

Reliability Analysis of DSRC Wireless Communication for Vehicle Safety Applications

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Abstract—The 802.11-p based Dedicated Short Range Communication (DSRC) is being seriously considered as a promising wireless technology for enhancing transportation safety and highway efficiency. However, to-date, there is very little research done in characterizing the reliability of DSRC communication based on real-world experimental data, and its effect on the reliability of vehicle safety applications.

Our experimental set-up includes a fleet of three vehicles equipped with DSRC communication system, GPS receiver and a number of vehicle safety applications based on vehicle-to-vehicle communication. This paper analyzes the link-level behavior of DSRC vehicle-to-vehicle communication in a wide variety of traffic environments based on real-world experimental data. In addition, we also characterize the application level reliability of DSRC for vehicle safety communication (VSC) system. Based on our experiments, we show that the reliability of DSRC vehicle-to-vehicle communication is adequate since packet drops do not occur in bursts most of the time. We also show that the application level reliability of VSC applications based on DSRC communication is quite satisfactory. Finally, we develop an analytical model to relate application level reliability with communication reliability and VSC system parameter, laying out a clear way to improve reliability of VSC applications under harsh traffic environments.

To the best of our knowledge, this paper is the first to characterize the application-level reliability of DSRC communication for VSC applications based on real-world experimental data. Our findings develop a deep insight into significant characteristics of DSRC communication for highly mobile vehicle-to-vehicle wireless network, which will contribute to better design and evaluation of communication protocols for VSC applications in the future.

I. INTRODUCTION

Traffic accidents and highway congestion continues to remain a serious problem world-wide. Annually, in the United States, traffic accidents result in approximately 44,000 fatalities, 6 million crashes and about \$250 billion in economic costs. Active safety applications, that use autonomous vehicle sensors such as radar, lidar, camera, etc., are being developed and deployed in vehicles by automakers to address the crash problem. Moreover, the FCC has recognized the importance of having a dedicated wireless spectrum for improving traffic safety and highway efficiency. In the US, the FCC has allocated 75 MHz of spectrum in 5.9 GHz band as Dedicated Short Range Communication (DSRC) for the primary purpose of improving transportation safety and highway efficiency but the spectrum may also be shared by

commercial vehicular applications [15]. The rule making for the lower layer standards for DSRC have been developed and accepted by the FCC [13]. The lower layer standards for DSRC are now being revised under the IEEE 802.11p task group [14]. The 802.11p based DSRC is being seriously considered as a promising wireless technology for enhancing transportation safety and traffic efficiency. Major automotive OEMs, wireless radio manufacturers, research universities, public agencies and private enterprises are aggressively evaluating use of DSRC for vehicle-to-vehicle and vehicle-to-infrastructure applications [20] [1] [2] [3] [16] [17]. The deployment of DSRC for improving transportation safety and efficiency is being addressed under major USDOT initiatives [19] [18].

The 802.11p-based DSRC communication had not yet be fully evaluated and analyzed through field experiments in a systematic manner. Meanwhile, the observations made based on WLAN technology cannot be applied to DSRC-based wireless communication system, due to different spectrums used and several technical and environmental differences. Thus characteristics of DSRC wireless communication and its link-level behaviors remain unclear to the research community, which may hinder efficient design and rigorous evaluation of the VSC system. Our paper attempts to address this problem. To achieve this objective, we focus our effort to systematically and extensively evaluate and analyze the most critical performance of DSRC communication for VSC applications: **Reliability**. The major aspect of communication performance of interest to researchers and engineers is reliability of DSRC wireless communication itself, while end users (drivers) mainly care about whether VSC applications based on DSRC wireless communication can provide a reliable and trustable application service. In this paper, we aim to answer the following sets of questions:

- 1) Which metrics can better illustrate the fundamental characteristics of communication reliability itself? How reliable is DSRC wireless communication?
- 2) Which metric can accurately represent the reliability properties of VSC applications that end users experienced? How reliable are these DSRC-based VSC applications?
- 3) What is the difference between communication reli-

ability and application-level reliability? What is their relationship (if any)?

