is assumed to be 4 meters, whereas the median width is 25 meters. We assume that vehicles do not change lanes throughout a simulation run, which is a reasonable assumption given the short freeway segment. Finally, we assume that once a vehicle reaches the end of the freeway it wraps around to the other end of the freeway. This is of paramount importance to maintain fixed vehicle density and, hence, same levels of interference throughout the simulation run. It should be noted that statistics gathering does not involve any node that is within 150 meters of either end of the freeway in order to avoid edge effects. Next, we describe the parameters associated with the high and low-density scenarios.

Among many possible high-density scenarios, we focus on a scenario where vehicles are moving on one side of the freeway and stopped on the other side due to an accident or road hazard. The average vehicle separation in the moving side is about 10 meters, whereas the vehicle separation in the stopped side is set to 5 meters. In addition, we assume that vehicle speeds vary within the same lane and across lanes on the moving side of the freeway. The average speeds in the four lanes are assumed to be 20.5 mph (slowest lane), 23.5 mph, 26.5 mph and 29.5 mph (fastest lane). Finally, the instantaneous speeds of vehicles within each lane are randomly drawn from a Gaussian distribution with the aforementioned mean values and 3 mph standard deviation. The total number of vehicles under this scenario turns out to be 1920.

Under the low-density scenario, vehicles are moving on both sides of the freeway where the average vehicle separation in each side is approximately 61 meters, which translates to about 26 vehicles per lane. The average speeds in the four lanes are assumed to be 56 mph (slowest lane), 62 mph, 68 mph and 74 mph (fastest lane). The instantaneous speeds of vehicles within each lane are randomly drawn from a Gaussian distribution with the aforementioned mean values and 5 mph standard deviation. The total number of vehicles in this scenario is 208.

3.2 Forward Collision Warning (FCW)

In this section, we present details of the Forward Collision Warning (FCW) application, and how it was modeled in our simulator. We also present related terminology that is referenced frequently in later sections.

In FCW, it is assumed that each vehicle has some type of localization device (e.g. GPS) in addition to a wireless communication device (e.g. DSRC). When operational, each vehicle periodically broadcasts a small message containing information about its current status (e.g. location, velocity, control settings) to all neighboring vehicles in transmission range. The neighboring vehicles that receive these messages use the information inside, along with the knowledge of their own status, to compute the likelihood that they are on course to collide. For FCW, the only vehicles of concern are those that lie directly ahead of the receiving vehicle. If a collision is imminent, the driver is warned to take appropriate action.

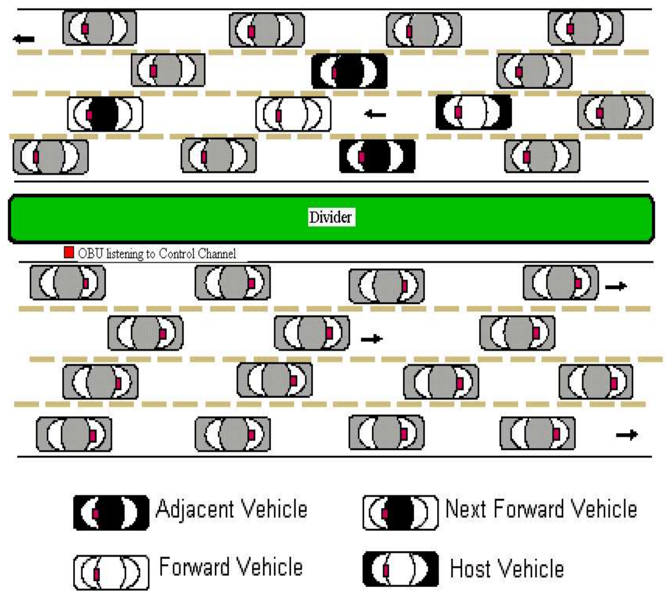


Figure 1: Illustration of Cooperative Collision Warning (CCW) Applications

For clarity, consider the simple scenario shown in Figure 1. Here, *Host Vehicle (HV)* refers to the vehicle of interest, and the vehicle directly in front of it in the same lane is called the *Forward Vehicle (FV)*. For the HV, only messages from the FV are considered in the collision computation, although messages received from all other vehicles are tracked so changes in the FV can be detected.

In addition, Figure 1 illustrates two other application models: i) Lane Change Assistance (LCA), where the HV is interested only in messages from the *Adjacent Vehicle (AV)*, and ii) Electronic Emergency Brake Light (EEBL), where the HV is interested in messages from the *Next Forward Vehicle (NFV)*. However, this model can be easily generalized to assess the quality of reception from vehicles further ahead of the NFV, as in real EEBL scenarios. Clearly, the feasibility of communication-based cooperative collision warning hinges on the availability of GPS devices with positioning accuracy typically in the range of 1 to 1.5 meters in the lateral direction in order to correctly associate vehicles with lanes [8]. These requirements are less than half a lane width, which ranges from 3.2 to 4 meters, in order to tolerate GPS inherent noise/errors. There are a number of differential GPS (DGPS) receivers that could provide this level of accuracy when used with differential corrections such as the Wide Area Augmentation System (WAAS) or the US Coast Guard's DGPS Service.

