Vehicular Radio Access to Unlicensed Spectrum

Shao-Yu Lien, Der-Jiunn Deng, Hua-Lung Tsai, Ying-Pei Lin, and Kwang-Cheng Chen

Abstract

Connection to/among vehicles has been bound to one of the dominant wireless use cases in the upcoming decade. To support the booming applications, scarce bandwidth allocated for vehicle connection has become a performance bottleneck and rigidifies further evolution of future technologies. This concern consequently drives the utilization of unlicensed spectrum with ample bandwidth, on which communications nevertheless should comply with regulatory requirements such as listen-before-talk, which results in unique challenges. For next generation vehicular radio access to unlicensed spectrum, in this article, we develop dual designs to inherit the distinct engineering spirits of 3GPP LTE and IEEE 802.11ax. The proposed LTE-based vehicular radio access should integrate 3GPP vehicle-to-everything connection, licensed assisted access, and device-to-device proximity services to address the particular issues of sidelink shared channel collision and resource uncertainty on uplink, downlink, and sidelink. The proposed IEEE 802.11ax-based vehicular direct radio access emphasizes providing a qualityof-service-guaranteed sidelink access scheme to enable direct vehicle data exchange. The proposed designs pave a foundation to deploy vehicle-to-everything in unlicensed spectrum.

Introduction

The concept of connecting a vehicle to other vehicle(s) and/or to other objects (e.g., roadside units, RSUs) has been advertised and launched into practice for more than a decade. Over the past decade, the services of vehicular connections have mainly lain in electronic toll collection (ETC), vehicle safety, and commercial data exchange through vehicles. These services thus drove the development of IEEE 802.11p and IEEE 1609 (on top of IEEE 802.11p) to enable a vehicle equipped with an onboard unit (OBU) to connect with other vehicles or RSUs. The radio access technology of IEEE 802.11p originated from the American Society for Testing and Materials (ASTM) E2213-03 project, which aimed at developing dedicated short-range communications (DSRC). The primitive DSRC operated on 915 MHz bands using time division multiple access (TDMA), and the supported data rate was limited to 0.5 Mb/s. Under such a limited data rate, only the application of ETC was provided. In 1999, the Federal Communications Commission (FCC) of the United States allocated 5.9 GHz bands (5.85–5.925 GHz) with a total bandwidth of 75 MHz specifically for intelligent transportation systems (ITS). Being deployed in the 5.9 GHz bands, the radio access of DSRC migrated to IEEE 802.11a using carrier sense multiple access (CSMA) and orthogonal frequency-division multiplex (OFDM), and the data rates were enhanced up to 54 Mb/s. In 2003, the standardization activity of DSRC was launched by the IEEE 802.11p Working Group to further support safety message exchange, emergency vehicle services, and even Internet browsing. Succeeding from IEEE 802.11a, the radio accesses of IEEE 802.11p and IEEE 802.11a are fundamentally similar [1–3].

On the other hand, in 2015, a new standardization activity was started by the Third Generation Partnership Project (3GPP) to address the issue of providing ubiquitous vehicle connections over a wide geographic area. By leveraging LTE infrastructure, LTE based vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), and vehicle-to-infrastructure (V2I) features, generally known as vehicle-to-everything (V2X) [4], offer better quality of service (QoS), communication reliability, and cost efficiency in practical deployment and operation [5]. V2X is supported by 3GPP Releases 14, and Release 15 further supports enhanced V2X (eV2X). The radio access of 3GPP V2X substantially reuses the 3GPP PC5 interface, which is designed for device-to-device (D2D) direct communications in 3GPP Releases 12 and 13 [16]. As a result, similar to IEEE 802.11p enabling a vehicle to connect to an RSU, vehicles are able to receive wireless services via V2I from LTE infrastructure. Furthermore, vehicles in physical proximity are also able to exchange data directly to reduce latency.

In the upcoming decades, manifold applications (e.g., navigation, anti-crash, traffic offloading, remote control, unmanned pilot, vehicle social networks) are envisioned in the next generation driving machines. To support these emerging applications, one of the requirements is to reduce end-to-end latency (the target of 3GPP Release 14 V2V is to restrict the radio access latency within 100 ms, while this target in 3GPP New Radio is 1 ms), which is a sophisticated issue involving a number of functions at different network layers. Nevertheless, from the perspective of radio access, wider bandwidth suggests shorter symbol duration (and thus may lead to shorter scheduling and transmission/feedback cycles) to shorten

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latency in radio access. Consequently, a wider bandwidth than 75 MHz is urgently desired, and utilizing unlicensed bands turns out to be a realistic approach to break through the existing fixed spectrum allocation policies. Currently, the feasible spectrum on the unlicensed bands can be 5 GHz (a 295 MHz bandwidth is available in the United States) and 60 GHz (a 14 GHz bandwidth is available in the United States, 9 GHz in Europe, 7 GHz in Korea and Japan, and 5 GHz in China). However, as communications on the 60 GHz unlicensed bands still require further field trials to verify the performance in practice, and corresponding regional regulations are still unclear, 5 GHz bands are promising for the first phase of the fifth generation (5G) vehicular radio access.

Currently, two systems are promising as the foundation to evolve the 5G radio access on the unlicensed bands (known as 5G-U): 3GPP licensed assisted access (LAA) [7–10] and IEEE 802.11ax [11]. To develop 5G-U empowered vehicular radio access, taking technological harmonization to 3GPP LAA and IEEE 802.11ax into design consideration enjoys engineering merits of smooth backward compatibility to existing LAA/IEEE802.11ax and forward compatibility to 5G-U. As 3GPP LTE and IEEE 802.11 originate from distinct engineering spirits, the 5G-U empowered vehicular radio access may not be a unified design. Consequently, in this article, we propose dual designs, one for LTE-based 5G-U vehicular radio access and another for IEEE 802.11ax-based vehicular radio access. This article begins from providing insightful knowledge on 3GPP V2X, PC5 interface, LAA, and IEEE 802.11ax. Next, for LTE-based 5G-U vehicular radio access, we solve the particular issues of resource uncertainty and physical sidelink shared channel (PSSCH) collision to integrate LAA, PC5, and V2X. Although station-to-station sidelink transmissions are initially supported in IEEE 802.11ax, the lack of quality of service (QoS) guarantee may obstruct the application to V2V. We subsequently propose IEEE 802.11ax-based 5G-U vehicular direct radio access to provide QoS-guaranteed V2V direct transmissions. Our approach therefore serves as a foundation of 5G-U V2X for further analytical and standardization studies.