To answer these questions, we first conduct extensive experiments to collect necessary real-world data by using 3 vehicles equipped with the VSC system consisting of a DSRC communication system, GPS receiver and a number of VSC applications based on vehicle-to-vehicle communications. The data is collected under different traffic environments, including both idealistic open field environment and harsh freeway environment of metropolitan area. Realizing that there exists differences between communication reliability and application-level reliability, we define two reliability metrics at communication level (*packet delivery ratio* and *distribution of consecutive packet drops*) and one application-level reliability metric (*T-window reliability metric*). Using these metrics to analyze the experiment data, our study indicates that reliability of DSRC wireless communication seems to be adequate most of the time (however, its detailed behavior depends on the specific environments). At the same time, reliability of DSRC-based VSC applications is quite satisfactory even under harsh environment due to the memory-less nature of VSC application requirements, non-bursty characteristic of packet losses and the design philosophy of repetitive broadcasts. To clearly understand the complicated interaction between communication reliability, application-level reliability of VSC applications and design of VSC applications, we develop a first-order analytical model to quantitatively relate them with each other.

The remaining part of this paper is organized as follows: The related work is introduced in Section II; VSC system design, experiment setting and data process methodology are discussed in Section III; Two communication reliability metrics are defined and then used to evaluate DSRC wireless communication in Section IV; Application-level reliability of VSC applications is defined and then used to evaluate four VSC applications (developed at General Motors Research Center) in Section V; In Section VI, we give an analytical model to relate application-level reliability with communication reliability and VSC system parameter, and then we discuss its potential usage; Finally, we conclude this paper and discuss our future research direction in Section VII.

II. RELATED WORK

Wireless communication characteristics and system performance of Infrastructure-based wireless networks, from small-scale WLAN network [4] to large-scale campus-wide network [5], have been extensively measured and studied in the past. However, the results of these studies cannot be directly applied to the vehicle-to-vehicle communication scenarios because of the fundamental differences between infrastructure-based wireless network environments and vehicular ad hoc network environments.

Recently, several research have been conducted to analyze and study the communication characteristics of wireless ad hoc networks, including mobile ad hoc network, wireless mesh network and wireless sensor network. A mid-size test-bed was first constructed at Carnegie Mellon University to

evaluate the protocol performance of ad hoc network routing protocols [6]. To better understand the wireless communication in sensor network, systematic and thorough experiments have been conducted to analyze packet delivery performance and its temporal-spatial characteristics in a 60-node sensor network [7], under various environments. A similar study of packet loss pattern and rigorous investigation into the potential reasons for packet drops was conducted, on a 38-node Roofnet network composed of 802.11b radio devices in Boston urban environment [8]. These papers, among others, point out that the unpredictability and wide variability of communication links [9] may invalidate many well accepted concepts and principles widely used in network design, such as shortest path routing [10].

Empirical determination of DSRC channel characteristics based on both optimistic two-ray-ground signal propagation model and pessimistic Nakagami model have been presented [12]. Evaluation of priority access protocol for broadcast performance of vehicular ad hoc network is presented in [11]. This paper studies average packet drop rate from a theoretical perspective, which is different with our focus on using experiment data to analyze packet delivery pattern (in both average value and distribution).

Our paper has been partly inspired by the initial research mentioned above. However, nearly all of these studies are based on wireless network only composed of stationary devices while mobility factor of vehicular networks has not been taken into consideration. To the best of our knowledge, this paper is among the first to investigate the reliability issue of DSRC wireless communication for highly mobile vehicle-to-vehicle network under different traffic environments, through extensive experiments.

The contributions of our paper are threefold:

- 1) Isolate the concept of communication reliability from application-level reliability that end users may experience, and quantitatively define appropriate metrics to capture the key characteristics of both of them;
- 2) Conduct experiments under different traffic environments to evaluate both communication reliability and application-level reliability based on real-world data. Based on our study, we show that reliability of DSRC wireless communication is adequate (i.e. packet losses do not occur in bursts) while reliability of VSC applications is satisfactory;
- 3) Establish an analytical model to relate application-level reliability with communication reliability. Moreover, we also point out the research direction to improve reliability of VSC applications in traffic environments yielding very lossy wireless channels;

III. EXPERIMENT METHODOLOGY

In this section, we describe our experimental setup and experimental methodologies used to collect real-world data. This section will help readers to better understand the systematic experiments conducted in real vehicular traffic environments, as well as the procedure that was adopted to collect the experimental data.

