LTE-V: A TD-LTE based V2X Solution for Future Vehicular Network

Article · September 2016

DOI: 10.1109/JIOT.2016.2611605

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LTE-V: A TD-LTE-Based V2X Solution for Future Vehicular Network

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***Abstract*—Diverse applications in vehicular network present specific requirements and challenges on wireless access technology. Although considered as the first standard, IEEE 802.11p shows the obvious drawbacks and is still in the field-trial stage. In this paper, we propose long-term evolution (LTE)-V as a systematic and integrated V2X solution based on time-division LTE (TD-LTE) 4G. LTE-V includes two modes: 1) LTE-V-direct and 2) LTE-V-cell. Comparing to IEEE 802.11p, LTE-V-direct is a new decentralized architecture which modifies TD-LTE physical layer and try to keep commonality as possible to provide short range direct communication, low latency, and high reliability improvements. By leveraging the centralized architecture with native features of TD-LTE, LTE-V-cell optimizes radio resource management for better supporting V2I. LTE-V-direct and LTE-V-cell coordinate with each other to provide an integrated V2X solution. Performance simulations based on sufficient scenarios and the prototype system with typical cases are presented. Finally, future works of LTE-V are envisioned.**

***Index Terms*—Long-term evolution (LTE)-V, LTE-V-cell, LTE-V-direct, time-division long term evolution (TD-LTE), vehicular network.**

I. Introduction

VEHICULAR network is one of the key technologies in intelligent transportation system (ITS) to provide wireless connectivity among vehicles, road sides' drivers, passengers, and pedestrians. Despite of great potential industrial and market opportunities [1], V2X communications technology is still in the field trial stage in general [2].

Applications in vehicular networks can be classified into road safety, traffic efficiency, and infotainment types with different performance requirements. With vehicle-to-vehicle (V2V) communications, road safety applications require low delay and high reliability. Relying on both V2V and vehicle-to-infrastructure (V2I) communications, traffic efficiency applications have no strict requirements on delay and reliability but the quality degrades with increasing in packet loss and delay [1]. Infotainment applications are based on V2I communications with high-bandwidth and QoS-sensitive requirements.

Various wireless access technologies are available to provide the radio interface required by the vehicular communications, including traditional Wi-Fi, IEEE 802.11p, cellular systems, and infrared communications [3], [4]. They operate in different frequency bands and provide disparate features in communication range, data rate, channel bandwidth, and mobility supporting capability [3], [4]. Wi-Fi and infrared communication are not suitable to support high mobility with the small communication range [3]. In these wireless technologies, although IEEE 802.11p is considered as the first standard specifically designed for on-the-road communications, it showed obvious drawbacks such as low reliability, hidden node problem, unbounded delay, and intermittent V2I connectivity [1], [5]–[7]. From industrial perspective, widely deployment of IEEE 802.11p requires huge investments on network infrastructure. New efforts have been put into using long-term evolution (LTE) 4G as a potential wireless access technology to support vehicular applications [1], [8], [9], motivated by these drawbacks of IEEE 802.11p and due to the fast global deployment and commercialization of LTE 4G.

LTE possesses natural benefits in providing V2I communications because of its high data rate, high penetration rate, comprehensive QoS supporting, and large coverage. But LTE faces challenges when applying in V2V communications due to: its centralized architecture lacks of support to V2V communication; the heavy load generated by periodic messages strongly challenges LTE capacity and potentially penalizes the delivery of traditional applications [1]. Because the relationship between cellular and ad-hoc communications technologies is suggested to be complementary instead of competing [10], it will be a promising solution to extend LTE with direct communication capability between vehicles to become an integrated V2X solution.

Motivated by the above observations from both technical and industrial perspectives, LTE-V is proposed in this paper, as a systematic and integrated solution for V2X communications based on time-division LTE (TD-LTE). LTE-V provides two communication modes, which are complementary to each other and thus coordinate to support V2X applications.

1) LTE-V-direct is specially proposed for V2V communications in decentralized architecture. It supports mesh

Manuscript received July 8, 2016; revised September 6, 2016; accepted September 9, 2016. Date of publication September 20, 2016; date of current version January 10, 2017. This work was supported in part by the National Science Fund for Distinguished Young Scholars under Grant 61425012 and in part by the National Science Foundation Project under Grant 61300183.
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Digital Object Identifier 10.1109/JIOT.2016.2611605

topology and provides direct V2V communication to support road safety applications with low-latency and high-reliability.

2) LTE-V-cell is the centralized system of LTE-V for supporting V2I communications using star topology. The design philosophy of LTE-V is to keep LTE-V-direct and LTE-V-cell reasonable commonality based-on TD-LTE, so the same hardware platform can be shared between TD-LTE and LTE-V to achieve the cost-effective solutions.

LTE-V can be a promising integrated solution with the advantages such as ecosystem, large subscriber basis, economic size, and potential market opportunities for the vehicular networks.

