Toward 5G Spectrum Sharing for Immersive-Experience-Driven Vehicular Communications

Haibo Zhou, Wenchao Xu, Yuanguo Bi, Jiacheng Chen, Quan Yu, and Xuemin (Sherman) Shen

Abstract

Dynamic sharing of 5G and the DSRC spectrum has been considered as an attainable paradigm to provide VANETs with massive system capacity, reduced latency, and lowered cost. It can meet the ever growing expectations of tailor-made vehicular services. However, due to the high mobility of vehicles and heterogeneity of 5G spectrum, how to achieve efficient dynamic spectrum sharing for better quality of vehicular communication experience is very challenging. To address this issue, this article investigates dynamic sharing of 5G spectrum for immersive experience (IE) driven vehicular communications. We first introduce the concept of vehicular IE features and related vehicular applications. We then present the existing spectrum sharing approaches for vehicular communications and the detailed technology parameter comparisons. We propose a sharing architecture of DSRC and 5G spectrum for IE driven vehicular communications. Finally, we highlight the key technical challenges and pinpoint future research directions toward dynamic sharing of 5G spectrum for IE driven vehicular communications.

Introduction

Vehicular ad hoc networks (VANETs) have been envisioned to play a crucial role in the future intelligent transportation system (ITS), in which vehicles can be connected to infrastructures, devices, and participants for supporting diverse tailor-made vehicular services [1]. By leveraging the enabling wireless communication technologies, VANETs can further improve driving safety, provide in-vehicle entertainment, enhance the on-road driving experience, and facilitate transportation efficiency. Recently, the fifth generation (5G) wireless communication enabled VANETs paradigm has received considerable attention due to the attractive features for vehicular communications (e.g., massive system capacity, enormously reduced latency, and lowered cost) [2]. The dynamic sharing of licensed and unlicensed wireless spectrum, including the underlay shared cellular spectrum [3], TV white space (TVWS) [4], and millimeter-wave (mmWave) [5], is a key solution of the 5G wireless communication paradigm, which can facilitate the utilization of available spectrum for 5G-enabled vehicular applications and achieve higher quality of vehicular user experience. Even though the research on dynamic spectrum utilization for vehicular applications has recently achieved tremendous progress, academia and the automotive industry still need to respond promptly to the current challenges in the context of 5G spectrum sharing for vehicular communications.

The first major challenge is how to improve the efficiency of 5G spectrum utilization in vehicular environments by considering the heterogeneity of 5G spectrum and dynamics of spectrum sharing behavior of vehicles. With the integration of allocated 5.9 GHz dedicated short-range communications (DSRC) spectrum, dynamic sharing of heterogeneous 5G spectrum aims to explore both licensed and unlicensed spectrum for efficient and flexible utilization [6], including the underlay shared licensed cellular spectrum band, TV white space spectrum band ranging from 470 to 790 MHz, and mmWave spectrum band ranging from 30 to 300 GHz. Specifically, by leveraging vehicular device-to-device (V-D2D) communication technology [7], neighboring vehicular users can directly communicate with each other over the underlay shared licensed cellular band. Due to the high mobility of vehicle users, it is very important to deal with the interference and collision problem in all V-D2D links when the cellular frequency reuse strategy is applied in V-D2D communications to improve the utilization of underlay shared spectrum resource. For TVWS, the channel availability changes over time and location. Such dynamics of TVWS channel availability impose considerable challenges in enhancing the TVWS spectrum utilization and configuring TVWS channels in terms of transmit power and communication channel number in fast changing vehicular network topologies [4]. In addition, considering several unique propagation features of mmWave spectrum resource, such as high propagation loss, short coverage range, and particularly the easy blockage by obstacles in vehicular line-of-sight (LOS) transmission environments, it is crucial to decide when and how to effectively utilize the mmWave spectrum resource in VANETs by considering the vehicle location information and vehicular service requirements [5].

