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Abstract
This paper provides a comparative analysis of two vehicular wireless communication technologies for vehicle-to-everything (V2X) safety and non-safety applications: dedicated short-range communication (DSRC) based on IEEE 802.11p and 3GPP Rel-14 LTE-V2X, which is recently standardized by the cellular industry. First, we provide a brief overview of the two technologies and their technical differences. Then, we show system-level simulation results of DSRC and Rel-14 LTE-V2X PC5 mode 4 (i.e., UE autonomous mode) using congestion control mechanisms in 5.9 GHz band in freeway scenarios for several vehicle densities. The performance metrics that we evaluated are packet reception ratio, packet inter-reception, information age, and end-to-end latency. For a given specific simulation configuration, the simulation results show that in a lower vehicle density case, the two technologies are comparable or LTE-V2X provides a longer V2V communication range, whereas in a high vehicle density case, DSRC achieves superior performance than LTE-V2X PC5 mode 4. Further, in both vehicle density scenarios, we show that DSRC achieves a shorter end-to-end latency.

Keywords:
ITS, DSRC, LTE-V2X

1. Introduction

Vehicle-to-everything (V2X) communication is a wireless communication technology that can improve driving safety and traffic efficiency. V2X communication primarily relies on direct wireless communication between vehicles, infrastructures, and vulnerable road users for cooperative situational awareness, e.g., to exchange vehicle safety messages such as SAE Basic Safety Messages (BSMs) [1] in the U.S. and ETSI Cooperative Awareness Messages (CAMs) [2] in Europe. As of today, there are two major V2X technologies: dedicated short-range communication (DSRC) [3] based on IEEE 802.11p [4] and 3GPP LTE-V2X [5], [6].

DSRC is a vehicular wireless communication technology for V2X safety and non-safety applications.

DSRC employs IEEE 802.11p for its PHY and MAC layers. ETSI ITS-G5 in Europe and ITS Connect in Japan are equivalent to DSRC in the U.S. The automotive industry has worked on the development, standardization, and commercialization of DSRC for more than a decade in several international and regional standardization development organizations such as IEEE, SAE, ETSI, ARIB, etc. In addition, DSRC was verified with various testing and large-scale field trials by the automotive industry and thus is a mature technology. Indeed, the commercial deployment was already started in Japan from 2015 and the U.S. from 2017. Further, in Europe, CAR 2 CAR Communication Consortium (C2C-CC) announced that the initial commercial deployment of ETSI ITS-G5 could begin as soon as 2019.

LTE-V2X is another vehicular wireless communication technology developed in 3GPP based on LTE technologies to support V2X safety and non-safety applications. The initial standardization of LTE-V2X was completed in 3GPP in March 2017 as a part of its Rel-14 features. Its communication performance is being tested through numerical simulations, and laboratory and field tests [7]-[10]. In China, Ministry of Industry and Information Technology (MIIT) assigned 5.905 – 5.925 GHz frequency band in 2016 for LTE-V2X trials in six major cities. In October 2018, MIIT in China allocated this band for LTE-V2X PC5. In 3GPP Rel-15 standardization, several enhancements of LTE-V2X were specified to support higher data rate and reliability and lower channel access latency [11]. Moreover, 3GPP works on yet another V2X technology based on New Radio (NR), referred to as NR-V2X, as a part of Rel-16 features [12].

In the literature, there are several works on comparative analysis of LTE-V2X and DSRC through link-level simulations, system-level simulations, and field trials [7]-[10]. Nevertheless, to the best of our knowledge, the performance comparison of the two V2X technologies using congestion control mechanisms has not yet been investigated. The primary contribution of this paper is to analyze the performance of DSRC and 3GPP Rel-14 LTE-V2X PC5 mode 4 (i.e., UE autonomous mode) using congestion control mechanisms in high vehicle density scenarios.

In this paper, we provide a brief overview of the two V2X technologies and their technical differences. Then, we analyze the vehicle-to-vehicle (V2V) communication performance of DSRC and 3GPP Rel-14 LTE-V2X PC5 mode 4 in 5.9 GHz band in freeway scenarios for several vehicle densities. Particularly, we put emphasis on the scalability of the two technologies with congestion control in high vehicle density scenarios. The performance metrics that we evaluated are packet reception ratio, packet inter-reception, information age, and end-to-end latency. Based on the simulation results, we show that DSRC achieves superior performance than LTE-V2X PC5 mode 4 in a high vehicle density scenario, whereas the two technologies are comparable in a low vehicle density scenario, for a given specific simulation configuration.