In our simulations, we model FCW as follows. All vehicles are equipped with location devices with perfect precision, and DSRC radios, and all vehicles act as both transmitters and receivers of status messages. At the start of a simulation run, all vehicles on the freeway begin transmitting fixed size (100 Byte) messages in UDP broadcast packets, after an appropriately staggered startup delay and additional random dithering (to avoid recurring collision/backoff events), and continue transmitting until the end of the run. For every message that is transmitted, every vehicle within range that is able to correctly receive the message decodes the information and computes the relative location of the transmitting vehicle. If it is determined that the vehicle does not lie directly ahead, then the message is ignored. Otherwise, the message is consumed and recorded for later statistical data gathering.

3.3 DSRC Vehicular Networks

The results in this paper were generated using the $QualNet^{TM}$ simulation tool, with appropriate modifications necessary to represent the unique characteristics of the DSRC radio and channel to a sufficient level of detail necessary for our comparative analysis of CCW under extreme vehicle densities. QualNet is a widely-used simulation tool that contains, among other things, detailed 802.11a radio and channel models, including widely-accepted models for wireless propagation and interference. For more information on QualNet, please refer to [17].

For our purposes, we modified the 802.11a models to represent DSRC in accordance with the ASTM draft standard [1], as follows. The carrier frequency is set to 5.9GHz and the channel bandwidth is 10MHz. Accordingly, the short symbol length and the OFDM symbol length are doubled. All communication was fixed at 6Mbps (QPSK modulation scheme - 1/2 rate convolutional coding) with a transmission power of 16.18dBm and a receiver sensitivity of -83dBm, using omni-directional antennas. We focus on the single channel operation of DSRC (control channel supporting safety applications). The problem of DSRC multi-channel operation, for supporting the coexistence of safety and non-safety applications, lies out of the scope of this paper and is a subject of ongoing research.

The bit-error rate (BER) as a function of signal-to-noise (SNR) at 6Mbps for a DSRC radio is unknown, so we derive an estimate of the BER vs. SNR curve using empirical measurements of actual DSRC radio prototypes. Subsequently, an estimate of the noise power of the radios was also determined in the process, which was roughly -97dBm. Models of the DSRC wireless channel are also unavailable, so we conducted extensive fixed and mobile field measurements using the DSRC radio prototypes to generate an estimate of the pathloss (slow-fading) exponent of the channel. The result is an exponent of 2.15, out to a distance of approximately 150m. Statistical fading models in the literature are hard to justify for DSRC V2V channels. Therefore, we adopted a channel model that incorporates measured BER-SNR curves and pathloss exponent for the simulation scenarios of interest. It constitutes a measurement-based approximation of line of sight (LOS) communication scenarios.

The simulation time is fixed at 30 sec, where 290 packets are transmitted by each vehicle at 10 packets/sec starting at the first second. We conducted 20 simulation runs and computed 95% confidence intervals (CI) in order to prove the statistical significance of the gathered data. The relative statistical error over all studied scenarios, given by $\frac{CI}{2*Mean}$, is less than 19% and 3% for the two performance metrics of interest. This indicates a small statistical error according to [18] and, hence, confirms that 20 runs provide a sufficient sample set to yield statistically significant data for the types of periodic broadcast applications under extreme vehicle densities. This is primarily attributed to the spatial and temporal traffic uniformity across the entire network that leads to similar wireless contention seen by any host vehicle on the average.

4. COMMUNICATIONS PERFORMANCE OF FORWARD COLLISION WARNING

In this section, we introduce the metrics used for quantifying the communications performance of CCW applications. Afterwards, we present detailed performance results of FCW under extreme vehicle density scenarios.

4.1 Performance Metrics

In this section we introduce a novel application latency metric, that goes a step beyond classical metrics, in order to gauge the latency performance of periodic broadcast-based CCW as perceived by the application. For instance, the end-to-end per-packet latency, defined as the time spent by a successful packet to travel from its source to final destination, is a classical networking metric. Even though this metric brings key insights about transmission, propagation, and queuing latencies, especially in multi-hop scenarios, it is not adequate to capture the performance of broadcast-based safety applications. This is attributed to the fact that this metric is gathered only for successful packets, i.e. it does not capture the impact of packet losses and collisions on the latency perceived by periodic applications. Thus, we introduce a novel latency metric that reflects the critical role played by successive packet collisions in degrading the performance of periodic safety applications as follows:

- *Packet inter-reception time (IRT) at the HV for packets sent by a given transmitter:* defined as the time elapsed between two successive successful reception events at the HV of packets broadcast by a specific transmitter (i.e. FV, NFV, or AV depending on the application) and plotted against simulation time. This metric accommodates the following types of latencies: queuing time due to MAC back off and 802.11 DCF Inter-frame Spacing (DIFS) and the number of consecutive packet losses attributed to the wireless channel impairments and interference.

