An Empirical Study on Urban IEEE 802.11p Vehicle-to-Vehicle Communication

Feng Lv[1], Hongzi Zhu[1], Hua Xue[1], Yanmin Zhu[1], Shan Chang[2], Mianxiong Dong[3], Minglu Li[1]
[1]Shanghai Jiao Tong University, China
[2]Dong Hua University, China
[3]Muroran Institute of Technology Japan
{fenglv, howardsid}@sjtu.edu.cn, {hongzi, yzhu, li-ml}@cs.sjtu.edu.cn, changshan@dhu.edu.cn, mx.dong@ieee.org

***Abstract*—IEEE 802.11p based Dedicated Short Range Communication (DSRC) has been considered as a promising wireless technology for enhancing transportation safety and traffic efficiency. However, with limited literature available, there is lack of understanding about how IEEE 802.11p performs for vehicle-to-vehicle (V2V) communications in urban environments. In this paper, we conduct intensive statistical analysis on V2V communication performance, based on the empirical measurement data collected from off-the-shelf IEEE 802.11p-compatible onboard units (OBUs). We have several key insights as follows. First, both line-of-sight (LoS) and non-line-of-sight (NLoS) durations follow power law distributions, which implies that the probability of having long LoS/NLoS conditions can be relatively high. Second, the packet inter-reception (PIR) time distribution follows an exponential distribution in LoS conditions but a power law in NLoS conditions. In contrast, the packet inter-loss (PIL) time distribution in LoS condition follows a power law but an exponential in NLoS condition. Third, the overall PIR time distribution is a mix of exponential distribution and power law distribution. The presented results provide solid ground to validate models, tune VANET simulators and improve communication strategies.**

***Index Terms*—vehicular networks; Dedicated Short Range Communication; non line of sight; urban environment**

I. INTRODUCTION

Driving safety has been number one priority of most people living in cities. According to the most recent report of U.S. Department of Transportation, in 2013, there were an estimated 5,687,000 police-reported traffic crashes happened in U.S., in which 32,719 people were killed and an estimated 2,313,000 people were injured [1]. The inability of drivers to react in time to emergency cases is the major reason, which paves a new direction for creating cooperative Vehicle Safety Communications (VSC) systems to provide dangerous warnings to vehicles and drivers in advance. The IEEE 802.11p-based Dedicated Short Range Communication (DSRC) [2] is a draft standard customised for highly mobile, severe-fading vehicular environments. Based on DSRC, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications are indispensable for building cooperative VSC systems. Understanding the characteristics of 802.11p-based DSRC, especially in urban environments, is of great importance to realistic vehicular network models, simulators and reliable network protocols.

To characterize the behaviour of V2V communications in urban environments, however, is very challenging for two reasons. First, urban environments can be highly dynamic and complex with too many uncontrollable factors such as many types of roads, time-varying traffic condition and all different surrounding buildings and trees, which makes it very hard to separate the impact of each factor to the final performance of DSRC. Second, to conduct realistic studies on V2V communications in urban scenarios, experiments which involve various road types, different traffic conditions and cover a sufficiently long time period are essential. The lack of real-world data makes it hard to conduct practical analysis and modelling.

In the literature, there have been several measurement-based studies on characterizing DSRC performance in vehicular networks. For example, Bai et al. [3] conduct an extensive empirical analysis on packet delivery ratio (PDR), which refers to the probability of the receiver successfully receiving a packet transmitted from the sender, in different scenarios to study the impacts of controllable (e.g., mobility speed and transmission power) and uncontrollable (e.g., propagation environment) factors to the performance of V2V communications. Martelli et al. [4] study the distribution of packet inter-reception (PIR) time, which refers to the interval of time elapsed between two successfully received packets, and its relationship with PDR and other environmental factors such as speed and distance between vehicles. They disclose that the distribution of PIR time is a power law. However, both pieces of work did not discriminate between different channel conditions in terms of line-of-sight (LoS) and non-line-of-sight (NLoS) and drew their conclusions based on all aggregated measurements, which could bias from the ground truth. Identifying the significant impact of LoS and NLoS conditions to DSRC performance, some studies focus on modelling LoS and NLoS channels. For example, Meireles et al. [5] confirm that the channel quality such as RSSI (Received Signal Strength Indicator) and PDR is heavily influenced by LoS and NLoS via an experimental study. In addition, there are also some reports on physical layer channel measurements

978-1-5090-1732-4/16/$31.00

[6] [7] [8] [9] [10] where the path loss, doppler spectrum and coherence time are analyzed in DSRC channels. Nevertheless, there is no statistical study on the impact of channel conditions in terms of LoS and NLoS to the DSRC performance and how these two conditions interact in urban scenarios.

In this paper, we conduct an empirical study on 802.11p-based V2V communications in urban environments. As large volumes of real-world data are essential to realistic analysis, we implement a V2V communication testbed consisting of two experimental vehicles, each of which has an 802.11p-compatible onboard unit (OBU), one GPS receiver and two tape records. With this testbed, V2V beaconing data and the simultaneous environmental context information can be collected. We conduct an extensive data collection campaign in three typical environments in our city, i.e., urban, suburban and urban express, which lasts for more than two months and covers a total distance of over 1,500 kilometres. Moreover, with the whole campaign typed, we visually label out all LoS and NLoS situations for all traces of different urban environments. With these valuable traces, we first analyze PDR across all traces and have two major observations as follows. *First, "perfect zone" (i.e., the portion of PDR larger than 80%) prevails throughout a wide communication range (e.g., 300 meters in our case) in urban vehicular networks*, which implies 802.11p V2V communication is particularly reliable across all urban environments. This observation is very unlike the "gray-zone phenomenon" reported in work [3]. *Second, within a rather long range (e.g., 500 meters in our case), it is the NLoS conditions instead of long distances that affect PDR the most*. The probability that a pair of vehicles being blocked by obstacles, such as in-lane traffic and slopes, increases as the distance between this pair of vehicles increases.