The rest of this paper is organized as follows. Section II analyzes motivation, opportunities, and challenges of LTE-V. The LTE-V solution with introductions on key technologies is introduced in Section III. The performance of LTE-V is evaluated in Section IV. Finally, Section V presents the prototyping efforts in LTE-V for typical application, followed by the conclusions in Section VI.

II. Motivations, Opportunities, and Challenges of LTE Enhancement for Vehicular Network

A. Motivation and Opportunities

Motivation of this paper comes from comparisons between IEEE 802.11p and LTE from both technical and industrial perspectives, as shown in Table I, which presents LTE opportunities to become a competitive candidate for wireless access.

TABLE I
Comparisons Between IEEE 802.11p and LTE in Vehicular Networks

Feature		802.11p	LTE for V2X
Technical perspective	Capacity	Medium	High
	Mobility support	Medium	Very high (up to 350 km/h)
	Coverage	Intermittent, thus short-lived V2I connectivity [1]	ubiquitous
	Delay	Unbounded, incurred by carrier sense multiple access with collision avoidance (CSMA/CA) [6]	The system performance goal is 100ms (C-plane), 10ms round-trip and 5ms (U-plane)
	Reliability	Low, unable to provide the required time-probabilistic characteristics [7]	High, provide the predicted delay and less interference
	Media access control (MAC) protocol	With hidden terminal problem, packets collision will happen and leads to difficulties in media access control [7]. Some MAC methods are provided, but the interference control is limited to provide the reliability of applications, and the convergence is inefficient with the cellular network.[11, 12, 13]	With the enhancement of slotted MAC, hidden terminal problem is prevented. The interference is controlled with reliability for the applications. Easy to combined with the cellular network.
	V2I support	Yes, but only intermittent and short-lived connectivity	Native, due to its centralized architecture, with some necessary enhancements
	V2V support	Native (Ad Hoc), with some necessary extensions in MAC protocols	Potentially, through device-to-device (D2D) extension
Industrial perspective	Network infrastructure	Requiring huge investment on network backbone devices	Existing large-scale 4G network deployed globally can be shared for V2I communications
	Chipset on on board unit (OBU)	Chipset of OBU is combined with Wi-Fi, separated with LTE chipset in multi-mode	Chipset of OBU and LTE terminal chipset are based on common hardware and thus to decrease cost because of scale economies.
	Inter-operate ability with commercial operators	Via backbone and gateway, not easy	Direct and available connections

B. Challenges

Despite of the above advantages, LTE still has its gaps while providing a systematic V2X solution. The major challenges include the following.

1) How to Provide Efficient V2V Communications: D2D technology [14] in 3GPP enables terminals in proximity communicating directly. It becomes an appealing solution for local data exchange among vehicles. LTE D2D is designed to support the public safety services such as VoIP for low speed mobile terminals. But the requirements of V2V communications are low-latency and high reliability in high speed vehicular environments with broadcast messages. The resource allocation scheme of LTE D2D is based on random selection, and the hidden terminal problems are not solved thoroughly. Because transformation of beaconing for vehicular safety applications is not efficient in LTE [15], necessary modifications and extensions have to be made to support V2X communications.

2) How to Avoid System Overload Due to the Heavy Traffic: During peak hours or in dense areas, heavy load of periodic messages are generated by the road safety and traffic efficiency applications. Because the periodic messages are broadcast, without the congestion control scheme, the payload of the messages will cause serious message latency and challenge LTE capacity seriously.

3) How to Offer Better Support for Vehicular Applications in High Mobility Environment: Although the downlink peak rate of LTE is offered as 100 Mbps with speed of 350 km/h, rapid network topology change, frequent and fast handover, heavy broadcasting with QoS guarantee are still huge challenges in LTE network.

4) How to Simplify the Equipment: Because both on board unit (OBU) and road side unit (RSU) have adequate power supply, the power management module can be removed. By using the same transceiver for both V2I and V2V application, the system design and cost can be reduced efficiently.

Frequency division duplex (FDD) and time division duplex (TDD) are different types of duplex scheme. TD-LTE is the representative LTE TDD standard in 4G mobile communications [16]. Though TD-LTE and LTE FDD has the difference of duplex essentially, the two systems share the commonality mostly. When compared with LTE FDD, TD-LTE has the following advantages for V2X communications.

1) *Unpaired Spectrum:* Not requiring the paired spectrum, TD-LTE terminals can contain only one transceiver. It is hard to obtain a block of paired spectrum for LTE FDD, and the cost of LTE FDD terminals is increased with two transceivers for transmitting and receiving, respectively.
2) *Efficient Resource Coordination:* In LTE FDD, if UEs are allowed to use either uplink or downlink carriers in different bands of paired spectrums in LTE FDD to transmit the vehicular safety messages, the transmitting UEs and the receiving UEs have to tune into the same carriers to communication in ad hoc mode. But without the coordination of central node, the transmitting UE and the receiving UE are difficult to use the same carriers at the same time. But in TD-LTE, the uplink and downlink transmissions share the same carriers in the same band, the transmitting UE and the receiving UE can communicate with each other even without the coordination of central node in ad hoc mode. Though the central node in TD-LTE should allocate the resource of time slots by scheduling or configuration, but the carriers resources for direct communications need not to be coordinated.