3GPP V2X, LAA, and IEEE 802.11ax

PC5-Based V2X Radio Access in 3GPP

3GPP V2X radio access aims at enabling a vehicle to exchange data with other vehicles (V2V), pedestrians (V2P), and infrastructure (V2I), where infrastructure can be an eNB type RSU or a user equipment (UE) type RSU. The supported scenarios in V2X taxonomy are illustrated in Fig. 1. In V2I, if infrastructure is an eNB type RSU, the Uu interface is reused, where Uu is the legacy interface for downlink/uplink transmission between a UE and an enhanced NodeB (eNB). In V2V, V2P, and V2I (in the case that infrastructure is a UE type RSU), PC5 is utilized, where PC5 is the interface for sidelink direct transmission between two or a group of UEs. In 3GPP Releases 12 and 13, PC5 was developed for D2D proximity services targeting public safety, and the radio access of PC5 is degenerated as broadcast communications (i.e., there is no feedback channel), which is largely different from Uu in which both forward and feedback physical channels are provided.

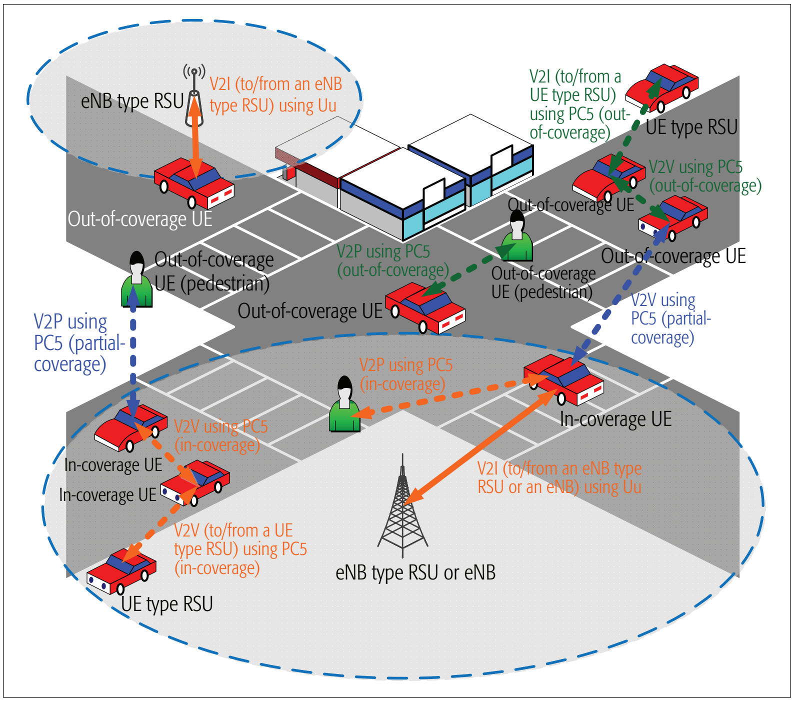

FIGURE 1. 3GPP V2X iincludes V2V, V2P, and V2I. Through reusing the PC5 interface designated for direct UE communications, in-coverage, out-of-coverage, and partial-coverage scenarios can be supported.

On Un, radio resources for uplink/downlink transmissions are allocated/scheduled by an eNB. However, for PC5, there are two radio resource allocation schemes (Mode 3 and Mode 4) depending on the following deployment scenarios. Please note that Mode 1 and Mode 2 were used for Release 12 and 13 D2D.

- **In-coverage.** In this scenario, all vehicles/pedestrians are under coverage of an eNB, and both of the following two resource access modes can be adopted:
  1. Radio resources used for sidelink transmissions are scheduled by the eNB, which is known as Mode 3.
  2. Each vehicle/pedestrian on its own randomly selects radio resources from the pre-configured resource pool(s) to perform sidelink transmissions, which is known as Mode 4.
- **Out-of-coverage.** In this scenario, all vehicles/pedestrians are out of an eNB's coverage, and only Mode 4 is supported as there is no eNB able to perform resource scheduling.
- **Partial-coverage.** In this scenario, some vehicles/pedestrians are in-coverage, while others are out-of-coverage. Both Modes 3 and 4 can be applied to this scenario.

Compared to legacy scheduling-based radio access in Mode 3, Mode 4 is an unprecedented resource access scheme in cellular networks. Using Mode 3, when a transmitter UE wishes to transmit direct data to a receiver UE, the transmitter UE randomly selects radio resource on its own (from a pre-configured resource pool). Then the transmitter UE needs to inform the receiver UE about the time-frequency locations (known as physical sidelink shared channel, PSSCH) of the selected resources carrying data. This information is known

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as scheduling assignment (SA), which is carried via the physical sidelink control channel (PSCCH). The time-frequency locations of PSCCH are also randomly selected by the transmitter UE from a pre-configured resource pool. As a result, the transmitter UE first transmits PSCCH, which is followed by physical sidelink shared channel (PSSCH) carrying direct data in the time domain, as illustrated in Fig 2a. A receiver UE needs to blindly detect the time-frequency locations of PSCCH to obtain SA. With SA, a receiver thus receives direct data at the correct time-frequency resources. Please note that PSCCH and corresponding PSSCH do not have to be located at the same frequency band, as shown in Fig. 2a. Since there is no feedback channel in PC5, transmission repetition is applied to both PSCCH and PSSCH to facilitate successful reception at the receiver side.