Given the importance of NLoS conditions, we then examine the durations of LoS and NLoS conditions and find that *both LoS and NLoS durations follow a power law distribution*, which implies that not only the probability of meeting long LoS conditions is high but also the probability of seeing long NLoS conditions is also high. We further investigate the interactions between LoS and NLoS conditions by examining the distribution of PIR and packet inter-loss (PIL) times, which refers to the interval of time elapsed between two dropped packets. We have two key insights as follows. First, *PIR time follows an exponential distribution in LoS conditions but a power law in NLoS conditions*. This means that consecutive packet reception failures can rarely appear when in LoS conditions but can constantly appear when in NLoS conditions. This is cross verified by the observation that PIL time follows a power law distribution in LoS conditions but an exponential in NLoS conditions. Second, unlike the observation that PIR time follows a power law distribution reported in work [4], *the overall PIR time distribution is actually a mix of an exponential distribution of small PIR times in LoS conditions and a power law distribution of PIR times in NLoS conditions*.

We highlight our major contributions made in this paper as follow:

- We collect three large-volume 802.11p-based V2V communication traces under three different urban scenarios. In addition, we label out LoS and NLoS conditions based by watching the taped videos. We would also open the data for public access when ready.
- In general, "perfect zone" in terms of PDR is prevalent over all urban environments. Nevertheless, NLoS conditions induced by large blocking vehicles or slopes can cause severe link performance degradation. In addition, the impact of signal power attenuation to the link performance is not obvious at least within a sufficiently long range of 500 meters.
- Frequent packet loss can be found in NLoS conditions and the distribution of PIL times follows an exponential distribution whereas that of the PIR times follows a power low. Moreover, severe NLoS conditions can last for rather long periods of time. In contrast, link performance is rather reliable in LoS conditions despite a long distance between two communicating vehicles. In LoS conditions, the distribution of PIR times follows an exponential distribution whereas that of the PIL times follows a power low.

The remainder of this paper is organized as follows. Section II introduces the related work. In Section III, we describe the experiment platform and real-world experiments that we have conducted. We first look at the overall performance of 802.11p in terms of PDR and delve into the key factor of link performance degradation in Section IV. In Section V, we further investigate the interaction of LoS and NLoS channel conditions and their impact to 802.11p. Finally, we conclude and direct future work in Section VI.

II. RELATED WORK

This work is most related to studies based on real measurements in vehicular networks and studies modelling LoS and NLoS channels.

Measurement-based Studies in Vehicular Networks: In the work [3], the authors present an extensive analysis on PDR in different scenarios for characterizing the impacts of transmission distance, propagation environment, mobility speed and power to the V2V communication performance. In addition, the authors analyze the temporal, spatial and symmetric correlations of PDR. It details the PDR characteristics with respect to different parameters. However, using only PDR metric is insufficient to characterize the DSRC behaviour in complex urban scenarios. The metric PIR time is studied [4], the authors disclose that the distribution of PIR is a power-law and the PIR is only loosely correlated with PDR. Moreover, they reveal that the PIR time is almost independent of speed and distance between vehicles. These observations are of great importance for vehicular network engineers. However, the characteristics of these metrics may be changed in varying channel conditions. In the paper [11], the authors characterize the application-level reliability of DSRC communication for VSC applications based on real-world experimental data and find

Fig. 1: Illustration of an experiment car.

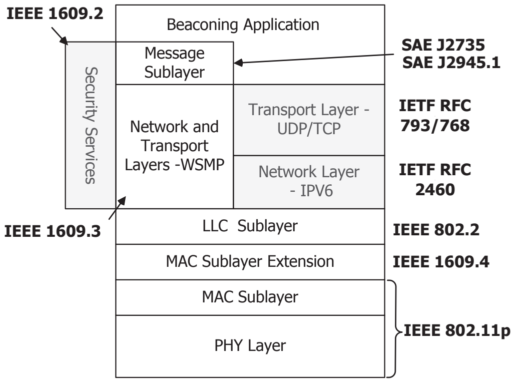

Fig. 2: Beaconing application implemented on WAVE protocol stack, where grey blocks are not involved.

that the reliability of DSRC vehicle-to-vehicle communication is adequate since packet drops do not occur in bursts most of the time while the conclusion is not fine-grained enough for reliable communication strategies designing. To characterize the quality of IEEE 802.11p V2I communications in urban environments, J. Gozalvez et al. [12] present the results of an extensive field-testing campaign. The reported results show that the street layout, urban environment, traffic density, the presence of heavy vehicles, trees, and terrain elevation have an effect on V2I communications, and should be taken into account to deploy and configure urban RSUs. There are also some reports on physical layer channel measurements [6] [7] where the path loss, doppler spectrum and coherence time are analyzed in DSRC channels. For example, wireless channel impairments on DSRC Vehicular Communications [6] are measured and analyzed which suggests that while the proposed DSRC standard may account for doppler and delay spreads in vehicular channels, large packets may face higher error rates due to time-varying channels. In the work [7], the authors use differential global positioning system (DGPS) receivers to enable dynamic measurements of how large-scale path loss, doppler spectrum, and coherence time depend on vehicle location and separation. A Nakagami distribution is used for describing the fading statistics and the Speed-Separation diagram is introduced to model and predict channel doppler spread and coherence time using vehicle speed and separation. However, all these characteristics present diversely when in different channel conditions in terms of LoS and NLoS and aggregating measurements together to draw conclusions may generate bias from the ground truth.