Therefore, in this paper, based on TD-LTE, LTE-V is proposed to address the requirements of vehicular networks.

III. LTE-V AND KEY TECHNOLOGIES

A. LTE-V-Direct: Modification and Extension of TD-LTE

LTE-V-direct, the decentralized mode of LTE-V enables TD-LTE with short range direct communications. Through real-time information sharing among vehicles and infrastructures, each vehicle can obtain the current information of surrounding environment, which lays the basis for road safety and traffic efficiency applications.

It is expected that low latency and high reliability requirements of the road safety applications can be applied to both V2V and V2I communications. The key technologies of LTE-V-direct are proposed as following.

1) Physical Layer of LTE-V-Direct: The vehicular environment presents the unfavorable characteristics for wireless communications, such as rapid change of the network topology, multiple reflecting objects to degrade the quality of the received signal. However, the commonality of physical layer of TD-LTE has to be considered when designing LTE-V-direct.

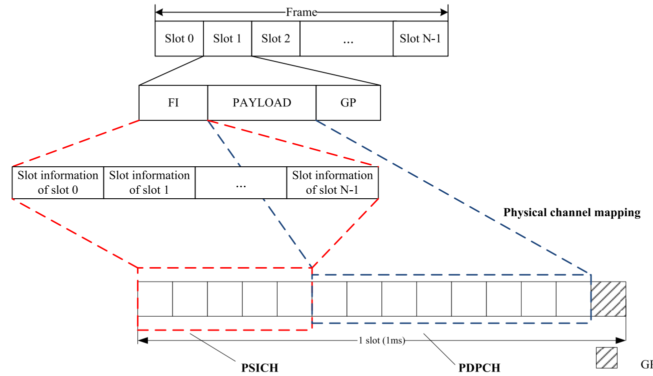


Fig. 1. Frame structure and physical channel mapping of LTE-V-direct.

The main modifications of TD-LTE are summarized as follows.

1) *The Slot Structure:* Time is divided into frames and further into slots. The length of the state update ALOHA (SU-ALOHA) slot is same as TD-LTE in the basic unit 1 ms. As shown in Fig. 1, in the slot, physical slot information channel (PSICH) consists of five orthogonal frequency division multiplexing (OFDM) symbols to transmit frame information (FI) and physical data payload channel (PDPCH) has eight OFDM symbols to transmit data payload of road safety applications. The last OFDM symbol is guard period (GP) to be reserved as the transmitter and receiver (TX/RX) switching time and the propagation delay.
2) *Modulation:* OFDM is used both in TX and RX to compensate both time- and frequency-selective fading because OFDM can cope with the dispersive linear channels in mobile environments. Because the slot structure and modulation are adapted to the typical vehicular messages size, the messages can be transmitted without segmentations to mitigate the impact of delay of buffering and combining.
3) *Timing/Synchronization:* Coordinated universal time (UTC) signaling (e.g., global positioning system, Beidou) is adopted as the default timing resource. When the synchronization from UTC signaling is lost, the self-synchronization procedure will be triggered. The self-synchronization preamble to adjust the timing has different levels to identify the timing precision and resource. Thus, the coordinated synchronization is achieved to improve the reliability.

Based on the above modifications of TD-LTE, LTE-V-direct can be a cost-effective enabler of V2X services.

2) Slotted MAC Mechanism: SU-ALOHA is proposed as a distributed resource allocation scheme and a novel time division multiple access protocol in LTE-V-direct mode. In SU-ALOHA, resources are allocated according to the status of slots and are reserved periodically.

A frame consists of N slots, and the slot number in each frame is from 0 to $N-1$. Each slot contains three parts of information.

1) *FI:* FI indicates the occupancy state, service priority and node information of each slot in a frame.

TABLE II
COMPARISONS BETWEEN TD-LTE AND LTE-V-DIRECT

	TD-LTE	LTE-V Direct
Frame	A radio frame is 10 ms. According to the system requirements not the periodicity of the services, the radio frame support flexible configuration with different uplink/downlink subframe ratio and changeable special subframe.	A frame consists of N slots, according to the periodicity of the services.
Slot structure	The 1ms subframe is composed of two 0.5ms slots. The control information is in the front OFDM symbols of each slot.	Without subframe, the time is divided into frame and 1ms slot. The control information is in the front OFDM symbols of each slot.
Modulation	Uplink: single-carrier frequency division multiple access (SC-FDMA) Downlink: OFDM	Uplink: OFDM Downlink: OFDM
Synchronization	Out of coverage: None; In coverage: the terminal get synchronization from eNB;	Out of coverage: self-synchronization; In coverage: the terminal can get synchronization from UTC of its own timing module.
Exchange information	In centralized way, forwarding through the eNB.	In distributed way, exchange the FI/PAYLOAD among the nodes.
Hidden terminal problem	The resource allocation is in the granularity of cells. Not solved in nature.	With the exchanged information, the hidden terminal problem is solved completely.