The rest of this paper is organized as follows. Section 2 provides a brief overview of DSRC and 3GPP Rel-14 LTE-V2X. Section 3 describes the simulation scenarios and parameters for DSRC and 3GPP

Rel-14 LTE-V2X PC5 mode 4. Section 4 presents system-level simulation results and our analyses, and concluding remarks are given in Section 5.

2. Overview of DSRC and 3GPP Rel-14 LTE-V2X

In this section, we provide a brief overview of DSRC and 3GPP Rel-14 LTE-V2X and their technical differences.

Overview of DSRC

DSRC employs IEEE 802.11p [4] for its PHY and MAC layers. It is based on IEEE 802.11 family protocols (e.g., IEEE 802.11a, g) with several modifications to meet challenges and communication requirements unique to vehicular environments. At the PHY layer, orthogonal frequency division multiplexing (OFDM) with convolutional coding is employed, as in IEEE 802.11a. IEEE 802.11p typically operates in a channel of 10 MHz bandwidth rather than 20 MHz in IEEE 802.11a and uses doubled OFDM symbol duration and guard interval to counter larger delay spreads in outdoor vehicular scenarios than ones in indoor scenarios. Therefore, the subcarrier spacing is halved (i.e., 156.25 kHz). At the MAC layer, IEEE 802.11p inherits Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) mechanism. To enable low latency communications and bypass the time-costly procedure of setting up a Basic Service Set (BSS) required in the traditional 802.11 family protocols, IEEE 802.11p uses new lightweight rules called "Outside the context of a BSS (OCB)", which allow vehicles to transmit signals without prior association.

To mitigate packet collisions in congested scenarios, decentralized congestion control techniques were defined, which adapt transmission behavior to react to channel congestion. SAE and ETSI specified decentralized congestion control (DCC) mechanisms for DSRC in SAE J2945/1 [13] and in ETSI TS 102 687 [14], respectively. In this paper, we focus on ETSI DCC. ETSI TS 102 687 outlines two different approaches: a reactive approach and an adaptive approach. In both of the approaches, transmission behavior is adapted at least every 200 ms based on a channel busy ratio (CBR), which is a fraction of time that a channel is sensed busy and is measured periodically (e.g., every 200 ms) by each station. The reactive approach is based on a finite state machine composed of multiple states corresponding to CBR ranges. In each state, different transmission parameters (the packet rate, transmission power, and/or data rate) can be set to control the network load. In the adaptive approach, based on the measured CBR, each station updates the channel occupancy limit, which is the maximum fraction of time that the station is allowed to transmit packets in the channel over a certain interval, every 200 ms in such a way that the CBR converges to a specified target CBR. Then, each station adapts the message interval to meet the channel occupancy limit.

Overview of 3GPP Rel-14 LTE-V2X

LTE-V2X [5], [6] has two main operation scenarios: Uu-based and PC5-based. Uu is the name of interface between user equipment (UE) devices and a base station (eNB: Evolved Node B), and PC5 is the one between UEs. Uu-based LTE-V2X utilizes downlink and uplink of LTE networks for communication among UEs. In contrast, PC5-based LTE-V2X uses sidelinks (i.e., direct links between UE devices) for communication among UEs, with and without the support of eNBs. PC5-based LTE-V2X is further divided into two modes: mode 3 and mode 4. In PC5 mode 3, sidelink resources of each UE are allocated by eNBs, and the UE broadcasts packets using the allocated sidelink resources. In PC5 mode 4, each UE autonomously selects sidelink resources and broadcasts packets using selected sidelink resources. Therefore, the operation scenario of PC5 mode 4 is similar to one in DSRC in the sense that both protocols do not require the help of base stations and the channel access mechanisms are fully distributed. Since LTE-V2X PC5 mode 4 is of main interest of this paper, we focus on it in the reminder of the paper.