LoS and NLoS Modelling: The observation that the channel quality is heavily influenced by LoS and NLoS has been confirmed by the experimental study [5]. In that work, the authors collect received signal power and packet delivery ratio information in a multitude of relevant scenarios and quantify the impact of obstructions. For example, a single obstacle can cause a drop of over 20 dB in received signal strength when two cars communicate at a distance of 10 m and at longer distances, NLoS conditions affect the usable communication range, effectively halving the distance at which communication can be achieved with 90% chance of success. Based on the the Gilbert model, the authors establish a vehicular link model called L/N-model to mimic beacon reception behaviour for what concerns the impact of LoS and NLoS [4]. By using Nakagami distribution to analyze the received signal strength [13], the authors characterize the fading statistics as a function of distance in vehicular environment and they present a measurement-based statistical channel fading model which can be used to identify LoS and NLoS scenarios. The parameters of pass loss model over LoS and NLoS conditions are investigated based on channel measurements data [14]. The influences of channel propagation models in safety applications are evaluated by traffic simulators [15] [16]. Many of other studies deal with static obstacles [7] [17] [18] [19] which are not the most common NLoS scenarios in urban environments. In our work, we do not model a LoS or NLoS channel but study the interaction between LoS and NLoS conditions and the impact on the V2V communication performance.

To our best knowledge, there is no statistical study on the impact of channel conditions in terms of LoS and NLoS to the DSRC performance and how these two conditions interact in urban scenarios.

III. COLLECTING V2V TRACE

A. *Experiment Platform Description*

To collect 802.11p V2V communication data and the associated context information, we implement a V2V communication testbed, consisting of two experimental vehicles. As illustrated in Figure 1, each car has the following components:

DSRC Module. We adopt an off-the-shelf Arada LocoMateTM OBU [20] as the DSRC module, which implements IEEE 802.11p and IEEE 1609 standards for the wireless access in vehicular environments (WAVE). Figure 2 shows the WAVE protocol stack, where IEEE 802.11p is served as the physical and the MAC layer to deal with faster fading and more Doppler frequency shift. The 802.11p radio operates in the frequency range from 5.700GHz to 5.925GHz and supports

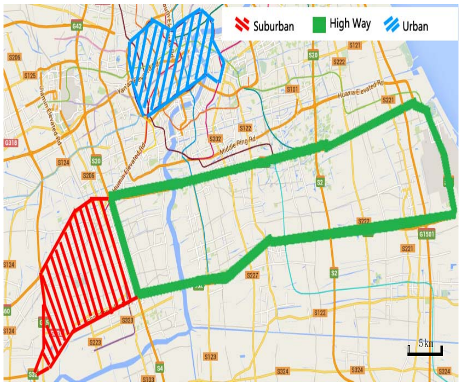

Fig. 3: Various urban environments are selected to conduct data collection.

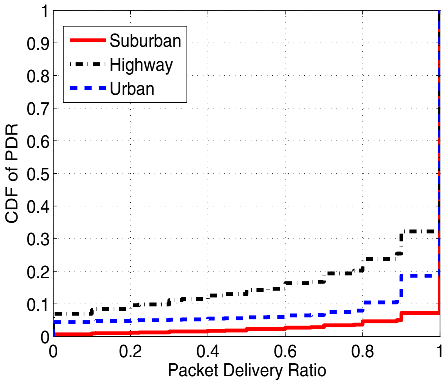

Fig. 4: CDFs of PDR over all traces

one Control Channel (CCH) and multiple Service Channels (SCHs) with two optional bandwidths of 10MHz and 20MHz. The CCH is used to transmit WAVE Short Messages (WSMs) and announce WAVE services and SCHs are used for application interactions and transmissions over IP. The maximum transmission power is 14dBm and the supported data rates of a 10MHz channel ranges from 3Mbps to 27Mbps [21]. In our experiments, we use 10MHz channels with the lowest data rate of 3Mbps and the maximum transmission power of 14dBm in order to achieve the most reliable V2V communication (i.e., the derived results thus provide the "upper bound" of performance of 10MHz 802.11p channels). In addition, the DSRC module has one 680MHz MIPS processor running Linux, a 16MB Flash, a 64MB memory and one Gigabit Ethernet interface.

GPS Module. In the OBU, there is an integrated high-performance Global Positioning System (GPS) receiver with an external RF antenna. We use this GPS receiver to obtain location information such as the latitude, the longitude, the altitude and the velocity of the experimental vehicle. Moreover, we use the GPS modules to synchronise both OBUs at the rate of every 200 ms.

Mobile computer. We connect the OBU via its Gigabit Ethernet interface to a ThinkPad X240 laptop, which runs Linux and is used to control the OBU through the `telnet` protocol. Furthermore, as the memory and storage on the OBU are quite limited, we first buffer all transmitted and received 802.11p packets on the OBU and periodically download those packets from the OBU to the laptop.