A. DSRC Communication System and VSC Applications

The experimental setup consists of hardware and software installed in three GM vehicles capable of demonstrating several VSC applications based on DSRC communication. Each of the three experimental vehicles are equipped with an 802.11p-based DSRC radio, an omni-directional roof-mounted antenna, a GPS receiver and software application in a processor allowing exchange of information via vehicle-to-vehicle communication. In addition to the DSRC wireless communication system, the vehicles are equipped with a number of VSC applications capable of providing driver assistance information via driver vehicle interfaces consisting of haptic, visual and auditory warnings. In order to execute the VSC applications, each vehicle periodically broadcasts its current GPS position, velocity, heading and other sensor information (e.g., braking status, acceleration, etc.) so that all the neighbor vehicles within the transmission range (typically, 300m) would receive the message. The periodic DSRC message broadcast rate from each vehicle is 100 milliseconds. By using appropriate algorithms to process the information, the receiving vehicle is able to evaluate whether there is a dangerous driving situation at each moment of time and appropriate safety alerts, based on the implemented VSC applications, are provided to drivers, if necessary.

Since July 2005, we have demonstrated Vehicle Safety Communication (VSC) applications using our fleet of three experimental vehicles widely to the press nationwide, to the external research community, public demonstrations at the ITS World Congress in San Francisco, etc. The demonstrations include four types of VSC applications - Stop/Slow Vehicle Ahead (SVA) Advisor, Emergency Electronic Brake Light (EEBL) Advisor, Forward Collision Warning (FCW), Lane Change (& Blind Spot) Advisor (LCA). In SVA application, host vehicle monitors messages from other vehicles up to 300m ahead on the road and advises driver when any vehicle ahead is stopped or traveling 20 mph slower than the host; In EEBL application, host vehicle monitors messages from other vehicles up to 250 m ahead on the road and advises driver when any vehicle ahead suddenly 'brakes hard' (sudden deceleration); In FCW application, host vehicle monitors messages from other vehicles up to 150 m ahead in the same lane and provides warning to driver when it is in danger of rear-end collision with vehicle ahead in lane; In LCA application, host vehicle provides advisory information to the driver when there is another vehicle occupying its blind zone, and provides warning to the driver when there is a vehicle on adjacent lanes predicted to pass the host vehicle, up to 100m behind. The application range D for warning message coverage and tolerance time window T to receive the warning message, for different applications, are listed in Table I.

B. Experiment Settings

The experiments were conducted on July 27, Sep 28 and Oct 10, 2005. Experiments on July 27 and Oct 10 were conducted along I-696 freeway, between General Motors Warren Technical Center (WTC) and General Motors Milford

TABLE I
APPLICATION RANGE D AND TOLERANCE TIME WINDOW T FOR
DIFFERENT VSC APPLICATIONS

VSC Applications	Application Range	Tolerance Time Window
SVA	300m	0.5-3.0 sec
EEBL	250m	0.3-2.0 sec
FCW	150m	0.3-1.0 sec
LCA	100m	0.3-2.0 sec

Proving Ground (MPG), representing a realistic freeway environment of metropolitan/suburban area. Number of walls, tunnels and overhead bridges are present along this section of the freeway, which represents a harsh environment for wireless signal propagation. Experiments on Sep 28 was conducted on test tracks at the General Motors Milford Proving Ground (MPG), representing an idealistic open field environment without any hostile environmental and traffic factors affecting the signal propagation. In each set of experiments, 3 vehicles equipped with experimental platform were driven at driver's free will, in order to emulate the normal driving behavior. As a result, the distance between different vehicles varied from 10m to 1km. The experiments on July 27, Sep 28 and Oct 10 lasted about 2, 3 and 2 hours, respectively, thus we believe the experimental date is large enough to draw statistically meaningful conclusions.

The transmission power and transmission rate of DSRC communication was set to 20dBm and 6Mbps, respectively. At an update rate of 100 milliseconds, each vehicle broadcasted one single packet consisting of its GPS location, speed, heading and other sensor information. Because internal clocks on different vehicles are not perfectly synchronized, the periodic broadcast from the vehicles is typically asynchronous, so that MAC-level collision does not impose a significant effect on DSRC wireless communication. Every 100 milliseconds, each vehicle records its own GPS location, speed, heading and other sensor data information in its log file. At the same time, based on received messages from other vehicles, GPS location, speed, heading and other sensor data information of other vehicles as well as the Received Signal Strength Indicator (RSSI) value of the received packets are recorded in log files as well. We also recorded the video during our experiments by using the camera equipped in the vehicles.