LTE-V2X PC5 mode 4 employs discrete Fourier transform spread orthogonal frequency division multiplexing (DFT-s-OFDM) for sidelink at the PHY layer. Time-frequency radio resources are divided into subframes in the time domain and sub-channels in the frequency domain. Each subframe is 1 ms length and consists of 14 DFT-s-OFDM symbols. Each sub-channel consists of multiple contiguous physical resource blocks (PRBs), where each PRB occupies 180 kHz and consists of 12 subcarriers, and the size of sub-channel (i.e., the number of PRBs per sub-channel) is configurable. To cope with high Doppler caused by high relative speed in vehicular scenarios, the density of demodulation reference signal (DMRS), which is used for frequency offset compensation and channel estimation, is set to four per subframe. Each UE broadcasts data (TB: transport block) in the physical sidelink shared channel (PSSCH) as well as sidelink control information (SCI) Format 1 in the physical sidelink control channel (PSCCH). PSCCH occupies two contiguous PRBs, whereas the number of PRBs for PSSCH is the largest integer in a form of $2^{\alpha_2} \cdot 3^{\alpha_3} \cdot 5^{\alpha_5}$ that is lower than or equal to the size of the selected sub-channels minus 2 PRBs for PSCCH, where α_2, α_3, and α_5 are non-negative integers. SCI Format 1 contains necessary information to decode its corresponding TB in PSSCH and facilitate UE autonomous resource selection, such as modulation and coding scheme (MCS), per packet priority, resource reservation interval, retransmission index (indicator whether the packet is the retransmitted packet or not), and time gap between the initial transmission and retransmission. The resource reservation interval can be set to one of the allowed values (20, 50, 100, 200, 300, …, 1000 ms). PSCCH and the corresponding PSSCH needs to be transmitted in the same subframe in either adjacent or non-adjacent PRBs in the frequency domain. For channel coding, turbo coding and tail-biting convolutional coding are employed for PSSCH and PSCCH, respectively.

UE autonomous resource selection using semi-persistent scheduling (SPS) was introduced for Rel-14 LTE-V2X PC5 mode 4 to efficiently support periodic packet transmissions. The procedure of UE autonomous resource selection using SPS is shown in Figure 1. Each UE selects a single-subframe resource in a uniformly random manner among candidate single-subframe resources in a (pre-)configured selection window $[T_1, T_2]$, where $T_1 \le 4$ and $20 \le T_2 \le 100$. To determine candidate resources, the UE performs channel sensing by analyzing resources in the last 1000 subframes, except for those in which its own transmissions occurred. The UE excludes candidate resources by considering its own past transmissions and resource reservation information obtained from other UEs' SCI Format 1. Then, the UE calculates the corresponding S-RSSI (Sidelink Received Signal Strength Indicator) of each candidate resource as a linear average over the S-RSSIs of the monitored resources with a certain interval (the averaging interval is 100 ms for a resource reservation interval of greater than or equal to 100 ms). Finally, the UE determines 20% best resources in terms of lowest average S-RSSI as the candidate resources among the total resources in the selection window. In SPS, once a UE selects a resource, it keeps using the same resource with the selected resource reservation interval for multiple consecutive transmissions. At resource reselection, the UE sets a resource reselection counter to an integer value randomly selected in a certain range (the range is 5 to 15 for the resource reservation interval of greater than or equal to 100 ms) with equal probability. This counter is decremented every transmission. When the resource reselection counter reaches zero, the UE decides whether to keep the current resource for the subsequent transmissions or not based on a (pre-)configured probability (i.e., a probability to keep the current resource, which is configured by a higher layer in the values from 0 to 0.8 with a step of 0.2). When the UE decides to keep the current resource, it sets a new resource reselection counter value and keep using the same resource. Otherwise, it performs resource reselection. If the latency requirement for channel access is not met for the selected resource (e.g., due to the change of the message interval and/or a mismatch between the resource reservation interval and the message interval), it is up to UE implementation whether to perform resource reselection or perform a one-time transmission with independent resource selection while keeping the current SPS resource to meet the latency requirement.