The second major challenge is how to enhance the vehicular communication experience by leveraging the 5G spectrum sharing

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paradigm in VANETs. The statistics of the connected vehicles market shows that by 2020 the number of vehicles with built-in connectivity in the future car market will increase from 10 percent of overall market to 90 percent [8]. In addition, with the maturity of wireless networking and multimedia processing technologies, vehicular demand for high data rate vehicular services, such as video streaming and vehicular social networking, has increased dramatically [1]. The Federal Communications Commission (FCC) has allocated 75 MHz bandwidth at 5.9 GHz spectrum band for vehicular communications. However, the ever increasing need for vehicular services creates a huge demand for wireless spectrum, and it is still challenging to achieve high data rate and reliable vehicular communications for diverse tailor-made vehicular services, especially in highly dynamic and often densely populated vehicular networking environments due to the vehicular network congestion [9]. Technically, allowing the dynamic vehicular utilization of both available licensed and unlicensed wireless spectrum and supporting the seamless interworking among different wireless access networks can enable high data rate, cost-effective, and reliable vehicular communications for many emerging vehicular applications. It is crucial to design the 5G spectrum sharing architecture and propose optimal dynamic vehicular access solutions when multiple wireless vehicular access techniques coexist.

For the aforementioned considerations and to effectively address the two targeted challenges, in this article, we investigate the dynamic sharing of 5G spectrum for high data rate, cost-effective, and reliable vehicular connectivity provisioning. As future vehicular users expect to obtain a safer, more secure, greener, more comfortable, and more convenient driving experience on the road, we target the enhancement of vehicular communication performance for tailor-made vehicular services. We first introduce the concept of immersive experience (IE)-driven vehicular communications, including the IE features in VANETs and IE-driven vehicular applications. Then we overview the spectrum utilization approaches for vehicular communications and make detailed comparisons of the vehicular access technologies. To better support the dynamic sharing of 5G spectrum for IE-driven vehicular communications, a general DSRC spectrum integrated 5G spectrum sharing architecture is proposed accordingly. We highlight the key technical challenges and pinpoint research directions toward dynamic sharing of 5G spectrum for IE-driven vehicular communications, which include vehicle-mobility-driven dynamic spectrum sharing, software defined vehicular spectrum resource management, and efficient interworking for vehicular spectrum access. Lastly we close the article with conclusions.

Immersive-Experience-Driven Vehicular Communications

In this section, we present the concept of IE-driven vehicular communications, including the vehicular IE features and typical IE-driven vehicular applications.

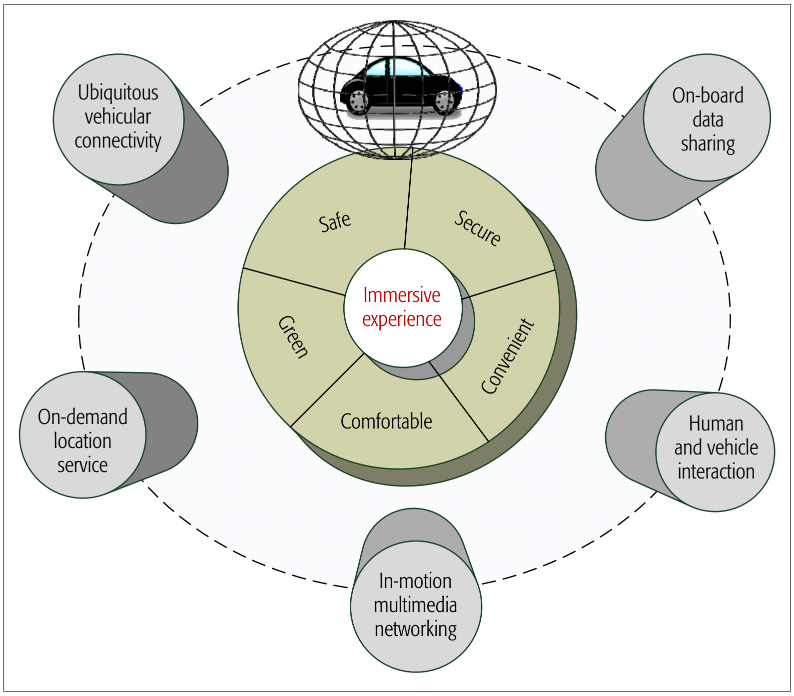

FIGURE 1. Vehicular immersive experience features.