- *Cumulative number of packet receptions at the HV from a given transmitter:* this metric is used for illustration purposes to highlight the direct impact of consecutive packet losses on the IRT metric. It is defined as the cumulative number of packets successfully received at the HV from a transmitter (whether FV, NFV, or an AV) plotted against simulation time.

In addition, we use two classical metrics, namely packet success probability and per-packet latency, which provide insights about packet level reliability of DSRC broadcasts in addition to the major contributors to broadcast packet latencies.

- *Packet success probability (PSP) at the HV from a given transmitter:* this metric is similar to the packet delivery ratio (PDR) metric used by the networking research community. It is defined as the percentage of packets that have been successfully received at the HV from a transmitter (specified by the CCW application of interest) throughout a simulation run.

- *Per-packet latency at the HV for packets sent by a given transmitter:* measured for each broadcast packet, from a given transmitter, that is successfully received at the HV and plotted against the simulation time. It is defined as the time elapsed between generating a packet at the application layer of the sender and successfully receiving the same packet at the application layer of the HV. This measure enables us to quantify the maximum, minimum and mean time incurred for a specific broadcast packet to get from the sender to the HV under extreme interference conditions. Unlike IRT, this measure does not account for packet losses. The main contributors to this latency are the packet transmission time and MAC backoff.

4.2 Simulation Results

In this section, we present the results for the FCW application under high and low vehicle densities. LCA and EEBL scenarios exhibit performance highly similar to FCW, on the average, due to the short distances between transmitter-receiver pairs, especially under high density scenarios.

4.2.1 High Vehicle Density

In this section, we analyze the aforementioned performance metrics for a specific HV-FV pair in order to illustrate the IRT metric and distinguish it from per-packet latency metrics.

Under this scenario, the HV-FV distance varies over a small range (1.1 to 29.9m) and, hence, does not exhibit any correlation to the packet loss events. In Figure 2(a), the cumulative number of packet receptions at HV from FV is shown over the course of a 30 sec simulation run. We observe that out of the 290 packets sent by the FV, the HV receives 244 packets successfully which translates to about 84% packet success probability (PSP). We mark 6 segments in the graph where the number of consecutive packet losses is greater than or equal to 2. The maximum number of consecutive packet losses (i.e. 3) in this trace occurred twice, around the 8^{th} and the 10^{th} seconds. Finally, single packets were intermittently lost at the HV 29 times. Characterizing the patterns of consecutive packet losses throughout a simulation run enables us to understand the behavior of the proposed IRT metric given in Figure 2(b).

In Figure 2(b), the IRT metric is plotted, versus the simulation time, for each packet successfully received at the HV from the FV. IRT values can be classified to four major categories depending on the number of consecutive packet losses. First, IRT achieves its lower bound of 100 msec (or slightly greater in case of MAC backoff) most of the time when no packet collisions are encountered. Second, IRT increases to around 200 msec in case of the 29 single packet loss events discussed in Figure 2(a). Finally, IRT increases to the ranges of 300 and 400 msec in the cases of 2 and 3 consecutive packet loss events respectively. This confirms that the proposed IRT metric is dominated by the interplay between the patterns of consecutive packet collisions and inter-broadcast time, as opposed to MAC backoff events. Moreover, it may suggest that sending the FCW warning messages more frequently (say every 50ms) is a favorable design choice from the perspective of minimizing IRT. However, broadcasting more frequently increases the temporal network load which potentially leads to increasing the maximum number of consecutive packet losses. Hence, we conjecture the existence of an optimal broadcast interval that strikes a balance between minimizing the maximum number of consecutive packet losses and minimizing the packet inter-broadcast time in an attempt to minimize the IRT latency perceived by the application. This trade-off is captured and analyzed further in Section 5.2.

In Figure 2(c), the per-packet latency is plotted, versus the simulation time, for packets successfully received at the HV from the FV. Comparing per-packet latency to IRT, we distill two key observations: i) per-packet latency varies over a range much narrower than IRT primarily due to its independence of consecutive packet loss events, and ii) it depends solely on the packet transmission time over the air (which constitutes the lower bound of approx. 0.321 msec for a 100 byte payload at 6 Mbps link rate) and MAC backoff (which amounts to only 17 msec for the given simulation run). This, in turn, explains the marginal impact of MAC backoff on the IRT measure compared to the interplay between inter-broadcast time and consecutive packet loss patterns.