2) *Payload:* The service data is filled in the payload in the predefined format.
3) *GP:* Then FI and the payload are mapped into PSICH and PDPCH, respectively.

Entering LTE-V-direct mode, the nodes must monitor the radio channel for a whole frame to find the nearby peer users and get the slot occupied information. Then nodes can choose the available slot to transmit the FI and the data payload. The slot is reserved periodically by the transmitting node with FI. Receiving a new FI, each node maintains the status of all the slots and refreshes the state. The resource collision can be detected immediately, and then the node should reselect an available timeslot.

The maximum latency can be guaranteed by the slot reservation with periodic attribute. In IEEE 802.11p, the MAC method is CSMA/CA using carrier sensing the channels. CSMA/CA is affected significantly by the hidden nodes problems. With the FI enhancement, SU-ALOHA provides the efficient way to exchange the resource occupancy information to prevent hidden terminal problem thoroughly, and timely update of the resource reservation information by transmission FI to guarantee the periodic services.

Table II summarizes the differences between TD-LTE and LTE-V-direct.

B. LTE-V-Cell: Enhancement and Optimization of TD-LTE

LTE-V-cell is the centralized architecture of LTE-V with new features and enhancements to support V2I communication efficiently. The radio resource utilization is optimized and QoS is guaranteed with central control nodes with considering the characteristics of V2I applications, such as in high mobility environments, services with high-bandwidth, QoS-sensitive requirements, etc. The key enhancements of TD-LTE are listed as follows.

1) Deployment and RRM Optimization: Because of the obstructions or the shape of the road, the vehicles cannot communicate directly. For example, the vehicles are at the intersection or at the curve. Then the eNB can find the non line of sight (NLOS) scenario and relay the broadcast messages to the related vehicles to avoid collision risk. According to the gain of the relaying, the network planning can be optimized. When V2I applications are applied at toll collection area, RSU can be installed to provide fast V2I services access.

The density of the road is different for rush hours and off-peak hours, thus radio resource management (RRM) algorithms can be designed according to the obvious time-geometry attributes to allocate the different radio resource pools to vehicles to adapt the changing density and alleviate the congestion problem. To support fast moving vehicles, the trajectories of vehicles are predicted with the path information, then the smooth handover scheme is achieved to keep the service continuity.

After determined by the core network, QoS of TD-LTE is mapped into the requirements of radio resources of the cells scheduled by the eNB. Because V2I applications are regionally related to the transmitting node, RRM algorithms of the LTE-V-cell have to allocate the resources and control the interference with regional optimization. When the nodes report the services priority to eNB in LTE-V-cell, QoS is guaranteed with no modification in eNB with the requirements of the RRM strategies.

2) Lightweight Broadcast Procedure Design: Most V2I applications are broadcasted with heartbeat messages from RSU to OBUs within its coverage. Multimedia broadcast multicast services delivery is considered to be a potential solution, but the signaling overhead is the primary drawback [1].

Local lightweight broadcast scheme is developed to support the vehicular applications. Because the acknowledge modes are not necessary, repeat transmission procedure in radio link control is abolished, and the long-latency per-user based subscribe and join procedure are canceled before the services initialization.

With above optimization based on TD-LTE, LTE-V-cell can take full advantages of the ubiquitously deployed cellular networks to promote connected vehicle applications, and reduce the cost of the vehicular network deployment.

C. Coordination Between LTE-V-Cell and LTE-V-Direct

Complementary to each other in LTE-V, LTE-V-direct, and LTE-V-cell are coordinated systematically to support the vehicular network applications effectively.

1) Transmission Mode Selection: Transmission mode is chosen based on the service type. The heartbeat messages are carried by LTE-V-direct, and infotainment services are provided by LTE-V-cell. However, for certain applications, hybrid mode is used to satisfy the services requirements. For floating car data application, it is reported that if the vehicles are organized into centralized clusters using LTE, the better performance is achieved than the decentralized clustering mechanisms [17]. Based on the results, LTE-V-direct and LTE-V-cell can cooperate with each other for efficient data collection and reduce the heavy load to the network.

2) Interference Management: If the two modes operate on the same frequency bands in the deployments, the RRM to minimize interference has to be considered carefully. With the central node, LTE-V-cell can coordinate interference to guarantee the performances. The central node can allocate the radio resource pools for direct communications and broadcast the information to all of the vehicles within its coverage. The central node can also control some vehicles to enter direct transmission mode based on the interference cancellation criteria. If the two modes operate on different frequency bands, interference management requirements can be relaxed for the band separation. However, these may cause extra cost for devices with multiband/multimode.

3) Coverage and Mobility: Vehicles can obtain the information from the surrounding vehicles with LTE-V-direct. In the low density in rural scenarios, LTE-V-cell can be used to extend the connectivity and improve the reliability of the vehicular applications because of the rapid topology changing, and serious fading conditions.