Vehicular Immersive Experience Features

Vehicular users expect to obtain better driving experience in the future by leveraging the VANET technologies. In this article, the investigated IE is to enable ubiquitous interactions with vehicular environments including the infrastructures, devices, and participants for supporting custom-designed vehicular services and providing a safe, secure, green, comfortable, and convenient driving experience. As shown in Fig. 1, the features of an immersive driving experience mainly include the following five aspects:

1) Ubiquitous vehicular connectivity: To provide various tailor-made connected services and particularly Internet access for vehicular users, ubiquitous, high-rate, but cost-effective vehicular connectivity is the precondition for realizing the IE featured tailor-made vehicular services.

2) On-demand location services: As vehicular users expect to enjoy more and more cloud-based vehicular services and automotive telematics, the provision of vehicular location services becomes one of the core functions of VANETs, which can improve road safety, provide in-vehicle entertainment, and enhance transportation efficiency in the future ITS.

3) Human-vehicle interaction: With the advances of communication and automation technologies, human-vehicle interactions through voice or tactile sense will play an important role in the intelligent transportation system for vehicular information acquisition and dynamic information sharing, which can make vehicular communications greener and more convenient.

4) Onboard data sharing: By leveraging the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies, various types of onboard data can be shared in VANETs, including real-time vehicle driving status and online vehicular social networking information,

The traditional two-dimensional road network plane will gradually evolve into a three-dimensional road network space in the future, which requires wider vehicular network coverage and better vehicular communication service ability. In addition, with the enhanced vehicular service abilities for on-demand vehicular location services and in-motion vehicular multimedia networking, people expect to get the same services as they have at home.

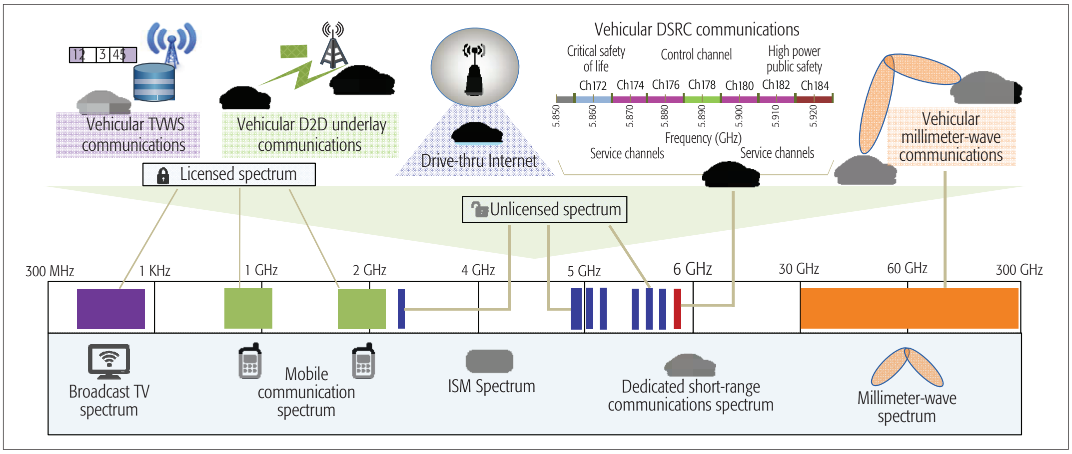

FIGURE 2. Overview of the spectrum utilization for vehicular communications.

to improve both the vehicular safety and entertainment.

5) In-motion multimedia networking: Motivated by the strong interest in vehicular social networking on the road and various Internet-based onboard multimedia services (e.g., real-time navigation video reporting and location-aware video advertising), the in-motion vehicular multimedia networking would become an indispensable technology for connected vehicles to facilitate a more comfortable and convenient driving experience.