Tape recorders. We deploy two tape recorders on each vehicle with one mounted on the front glass and the other fixed on the back glass, which tape the whole process for offline analysis.

V2V Beaconing Application. We implement a beaconing application on the WAVE protocol stack as shown in Figure 2, which utilizes the Wave Short Message Protocol (WSMP). Compared with the traditional IP protocol, WSMP allows applications to directly specify lower-layer parameters, such as specifying the channel, the transmitting power, the data rate and the MAC address of the receiver. As a transport layer protocol, WSMP, similar to UDP, does not provide any retransmission or ACK mechanisms. Our beaconing application consists of two programs, i.e., one *transmitter* and one *receiver*. The transmitter periodically transmits a 300-byte packet (the maximum payload size of a WSMP packet is 1,300 bytes), which consists of a sequence number, the latitude, the longitude, the altitude and the speed information of the transmitter. Meanwhile, both the transmitter and the receiver log all the packets transmitted and received. For the receiver, it also logs the RSSI values when receiving a packet. Following the requirement of safety applications [22], beacon intervals are set to 100 ms. By offline comparing the transmitted packets and the received packets logged on the transmitter vehicle and the receiver vehicle, respectively, the performance of 802.11p V2V communication can be evaluated.

B. Data Collection Campaign

We conduct an extensive data collection campaign, aiming to cover all typical road conditions in urban settings. In specific, we consider three major road types: 1) *urban*: roads can be unidirectional 1- or 2-lane wide and bidirectional 4- to 8-lane wide, with a large number of tall buildings, tunnels and overhead bridges and elevated roads, as well as heavy vehicle traffic; 2) *suburban*: roads are normally bidirectional and 4- to 6-lane wide with open lands, remote houses and light traffic; 3) *highway*: bidirectional 8-lane urban freeway with a large number of walls and time-varying traffic.

We run our testbed within areas of the above three road types in our city as shown in Figure 3. For each type of roads, we collect V2V communication data twice a day (during the rush hour from 5pm and during off-peak time from 8pm) for at least ten days. During each data collection, we control the distance between both vehicles (calculated with the GPS location information obtained with a public mobile network) to be no more than 500 meters and have no other requirements on how the drivers drive. The overall campaign lasts for over two months from March 24th to June 11th with an accumulated distance of over 1,500 kilometers. As a result,

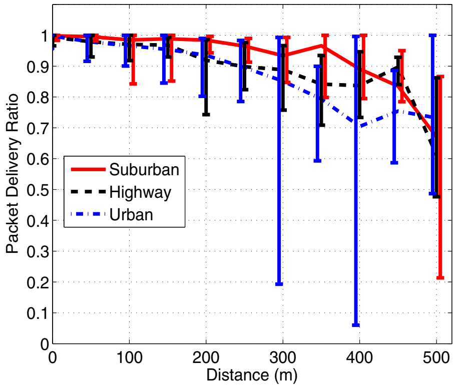

Fig. 5: PDR vs. distance between a pair of vehicles.

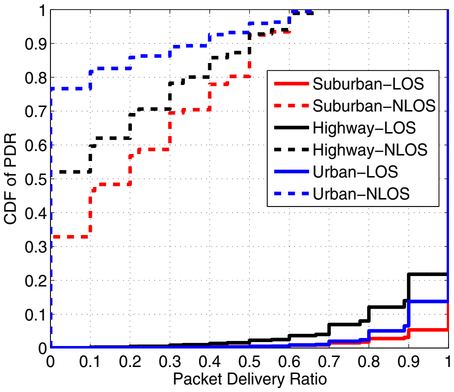

Fig. 6: CDFs of PDR in LoS/NLoS conditions.

for each road condition, we obtain a trace, denoted as **trace** $\mathcal{U}$ (urban condition), **trace** $\mathcal{S}$ (suburban condition) and **trace** $\mathcal{H}$ (highway condition). The total amount of all traces adds up to 110 GB. In addition, we combine all three traces of different environments together to form a universal trace, denoted as **trace** $\mathcal{A}$, for analysis.

IV. OVERALL URBAN V2V PERFORMANCE ANALYSIS

We first examine the overall V2V communication performance in different urban environments by checking PDR. In practice, it is often calculated as the ratio of the number of data packets received at the receiver to the total number of packets transmitted at the transmitter within a pre-defined time window. We calculate PDR using a time window of one second.

A. Observing Prevalent Perfect Zone

To gain an overall picture, we examine the cumulative distribution function (CDF) of PDR for all traces, as shown in Figure 4. We can easily observe the ideal case of V2V communication where packets are perfectly received (i.e., PDR = 100%). The probability of this happening is 81.4%, 92.9% and 67.8% in urban, suburban and highway environments, respectively. In contrast, the worst case where no packet can be received (i.e., PDR = 0%) also happens with the probability of 4.3%, 0.7% and 6.9% in the respective environments. It is also interesting to compare our results with previous work [3] that studied communication characteristics in rural and suburban vehicular networks. As shown in Figure 2 of [3], the authors observed the "gray-zone phenomenon" where intermediate reception (20%≤PDR≤80%) prevails throughout the whole communication range with the probability 50.6% while the perfect reception (PDR≥80%) zone is not always guaranteed with the probability 35.2%. *Unlike their observation, we find that 802.11p performs rather reliably in urban environments and "perfect zone" prevails with a wide communication range up to 350 meters.* For example, the probability of perfect reception in urban, suburban and highway environments is 89.6%, 95.4% and 76.2%, respectively.