C. Data Processing Methodology

Before analyzing experimental results, we also pre-process the experimental data to eliminate the effects of experimental anomaly caused by asynchronous clocks in the internal vehicle system bus and wireless transceiver, long-duration outages primarily caused either by the large inter-vehicle distances (i.e., larger than 600m) or by environmental obstacle blockage confirmed via recorded video and logged data. We removed the beginning and ending part of log data, to remove initial transients in the experimental data and for ensuring that the data analyzed is only recorded in a stable (normal operation) condition of DSRC wireless communication. We believe such pre-processing is necessary

so that the data used for analysis correctly represents the real-world characteristics of DSRC-based communication systems when widely deployed.

IV. RELIABILITY OF DSRC WIRELESS COMMUNICATION

Through the study, we realize that wireless communication reliability is a combined function of wireless channel model and modulation technique¹. However, DSRC communication reliability and its relationship to the reliability of VSC applications must be clearly established since the later is what end-users of this technology would experience. Based on this thought, we believe that it is necessary to isolate the two closely related concepts: **Communication Reliability** and **Application-level Reliability**. In this section, we focus on the reliability of DSRC wireless communication with emphasis on examining average packet drop rate and packet drop pattern under various traffic environments. The experiment results illustrate to what degree DSRC wireless communication is trustable from perspective of DSRC communications system design.

A. Communication Reliability Metrics

To better capture the reliability of DSRC wireless communication and to quantitatively measure its potential impact on VSC applications, we make use of two reliability metrics for DSRC communication: *Packet Delivery Ratio* and *Distribution of Consecutive Packet Drops*.

Packet Delivery Ratio (PDR), a widely used metric in the literature, is the probability of successfully receiving a packet at the receiver after this packet is transmitted at the sender. In practice, it is often calculated as a ratio of the number of data packets received at the receiver to total number of packets transmitted at the sender within some pre-defined time window².

However, the PDR metric illustrates packet drop patterns purely based on average value. Here, we also attempt to examine the detailed probability distributions of packet drop pattern across various traffic environments. We believe that this approach might give us a deeper understanding of impact of potential packet drops on VSC applications. Therefore, we propose another statistical metric, **Distribution of Consecutive Packet Drops**, which illustrates the probability distribution of consecutive packet drops for DSRC wireless communication.

Based on these two metrics, one describing packet drop in an average sense and the other providing the probability distribution of consecutive packet drops, we are able to systematically analyze the reliability characteristic of DSRC wireless communication.

¹In fact, the in-depth questions in wireless communication are the following: *How erroneous and lossy is the wireless channel?*, and *How robust is the modulation scheme over lossy and erroneous channel?* In this paper, we have not examined the detailed channel models under different environments and their impact on various modulation schemes because it was not within the scope of this study.

²Another commonly used metric, *Packet Loss Ratio (PLR)*, is a complement to Packet Delivery Ratio which is used to define the same lossy characteristic of wireless communication from the packet loss perspective.

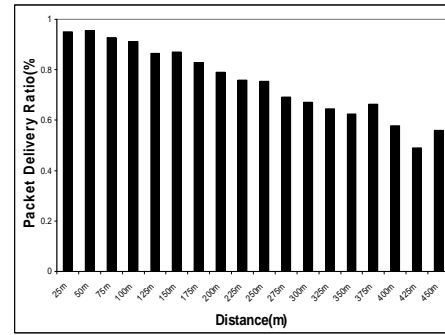


Fig. 1. Packet Delivery Ratio vs. Distance Between Vehicles, Under Freeway Environment

B. Packet Delivery Ratio

We now focus on obtaining the detailed statistics of packet delivery ratio across the different traffic environments where our experiments were conducted.

By analyzing the sequence numbers of packets received at each receiver's log file, we are able to measure the packet delivery ratio. For a given time window, the packet delivery ratio is simply calculated as ratio of received packets to total transmitted packets during this duration³. Average distance between transmitter vehicle and receiver vehicle can be calculated as well, giving us a relatively accurate estimation of their distance within this time window. With calculated information of packet delivery ratio and average distance, we sort the data samples into different distance bins (granularity of bin is set to 25m) and then calculate average packet delivery ratio for each distance bin. Finally, we visualize packet delivery ratio as a function of distance by plotting average packet delivery ratio at different distance bins in Fig.1 and Fig.2. Here, the packet delivery ratio is plotted (in the form of vertical bar) as y-axis and different distance bins are plotted as x-axis.