Immersive Experience Driven Vehicular Applications

With the ubiquitous vehicular connectivity and the capabilities for human-vehicle interaction and high data rate vehicular information sharing, VANETs have been envisioned to realize smart control of vehicles, achieve the significant advantages of the next generation of ITS, and satisfy the vehicular demands for a safer, more secure, greener, more comfortable, and more convenient driving experience on the road [1]. There are many attractive key performance indicators for 5G-enabled vehicular applications with IE [10], for example, multi-gigabit-per-second high data rate, end-to-end latency on the order of 1 ms, and high reliability with a failure rate even below 10^{-7}. In the next generation of ITS, future VANETs consist of smart vehicles, electric vehicles, driverless vehicles, and even unmanned aerial vehicles (UAVs). The traditional two-dimensional road network plane will gradually evolve into a three-dimensional road network space in the future, which requires wider vehicular network coverage and better vehicular communication service ability. In addition, with the enhanced vehicular service abilities for on-demand vehicular location services and in-motion vehicular multimedia networking, people expect to get the same services as they have at home. VANETs can support a variety of customized vehicular applications through V2V and V2I communication techniques, ranging from Internet access services and road safety related vehicular applications to bandwidth-hungry vehicular applications, such as onboard driving safety information sharing, location-aware vehicular advertisement broadcasting, real-time traffic navigation, vehicular video streaming, online gaming in vehicular social networks, intelligent parking, cost-effective electric vehicle (EV) charging, and UAV services.

Dynamic Sharing of 5G Spectrum for Vehicular Communications

In this section, to enhance the efficiency of 5G spectrum utilization and to provide better quality of vehicular communication experience, we first present the existing vehicular spectrum utilization approaches, as shown in Fig. 2. We then propose an architecture of DSRC spectrum and 5G spectrum sharing for IE-driven vehicular communications.

Overview of Vehicular Spectrum Utilization

The FCC has allocated 75 MHz bandwidth for DSRC at 5.9 GHz spectrum bands, which is for exclusive utilization of vehicular communications. However, the main limitation of DSRC spectrum utilization is the small network capacity due to the narrow bandwidth. Intuitively, the vehicular communication performance of DSRC would be significantly degraded in high-density vehicular communication environments, which makes it hard to support the data-intensive vehicular applications. The widely investigated vehicular spectrum resource includes the industrial, scientific, and medical (ISM) spectrum and cellular spectrum. Specifically, vehicular users are able to acquire temporary and opportunistic vehicular connections when driving through the coverage of wireless gateway points along the road by dynamically sharing the 2.4 GHz and 5 GHz ISM spectrum resource, which is called drive-thru Internet [11]. As the cellular network with off-the-shelf technologies is widely available, it can provide efficient vehicular communication services and Internet-based vehicular applications [12]. However, using cellular services for vehicular applications could be very expensive, especially since cellular networks are becoming more and more congested recently due to the dramatic growth of mobile data. Current VANETs are facing the challenge of spectrum scarcity, and therefore we should look for alternative cost-effective and high-rate data pipes for vehicular communications [13]. Fortunately, by means of cognitive radio technology, vehicular users can dynamically utilize the licensed spectrum resource, such as underlay shared cellular spectrum and TVWS spectrum [12]. Specifically, when the licensed spectrum is available (i.e., licensed users are not transmitting), vehicular

Feature name	Cellular	DSRC	Drive-thru Internet	TV white space	Millimeter-wave
Standardization	3GPP LTE-A	IEEE 802.11p/WAVE	IEEE 802.11a/b/g/n	IEEE 802.11af/802.22	IEEE 802.11ad/802.15.3
Frequency band	Licensed band	5.86–5.92 GHz	2.4 GHz/5 GHz	470–790 MHz	30–300 GHz
Mobility support	≤ 350 km/h	≤ 140 km/h	≤ 120 km/h	≤ 114 km/h	≤ 140 km/h
Data rate	≤ 300 Mb/s	3 ~ 27 Mb/s	≤ 150 Mb/s	420 Mb/s (4 bonded channels)	≤ 6.756 Gb/s
Coverage range	≥ 5 km	300 ~ 1000 m	~ 500 m	1 km/17 ~ 33 km	~ 200 m
Access method	D2D	Ad hoc	Ad hoc	D2D	Ad hoc

TABLE 1. The comparison of heterogeneous radio resource sharing technologies for vehicular communications.