Currently, all kinds of requirements for the vehicular network are not fulfilled with singular communications technology. LTE-V-direct is used to support direct communications as the complementary scheme for LTE-V-cell to support vehicular network applications. The two modes can be utilized simultaneously considering on the allocation of spectrums of LTE. If the dedicated spectrums are allocated for LTE-V-direct and the legacy spectrums are used for LTE-V-cell, the vehicle may have two individual transceivers to operate for LTE-V-cell and LTE-V-direct, respectively. If the shared spectrums are allocated for LTE-V-direct and LTE-V-cell, the interference has to be coordinated and the two modes of the vehicle will work in TDM with only one transceiver. Because the two modes can cooperate with each other, LTE-V can be designed as an integrated and promising solution for the vehicular applications.

IV. Performance Evaluation

The cellular technologies have been evaluated to have obvious benefits for V2I when compared to IEEE 802.11p, as shown in [1]. In this section, we focus on LTE-V-direct through the system simulation conducted in OPNET in this section. Simulation results show the overall LTE-V performance in highway and city scenarios.

A. Comparison With IEEE 802.11p

1) Simulation Assumptions: The scenario is a segment of a two-way highway. The vehicles appear as Poisson distribution and the speed follows a Gaussian distribution with the given mean values depending on the lane.

Nakagami *m* model is selected as the channel model with the distance between transmitter and receiver [7]. Both large scale fading and small scale fading are considered with Nakagami *m* model.

The traffic model uses heartbeat messages generated at the frequency of 10 Hz with packet size of 300 bytes. Then 100 ms maximum tolerant latency and 20 dBm TX power are set in evaluation. The detailed parameters are listed in Table III.

Packet delivery ratio (PDR) is selected as the performance metric for transmission reliability. It is defined as the ratio that a transmitted message can be successfully decoded by the receiving node at the specific distance from the transmitter. In simulation, PDR is measured as the reception ratio of messages without retransmission for different distance between transmitting nodes and receiving nodes.

The bounded latency of LTE-V-direct can be provided by the slot reservation with periodic attribute. As long as LTE-V-direct can transmit the packet with high reliability, the latency of the payload will be guaranteed within the requirements of road safety services. But for IEEE 802.11p, the latency of CSMA/CA is unbounded with the hidden nodes problem. It is meaningless to compare the latency between the two systems directly without the restriction of reliability. So the latency performance is not considered as the performance metric.

2) Simulation Results: Fig. 2 shows the PDR comparison between IEEE 802.11p and LTE-V-direct using Nakagami *m* channel model in highway scenario. We note that both methods have the packet reception probability of more than 95% when the receiving node is close to the transmitting node within 100 m. However, when the distance between the receiving and transmitting nodes increases, the results show that LTE-V-direct performs better than IEEE 802.11p. For distance between 250 and 300 m, LTE-V-direct has roughly 16% PDR gain compared to IEEE 802.11p. The receiving performance is degraded of the simultaneous transmissions interference within the radio range in IEEE 802.11p. Without the hidden terminal problem, the radio resources are scheduled efficiently

TABLE III
SIMULATED PROTOCOLS AND PARAMETERS

Symbol	Parameter	Value
Traffic model Parameters	Highway length	6900m
	Lane	6 (3 in each direction)
	Width of lane	3.5m
	Vehicle distribution	Poisson distributed, mean inter-arrival time 3s
	Vehicle density for1 km of highway	60 vehicles
	Vehicular mobility model	Gaussian distributed, mean values of speed are 23 m/s, 30 m/s and 37 m/s from center to side, standard deviation is 1 m/s
LTE-V -Direct Parameters	Bandwidth	10 MHz
	Modulation scheme	OFDM, normal cyclic prefix (CP)
	PSICH configuration	1500bit, quadrature phase-shift keying (QPSK), Turbo code
	PDPCH configuration	3000bit, QPSK, Turbo code
	Channel estimation and channel detection	Least-square (LS), minimum mean square error (MMSE)
	Frame	100ms with 100 slots, a slot is 1ms
IEEE 802.11 p Parameters	Bandwidth	10 MHz
	Data rate	6 Mbps
	Clear channel assessment (CCA) sensitivity	-85 dBm
	Noise floor	-99 dBm
	Signal to interference plus noise ratio (SINR) threshold for frame body capture	8 dB
	SlotTime	13 us
	Short inter frame space (SIFS) Time	32 us
	Physical layer convergence protocol (PLCP) Preamble	32us
	PLCP Signal	8 us

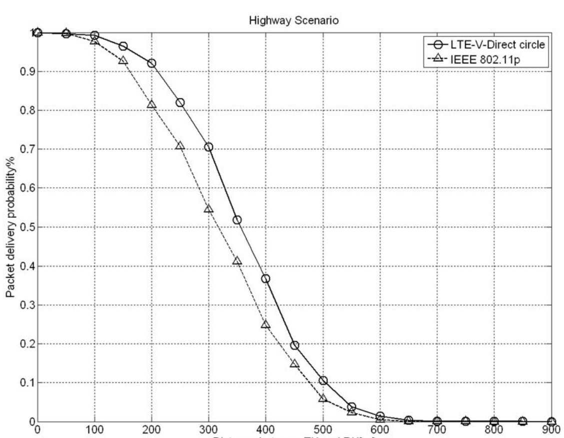


Fig. 2. PDR of 802.11p and LTE-V-direct for highway scenarios.

in time, space, and frequency dimensions with LTE-V-direct. Consequently, LTE-V-direct can be more reliable than IEEE 802.11p.