Since there is no resource coordination among UEs in Mode 4, multiple transmitter UEs may select the same radio resource(s) as their PSCCHs. In this case, these PSCCHs collide with each other, and receiver UEs may lose the following PSSCHs. To mitigate PSCCH collisions, an enhancement of Mode 4 is provided in 3GPP Release 14 V2V. When a transmitter vehicle attempts to launch a transmission burst, it senses the resources in a measurement window, and only selects resources not being occupied by other transmitters to transmit PSCCH, as shown in Fig. 2b. Nevertheless, as the resources carrying PSSCH are also randomly selected by each transmitter, it is still possible that there is no collision among PSCCHs while collisions may occur among PSSCHs from different transmitters.

In Releases 12 and 13 PC5, PSCCH and PSSCH are multiplexed in the time domain. However, to reduce radio access latency in V2V, PSCCH and PSSCH are multiplexed in the frequency domain, as illustrated in Fig. 2b. In this case, a receiver needs to receive signals over all resources within a particular time window (i.e., PSCCH/PSSCH transmission window), blindly detect corresponding PSCCH, and retrieve data at PSSCH. This design may not be cost-efficient in terms of complexity and energy, as the "space" for blind detection is largely extended. Nevertheless, complexity and energy may not be issues for a vehicle in practice. This design further enhances reliability in data reception, as a receiver receives signals within a PSCCH/PSSCH transmission window, rather than randomly selecting some resources to perform detection. However, the concern of **PSSCH collision** still exists, and how to alleviate this concern is discussed below.

LAA on 5 GHz Unlicensed Spectrum

Cellular networks (e.g., GSM/GPRS, UMTS, LTE/LTE-A) have traditionally been designed to be deployed in licensed bands, while a new feature, LAA, to deploy LTE-A networks to the 5 GHz unlicensed bands was recently created in 3GPP Releases 13 and 14. Very different from communications on the licensed bands with limited constraints, transmissions on unlicensed bands are restricted by a number of regulations imposed by different countries. These regulations include maximum transmission power, maximum channel occupation time (MCOT), a predefined set of power spectrum density and the mandatory listen-before-talk (LBT) mechanism, and so on. The maximum transmission power and power spectrum density regulations significantly limit the transmission range of LAA (as a small cell). To be deployed on the unlicensed bands, LTE-A also encounters an unprecedented challenge, suffering interference form WiFi (IEEE 802.11a/ac/ax), and this sort of interference is uncontrollable by any eNB, which makes communications on the unlicensed bands unreliable sometimes. In this case, carrier aggregation (CA) technology is mandatory in LAA. That is, radio resource control (RRC) signaling and some data are transmitted via a primary carrier on the licensed bands, while additional data exchanges can be supported via a secondary carrier on the unlicensed bands to offer best effort services. As a result, LAA networks cannot operate on the unlicensed bands on a standalone basis, and a licensed carrier must coexist, which fully elaborates the name of LAA.

To avoid interference to/from WiFi, one of the regulations in Europe and Japan compels every transmitter to perform LBT on the 5 GHz unlicensed bands. If a transmitter attempts to transmit, it needs to perform clear channel assessment (CCA) using energy detection (ED) on the channel. If interference power does not exceed a threshold (the channel is sensed to be idle), a transmission burst can be launched for an MCOT; otherwise, the transmission burst should be postponed for a defer period and a backoff period. The downlink radio access (LBT) of LAA is illustrated in Fig. 2c. If an eNB attempts to launch a transmission burst to a UE, the eNB senses the channel for a defer period T_d, which is composed of T_f =16 μs and m_p CCA slots. The length of each CCA slot is 9 μs, and the value of m_p depends on the LBT priority class. If, unfortunately, the channel is sensed to be occupied, the eNB should keep sensing the channel for another T_d. Such a defer period aligns with the length of different interframe space (IFS) in IEEE 802.11a/ac. If the channel is not occupied within a defer period, the eNB should sense an idle channel for N CCA slots, where N is randomly drawn from a contention window (CW) ranging from $CW_{\mathrm{min},p}$ to $CW_{\mathrm{max},p}$. The values of $CW_{min,p}$ and $CW_{\mathrm{max},p}$ depend on the LBT priority class and the channel congestion condition, as specified in Table 1. If the channel is still idle when the counter reaches zero, the eNB can launch a downlink transmission burst to occupy the channel for an MCOT (denoted by $T_{MCOT,p}$), whose value also depends on the LBT class. However, if the channel is sensed to be busy before N = 0, the eNB should sense the channel for an additional deter period. In 3GPP Releases 10 and 11, a number of schemes were developed to avoid interference among LTE-A cells/eNBs (intra-system interference), whereas mitigating interference to/from WiFi is the prime purpose of the downlink radio access in LAA, rather than mitigating intra-system interference.

As a subsequent evolution of LTE-A, LAA adopts a scheduling-based radio access. That is, an eNB has to inform a UE about the time-frequency resources at which downlink/uplink transmissions take place. If an eNB has continuous downlink transmissions to a UE, SA for subsequent downlink/uplink transmissions can be sent piggybacked with downlink data; otherwise,