Next, we shed some light on the following question central to the issue of scalability: Is the load imposed on the network by the simulated high density scenario, where all vehicles periodically generate single-hop broadcasts every 100 msec, sufficient to stress the DSRC MAC? In order to address this question, we introduce the notion of channel access capacity defined as the maximum number

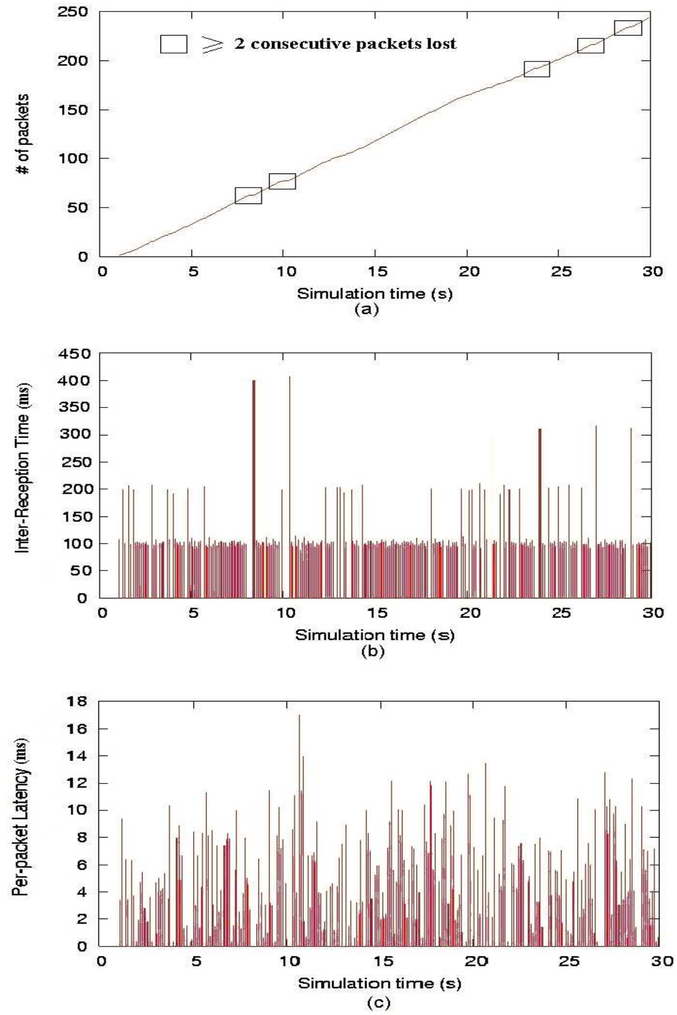


Figure 2: FCW Performance under High Vehicle Density (a) Cumulative number of packet receptions at Host Vehicle from Forward Vehicle, (b) Packet inter-reception time (IRT) at Host Vehicle for packets sent by Forward Vehicle, (c) Per-Packet latency at Host Vehicle for packets sent by Forward Vehicle

of transmitters that can access the wireless channel once during a single broadcast interval, assuming an ideal slotted MAC that guarantees collision free transmissions. It should be noted that despite the fact that DSRC uses CSMA/CA which is contention-based, the aforementioned channel access capacity reveals insights about the performance limits of DSRC over the duration of a broadcast interval.

Based on the following simulation parameters: message payload size of 100 bytes, 60 bytes of UDP, IP and MAC headers, data rate of 6 Mbps and DIFS wait period of 64 μsec, a single broadcast transmission time turns out to be approximately 0.278 msec. Thus, it is straightforward to determine that the channel access capacity of 360 vehicles can be supported in a collision free manner over a broadcast interval of 100 msec. The question that arises next is how close the high density scenario to the 360 vehicles channel access capacity. To address this question, we need to quantify the average number of vehicles within the 150m radio range of an arbitrary host vehicle. Based on the road simulation parameters (4m lane width

Table 1: FCW Maximum IRT Statistics over 20 runs

Statistic	High Density	Low Density
Mean (ms)	372.1	238
SD (ms)	66.3	74.4
95% CI (ms)	58.1	65.2

and 25m median width) along with the inter-vehicle distance (5m on one side and 10m on the other side), it can be determined that a host vehicle would have approximately 118 and 230 vehicles, on both sides of the freeway, within its radio range. This yields a total of 348 vehicles on the average attempting to access the channel simultaneously which confirms that the simulated high density scenario not only overloads the road from a transportation engineering point of view but also from the wireless channel access capacity perspective.

The above results presented for high interference scenarios suggest that DSRC could be a successful platform for FCW, yet, further analysis is needed. Interesting observations can be extracted from these results when compared to scenarios with lower vehicle densities presented in the next section.