users can access the licensed spectrum bands. But when licensed users start transmitting, vehicular users must stop using it. Since the transmission actions of licensed users change over time and location, and vehicles can move into or out of a given coverage area, the spectrum is spatially and temporally opportunistic for vehicular utilization. By using D2D communications, vehicular users can reuse the cellular spectrum resource and communicate with each other directly, without packet relaying through base stations, to achieve low latency and high spectrum efficiency. However, due to the spectrum reuse feature, D2D transmissions should avoid severe interference to the normal licensed cellular transmissions; otherwise, the D2D transmissions should be terminated. From this viewpoint, D2D communications are also opportunistic. In addition, mmWave spectrum band has several unique propagation features, such as higher propagation loss and short coverage range. Particularly, mmWave spectrum band can easily be blocked by obstacles in line-of-sight transmissions [5]. It is important to utilize the mmWave spectrum resource at the right time and right location, and with the right user pair selection for achieving the quality of service guarantees of vehicular communications. Furthermore, Table 1 shows the detailed comparisons of vehicular communication technologies and parameter settings by utilizing different spectrum resource from cellular networks, DSRC, drive-thru Internet, TVWS networks, and mmWave networks, respectively. We demonstrate the dynamic spectrum sharing features of those technologies from the aspects of the standardization, frequency band, mobility support, data rate, coverage range, and channel access method.

5G Spectrum Sharing Architecture

We propose a sharing architecture of DSRC spectrum and 5G spectrum for IE-driven vehicular communications, as shown in Fig. 3, which mainly includes the following four components: heterogeneous vehicular network, radio resource sharing cloud, Internet, and channel access.

Heterogeneous vehicular network: By integrating different types of vehicular access technologies for dynamic resource sharing, including DSRC spectrum, cellular spectrum, TVWS, mmWave, and so on, vehicular users expect to enjoy enormous ITS services in vehicular networks, ranging from the vehicular safety applications and traffic management to mobile Internet access.

Radio resource sharing cloud: Explicitly taking into account both the availability of radio resource and high vehicle mobility, the radio resource sharing cloud can enable location-based spectrum information sharing, including local vacant radio channel query.

Internet: The geolocation database server (GDBS) can be ubiquitously connected to provide availability of spectrum information query in the geolocation database via the Internet. In addition, diverse Internet-based vehicular services can be distributed to vehicular users with different service requirements.

Channel access: To jointly utilize the diverse radio spectrum resource, vehicular users can make adaptive channel selection for dynamic spectrum sharing by applying the multi-radio dynamic spectrum sharing paradigm, which allows the tightest possible seamless interworking for high data rate and cost-effective dynamic vehicular access. The multi-radio dynamic spectrum sharing paradigm and channel access approach can efficiently utilize all the spectrum resource from the cellular band, DSRC band, TVWS band, mmWave band, and so on.

5G Spectrum Sharing Challenges in IE-Driven Vehicular Communications

In this section, we present the challenges of 5G spectrum sharing in IE-driven vehicular communications, which can be summarized as follows: high vehicle mobility vs. spectrum sharing behavior, radio resource heterogeneity vs. spectrum sharing efficiency, and vehicular service diversity vs. spectrum access performance.

High Vehicle Mobility vs. Spectrum Sharing Behavior

High vehicle mobility becomes a major constraint in VANETs [14]. The dynamic spectrum sharing behavior of vehicular users on the road is closely related to the road topology, vehicle traffic condition, and vehicular service demand, as well as the availability of spectrum. On one hand, the high vehicle mobility impacts the availability of heterogenous 5G spectrum resource. For example, there are three types of TVWS channels that can be utilized for vehicles in the designed locations: fixed devices, mode-II devices, and mode-I devices. However, for different designated locations, TVWS channel configurations for vehicle utilization in a geolocation database would be different in terms of the TVWS channel number and transmit power constraints. In addition, due to high and variable relative speeds of vehicles, VANETs are subject to frequent spatio-tempo-