Furthermore, as it can be seen in Figure 4, multi-path fading effects are much more severe in the urban and highway environments than in the suburban environment. For instance, the probability of poor reception (PDR≤20%) in urban and highway environments is 5% and 9.6%, respectively, while the value drops to 1.2% in the suburban environment. The reason is that there are few obstacles or vehicles in the suburban environment, resulting in little multi-path effects. In contrast, in the urban and highway environment, a large number of buildings (stationary scatter) and numerous high-speed vehicles (mobile scatter) are present, injecting multiple paths into the channel. It is clear that both environments tend to generate poor PDRs.

B. Analyzing Key Factors of Performance Degradation

We then examine the impact of the distance between a pair of vehicles. As shown in Figure 5, PDR gradually drops as the distance increases across all the environments studied. It is surprising to find that the variation of PDR dramatically increases as the separate distance increases, especially for the urban environment. For example, in urban environment, PDR can often reach up to 100% but can also drop to below 10% as supposed at a separate distance of 400 meters. To explain the reasons that may cause such large variations, we check with videos recorded during the data collection campaign and mark all NLoS situations when two vehicles cannot visually see each other. [1] For example, big obstacles such as trucks and buses, slopes, and turns may be present in between two communicating vehicles, causing NLoS situations.

NLoS Conditions instead of Separate Distance Affect Link Performance Most. We then divide the data in each trace into two parts according to found NLoS and LoS conditions. Figure 6 shows the CDFs of PDR calculated with NLoS and LoS data, respectively, across all traces. It can be seen that most packet reception failures happen under NLoS conditions. For example, the probability of poor reception (PDR≤20%)

---

[1] Note that although NLoS conditions found by cameras are not necessarily to be NLoS for RF radios, those visually NLoS conditions are still good approximations of real radio NLoS conditions and valuable for analysis.

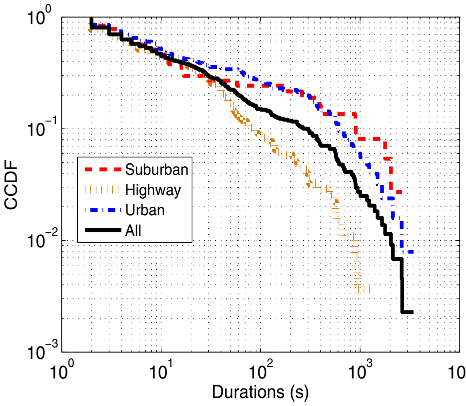

Fig. 7: CCDFs of LoS durations.

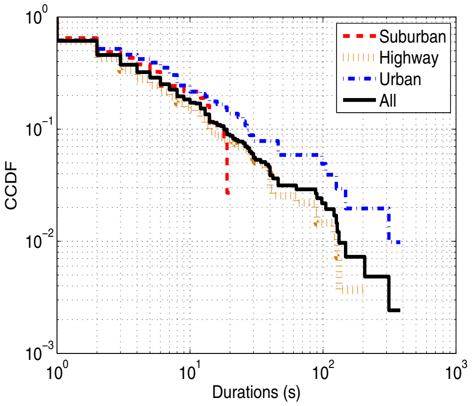

Fig. 8: CCDFs of NLoS durations.

under NLoS conditions in urban, suburban and highway environments is 82.6%, 48.3% and 62.1%, respectively, while the probability of perfect reception under NLoS conditions is zero in all environments. In contrast, the probability of perfect reception under LoS conditions in urban, suburban and highway environments is 93.5%, 96.9% and 86%, respectively, while the probability of poor reception under LoS conditions is less than 1% in all environments. We have the insight that it is NLoS conditions instead of separate distance that contribute most packet reception failures. Although the separate distance is not the direct reason of poor PDR, it is true that the probability of encountering a NLoS condition increases as the separate distance increases, which explains the large variations of PDR at long separate distances.

V. Interactions between LoS and NLoS

To gain insights about the characteristics of DSRC channels under different channel conditions, we examine the interactions between successful packet receptions and failed ones. We adopt the metrics of PIR time [4] and PIL time as illustrated in Figure 9, to analyze the 802.11p channel behaviour in urban settings. In Figure 9, a time sequence of packets are illustrated, where white blocks denote successfully received packets and colored blocks represent packet reception failures. The PIR time refers to the interval of time elapsed between two successfully received packets which is the time period between two adjacent white blocks. Similarly, the PIL time refers to the time interval elapsed between two dropped packets which is the time period between two adjacent dark blocks.

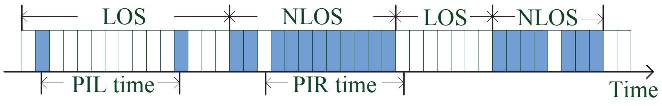

Fig. 9: An example sequence of packets, where white blocks denote successfully received packets and dark blocks denote packet reception failures

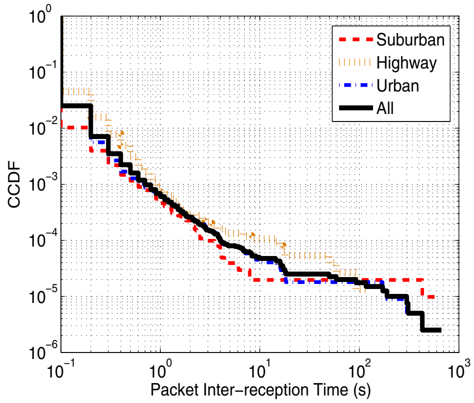

Fig. 10: CCDFs of overall PIR times, in log-log scale.