4.2.2 Low Vehicle Density

Under this scenario, the distance between HV and FV varies over a wider range between 71 and 88.9m. However, no correlation was observed with the pattern of packet losses. This is primarily due to the low interference experienced under this scenario, as illustrated in the next section.

For the experiment shown in Figure 3, only seven packets are lost, out of the 290 packets sent by the FV, which yields less than 3% packet loss. This is in complete agreement with intuition, due to the lower interference contributed by fewer vehicles. Furthermore, no consecutive packet losses occurred under this scenario, i.e. all packet losses are isolated single losses as shown in the figure. This translates to a maximum of 200 msec IRT for the given packet trace. In addition, it can be noticed from Figure 3(c) that most of the broadcast packets do not experience MAC backoff, due to the low contention for the wireless channel, and hence, the per-packet latency boils down to its lower bound, namely the packet transmission time over the air (approx. 0.321 msec). Moreover, the maximum per-packet latency is one order of magnitude less than the high density case due to the shorter backoff intervals the packets encounter under low density scenarios.

Beyond the sample runs shown in Figures 2 and 3, we conducted 20 simulation runs, using different choices of the HV, to show the statistical significance of the results. Tables 1 and 2 show the mean, standard deviation (SD) and 95% confidence interval (CI) for the FCW maximum IRT and PSP metrics under high and low vehicle densities. First, we note that the largest relative statistical error for the high and low density scenarios, $\frac{CI}{2*Mean}$, is given by $< 13.6\%$ and $< 1\%$ for the maximum IRT and PSP metrics respectively. Second, the statistical means confirm the superior IRT and PSP performance under low density scenarios as expected. However, it is interesting to note that the performance gap between the two extremes is not considerable, i.e. max. IRT is 56% lower and PSP is 12% higher under low density. Thus, we argue that high density performance could be significantly improved with the aid of broadcast enhancement techniques, discussed in the next section.

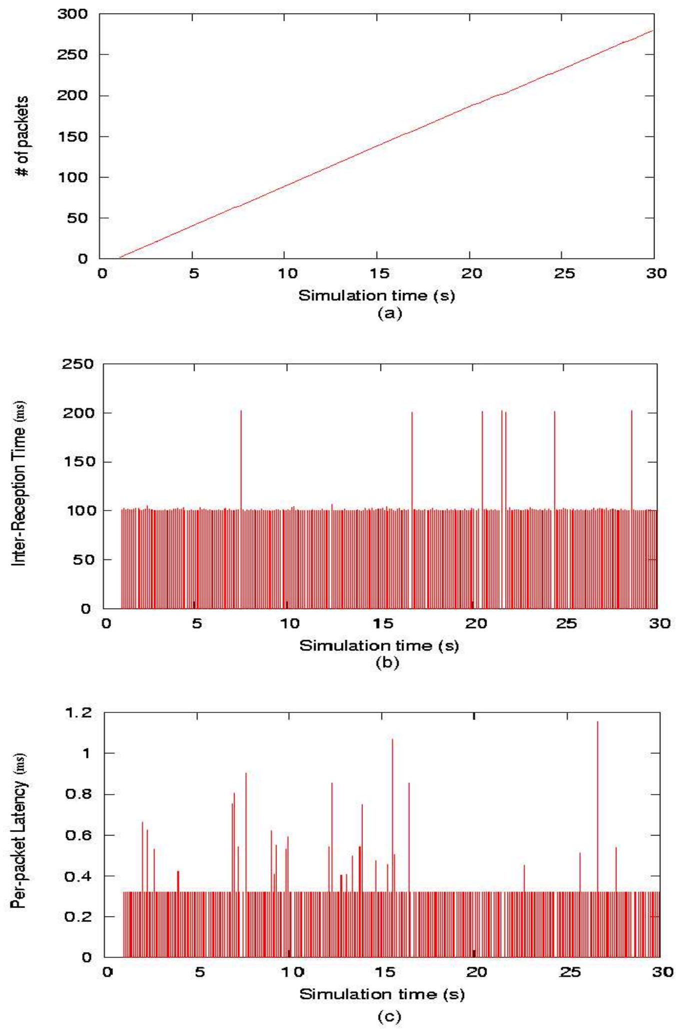


Figure 3: FCW Performance under Low Vehicle Density (a) Cumulative number of packet receptions at Host Vehicle from Forward Vehicle, (b) Packet inter-reception time (IRT) at Host Vehicle for packets sent by Forward Vehicle, (c) Per-Packet latency at Host Vehicle for packets sent by Forward Vehicle

5. DISTANCE TRENDS AND BROADCAST ENHANCEMENTS

In this section, we explore two important aspects pertaining to DSRC performance trends and its implications on broadcast-based safety applications. We present the simulation results of experiments targeted towards: i) characterizing the packet success probability trends with distance, ii) uncovering a trade-off related to optimizing the application broadcast rate, and iii) exploring performance trends with varying transmission range.