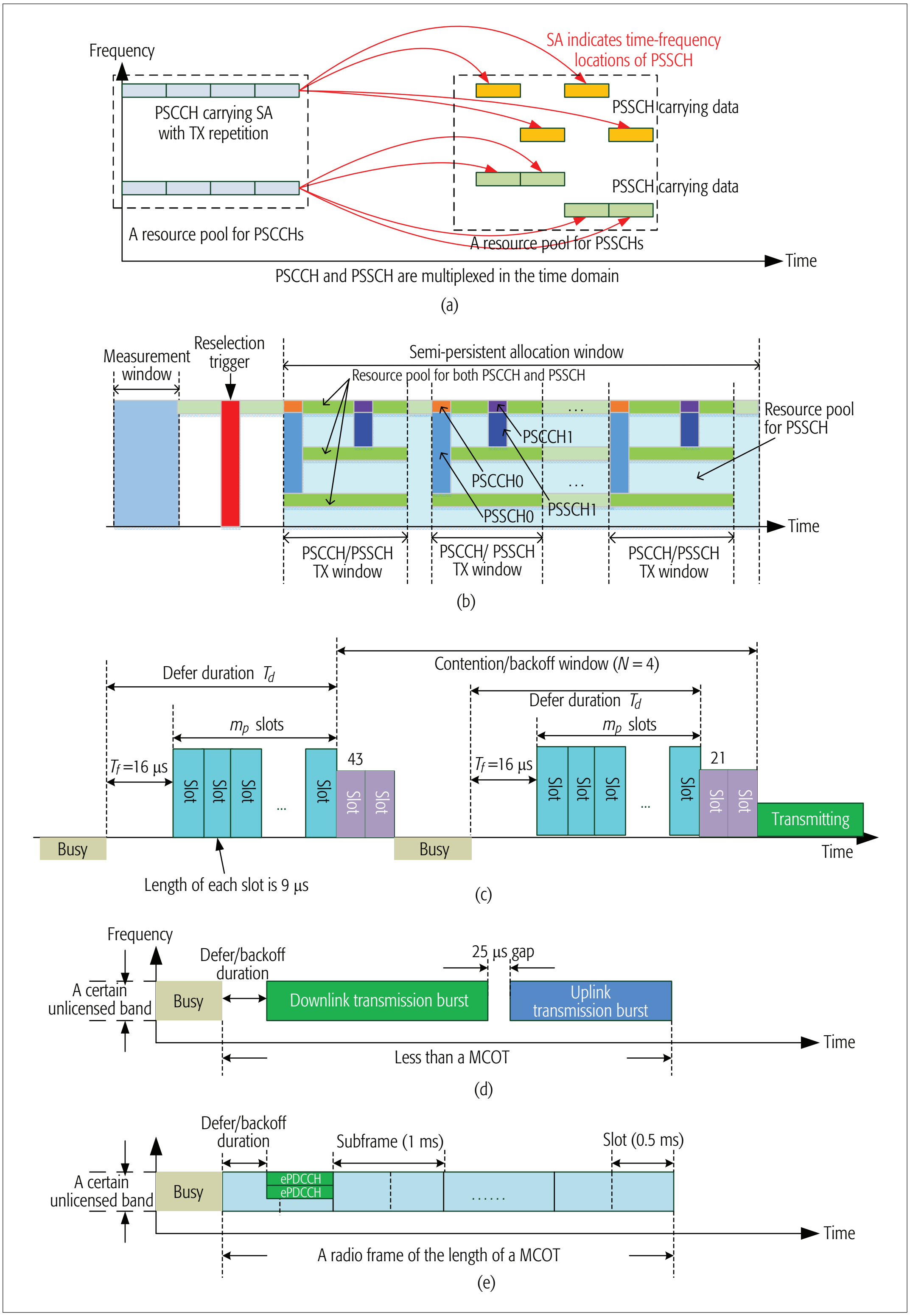

FIGURE 2. a) In 3GPP Releases 12 and 13 D2D, resource pools for PSCCH and PSSCH are multiplexed in the time domain. (b) in 3GPP V2V, resource pools for PSCCH and PSSCH are multiplexed in the frequency domain. A transmitter is able to sense the channel within a measurement window. After the channel sensing, a transmitter may send a re-selection trigger to inform a receiver about the resources for subsequent transmissions within the semi-persistent allocation window. In this allocation window, a transmitter only utilizes resources regarded as unoccupied in a measurement window to launch PSCCH and PSSCH in the following PSCCH/PSSCH transmission window. c) Downlink LBT of LAA. d) In LAA, when a downlink transmission is completed, an uplink transmission burst can be launched immediately after a 25 µs gap. e) The frame structure of LAA, where ePDCCHs carrying SAs are multiplexed with share channels. Please note that in LTE/LTE-A and LAA, an SA message announced by an eNB can carry radio resource allocation at least after future 4 ms. Thus, in b) andc), the length of downlink transmission piggybacked with SA should be longer than 4 ms.

Using the LBT procedures in LAA, a critical issue known as the resource uncertainty may occur. When an eNB announces SA for downlink/uplink transmissions, it is possible that the channel is not available at the allocated resources for data transmissions. This issue may severely jeopardize latency performance in vehicular radio access, particularly for urgent data transmissions.

IEEE 802.11ax revolutionarily adopts multiuser PHY technology in both uplink and downlink transmissions and implements several new mechanisms to serve more users consistent and reliable connections in dense environment. It is expected to be the next main stream wireless technology with cellular systems.

	LBT priority class (p)	$CW_{min, p}$	$CW_{max, p}$	m_p	TMCOT, p	Possible sets of CW sizes
Downlink	1	3	7	1	2 ms	{3, 7}
	2	7	15	1	3 ms	{7, 15}
	3	15	63	3	8 ms or 10 ms	{15, 31, 63}
	4	15	1023	7	8 ms or 10 ms	{15, 31, 63, 127, 255, 511, 1023}
Uplink	1	3	7	2	2 ms	{3, 7}
	2	7	15	2	4 ms	{7, 15}
	3	15	1023	3	6 ms or 10 ms	{15, 31, 63, 127, 255, 51, 1023}
	4	15	1023	7	6 ms or 10 ms	{15, 31, 63, 127, 255, 511, 1023}

TABLE 1. LBT parameters of LAA.

the eNB needs to perform downlink LBT to send SA. For downlink transmissions, an eNB should perform LBT (as the procedure elaborated above) before launching a downlink transmission burst at the scheduled resources. For uplink transmissions, there are two LBT schemes:

1. The downlink LBT procedure is reused for uplink transmissions (known as Category 4 LBT) with the LBT priority classes listed in Table 1.
2. When an eNB successfully occupies a channel for a downlink transmission burst, an uplink transmission burst is able to take place right after the downlink transmission with a 25 μs gap if the overall length of downlink/uplink transmission bursts including defer/backoff duration does not exceed the allocated MCOT, as illustrated in Fig. 2d.

Similar to the downlink LBT, the purpose of the uplink LBT aims at mitigating interference to/from WiFi, as intra-system interference can be avoided with resource scheduling by an eNB.