A. Power Law Distributions of NLoS and LoS Durations

To characterize the impact of channel conditions in terms of LoS and NLoS to the DSRC performance, we first consider durations of LoS and NLoS which are of great importance to design reliable communication strategies. The tail distribution of LoS and NLoS durations are examined and the results are shown in Figure 7 and Figure 8, respectively. We have two main observations. First, linear plots in log-log scale are found in both figures, implying that both LoS and NLoS durations follow power law distributions which means that not only the probability of meeting long LoS conditions is high but also the probability of meeting long NLoS conditions is also high. It should be noted that the the cutoff part of the tail distribution should not be considered due to the effect of limited observation duration, which has also been pointed out in studies on characterizing inter-contact time distribution of human [23] and vehicular [24] mobility. Second, LoS durations are in general longer than NLoS durations. For example, about 50% of LoS durations are longer than ten seconds whereas that probability falls to only 18% for

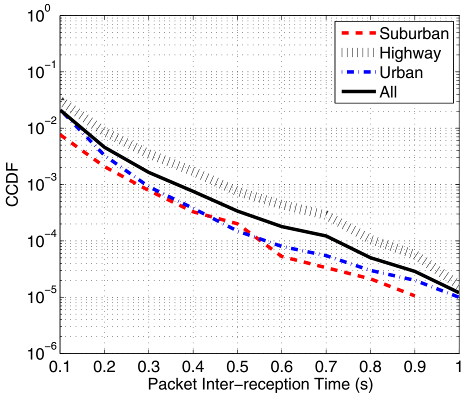

Fig. 11: CCDFs of PIR times in LoS conditions, in linear-log scale.

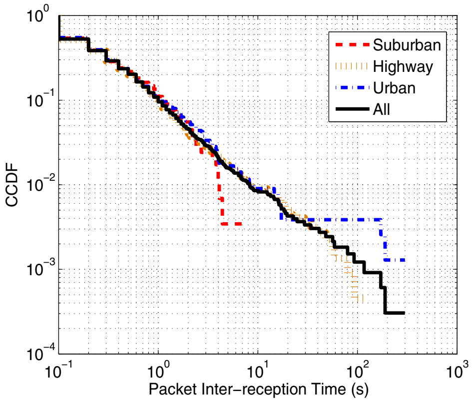

Fig. 12: CCDFs of PIR times in NLoS conditions, in log-log scale.

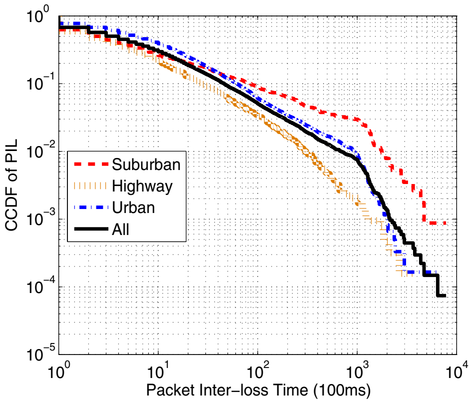

Fig. 13: CCDFs of PIL times in LoS conditions, in log-log scale.

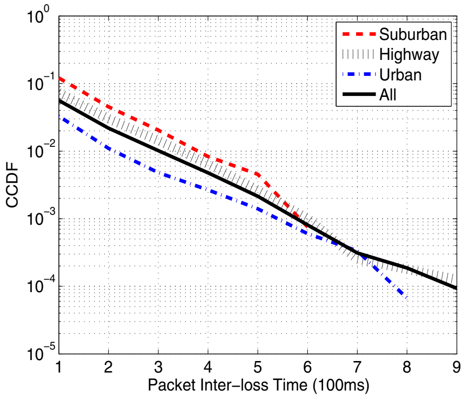

Fig. 14: CCDFs of PIL times in NLoS conditions, in linear-log scale.

NLoS durations. Nevertheless, heavy-tailed NLoS durations have important implications on the design of beacon-based applications (e.g., active safety), which shall be able to cope with relatively long and constant communication blackouts.

B. *Mixed Distributions of PIR Times*

Considering the importance of NLoS conditions, we further investigate the interactions between LoS and NLoS conditions by examining the distribution of PIR and PIL times. Figure 10 shows the complementary cumulative distribution function (CCDF) of PIR times over all traces in log-log scale. It is also interesting to compare our results with previous work [4] that studied 802.11p-based beaconing performance based on data collected during trips traveled among several Italian cities. As shown in Figure 4 of [4], the authors observed that the CCDF of PIR times satisfies a power law (identified by linear plots in log-log scale) and had the conclusion that the PIR time distribution is heavy tailed, which means that the probability of having relatively long PIR time is relatively high. *Unlike their observation, we find that the CCDF of PIR time appears linear in log-log scale only for large PIR times and has a much faster decay for small PIR times, which implies that the PIR time only partially follows a power law.* For example, as shown Figure 10, the CCDF of PIR times is not linear when PIR time is smaller than one second.