5.1 Packet Success Probability Trends with Distance

So far, we have focused on evaluating the quality of communications between specific pairs of vehicles, i.e. HV and FV for FCW, under the assumption that all vehicles are periodically broadcasting. In this section, we are interested in characterizing the packet success probability trends with increasing distance from the HV

Table 2: FCW PSP Statistics over 20 runs

Statistic	High Density	Low Density
PSP Mean	0.865	0.986
PSP SD	0.025	0.011
PSP 95% CI	0.022	0.01

under high and low vehicle densities. This is of paramount importance to understand how DSRC supports different applications depending on the spatial separation of its communicating parties. Thus, we focus on the HV and consider all packets received from broadcasting vehicles within its 150m radio range. We divide the 150m range to 10 concentric bins at 15m, 30m, 45m, . . . and so on. In this set of experiments, vehicles are stationary in order for any vehicle to stay within the same distance bin throughout the simulation run in order to simplify statistics gathering. For each broadcasting vehicle, we compute the fraction of packets received successfully at the HV and then average this over all vehicles that lie within the same distance bin.

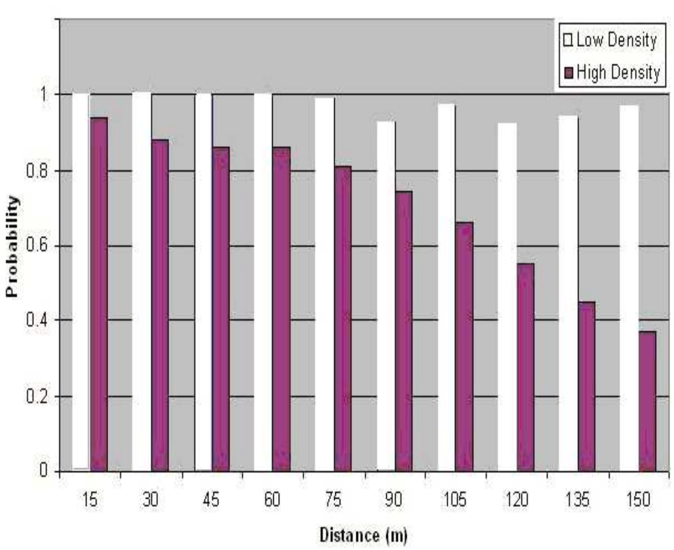


Figure 4: Packet Success Probability variation with distance from the receiver (Host Vehicle) under high and low vehicle densities

Figure 4 shows the packet success probability versus distance from the HV under high and low vehicle densities. For the high density case, it can be noticed that the success probability varies from 93% in the 0-15 meters range down to 38% in the 135-150 meters range. This wide range of variation gives rise to the following key observation: the quality of reception at the HV strongly depends on the distance to the relevant sender as specified by the application. Thus, an FCW application would generally experience different performance from other applications that require reliable reception from farther vehicles (e.g. EEBL involving farther vehicles). This, in turn, suggests that different applications may require different settings of the application and protocol parameters, e.g. broadcast rate, DSRC MAC backoff and transmission power depending on the vehicle density scenario and the relevant sender. This constitutes a potential avenue for developing DSRC broadcast enhancements for supporting different safety applications.

For the low density case, it can be noticed that the success probability hovers around 100% over all distance bins. As pointed out earlier, this is due to the low interference experienced which is insufficient to elevate the noise floor at the HV to a level where the packet can not be decoded and, hence, should be dropped. This, in turn, yields almost the same reception quality at the HV as long as the sender lies within the 150m range.

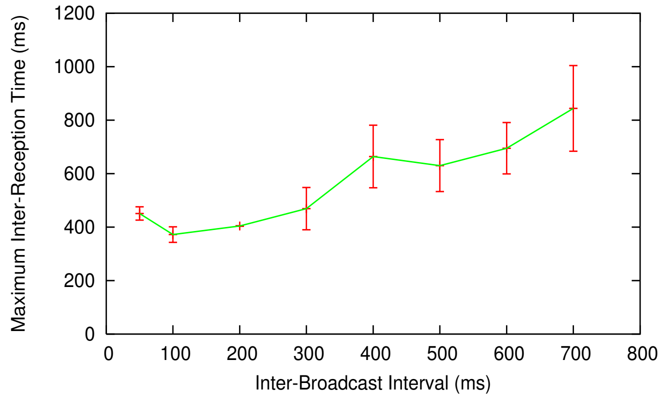
5.2 Broadcast Enhancements

Enhancing the broadcast performance of DSRC can be achieved through adapting a number of controllable parameters at different layers of the OSI protocol stack. For instance, adapting the minimum and maximum contention window (MAC parameters) to control the MAC aggressiveness constitutes a viable approach to balance the trade-off between waiting unnecessarily for an idle channel under low vehicle densities and encountering frequent backoffs due to a busy channel under high densities. In this section, we explore the benefits and the trade-offs associated with two other controllable parameters, namely packet broadcast rate (application parameter) and transmission range (radio parameter).