To accommodate LBT, a new frame structure distinct from that in LTE/LTE-A was created for LAA in Release 13, as illustrated in Fig. 2e. In this frame structure, the length of a radio frame is equal to the length of an MCOT, which is up to 10 ms maximum. A radio frame is composed of a number of subframes, and the length of each subframe is 1 ms. Each subframe is composed of two slots. Different from the legacy physical downlink control channel (PDCCH) in LTE/LTE-A transmitted on the first one to three symbols of each subframe, the control channel (known as enhanced PDCCH, ePDCCH) is multiplexed with physical downlink shared channel (PDSCH) in the frequency domain at the first subframe of a radio frame.

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IEEE 802.11ax

Wireless local area network (WLAN) devices are currently being deployed in diverse environments. Increasing interference from neighboring devices and severe collisions from channel contention in a crowded wireless environment give rise to network performance degradation. In view of this, the IEEE Standards Association (IEEE-SA) standards board approved IEEE 802.11ax in 2014. The scope of 802.11ax amendment is to define standardized modifications to both the IEEE 802.11 physical layer (PHY) and the medium access control (MAC) sublayer for high-efficiency operation in frequency bands between 1 GHz and 6 GHz [12]. IEEE 802.11ax has the goal of improving the average throughput per user by a factor of at least four times in densely deployed WLANs while maintaining power efficiency.

In the past, the standardization efforts have been very much focused on increasing the link throughput, rather than efficient use of spectrum and user experience. IEEE 802.11ax, in contrast, focuses on improving metrics that reflect user experience such as latency. This is accomplished by efficiently using the spectrum, spatial reuse, and interference management, and MAC enhancements, which includes orthogonal frequency-division multiple access (OFDMA) PHY, uplink multi-user multiple-input multiple-output (UL MU MIMO), spatial reuse, dynamic channel binding, station-to-station (STA-to-STA) operation, power saving with target wake time (TWT), and backward compatibility with legacy IEEE 802.11 devices.

IEEE 802.11ax revolutionarily adopts multi-user PHY technology in both uplink and downlink transmissions and implements several new mechanisms to serve more users with consistent and reliable connections in dense environments. It is expected to be the next mainstream wireless technology in cellular systems. Readers may consult [11, 13] regarding more new features and other new technological challenges in designing IEEE 802.11ax.

LTE-Based 5G-U Vehicular Radio Access

To support vehicular radio access to 5 GHz unlicensed bands, there are two technical obstructions. First, LBT should be introduced to both Mode 3 and Mode 4 resource allocation schemes of the PC5 interface. Second, the critical issues of PSSCH collision and resource uncertainty should be addressed.

LBT for Downlink, Uplink, and Sidelink Vehicular Radio Access

For the scenarios of in-coverage and partial-coverage, eNBs are able to facilitate resource allocation for downlink, uplink, and sidelink transmissions (i.e., Mode 3 resource allocation) among vehicles, and therefore the PSSCH collision issue does not exist. For downlink and uplink transmissions, LBT procedures adopted by LAA can be smoothly applied without significant system impacts. Nevertheless, for sidelink transmissions, an eNB needs to perform LBT to send SA (for sidelink) to both the transmitter and the receiver in the case of in-coverage, or to the in-coverage vehicle in the case of partial-coverage. Thus, this in-coverage vehicle should perform LBT again to relay SA to an out-of-coverage vehicle. After obtaining the time-frequency resources for sidelink transmissions, the transmitter vehicle then performs LBT on the allocated resources. The purpose of these operations is to follow the communication regulations on the 5 GHz unlicensed bands. However, as aforementioned, the uncertainty of resource availability may occur on the downlink/uplink/sidelink transmissions. In addition, for sidelink transmissions, LBT should be performed both by an eNB (to send SA) and an in-coverage vehicle or a transmitter vehicle (to send data burst or SA). These back-to-back LBT procedures may severely harm the latency performance of vehicular radio access. Furthermore, each LBT may suffer from resource uncertainty.

For sidelink transmissions using Mode 4, each transmitter vehicle autonomously selects resources to carry SA and data. As Release 14 V2V has supported channel measurement, LBT can be slickly applied to alleviate SA collisions. However, the PSSCH collision issue is a critical concern as multiple transmitters may select the same resources to carry data. To further alleviate the PSSCH collision, restrictions should be imposed on each vehicular transmitter for the resource selection of PSSCHs. However, such uncertainty does not need to be completely resolved.

Channel Pre-Occupation

Unlike LAA solely providing best effort services on the unlicensed bands, suppressing resource uncertainty is of crucial importance in vehicular radio access to enhance QoS (in terms of successful channel occupation and latency). To alleviate resource uncertainty in uplink, downlink, and sidelink (in both Mode 3 and Mode 4), an effective mechanism known as **channel pre-occupation** is consequently proposed. For both uplink and downlink transmissions, when an eNB successfully occupies the channel to send SA after performing LBT, the eNB keeps occupying the channel even after the SA transmission is completed (and the extra occupied resources may not necessarily carry information). Such channel occupation is referred to as **blank occupation**, which is allowed on the 5 GHz unlicensed bands as the length of an MCOT can be up to 8 to 10 ms. For downlink transmissions, radio resources carrying data can be allocated following the SA transmission with a certain length of time gap (e.g., in LTE/LTE-A, a 4 ms or longer gap is inserted between the end of an SA transmission and the beginning of allocated resources for data transmissions). In other words, the following durations are involved in the channel pre-occupation for downlink transmissions:

1. CCA and backoff
2. SA transmission
3. Signals without any data (blank occupation)

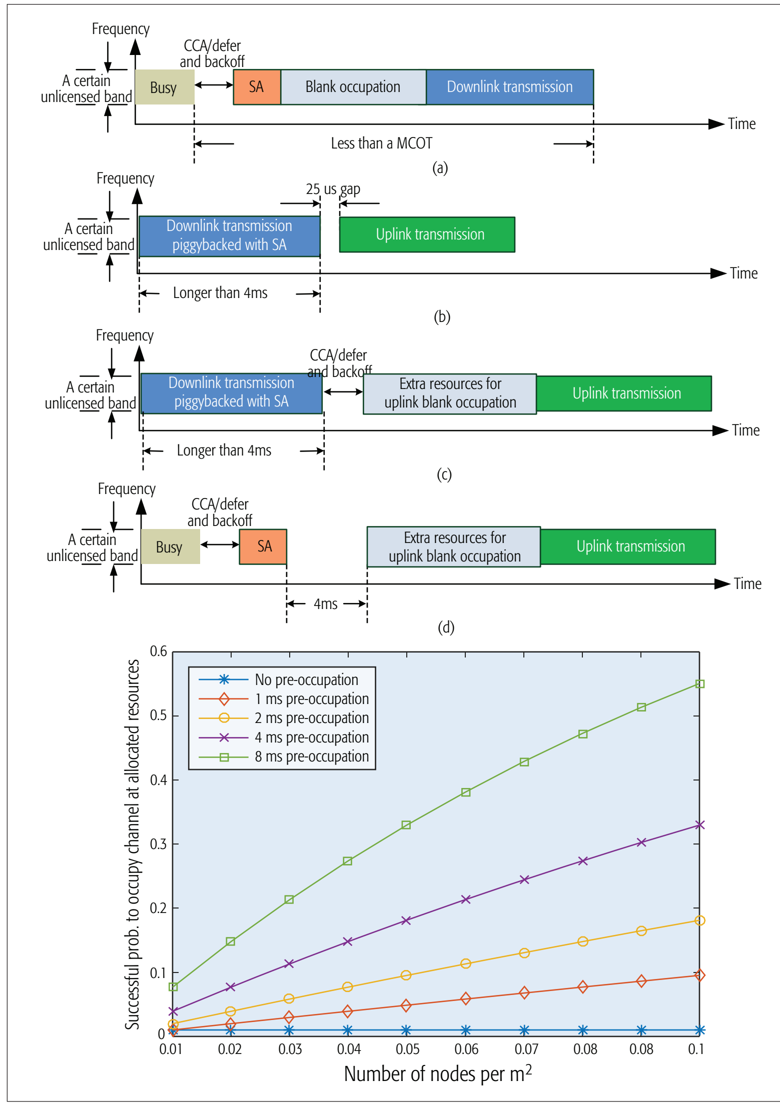

FIGURE 3. a) In downlink transmissions, an eNB continuously occupies the channel (blank occupation) after the SA transmission. b) SA for uplink transmissions can be piggybacked with a downlink transmission burst, and an uplink transmission burst can take place with a 25 μs gap after the downlink transmission. c) For uplink transmissions, an eNB may allocate extra resources to a UE to perform blank occupation. d) If there is no downlink data from an eNB, an eNB should perform LBT to transmit the SA and allocate extra resources for blank occupation. e) Simulation results of the proposed channel pre-occupation mechanism.

4. A downlink transmission burst, as illustrated in Fig. 3a

This operation is available if the overall length of the above four durations does not exceed a downlink MCOT. If an eNB has subsequent data to be transmitted, the SA can be piggybacked with a downlink transmission burst at 4, followed by:

5. Another blank occupation
6. Subsequent downlink transmission burst

For uplink transmissions, blank occupation is not easy to apply smoothly, since a UE performing blank occupation on specific radio resource non-allocated to this UE implies potential interference. To eliminate this concern, three alternative designs are consequently proposed. For the first alternative, if an eNB has continuous downlink data to be transmitted to a UE, the following durations are involved:

For Mode 4 resource allocation, since a transmitter vehicle/pedestrian needs to announce the SA first, then a transmission burst is launched at the selected radio resources. Such radio access behavior is similar to downlink transmissions, and therefore channel pre-occupation for downlink transmissions can be reused.

1. A downlink transmission burst piggybacked with the SA for uplink transmissions (if the length of a downlink transmission burst is 4 ms or longer)
2. 25 μs gap
3. An uplink transmission burst, as illustrated in Fig. 3b

For the second alternative, if an eNB has continuous downlink data to be transmitted to a UE, but the length of a downlink transmission burst is less than 4 ms, an eNB may allocate extra uplink radio resources in front of the resources for uplink data transmissions in the time domain to a UE. These extra uplink radio resources are utilized to perform blank occupation. In other words, the following durations are involved in uplink transmissions:

1. A downlink transmission burst piggybacked with the SA for uplink transmissions (the length of a downlink transmission burst is less than 4 ms)
2. CCA and backoff
3. Blank occupation and an uplink transmission burst, as illustrated in Fig. 3c

On the other hand, if there is no downlink data to be transmitted to a UE, the following durations are involved:

1. CCA and backoff
2. SA transmissions for uplink transmissions
3. A 4 ms gap
4. Blank occupation and an uplink transmission burst, as illustrated in Fig. 3d

The performance of channel pre-occupation is evaluated in Fig. 3e. In this simulation, nodes (including WiFi APs/STAs and eNBs/UEs) are randomly deployed over a 250,000 m^2 area with a 20 dBm transmission power level to transmit full-buffer FTP traffic using LBT. We can observe from Fig. 3e that if more extra resources (in the time domain) are utilized to perform blank occupation, the successful probability to occupy the channel at the allocated resource can be significantly increased, which shows the effectiveness of the proposed channel pre-occupation.

For sidelink transmissions with Mode 3 resource allocation, an eNB needs to announce the SA first; then a transmitter vehicle/pedestrian launches a transmission burst at the allocated resources. Such radio access behavior is fundamentally similar to uplink transmissions, and consequently channel pre-occupation for uplink transmissions as provided above can be smoothly applied. For Mode 4 resource allocation, since a transmitter vehicle/pedestrian needs to announce the SA first, a transmission burst is launched at the selected radio resources. Such radio access behavior is similar to downlink transmissions, and therefore channel pre-occupation for downlink transmissions can be reused.

Resource Binding

The subsequent issue for sidelink transmission using Mode 4 is PSSCH collision, which results from the resources carrying SA and resources carrying data being independently selected by a transmitter vehicle/pedestrian. Even though LBT can be applied to the selection of PSCCH, collision may still occur on the selection of resources carrying data. To alleviate this issue, there are two design alternatives. For the first alternative, if resources carrying SA and resources carrying data are multiplexed in the frequency domain, a transmitter vehicle/pedestrian needs to perform CCA on both the resource pool for PSCCH and the resource pool for PSSCH, and only selects unoccupied resources to deploy PSCCH and PSSCH. However, performing CCA may introduce additional overhead in resource utilization and may not obtain reliable sensing outcomes according to the operation in WiFi [13], and thus is technically unfavorable for vehicular radio access.