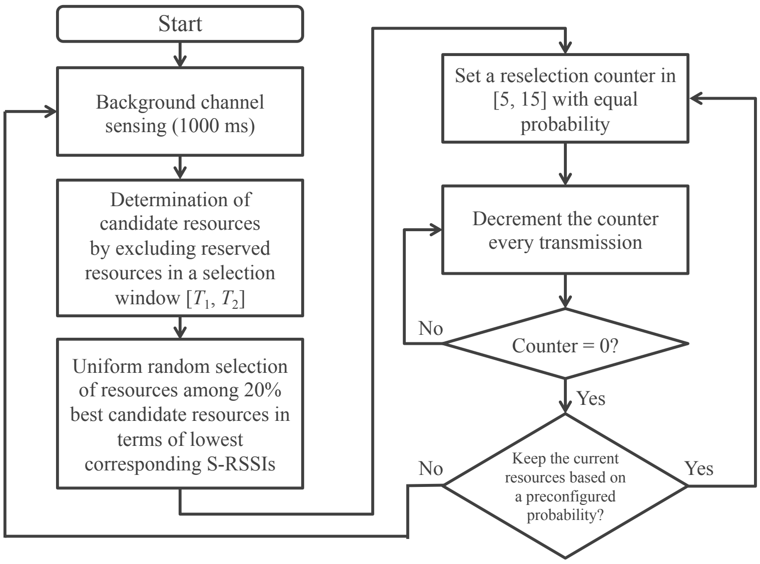


Figure 1. Procedure of Rel-14 LTE-V2X PC5 mode 4 semi-persistent resource selection

3GPP specified the framework of access layer congestion control for Rel-14 LTE-V2X PC4 mode 4. For access layer congestion control, each UE measures the CBR and evaluates the channel occupancy ratio (CR). The CBR indicates the congestion level of each sub-channel due to other UEs, which is defined as the portion of sub-channels whose S-RSSI measured by the UE exceed a (pre-)configured threshold, sensed in the past 100 subframes. The CR quantifies the channel occupancy by the transmitting UE for its transmissions, which is defined as the total number of sub-channels used by the transmitting UE for its transmissions, divided by the total number of configured sub-channels over a measurement period of 1000 subframes. Based on the measured CBR and CR, each UE adapts its transmission behavior to meet the CR limit corresponding to the CBR range that includes the measured CBR for a (pre-)configured table that specifies the ranges of CBR and the corresponding CR limits. 3GPP specifications do not specify on how to meet the CR limits and thus it is up to UE implementation or specified by other standardization development organizations.

3. Simulation assumptions of DSRC and 3GPP Rel-14 LTE-V2X PC5 mode 4

Table 1. Simulation scenarios and channel models

Parameter	Value
Scenario	Freeway (5 km long, 6 lanes/direction, and 4 m lane width)
Vehicle speed	100 km/h
Inter-vehicle distance	[4 sec, 1 sec] × vehicle speed [m/s]
Path loss	ITU-R P.1411-9 UHF street canyon LOS (median) [15]
Shadowing	No
Fast fading	3GPP TR 36.843 LOS [16]
Frequency offset	For both Tx and Rx, uniformly random in [-20, 20] ppm for DSRC and [-0.1, 0.1] ppm for LTE-V2X
ADC quantization error	10-bit ADC with -18 dB backoff [17]
In-band emission (only for LTE-V2X)	3GPP TR 36.885 [18]

Table 2. Simulation parameters

Parameter	IEEE 802.11p / DSRC	3GPP Rel-14 LTE-V2X PC5 mode 4
Carrier frequency	5.9 GHz	
System bandwidth	10 MHz	
Tx power	20 dBm	
Tx and Rx antenna gains	0 dBi	
Noise figure	9 dB	
Number of Tx and Rx antennas	1 Tx antenna and 2 Rx antennas with maximum ratio combining	
Antenna pattern	Omni 2D	
Tx and Rx antenna heights	1.5 m	
Message traffic	ETSI CAM with 10 ms resolution	
PHY payload size	317 bytes	300 bytes
Modulation and coding scheme	QPSK and 1/2-rate	MCS 7 (QPSK and ~0.57-rate)
Congestion control	ETSI TS 102 687 DCC adaptive approach in [14]	Update message interval at resource reselection using CR limit table in [20] (CBR threshold is -107 dBm / 180 kHz)
AIFSN and CW_{min}	AIFSN = 2 and CW_{min} = 15	N/A
Sub-channel size	N/A	25 PRBs (= 4.5 MHz)
HARQ	N/A	Disabled
Probability to keep the current resource	N/A	0.8
Resource reselection due to latency requirement	N/A	Resource reselection is triggered if the latency requirement (100 ms) is not met
Resource selection window	N/A	T_1 = 1 and T_2 = 100
Resource reservation	N/A	Enabled