Fig.1 and Fig.2 illustrate packet delivery ratio of DSRC wireless communication under freeway environment and open field environment, respectively. First, we observe that, as a general trend, packet delivery ratio decays with increased distance between vehicles, in both environments. Moreover, we also notice that packet delivery ratio decays much faster in freeway environment than in open field environment. For example, packet delivery ratios are 93% (open field) and 91% (freeway) at 100m, 86% (open field) and 78% (freeway) at 200m, 88% (open field) and 67% (freeway) at 300m, 76% (open field) and 58% (freeway) at 400m. Interestingly, the difference of packet delivery ratio between freeway environment and open field environment is minimal when the distance between vehicles is small (about 2%

³In our experiments, we set this time window to 2 seconds (i.e., 20 packets). If time window is set too small, granularity of packet delivery rate is so coarse that calculated result may not help us to draw any meaningful conclusions; On the other hand, if time window is set too large, average distance calculated may not accurately represent the real distance between vehicles for this long duration. However, through our careful study, we find the value of time window between 0.5 seconds and 5 seconds is a reasonable range. The results we calculated and graph plotted rarely change within these parameter range. Due to limited space, in this paper, we will not elaborate the topic on sensitivity study of time window.

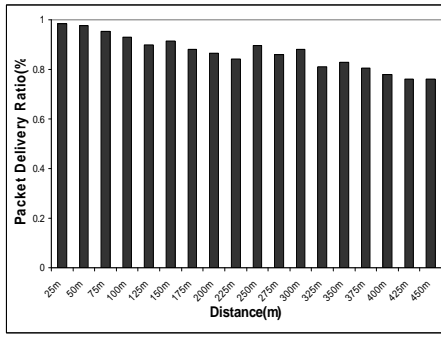


Fig. 2. Packet Delivery Ratio vs. Distance Between Vehicles, Under Open Field Environment

when distance is 100m), while this difference is too large when distance between vehicles is large (around 20% when distance is 400m). This observation also suggests the fading effect of DSRC wireless channel on metropolitan freeway is much more severe than in a test track environment, confirming our conjecture that freeway system represents a harsh environment for DSRC wireless communication. Finally, we also find that packet delivery ratio under open field environment does not decay monotonically (e.g., packet delivery ratio of 250m, 275m and 300m is higher than that of 200m, as illustrated in Fig.2). Since this graph is plotted based on a measurement with more than 16,000 packets, more likely, we can rule out the possibility of this variability resulting from insufficient sample points. Our ongoing study on signal strength analysis indicates that this phenomenon can be attributed to additive signal effect caused by a dominant two-ray wireless channel from roadway reflection that is increasingly prominent in the test track environment.

Generally speaking, communication reliability of DSRC communication (in terms of packet delivery ratio) highly depends on the underlying environment. For benign traffic environment such as the open field test track, reliability of DSRC communication is quite satisfactory. However, even in potentially harsh traffic environment, reliability of DSRC communication still seems to be adequate.

C. Distribution of Consecutive Packet Drops

We now attempt to investigate detailed distribution of packet drops. Among others, the metric that is of interest for VSC applications is the probability distribution of consecutive packet drops. This metric described whether packet drop over DSRC wireless channel occurs in bursts or not. 'Bursty packet drops', in wireless networking terminology, refers to situation that data packets are dropped in short and uneven spurts. The less frequently phenomenon of bursty packet drop happens, the more reliable the wireless channel is. Here, the x-axis is the number of consecutive dropped packets (M), and y-axis is the probability of M consecutive packets getting dropped together.

The status of packet drops between every pair of vehicles is monitored when we process log files. The number of consecutive dropped packets is calculated as the gap of packet sequence number between last received packet and next received packet, once some intermediate packets are

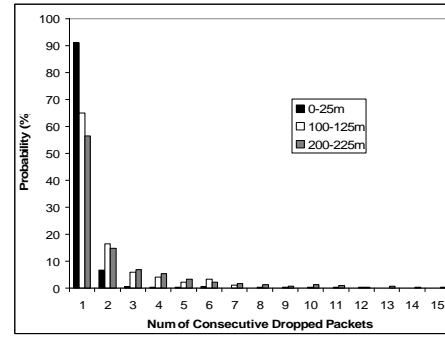


Fig. 3. Probability Distribution Function of Consecutive Packet Drops, Under Freeway Environment

lost. These instances of consecutive packet drops are then sorted into bins of 1, 2, ..., packets, based on exact number of consecutive dropped packets. After having sorted the samples of consecutive dropped packets into bins, we plot a histogram of these intervals of consecutive dropped packets for different distance scales and different environment in Fig.3 and Fig.4.