To avoid additional CCA, we thus propose the second alternative, known as **resource binding**. In this alternative, resources of PSCCH and PSSCH are associated. In other words, there is a mapping between each resource of PSCCH and resource of PSSCH. Each transmitter vehicle/pedestrian only needs to perform CCA on the resource pool for PSCCH. If an unoccupied resource for PSCCH is selected, a transmitter vehicle/pedestrian should utilize the corresponding/associated resource for PSSCH. By using resource binding, interference among vehicles/pedestrians using Mode 4 can be alleviated. To further avoid interference to/from WiFi, the proposed channel pre-occupation can be applied in conjunction with resource binding by multiplexing the resources for PCSSH and PSSCH in the time domain. If resources for PCSSH and PSSCH are arranged within an MCOT, a transmitter vehicle/pedestrian is able to launch blank occupation to reserve PSSCH once the resource for PCSSH can be successfully occupied.

IEEE 802.11ax-Based 5G-U Vehicular Direct Radio Access

LTE-A and thus LAA are synchronous systems, in which there is a strict timing synchronization between all UEs and an eNB. For such synchronous systems, an eNB is able to allocate radio resources at particular time-frequency locations, and a transmitter and a receiver can transmit/receive data at the allocated resources. As a result, a preamble does not need to be inserted at the beginning of a transmission burst by a transmitter to facilitate signal detection at the receiver side. On the other hand, the operation of IEEE 802.11ax does not rely on strict time synchronization among all STAs and the AP. Even though a scheduling-based radio access is adopted in IEEE 802.11ax, a preamble is still essential for signal detection at the receiver side. Nevertheless, a preamble may eliminate the resource uncertainty issue. For downlink transmissions, without sending SA prior to the data transmission, an AP is able to launch a transmission burst after LBT. Therefore, the selected resources for downlink transmissions may not be occupied by other systems, and an STA is able to detect a transmission burst with the facilitation of a preamble. For uplink transmissions, an STA is able to upload data immediately without performing LBT once a trigger frame is received. A preamble also boosts the detection of an uplink transmission burst at the AP side. As a result, the existing radio access scheme of IEEE 802.11ax can smoothly migrate to vehicular radio access in both downlink and uplink transmissions.

In IEEE 802.11ax, STA-to-STA sidelink transmissions or ad hoc transmissions using technologies other than IEEE 802.11ax are also allowed

[4]. Since other technologies may not recognize the buffer report and trigger frame messages defined in IEEE 802.11ax, concurrent transmissions of STA-to-STA sidelink and IEEE 802.11ax uplink/downlink may invoke considerable interference to degrade performance. As a result, in the state-of-the art IEEE 802.11ax design, concurrent sidelink transmissions are not allowed. For this purpose, a **quiet-time-period** mechanism is supported in IEEE 802.11ax [14]. When an STA attempts to proceed to STA-to-STA transmissions, it sends a request to an AP. When an AP receives a request, it may reply with an action frame to set up a quiet time period. During this quiet time period, only the scheduled STA-to-STA transmissions can perform, while uplink transmissions should be silent. However, this mechanism precludes the concurrent transmissions of sidelink and uplink, which may lead to low spectrum efficiency. To fully reuse spectrum, sidelink transmissions may be performed simultaneously with uplink transmissions, and therefore the key issue lies in avoiding interference between sidelink and uplink. In IEEE 802.11ax, LBT is still a mandatory function for a transmitter to identify interference. However, even though an unoccupied resource can be identified at the transmitter side, it is not guaranteed that the resource is also unoccupied at the receiver side (i.e., without interference). When a sidelink transmission and an uplink transmission coexist, there are two receivers, one for sidelink and another one for uplink transmission, and a sidelink transmission can be created simultaneously with an uplink transmission only if the signal-to-interference-plus-noise ratios (SINRs) at both receivers are acceptable, as illustrated in Fig. 4a. For this purpose, a new IEEE 802.11ax-based 5G-U vehicular direct radio access should be created.

As aforementioned, IEEE 802.11ax adopts a scheduling-based radio access scheme, which is unprecedented in the IEEE 802.11 family. In this case, an AP may coordinate radio accesses to ensure that receivers of both sidelink and uplink are able to enjoy the corresponding acceptable SINRs. The procedure of the proposed vehicular direct radio access is detailed as follows, which is illustrated in Fig. 4b.

•When a sidelink transmitter vehicle/pedestrian attempts to transmit, it determines a transmission power level (denoted by P^{side}) based on the QoS requirement. Then this sidelink transmitter vehicle/pedestrian sends a buffer report message to both the AP (uplink receiver) and sidelink receiver vehicle/pedestrian using LBT. The buffer report is transmitted using the maximum allowable transmission power, denoted by P^{max}, which is common knowledge among all vehicles/pedestrians and the AP. The buffer report message carries a value Δ, by which P^{side} can be derived by $P^{side} = P^{max} \cdot \Delta$.

•If the AP successfully receives a buffer message from a sidelink transmitter vehicle/pedestrian, it suggests that this sidelink transmitter wins an opportunity among other potential sidelink transmitters. In this case, the AP stores this message and waits a period of time for other potential buffer report messages from uplink transmitter vehicles/pedestrians.

–If a buffer report message from an uplink transmitter is received, since buffer report messages from uplink and sidelink are sent using P^{max}, the AP is able to estimate the level of channel fading so as the received SINR if concurrent transmissions of sidelink and uplink are allowed.

*If this SINR is acceptable, and concurrent transmissions are allowed, the AP replies with a trigger frame to sidelink transmitter and receiver vehicles/pedestrians, and the uplink transmitter vehicle/pedestrian.

- *Otherwise, the AP replies with a trigger frame to only the uplink transmitter vehicle/pedestrian. The sidelink transmission is not allowed.