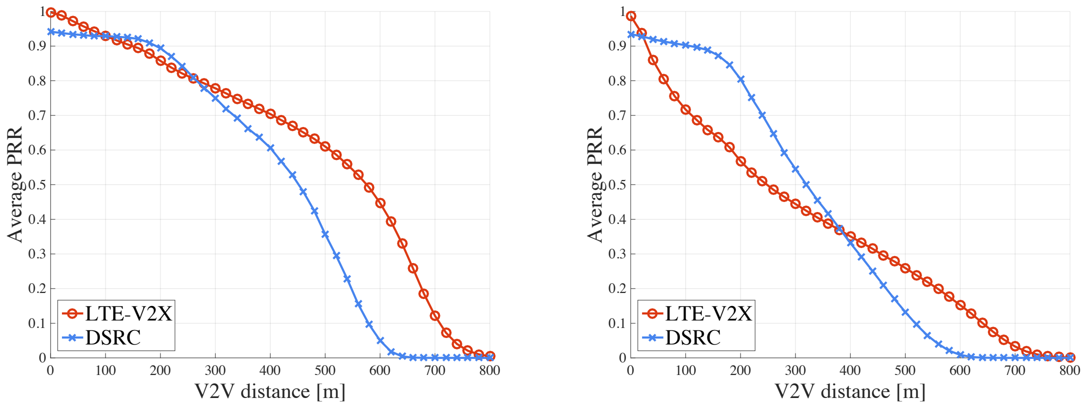
In this section, we describe the simulations scenarios and parameters of DSRC and 3GPP Rel-14 LTE-V2X PC5 mode 4 for system-level simulations. The simulation scenarios and channel models are summarized in Table 1. We assume a freeway scenario, which is a 5 km long straight road and has 6 lanes/direction (i.e., total 12 lanes) with 4 m lane width. We evaluate the center of 1 km length road to avoid the edge effect. The vehicle speed is set to 100 km/h. Different vehicle densities are evaluated by changing the average inter-vehicle distance, 4 sec and 1 sec multiplied by the vehicle speed [m/s]. The vehicle density is 108 vehicles/km for the 4-sec case and 432 vehicles/km for the 1-sec case.

The simulation parameters for DSRC and LTE-V2X are summarized in Table 2. Both protocols operate at 5.9 GHz carrier frequency with 10 MHz system bandwidth, 20 dBm transmission power, and 0 dBi antenna gain. Messages are generated based on ETSI CAM generation rule [2] with 10 ms resolution, in which at 100 km/h vehicle speed, messages are generated every 150 ms if channels are not congested. The PHY payload size is 317 bytes for DSRC and 300 bytes for LTE-V2X to take into account the difference of Layer 2 overheads in DSRC and LTE-V2X. For ease of analysis, we assume the same PHY payload size for all transmissions (i.e., no variation of packet sizes). Hybrid automatic repeat request (HARQ) in LTE-V2X is disabled as our focus is congested scenarios and it was reported that HARQ degrades the reception performance in congested scenarios [19]. For DSRC congestion control, we employ ETSI TS 102 687 DCC adaptive approach [14]. For LTE-V2X congestion control, we update the message interval at resource reselection to meet the CR limit, using the CR limit table in [20]. In LTE-V2X, we set the resource reservation interval as $\lceil \max\{T_{\text{interval}}, T_{\text{CC}}\}/100 \rceil \times 100$ [ms], where T_{interval} is the message interval of the latest two consecutive messages and T_{CC} is the message interval derived from the congestion control.

4. Performance comparison of DSRC and 3GPP Rel-14 LTE-V2X PC5 mode 4

In this section, we analyze the performance of DSRC and 3GPP Rel-14 LTE-V2 PC5 mode 4 for various performance metrics through system-level simulations. In our analysis, the following metrics are analyzed:

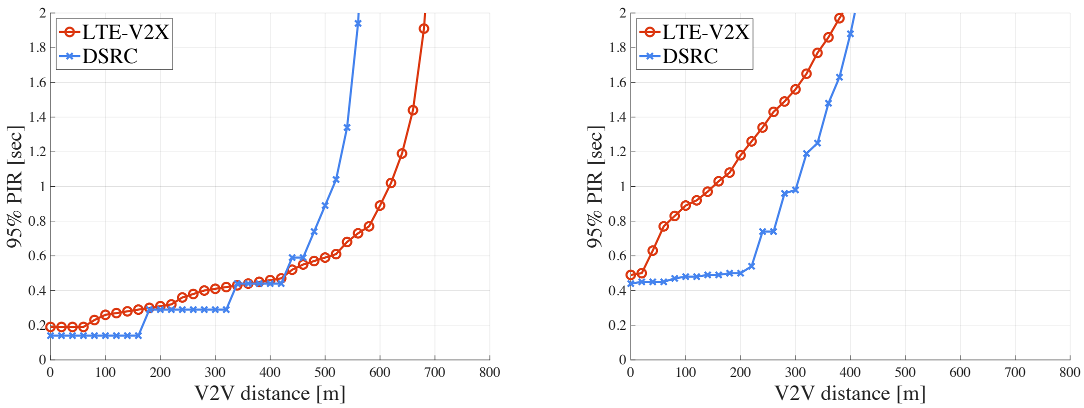
- *Packet reception ratio (PRR)*: A fraction of the number of vehicles with successful reception divided by the number of vehicles that are located in the range (a, b) [m] from a transmitter, where $a = i \times 20$ [m] and $b = (i + 1) \times 20$ [m] with $i = 0, 1, 2, \ldots$
- *Packet inter-reception (PIR)*: Time elapsed between two successive successful reception of two different packets transmitted from a vehicle A to a vehicle B
- *Information age (IA)*: Time between the current measuring timestamp ($i \times \Delta t_{\text{period}}$) and the packet generation timestamp at a transmitter contained in the last successfully received packet transmitted from a vehicle A to a vehicle B, where $i = 0, 1, 2, \ldots$, and $\Delta t_{\text{period}} = 100$ ms
- *End-to-end (E2E) latency*: Time difference between the time that a packet generated are delivered from the application layer to MAC layer at the transmitter and the time that the packet is received by the receiver for successfully received packets



(a) 4-sec inter-vehicle distance in time (108 vehicles/km) (b) 1-sec inter-vehicle distance in time (432 vehicles/km)

Figure 2. Average packet reception ratio (PRR) with respect to V2V distance

Figure 2 shows the average PRR with respect to the V2V distance for the inter-vehicle distances in time of 4 sec and 1 sec. In the 4-sec case, the PRR performance of DSRC and LTE-V2X are comparable for V2V distances up to about 300 m, whereas LTE-V2X achieves better PRR for V2V distances beyond 300 m, because of a better link budget of LTE-V2X. In the 1-sec case, for V2V distances up to about 400 m, DSRC achieves better PRR performance, whereas the PRR of LTE-V2X is degraded. The degradation in LTE-V2X for shorter V2V distances is seemingly caused by the two unique issues in LTE-V2X PC5 mode 4, i.e., the persistent packet collision and the persistent half-duplex problem due to SPS. In addition to these two issues, the in-band emission interference causes additional performance degradation in relatively longer V2V distances due to the near-far problem. HARQ can be used to mitigate these issues. However, HARQ doubles the traffic load and may degrade the performance. Analysis on the impact of HARQ is left for future research. By contrast, the degradation in DSRC is limited by virtue of well-designed congestion control.

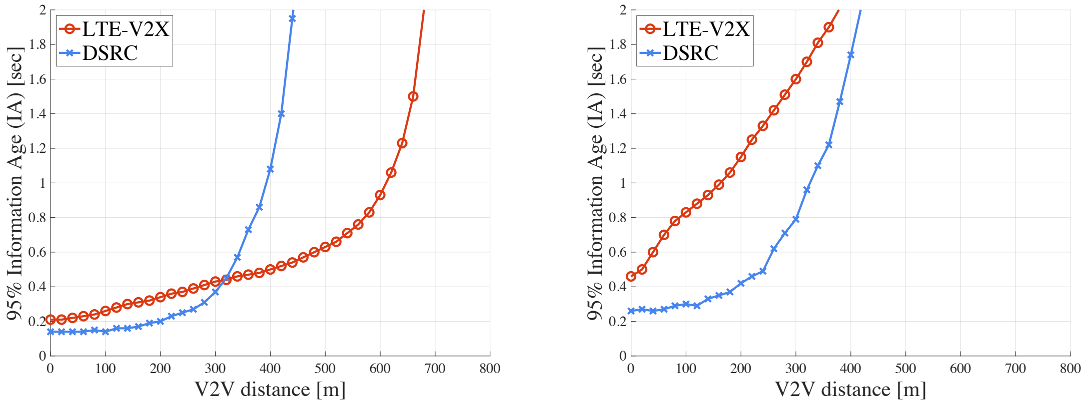


(a) 4-sec inter-vehicle distance in time (108 vehicles/km) (b) 1-sec inter-vehicle distance in time (432 vehicles/km)