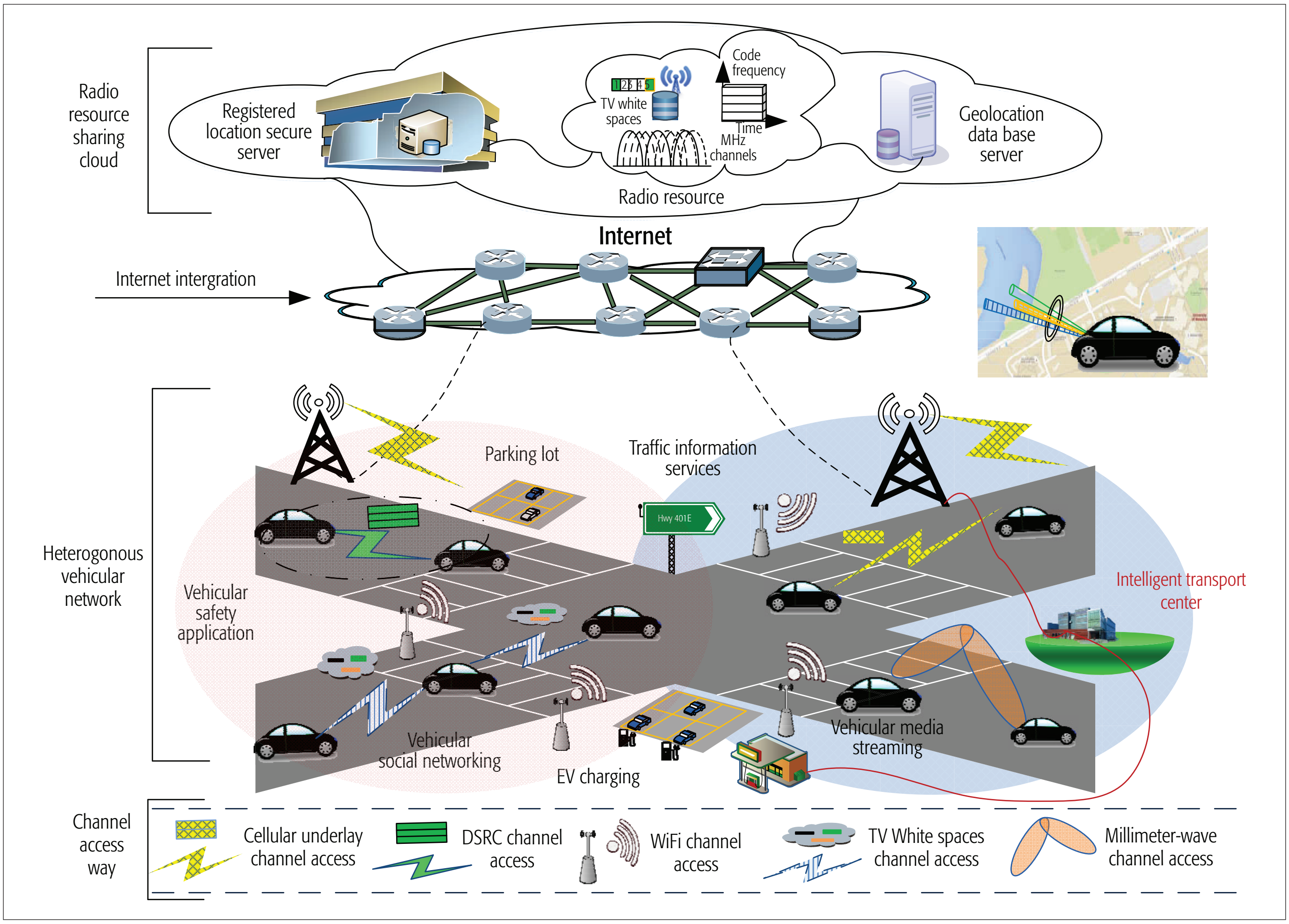

FIGURE 3. The spectrum sharing architecture of DSRC and 5G for vehicular communications.

ral variations in their topologies, and therefore introduce significant dynamics of wireless channel conditions for both the vehicular underlay sharing of cellular spectrum and vehicular mmWave communications. One the other hand, the development of location-based vehicular services further creates the dynamic spectrum sharing demand in VANETs, such as location-based vehicular advertising, V2V warning systems, and real-time traffic planning. Different location-based vehicular services need different types of spectrum resource support, and the diversity of vehicle distribution impacts the quality of radio links severely as well. Technically, we have to jointly study the high vehicle mobility impacts and dynamic vehicular spectrum sharing behavior for achieving better 5G spectrum resource utilization and location-based vehicular services experience, which is the first main challenge of 5G spectrum sharing in IE-driven vehicular communications.