–If there is no buffer report message from an uplink transmitter, the AP replies with a trigger frame to sidelink transmitter and receiver vehicles/pedestrians.

•Upon receiving a trigger frame (valid for sidelink transmitter and receiver, and the uplink transmitter), the uplink transmitter launches an uplink transmission burst to the AP.

–When the uplink transmission begins, the sidelink receiver estimates its received SINR based on the uplink interference and P^{side}. If the received SINR is acceptable, the sidelink receiver replies with a clear frame message to the sidelink transmitter. A clear frame message may carry recommended link adaptation schemes derived from the received SINR. Otherwise, no clear frame message is sent.

–When a sidelink transmitter receives a clear frame message from its sidelink receiver and a trigger frame from the AP, it is able to launch a transmission burst concurrently with the uplink transmission.

The performance of the proposed IEEE 802.11ax-based 5G-U vehicular direct radio access is shown in Fig. 5, in which the cumulative distribution function (CDF) of the received SINR at the receiver side is demonstrated. In this simulation, the locations of all STAs and AP are

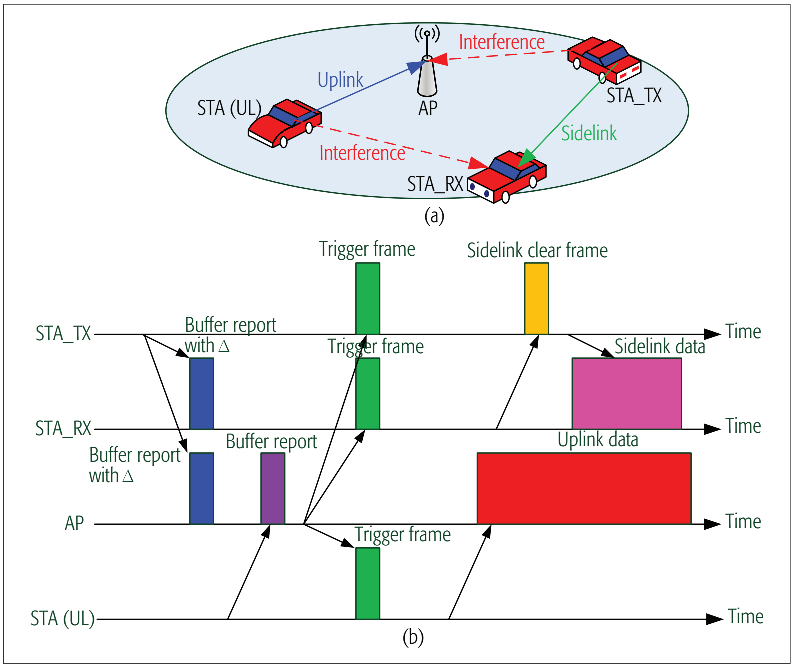

FIGURE 4. a) Sidelink and uplink transmissions can be performed concurrently if the received SINRs at both receivers are acceptable. b) The procedure of the proposed IEEE 802.11ax-based vehicular direct radio access.

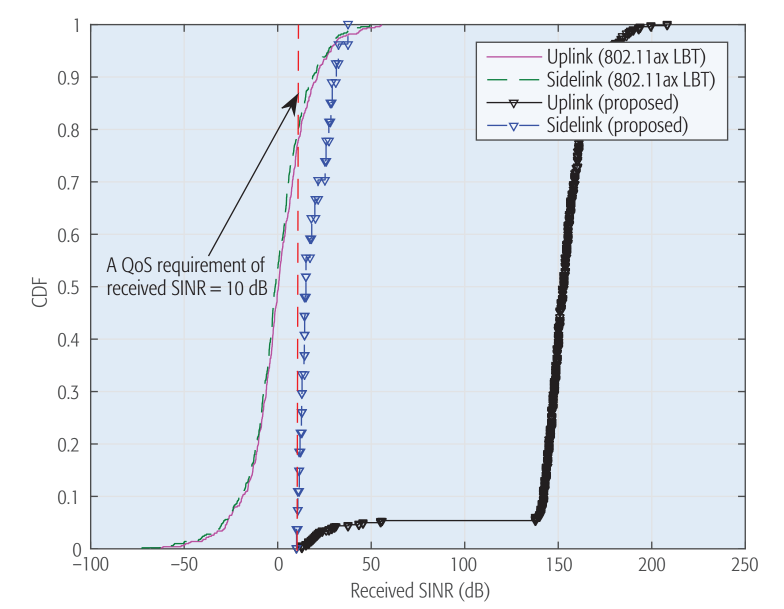

FIGURE 5. Simulation results of the proposed EEE 802.11ax based vehicular direct radio access. In this simulation, the QoS requirements for the receiver of sidelink and the receiver of uplink both have SINR larger than 10 dB.

randomly deployed over a 2500 m^2 area. The transmission power of each transmitter is 20 dBm. When the legacy IEEE 802.11ax LBT is applied, a sidelink transmitter is able to transmit if the received interference power (from uplink) does not exceed –62 dBm. For the proposed direct radio access, a sidelink transmission is able to take place only if the received SINRs at both receivers exceed the required value (e.g., 10 dB in this simulation). Figure 5 shows that the proposed direct radio access achieves QoS guarantee in terms of received SINR for both sidelink and uplink.

Conclusion

Efficiently utilizing unlicensed spectrum has been one of the most crucial technologies in the vehicular radio access evolution. In this article, analytical designs of vehicular radio access design harmonized to 3GPP LTE and IEEE 802.11ax are revealed and analyzed. To address the particular issues of resource uncertainty and PSSCH collision to deploy LTE V2X to unlicensed spectrum, channel pre-occupation and resource binding are developed to enhance QoS for uplink, downlink, and sidelink transmissions. To further enable IEEE-based V2X, a new STA-to-STA LBT procedure is provided to guarantee performance in terms of received SINR for concurrent transmissions of uplink and sidelink. Our designs thus provide practical knowledge and insight to enable V2X radio access in uplink, downlink, and sidelink. Nevertheless, this research is just the beginning stage in the development of vehicular 5G-U, and a number of issues and performance optimizations still remain open for further study.

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