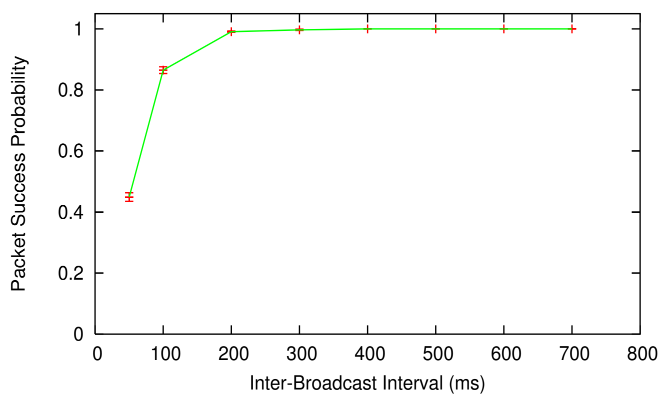
5.2.1 Application Broadcast Rate Adaptation

In this section, we focus on the application broadcast rate where we capture the trade-off between number of consecutive packet losses (favors low broadcast rates) and the time for the receiver to wait for a new broadcast in case of losing the last one (favors high broadcast rates). Thus, we fix the transmission range to 150m, the payload to 100 bytes, with all the 1920 cars in the mile long stretch periodically broadcasting and vary the broadcast interval from run to run between 50 and 700 msec. Once more, we focus on the performance of FCW applications and conduct 20 simulation runs for each broadcast rate with different choices of the host vehicle. For each value of broadcast rate, we set the simulation time such that the number of packets generated by each vehicle is 290 packets. This is of paramount importance to guarantee fairness comparison of different broadcast rates.

Figure 5(a) shows the mean of the maximum packet inter-reception times for different values of the broadcast interval. For each broadcast interval, we plot the mean and the 95% CI computed over the 20 simulation runs. We point out the convexity of the curve which suggests an optimal broadcast interval around 100 msec for this scenario. This is solely attributed to the trade-off between the number of consecutive packet collisions and inter-broadcast time. For small broadcast intervals (high temporal load evidenced by the low PSP in Figure 5(b)), IRT performance is dominated by the large number of consecutive packet losses (8 consecutive packet losses on the average at 50 msec as noticed in Figure 5(a)). As we increase the broadcast interval to 100 msec, the interplay between the decreasing number of consecutive packet collisions and the increasing time between successive broadcasts leads to a reduced IRT. Beyond 100 msec, the contribution of the longer broadcast interval starts to dominate performance, which explains the increasing IRT, even though successive packet collisions are decreasing. For broadcast intervals $\geq$ 500 msec, few/no packet collisions arise due to the light network load (shown in Figure 5(b)) and IRT becomes largely dominated by the time incurred between infrequent broadcasts. This justifies the linear growth of IRT with the broadcast interval in case of no collisions (i.e. broadcast intervals $\geq$ 500 msec) as demonstrated by the lower end of the CI in Figure 5(a). Notice also that the CI becomes wider as we increase the broadcast interval due to the effect of packet losses/collisions on IRT (e.g. the contribution of a single packet loss to IRT at 700 msec broadcast interval is seven times its contribution at 100 msec



(a) Max. Packet inter-reception time variation with the Application Broadcast Interval



(b) Packet Success Probability variation with the Application Broadcast Interval

Figure 5: Broadcast Interval Adaptation

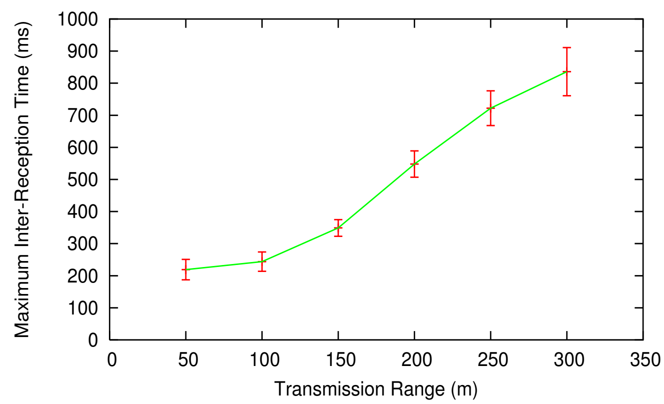
broadcast interval). The broadcast interval of 200 msec exhibits the narrowest CI since all 20 runs did not experience any consecutive packet losses.