As shown in Figure 6, with high probability, PDR in LoS conditions is greater than 80%, which means PIR in LoS conditions has many small values. On the contrary, as poor PDR is witnessed in NLoS conditions, PIR in NLoS conditions should have large values. We examine the distribution of PIR times in LoS and NLoS conditions, respectively. Figure 11 and Figure 12 show the CCDFs of PIR in LoS and NLoS conditions in linear-log and log-log scale, respectively. In both figures, clear linear plots can be observed. *This means that PIR time in LoS conditions follows an exponential distribution and that in NLoS conditions follows a power law distribution*. It implies that short PIR times (consecutive successfully-received packets) are more likely to happen in LoS conditions whereas the probability of having relatively long PIR time is relatively high under NLoS conditions. With this knowledge, we can well explain why the CCDF of overall PIR times in Figure 10 has a much faster decay than a power law distribution when the PIR times are small. It is because the resulted CCDF is a combination of an exponential distribution of small PIR times in LoS conditions, a power law distribution of PIR

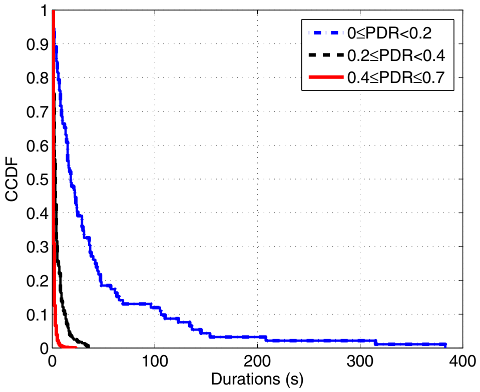

Fig. 15: CCDF of durations of different NLoS types.

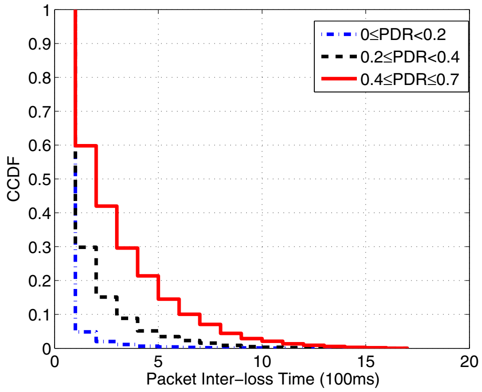

Fig. 16: CCDF of PIL times in different NLoS conditions.

times in NLoS conditions and a power law distribution of NLoS durations (see Figure 9). The main reason that we have distinct observations from previous work [4] where the overall distribution of PIR times follows a power law may be because the authors did not discriminate between LoS and NLoS conditions in their analysis and NLoS conditions might take an inappropriately large portion during the field testing. In addition, we have similar but opposite observation on the distribution of PIL times. In particular, as shown in Figure 13 and Figure 14, we find that PIL time in LoS conditions follows a power law distribution whereas that in NLoS conditions follows an exponential distribution, which implies that short PIL times are more likely to happen in NLoS conditions whereas the probability of having relatively long PIL time is relatively high under LoS conditions. This is reasonable as frequent packet failures are more likely to happen in NLoS conditions.

C. *Severe NLoS Conditions Hurt*

As analyzed above, NLoS conditions can last relatively long and have very poor packet delivery ratio. To better understand the DSRC performance under NLoS conditions, we further examine the distributions of NLoS durations and PIL times under different NLoS conditions, i.e., *severe* (PDR$\leq$20%), *intermediate* (20%$<$PDR$\leq$40%), and *normal* (40%$<$PDR$\leq$70%), using the combined **trace** $\mathcal{A}$, as shown in Figure 15 and Figure 16. We have two main observations as follows. First, as shown in Figure 15, most severe NLoS conditions have very long durations. For example, about 20% severe NLoS conditions are longer than one minute while intermediate and normal NLoS conditions are normally very short. In addition, the longest duration under severe NLoS conditions can reach up to 380 seconds while the value is only 40 and 30 seconds when under intermediate and normal NLoS conditions, respectively. Second, as shown in Figure 16, in severe NLoS conditions, the probability of a PIL time $\leq$100ms which equals to the beacon interval is 95%, which means, given that a packet is lost, with high probability ($\geq$95%), the next packet will also be lost. This probability drops to 70% and 40% when in intermediate and normal NLoS conditions, respectively.

VI. CONCLUSION AND FUTURE WORK

In this paper, we have studied the 802.11p-based V2V communication in urban environments based on real-world data traces. We have the following two major insights. First, 802.11p works very reliably in urban settings with a wide range of "perfect zone" found. Second, LoS and NLoS channel conditions play an very important role in V2V communication. In particular, they have very opposite characteristics with respect to the PIR and PIL time distributions. The intervals between a pair of successfully received packets have an exponential distribution in LOS conditions but turns out to be a power law when in NLOS conditions. One of our future directions is to investigate the physical layer characteristics of DSRC communications and their impact on upper layer applications. Another direction is to investigate how to utilize the unique characteristics of V2V channel behaviour in order to improve the performance of vehicular network applications. Finally, we will collect more DSRC communication data over multiple places, involving more communicating vehicles such as taxis in the network.

ACKNOWLEDGMENT

This research was supported in part by National Natural Science Foundation of China (Grants No. 61472255, 61420106010, 61373157, 61300199, 61472254), STCSM Grant 14511107500, JSPS KAKENHI Grant Number 26730056, and JSPS A3 Foresight Program.

REFERENCES

[1] NHTSA, "2013 Overview Traffic Safety Fact Sheet," http://www-nrd.nhtsa.dot.gov/Pubs/812169.pdf.
[2] ASTM, "Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems - 5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications," http://www.astm.org/Standards/E2213.htm.