Fig.3 and Fig.4 give the probability distribution of consecutive dropped packets at different distance scales, under freeway environment and open field environment, respectively. For better illustration, we only present the probability distributions of consecutive packet drops at several distance scales (i.e., 0-25m, 100-125m, 200-225m), rather than all of them. As discovered before, freeway environment generally represents a harsh environment, hence we focused on analyzing its detailed packet drop pattern shown in Fig.3.

Through the study, first, we realize that the majority of packet drops are either single-packet drops (about 90% at 0-25m, to 55% at 200-225m) or double-packet drop (about 5% at 0-25m, to 15% at 200-225m), under less reliable freeway environment. Even for long distance scenario (200-225m), the case that more than 5 consecutive packets drop together seldom happens in our experiments (less than 2%). This observation strongly indicates that inter-vehicular DSRC wireless communication does not occur in bursts most of the time. Secondly, we find that probability distribution function of consecutive packet drop is a function of distance between vehicles. As distance increases, the probability for single-packet drop decreases and probability for multi-packet drop increases. As a result, the probability distribution function begins to 'skew' to the right side of histogram and the DSRC wireless channel becomes slightly bursty when the distance between vehicles is very large. Finally, by comparing Fig.3 and Fig.4, we believe that two observations made above are also valid for open field environments, although the DSRC wireless channel is benign in open field traffic environment and less bursty than in an harsh freeway traffic environment.

In summary, we find that packet drop over DSRC wireless channel does not occur in bursts under both traffic environments. In other words, packet drops seem to be independent with each other in our experiments. Given this memory less property of packet drops over DSRC wireless communication, we are able to design VSC applications robust to packet drops by incorporating appropriate compensation

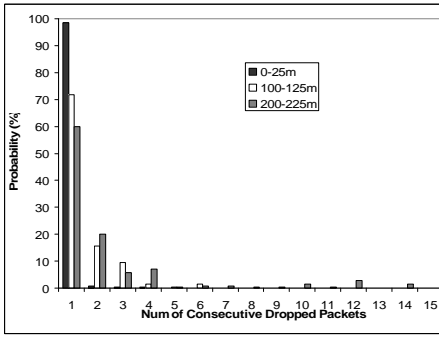


Fig. 4. Probability Distribution Function of Consecutive Packet Drops, Under Open Field Environment

mechanisms, as discussed in Section V.

V. RELIABILITY OF DSRC-BASED VEHICLE SAFETY COMMUNICATION (VSC) APPLICATIONS

Thus far, we have carefully examined the reliability of DSRC wireless communication, in terms of both average value and detailed probability distribution. In this section, we aim to investigate the reliability of DSRC-based VSC applications, from the viewpoint of end user application service.

A. Application-Level T -window Reliability Metric

For DSRC-based VSC application, the end user application service will not experience undesired effect when one or two individual packets are sporadically lost during the periodic routine broadcasts. As long as (at least) one packet from the neighbor vehicle is successfully received within a tolerance time window T^4 , the receiver vehicle should be able to predict and update the neighbor vehicle information accurate enough for VSC application processing. In line with this thought, to accurately describe the reliability of DSRC-based VSC applications, we propose to make use of a novel reliability metric – T -window reliability.

T -window reliability is defined as the probability of successfully receiving at least one single packet from neighbor vehicles during the tolerance time window T . Specifically, for each given time t_0 , if one packet (or more than one packet) is received during time interval $[t_0 - T, t_0]$, the VSC application is claimed to be reliable at time t_0 . This is because, the receiver vehicle can reliability predict the neighbor vehicle information based on the previously received packet in the time interval stating using estimation algorithms normally used in VSC applications. Otherwise, VSC application is said to be unreliable at time t_0 . Finally, T -window reliability is calculated as the ratio of number of 'reliable' time instances to number of all the time instances.

Here, we also briefly discuss the difference between communication reliability and application-level reliability and then explain our motivation to isolate them. In literatures on networking, packet delivery ratio (or, packet loss ratio) is commonly used to describe both communication reliability

⁴ T is the maximum tolerance time window. T is determined by the requirement of specific VSC applications, varying from application to application. We believe that T value for majority of VSC applications falls into range $[0.3sec, 1.0sec]$.