It should be noticed that the captured trade-off is inherent to the class of periodic broadcast-based safety applications (through the IRT measure), i.e. it does not prevail for the general per-packet latency measure. Thus, we conjecture that the optimal broadcast interval can be characterized through analytical optimization formulations for general network settings. This is a potential avenue for extending this work.

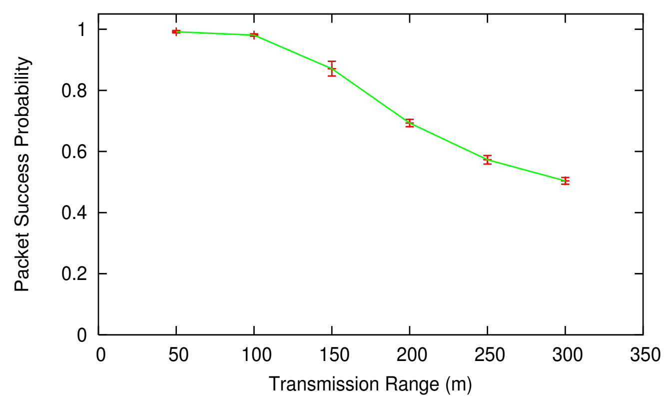
Finally, it should be noted that [12] addressed the problem of optimal number of message repetitions, yet from a different perspective. First, optimality is in the sense of minimizing the probability of reception failure (PRF) which is a throughput measure rather than a latency measure, as proposed in this paper. Second, PRF(L,τ) is defined as the probability that a randomly chosen message transmitted by a randomly chosen vehicle will not be received by a randomly chosen receiver at distance L within time τ[12]. Hence, the PRF metric hinges on knowing the latency requirement τ whereas the IRT metric quantifies the latency perceived by an application running on top of a given protocol suite. This suggests that IRT could be used for comparing different protocols and parameter settings even if the application latency requirements are not precisely known. Finally, the optimal with respect to IRT is a direct consequence of the interplay between consecutive packet losses and inter-broadcast time, which is not captured by the PRF metric.

5.2.2 Transmission Range Adaptation

Adapting the transmission power (range), depending on the vehicle density and application constraints, is known to reduce interference and, hence, improve the network capacity and application performance [16]. In this section, we analyze the communication performance of FCW under different transmission ranges. Thus, we fix the broadcast rate at 10 packets/sec, the packet payload at 100 bytes, the vehicle density at 1920 vehicles over the 1 mile stretch and vary the transmission range to take the values 50, 100, 150, ..., 300m.



(a) Max. Packet inter-reception time variation with the Radio Transmission Range



(b) Packet Success Probability variation with the Radio Transmission Range

Figure 6: Transmission Range Adaptation

Figures 6(a) and (b) show the FCW maximum packet inter-reception time (IRT) and packet success probability (PSP) for different values of the transmission range. For the high density scenario under focus, it is obvious that large transmission ranges give rise to higher levels of contention for the wireless medium and, hence, more packet collisions. This is confirmed by the gradually decreasing PSP and increasing IRT trends with larger transmission ranges. First, we point out that ranges less than 100 meters experience very high PSP ($< 4\%$ packet losses) and at most 3 consecutive packet losses (mean of the max. IRT 250 msec) for the given vehicle density. This suggests that, under high density scenarios, vehicles should use the minimum power required to reach the receiving vehicle of interest depending on the application, in order not to cause excessive interference unnecessarily. This gives rises to a trade-off between multiple access interference and application range constraints that should be taken into consideration while designing power adaptation schemes. Second, the degradation in performance from 50 to 300 meters is considerable, about 4-fold increase in the IRT and $< 40\%$ degradation in the PSP, on the average.

6. CONCLUSIONS

In this paper we conducted a performance evaluation study of cooperative collision warning applications using the emerging DSRC wireless standard. First, we presented communications performance results of the forward collision warning application under extreme vehicle densities. The results confirm the important role of the proposed IRT latency metric in capturing the effect of successive packet collisions on the latency perceived by periodic broadcast-based safety applications. Second, we explored potential broadcast enhancement techniques, namely broadcast rate and transmission range adaptation. This reveals an interesting trade-off pertaining to the IRT latency measure that is worth further analysis in order to characterize the optimal broadcast rate, from a wireless networking perspective, for more general settings. This work can be extended to investigate the impact of measurement-based wireless channel models that account for multi-path fading and vehicles' mobility on the gathered statistics. It can also be extended to develop distributed broadcast enhancement techniques that dynamically achieve the optimal broadcast rate and transmission range. Finally, application-level reliability metrics, as opposed to packet-level reliability metrics like the packet success probability, need further research.

7. ACKNOWLEDGMENTS

The authors would like to thank Vikas Kukshya and Jijun Yin at HRL for their input to the DSRC wireless channel simulations and Fan Bai at General Motors for helpful discussions on vehicular applications.

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