Radio Resource Heterogeneity vs. Spectrum Sharing Efficiency

Modern smart vehicles feature multiple wireless access techniques that work separately on different wireless spectrum bands. The essence of the DSRC spectrum and integrated 5G spectrum sharing technique lies in exploring both available licensed and unlicensed spectrum for ubiquitous, high-rate, reliable, but cost-effective vehicular communications. There will be typical radio resource heterogeneity in the dynamic vehicular spectrum sharing networks. Specifically, vehicular users can utilize both the high frequency of the mmWave spectrum band and the low frequency of the TVWS spectrum band, where the mmWave spectrum band can provide a massive amount of bandwidth for vehicular communications, and the TVWS spectrum band can be opportunistically exploited for wider coverage and higher link stability of vehicular connectivity. Due to the high vehicle mobility and location-based vehicular services in VANETs for different spectrum sharing demands, spectrum heterogeneity can greatly affect the spectrum sharing efficiency in VANETs. It is necessary to coordinate different vehicular users to dynamically share different types of spectrum resource to maximize the spectrum utilization while meeting the demand of connected vehicle services.

Vehicular Service Diversity vs. Spectrum Access Performance

VANETs have been envisioned to play a crucial role in the future ITS to enable diverse tailor-made connected vehicular services ranging from traditional IP-based vehicular applications to unique applications in vehicular environments [15]. For instance, the time-critical vehicular safety and real-time traffic management applications (e.g., traffic alert and collision avoidance) have strict latency constraints and very high reliability need for ubiquitous vehicular connectivity. For vehicular entertainment applications (e.g., video streaming and video on demand, web browsing and Internet access), delay-bounded QoS requirements and a massive amount of bandwidth support are necessary. Therefore, how to provide efficient vehicular access over heterogeneous 5G spectrum bands by considering the vehicular mobility and diverse vehicular application requirements is a key research issue. Moreover, vehicular connectivity disruptions can occur frequently due to the dynamics of vehicular network topology and the availability and distribution of 5G spectrum resource. We have to deal with the interworking issue for the seamless flow of vehicular data among different radio data pipes for the dynamic sharing of DSRC spectrum and integrated 5G spectrum.

5G Spectrum Sharing Opportunities in IE-Driven Vehicular Communications

In this section, by jointly considering the high vehicle mobility, heterogeneity of 5G spectrum resource, and better quality of vehicular communication experience, we pinpoint future research directions on exploiting 5G spectrum sharing opportunities in IE-driven vehicular communications: mobility-driven vehicular spectrum sharing, software defined vehicular spectrum management, and efficient interworking for vehicular spectrum access.