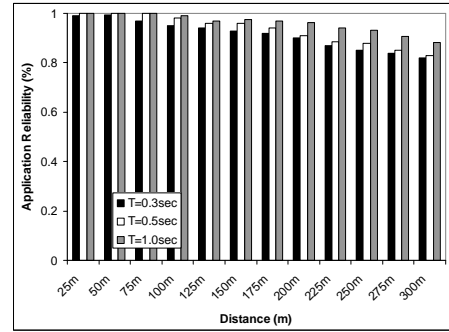


Fig. 5. T -window Application Reliability vs. Distance Between Vehicles, Under Freeway Environment

and application-level reliability. This is partly due to the dependency between packets in data transfer applications – In traditional network applications like Internet HTTP or FTP service, successful reception of each packet is highly dependent on successful reception of its previous packet. Once its previous packet gets lost, not only the current packet becomes useless but also the whole data transfer application will be interrupted. However, this is not the case for vehicle safety oriented VSC communication, where each packet with fresh information update 'overwrites' the previous packet with stale information. Because of this memory less property, VSC applications may not be affected even though several stale packets are lost (as long as a fresher packet can be received). It is this insight gained in our study that motivates us to isolate concept of application-level reliability from concept of communication reliability.

B. Reliability of VSC applications

Having defined the novel T -window application-level reliability metric, we now evaluate the reliability of VSC applications under different traffic environments. By examining the time stamps and sequence numbers of packets recorded in the log file, we analyze application-level reliability metric over the entire time. At each time instance when a packet is supposed to be received from a neighbor vehicle (these time instances are spaced 0.1 second between each other), we check whether there is any packet received from that neighbor vehicle within T second prior to the current time instance. If there is at least one packet received within T -window interval, the VSC application at this time instance is counted as being 'reliable' at that instance; Otherwise, it is treated as 'unreliable' at that instance. Based on the distance between vehicles at each time instance, we sort the data at different time instances into different distance bins (granularity of distance bin is 25m) and then calculate average T -window reliability metric for each distance bin. We plot the average application-level T -window reliability metric as a function of distance in Fig.5 and Fig.6, for freeway traffic environment and open field traffic environment, respectively. Here, the average T -window reliability metric is plotted as y-axis and different distance bins are plotted as x-axis.

Tolerance time window T is the key parameter of the definition for application-level reliability, varying with each VSC application. To illustrate the effect of T value on application-

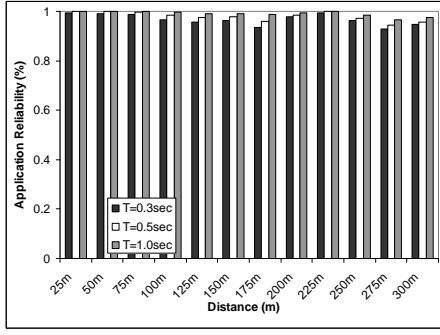


Fig. 6. T-window Application Reliability vs. Distance Between Vehicles, Under Open Field Environment

level T-window reliability metric, we choose several different T values ($T = 0.3sec$, $T = 0.5sec$ and $T = 1.0sec$ within the reasonable range) in our study. As shown in Fig.5 and Fig.6, most of application-level reliability values are more than 82% up to 300 meters (the maximal application range for our applications), which leads to conclusion that reliability of DSRC-based VSC applications is quite satisfactory. Specifically, according to the tolerance time window T and application range D values specified in Table.I, the application-level reliability values of SVA, EEBL, FCW and LCA applications (even under the worst-case scenarios, with largest D value and smallest T value) are above 85%.

We observe that T-window reliability is generally higher in open field traffic environment than in a freeway traffic environment, and we also find out that T-window reliability at shorter distance between vehicles is generally higher than for longer distance between vehicles. Both observations can be explained by the different values of communication reliability metric at different distance scales or under various traffic environments. Therefore, communication reliability is one key factor impacting application-level reliability, for a given T value. However, we also recognize that various VSC applications define the appropriate T values tolerances in order to provide reliable application service to the end user. Hence this tolerance metric clearly improves the application level reliability of VSC applications.