[3] F. Bai, D. D. Stancil, and H. Krishnan, “Toward Understanding Characteristics of Dedicated Short Range Communications (DSRC) from a Perspective of Vehicular Network Engineers,” in *Proceedings of ACM MobiCom*, 2010.

[4] F. Martelli, M. Elena Renda, G. Resta, and P. Santi, “A Measurement-based Study of Beaconing Performance in IEEE 802.11p Vehicular Networks,” in *Proceedings of IEEE INFOCOM*, 2012.

[5] R. Meireles, M. Boban, P. Steenkiste, O. Tonguz, and J. Barros, “Experimental study on the impact of vehicular obstructions in VANETs,” in *Proceedings of IEEE Vehicular Networking Conference*, 2010.

[6] I. Tan, W. Tang, K. Laberteaux, and A. Bahai, “Measurement and Analysis of Wireless Channel Impairments in DSRC Vehicular Communications,” in *Proceedings of IEEE International Conference on Communications (ICC)*, 2008.

[7] L. Cheng, B. Henty, D. Stancil, F. Bai, and P. Mudalige, “Mobile Vehicle-to-Vehicle Narrow-Band Channel Measurement and Characterization of the 5.9 GHz Dedicated Short Range Communication (DSRC) Frequency Band,” *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 8, pp. 1501–1516, 2007.

[8] X. Yin, X. Ma, K. Trivedi, and A. Vinel, “Performance and Reliability Evaluation of BSM Broadcasting in DSRC with Multi-Channel Schemes,” *IEEE Transactions on Computers*, vol. 63, no. 12, pp. 3101–3113, 2014.

[9] J. Jaime-Rodriguez, C. Gutierrez, J. Luna Rivera, D. Campos-Delgado, and R. Velazquez, “Comparative performance analysis of two channel estimation techniques for DSRC systems based on the IEEE 802.11p standard,” in *Proceedings of IEEE Central America and Panama Convention*, 2014.

[10] M. Soltani, M. Alimadadi, Y. Seyedi, and H. Amindavar, “Modeling of Doppler spectrum in V2V urban canyon oncoming environment,” in *Proceedings of Telecommunications (IST), 2014 7th International Symposium on*, 2014.

[11] F. Bai and H. Krishnan, “Reliability Analysis of DSRC Wireless Communication for Vehicle Safety Applications,” in *Proceedings of IEEE Intelligent Transportation Systems Conference*, 2006.

[12] J. Gozalvez, M. Sepulcre, and R. Bauza, “IEEE 802.11p Vehicle to Infrastructure Communications in Urban Environments,” *IEEE Communications Magazine*, vol. 50, no. 5, pp. 176–183, 2012.

[13] J. Yin, G. Holland, T. ElBatt, F. Bai, and H. Krishnan, “DSRC Channel Fading Analysis from Empirical Measurement,” in *Proceedings of Communications and Networking in China*, 2006.

[14] H. Fernandez, L. Rubio, V. Rodrigo-Penarrocha, and J. Reig, “Path Loss Characterization for Vehicular Communications at 700 MHz and 5.9 GHz Under LOS and NLOS Conditions,” *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 931–934, 2014.

[15] S. Biddlestone, K. Redmill, R. Miucic, and U. Ozguner, “An Integrated 802.11p WAVE DSRC and Vehicle Traffics With Experimentally Validated Urban (LOS and NLOS) Propagation Models,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 13, no. 4, pp. 1792–1802, Dec 2012.

[16] S. Carpenter, “Obstacle Shadowing Influences in VANET Safety,” in *Proceedings of IEEE 22nd International Conference on Network Protocols (ICNP)*, 2014.

[17] E. Giordano, R. Frank, G. Pau, and M. Gerla, “CORNER: a realistic urban propagation model for VANET,” in *Proceedings of Wireless On-demand Network Systems and Services (WONS)*, 2010.

[18] J. Otto, F. Bustamante, and R. Berry, “Down the Block and Around the Corner The Impact of Radio Propagation on Inter-vehicle Wireless Communication,” in *Proceedings of IEEE Distributed Computing Systems (ICDCS)*, 2009.

[19] A. Mukunthan, C. Cooper, F. Safaei, D. Franklin, and M. Abolhasan, “Studying the Impact of the CORNER Propagation Model on VANET Routing in Urban Environments,” in *Proceedings of IEEE Vehicular Technology Conference (VTC Fall)*, 2012.

[20] A. Systems, “LocoMate Classic On Board Unit OBU-200,” http://www.aradasystems.com/locomate-obu/.

[21] Y. J. Li, “An Overview of the DSRC/WAVE Technology,” in *Quality, Reliability, Security and Robustness in Heterogeneous Networks*. Springer, 2012, pp. 544–558.

[22] X. Ma, X. Chen, and H. H. Refai, “Performance and Reliability of DSRC Vehicular Safety Communication: A Formal Analysis,” *EURASIP Journal on Wireless Communications and Networking - Special issue on wireless access in vehicular environments*, vol. 2009, Jan. 2009.

[23] A. Chaintreau, P. Hui, J. Crowcroft, C. Diot, R. Gass, and J. Scott, “Impact of Human Mobility on Opportunistic Forwarding Algorithms,” *IEEE Transactions on Mobile Computing*, vol. 6, no. 6, pp. 606–620, 2007.

[24] H. Zhu, L. Fu, G. Xue, Y. Zhu, M. Li, and L. Ni, “Recognizing Exponential Inter-Contact Time in VANETs,” in *Proceedings of IEEE INFOCOM*, 2010.