B. LTE-V-Direct Capacity in Realistic Highway/City Scenarios

Furthermore, the performance of the LTE-V-direct is investigated in both highway and city scenarios using traffic models and channel models close to the realistic conditions.

1) Simulation Assumptions: The parameters for the realistic highway and city scenarios are summarized in Table IV, respectively.

The Manhattan grid for the city scenario and the two-way highway for the highway scenario are utilized to construct the interference environment. As shown in Figs. 3 and 4, the simulation zone is mapped into multiple wraparound zones. The simulation zone collects the data to avoid edge effects, and the wraparound parts are not considered to evaluate the performance.

Furthermore, the channel models are applied based on the characteristics of the vehicular radio environments. The large-scale fading in highway scenarios is the dual-slope attenuation pattern, and the extra fading is extended for the Manhattan grid to satisfy the NLOS environment. The small-scale channel models are based on urban microcell scenario (UMi) channel model with ITU M.2135 with the modification to adapt the vehicular environments such as angle spread [18]. The antenna configuration is same as TD-LTE of 1×2 in space frequency block code with two ports common reference signal. Because UMi channel model is double directional channel model with the geometry-based stochastic characteristics, the receiving diversity in LTE-V-direct is achieved by the separation of the propagation parameters and the antennas. Because the antenna configuration of IEEE 802.11p is 1×1, PDR is same as in the Nakagami m channel model without the receiving diversity.

2) Simulation Results: Fig. 5(a) shows PDR of the highway scenarios for capacity level 2/3 with TX power 20/30 dBm, respectively. The higher capacity level (level 3) results in more data traffic injected into the network.

We find that PDR is improved of more than 95% within 450 m for all the configurations. With the increasing of the distance between the receiving and transmitting nodes, PDR is lowered with the interference and the fading. For distance between 750 and 800 m, the PDR is degraded roughly 20% with 20 dBm from levels 2 to 3, and the PDR with 30 dBm is the same trend. However, PDR is not guaranteed to increase for higher output power with increasing communication distance. For distance between 250 and 300 m, the highest PDR is 30 dBm with level 2, the lowest PDR is 30 dBm with level 3, and the middle part is 20 dBm with level 2/3. Though the fading can be alleviated by the higher power, the interference is increased to affect the receiving reliability. The balance between the transmitting power and the interference has to be considered carefully.

Fig. 5(b) illustrates that PDR is differentiated into two categories of line of sight (LOS) and NLOS conditions in the city scenario. Because of the extra attenuation, the NLOS PDR is lower than the LOS PDR and affected by obstructs of the blocks severely with the drops corresponding to the size of the obstacles (560×560 m). PDR of the city scenario is presented with fitting PDR of LOS and NLOS. The curve of

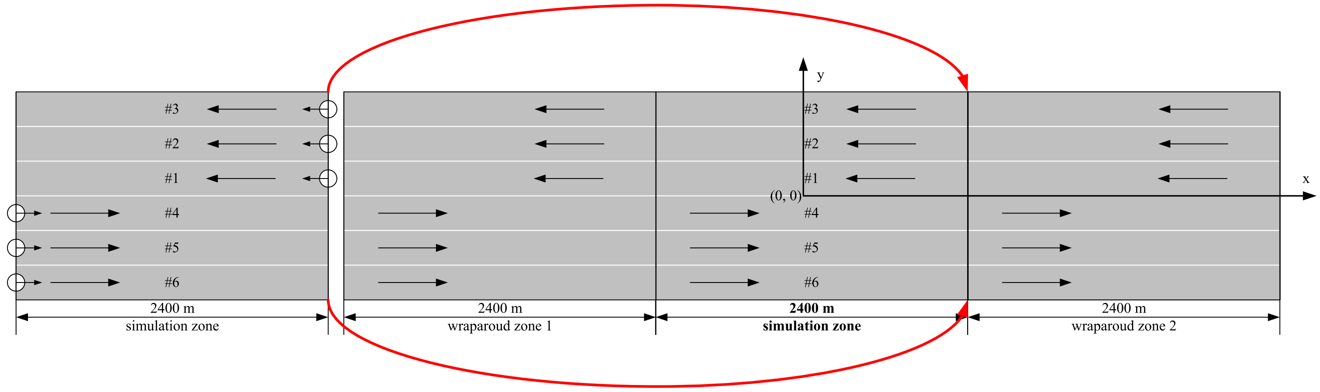


Fig. 3. Simulation zone is mapped into wraparound zones in highway scenario.