VI. RELATIONSHIP BETWEEN COMMUNICATION RELIABILITY AND APPLICATION-LEVEL RELIABILITY

In Section IV and Section V, we clearly established the difference between DSRC communication reliability and application level reliability. However, we also attempt to explore the relationship between these two reliability metrics by developing an analytical model. Before we do so, we first define (or restate) the commonly used variables here. Let

- 1) d : The distance between transmitter vehicle and receiver vehicle;
- 2) T : The maximum tolerance time window for VSC applications. As long as a packet is received within T , VSC applications are reliable. Different VSC applications may have different T values;
- 3) t : The update interval for routine packet broadcast from vehicles, which is a key system parameter of VSC applications. In our system, $t = 0.1sec$;

- 4) M : The number of packets transmitted during duration T , $M = \frac{T}{t}$;
- 5) $P_{comm}(d)$: The probability of successfully receiving each packet at distance d , i.e., communication reliability;
- 6) $P_{app}(d)$: The probability of successfully receiving at least a single packet at distance d for a given tolerance time window T , i.e., application-level reliability;

Then, let us give several assumptions for our derivation:

- 1) Each vehicle periodically broadcasts its status information to all its neighbors with fixed interval t , as discussed in Section III-A;
- 2) Communication reliability $P_{comm}(d)$ for different packets is independent of each other, as we discovered in Section IV-C;
- 3) Distance d between vehicles during tolerance time window T does not drastically change. i.e. the distance between two vehicles will not change significantly if tolerance time window T is small;

Next, we propose a simple model relating the VSC application reliability with DSRC communication reliability through a VSC system parameter. According to definition, application reliability $P_{app}(d)$ is the probability of successfully receiving at least one packet during tolerance time window T , at distance d . Since VSC application periodically broadcasts its information with given fixed broadcast interval t (*Assumption 1*), we know that application reliability $P_{app}(d)$ is the probability of successfully receiving at least one packet among M (here, $M = \frac{T}{t}$) consecutive packets. This, in turn, is equal to $1 - Pr(\text{receiving no packet among } M \text{ consecutive packet})$. Given the fact that distance d does not change significantly (*Assumption 2*) and packet drops are independent (*Assumption 3*), we know that $Pr(\text{receiving no packet among } M \text{ consecutive packets})$ follows a binomial distribution with probability $P_{comm}(d)$ and $n = 0$. Therefore, $Pr(\text{receiving no packet among } M \text{ consecutive packets}) = (1 - P_{comm}(d))^M$. By putting all the steps together, we obtain an analytical model linking VSC application reliability with DSRC communication reliability through the VSC system parameter, as follow

$$P_{app}(d) = 1 - (1 - P_{comm}(d))^M \quad (1)$$

$$= 1 - (1 - P_{comm}(d))^{\frac{T}{t}} \quad (2)$$

Based on Eqn.2, VSC application reliability $P_{app}(d)$ at distance d is a function of both wireless communication reliability $P_{comm}(d)$ at distance d and the VSC system parameter t . This simple model not only clearly illustrates how communication reliability under different traffic environments will significantly affect the corresponding VSC application reliability, but also provides a design input on how to use DSRC wireless communication to improve the overall reliability of VSC applications. For example, given a VSC application with a Tolerance Time Window T and application reliability requirement $P_{app}(d)$, the of the VSC DSRC communication system should be such that the broadcast interval t should be adjusted adaptively so as

to achieve the required application reliability under various traffic environments⁵.

VII. CONCLUSION AND FUTURE WORK

This paper analyzes the reliability of DSRC wireless communication and reliability of DSRC-based Vehicle Safety Communication (VSC) applications, under both open field traffic environment and freeway traffic environment. DSRC wireless communication is analyzed based on metrics packet delivery ratio and distribution of consecutive packet drops. Application level metric, T-window reliability, is used to analyze the reliability of VSC applications. The analysis based on extensive experimental data collected shows that DSRC wireless communication provides an adequate degree of communication reliability under both traffic environments, and that the packet drops do not occur in bursts even under the harsh freeway traffic environment. By incorporating appropriate estimation algorithms into the VSC application design neighbor vehicle status information can be predicted to improve the overall reliability of VSC applications in order to provide satisfactory application service to the end users. Moreover we have developed an analytical model that related the DSRC communication reliability and the VSC application reliability.

Our future work aims to investigate the effects of various important factors that could potentially affect the reliability characteristics of DSRC wireless communications. Using a systematically approach we plan to analyze the effect of vehicle relative speed, transmission power and transmission data rate, and other factors on DSRC communication under various traffic environments. By doing so, we would gain better overall understanding of DSRC wireless communication. We are also looking into the possibility of using adaptive parameter control mechanism (varying broadcast interval t , based on environment) to improve VSC application reliability.

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⁵However, we also want to point out that Eqn.2 only holds when packet drops are independent with each other (Assumption 2). Part of our future work would be investigating when Assumption 2 does not hold and how it will affect the application reliability under certain environment.