Figure 3. 95th-percentile packet inter-reception (PIR) with respect to V2V distance

Figure 3 shows the 95th-percentile PIR for the inter-vehicle distances in time of 4 sec and 1 sec. In the 4-sec case, the PIR performance of DSRC and LTE-V2X are comparable for V2V distances up to about 450 m. On the other hand, in the 1-sec case, DSRC achieves shorter PIR performance than LTE-V2X.

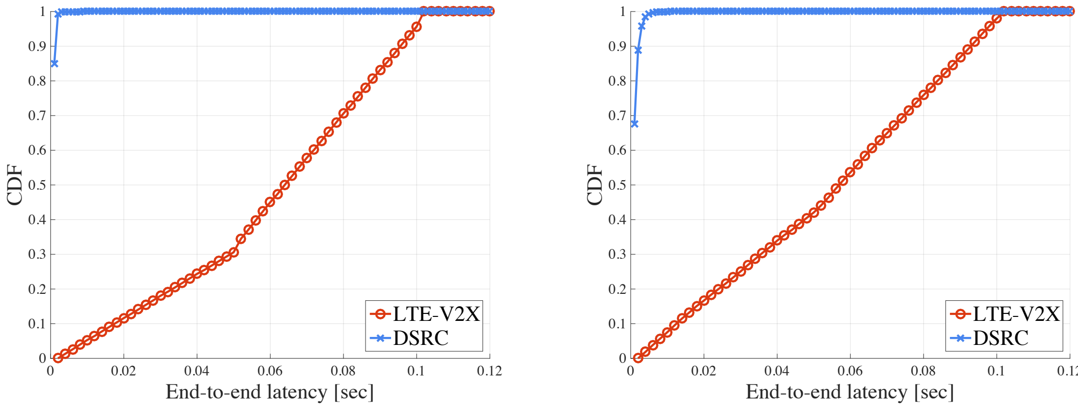
As in the PRR results, the PIR performance degradation in LTE-V2X is mainly caused by the persistent packet collision and the persistent half-duplex problem.



(a) 4-sec inter-vehicle distance in time (108 vehicles/km) (b) 1-sec inter-vehicle distance in time (432 vehicles/km)

Figure 4. 95th-percentile information age (IA) with respect to V2V distance

Figure 4 shows the 95th-percentile IA for the inter-vehicle distances in time of 4 sec and 1 sec. We observe that the IA results follow the same trend as the PIR results.



(a) 4-sec inter-vehicle distance in time (108 vehicles/km) (b) 1-sec inter-vehicle distance in time (432 vehicles/km)

Figure 5. CDF of end-to-end latency for V2V distance range [0, 320] m

Figure 5 shows the cumulative distribution function (CDF) of E2E latency for V2V distance range [0, 320] m for the inter-vehicle distances in time of 4 sec and 1 sec. In both cases, DSRC achieves significantly shorter E2E latency (e.g., the 90th-percentile value is less than 2 ms) by virtue of CSMA/CA. The E2E latency of LTE-V2X is approximately uniformly distributed up to 100 ms because of its SPS-based channel access mechanism and the resource selection window size (i.e., $T_1 = 1$ and $T_2 = 100$).

5. Conclusion

In this paper, we compared the performance of DSRC and Rel-14 LTE-V2X PC5 mode 4 using congestion control mechanisms in freeway scenarios for several vehicle densities. The simulation results show that in a lower vehicle density case, the two technologies are comparable or LTE-V2X provides a longer V2V communication range, whereas in a high vehicle density case, DSRC achieves superior performance than LTE-V2X PC5 mode 4. Further, in both high and low vehicle density scenarios, we showed that DSRC achieves a significantly shorter end-to-end latency. Note that the analysis in this paper is based solely on one configuration, focusing on freeway scenarios. Since there are a lot of configurable parameters in LTE-V2X PC5 mode 4 and other scenarios, it requires more thorough evaluation and analysis for different configurations and scenarios (particularly, congested scenarios) to make LTE-V2X PC5 mode 4 mature.

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