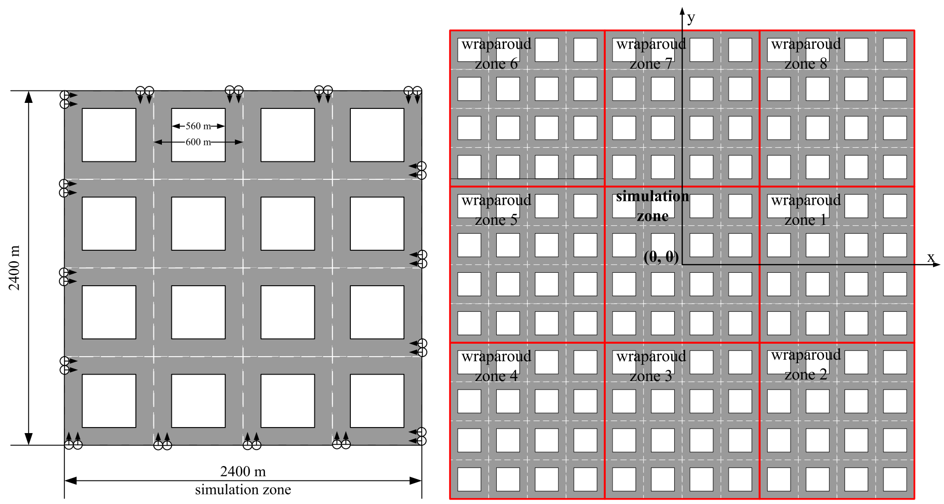


Fig. 4. Simulation zone is mapped into wraparound zones in city scenario.

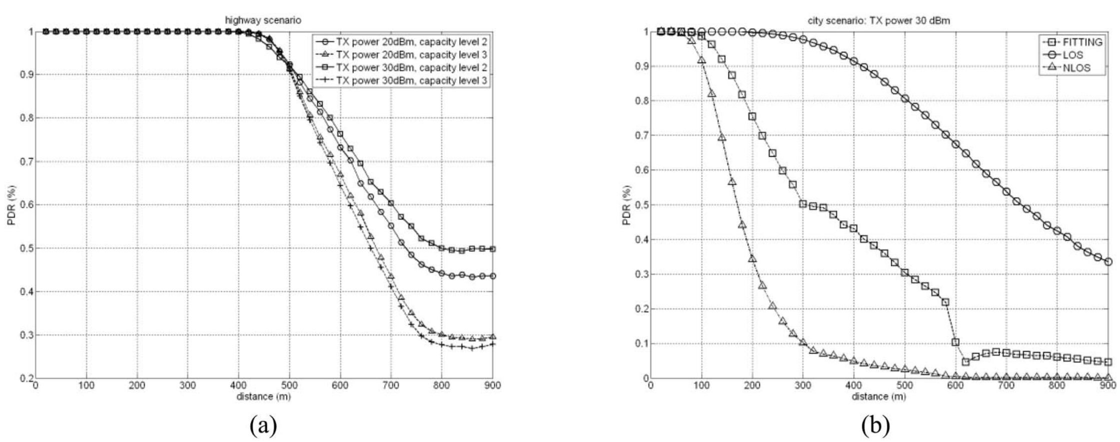


Fig. 5. PDR of LTE-V-direct for (a) highway scenarios and (b) city scenarios using realistic models.

"fitting" is not smooth because the ratio of the vehicles is not same under the NLOS and the LOS conditions. We note that LTE-V-direct can still guarantee the high PDR in proximity to the transmitter (over 95% in 100 m).

V. Experimental Validation

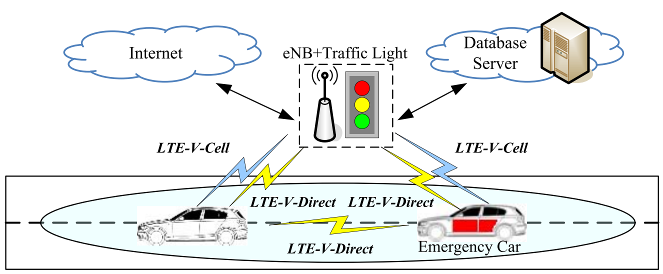
Based on the preliminary research, the LTE-V prototype system contains the communication module and typical V2X applications.

Fig. 6 shows the architecture and the hardware layout of the prototype system. As shown in Fig. 6(a), a vehicle can communicate with its surrounding vehicles and infrastructures (eNB) through LTE-V-direct. The vehicles can access the Internet and the database server with legacy techniques. Furthermore, eNB can relay the vehicles through LTE-V-cell.

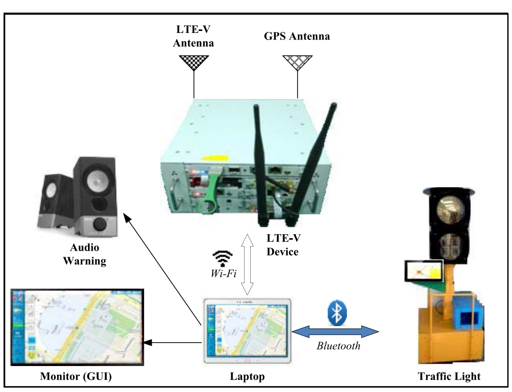
Fig. 6(b) illustrates the hardware layout of the prototype system. 5.9 GHz frequency band is used in LTE-V-direct, and the legacy LTE 2.6 GHz is used in LTE-V-cell. Installed on the vehicles, LTE-V device is the key component of the prototype

TABLE IV
REALISTIC TRAFFIC MODEL WITH SIMULATION PARAMETERS OF THE HIGHWAY AND CITY SCENARIOS

Highway scenario	Simulation zone	Length	2400m
		Lane	6 (3 in each direction)
		Width of lane	3.75m
	Speed	Uniform distributed, from inner lane to outside lane：(100, 200), (80, 100), (60, 80)	
	Transmit power	20/30 dBm	
	Highway capacity (from inner lane to outside lane)	Highway capacity level 2 1600 pcu/h, 1400 pcu/h, 1200 pcu/h	Highway capacity level 3 1950 pcu/h, 1800 pcu/h, 1500 pcu/h
	Traffic density	18 cars/km/lane	25 cars/km/lane
	Mean inter-arrival time (from inner lane to outside lane)	2.7 s, 4.4 s, 7.1 s	2.0 s, 3.2 s, 5.1 s
City scenario	Simulation zone	block	4
		Streets	The number of the horizontal streets is 5, and the number of the Vertical streets is 5.
		Width of lane	3.75m
		Width of barrier	0.5m
		Block size	600 ×600m
		Obstacle size	560 × 560m
		Lanes	4 (2 in each direction)
	Speed	Uniform distributed, same on the all lanes：(50, 60)	
	Transmit power	30 dBm	
	Street capacity	Same on the all lanes：900 pcu/h	
	Traffic density	18 cars/km/lane	
	Mean inter-arrival time	Same on the all lanes：7.3 s	



(a)



(b)

Fig. 6. (a) LTE-V prototype system architecture. (b) Hardware layout.

system. LTE-V device shares the common hardware platform of LTE eNB with extra 5.9 GHz transceiver and proper protocol modification. Through the laptop, LTE-V device can transfer the received V2X messages to the audio/visual tools and the traffic light, and then the V2X messages can be interpreted appropriately. Meanwhile, the traffic light can trigger the V2X messages to be sent in the air interface with LTE-V device. Typical V2X applications are supported, such as approaching emergency vehicle warning, emergency electronic brake lights, emergency vehicle signal preemption, delivery of the roadside information, etc. Using the LTE-V-cell mode, the road hazardous information is sent to the applications on the vehicles or on the smart phone under the cellular coverage. In the field trials, all the supported applications are verified and the functions of the system are validated as expected.

In 14th ITS Asia-Pacific forum, April 2015, the prototype system test of LTE-V including nine OBU nodes and three RSU nodes was conducted on the real road in Nanjing, China. Three categories of applications were demonstrated, including V2V safety warnings, speed advisory and pedestrians' detection. The demo of the applications and the capability of small-scale networking have been fully validated.

In next step, more work should be done to expand the functionality of the applications and verify the performance of LTE-V.

VI. CONCLUSION

In future ITS, the vehicular network is the basic infrastructure and plays a critical role. The vehicular communications have broad market and attracted more attentions recently.

In this paper, LTE-V is proposed as an integrated solution for V2X communications based on TD-LTE 4G technology. Compared with the most popular wireless technology, IEEE 802.11p, LTE-V inherits the advantages of TD-LTE, including natively supporting of V2I communication based on the centralized architecture, high mobility support, high capacity, and flexible spectrum distribution. LTE-V provides two complementary modes: 1) LTE-V-cell and 2) LTE-V-direct.

LTE-V-cell presents necessary enhancements on handover enhancement, fast adapting resource allocation, and coverage optimization of TD-LTE for better V2I communications. LTE-V-direct is designed as decentralized architecture of TD-LTE with direct communications, low latency, and high reliability improvements for both V2V and V2I communications. Simulations were conducted to verify the performance advantages of LTE-V. In addition, prototype systems with typical applications were presented.

Moreover, LTE-V have to develop new features to meet the challenges for V2V communications, such as congestion control with heavy density traffic, low cost broadcasting and simplified OBU, and RSU device design. The standardization of LTE-V has to be harmonized and collaborated with organizations and alliances.

Since LTE is the mainstream 4G mobile communication technology and with large industrial foundation, LTE-V based on TD-LTE can exploit economies of scale and with a short time to market. By leveraging the technology research and industry of TD-LTE with stakeholders and through the cross-industry cooperation, LTE-V will be actively promoted in the standard body and industry.

ACKNOWLEDGMENT

The authors would like to thank Prof. D. Liu of the Beijing Institute of Technology for his kindly review and revisions.

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