Mobility-Driven Vehicular Spectrum Sharing

Network mobility support has been considered as an important ITS standard to meet the ever growing expectations of tailor-made vehicular applications. As the location has a significant influence on both the actual availability of 5G spectrum resource (underlay shared cellular spectrum, TVWS, and mmWave spectrum) and the communication performance over those heterogeneous spectrum bands, the main challenging issue is how to utilize vehicle mobility prediction for dynamic vehicular spectrum sharing. Hence, understanding vehicular mobility is vital for realizing efficient dynamic spectrum sharing in VANETs. Generally, real-world traces and synthetic mobility models can be helpful to accurately describe the vehicle mobility on the road and facilitate the design of location-based dynamic spectrum sharing schemes in VANETs. However, there are still some open and unsolved problems, such as how predictable mobility is and how mobility predictability can be applied to model the dynamic vehicular spectrum sharing behaviors and enhance the vehicular spectrum sharing performance. For example, for the underlay shared cellular spectrum utilization leveraging the V-D2D communication technology, the interference and collisions in all V-D2D links should be efficiently coordinated by designing the dynamic power control and resource allocation schemes. In addition, considering the time-varying spatial distribution of vehicles on the road and challenging channel modeling due to the rapid change of vehicular network topology, how many vehicular D2D links can coexist in the licensed cellular networks to provide ensured protection to the primary cellular users and improve the spectrum utilization is also an interesting research issue. Moreover, there is much evidence that the TVWS and mmWave spectrum bands can be available to feed a large number of bandwidth-hungry V2V communication applications (e.g., V2V live video streaming). However, the availability of local TVWS channels changes over time and location, and the mmWave spectrum band has higher propagation loss and short coverage range; in particular, mmWave band can easily be blocked by obstacles in LOS transmissions, so it is necessary to optimize the 5G spectrum unitization by fully considering the vehicle mobility and the vehicular access demands on the road.

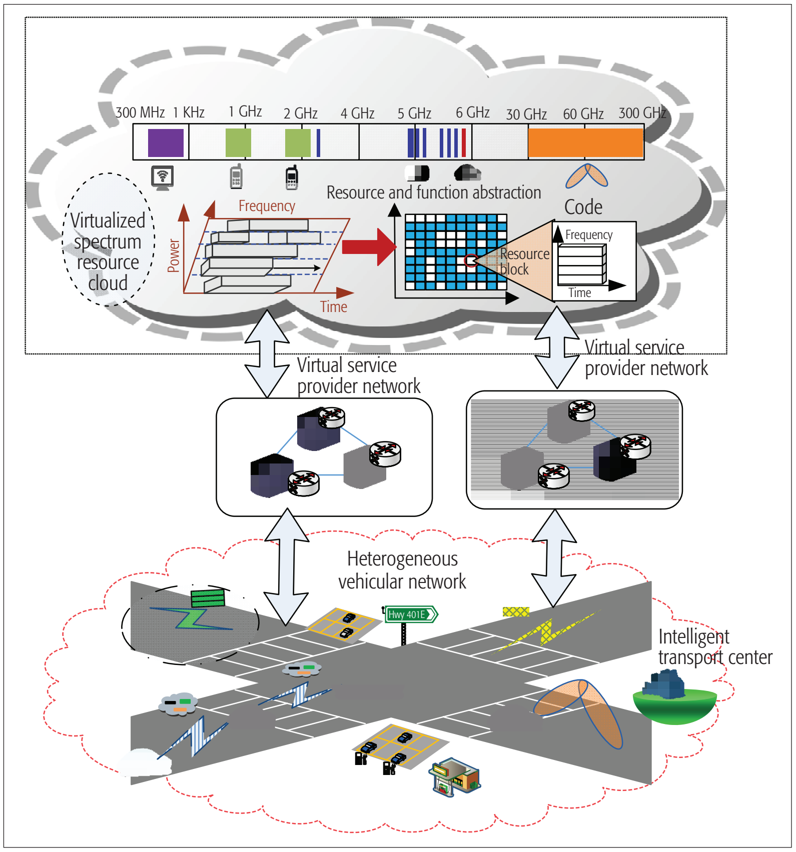

FIGURE 4. Software-defined dynamic spectrum sharing architecture for vehicular spectrum management.

Software Defined Vehicular Spectrum Management

The future vehicular demand for high-quality wireless connectivity provisioning is envisioned to be quite different from that in traditional VANETs. Due to the heterogeneity of 5G spectrum resource and the rapid growth of vehicular data traffic, the traditional spectrum resource management approaches in VANETs lack flexibility and efficiency, which will make dynamic vehicular spectrum management challenging. Software defined spectrum resource management has been emerging as a promising paradigm to realize efficient vehicular resource management in a systematic way and support tailor-made services for different vehicular users. As shown in Fig. 4, we introduce a software defined dynamic spectrum sharing architecture for vehicular access, which consists of a radio resource sharing cloud, a virtual service provider network, and heterogeneous vehicular networks. Specifically, in Fig. 4, the vir-

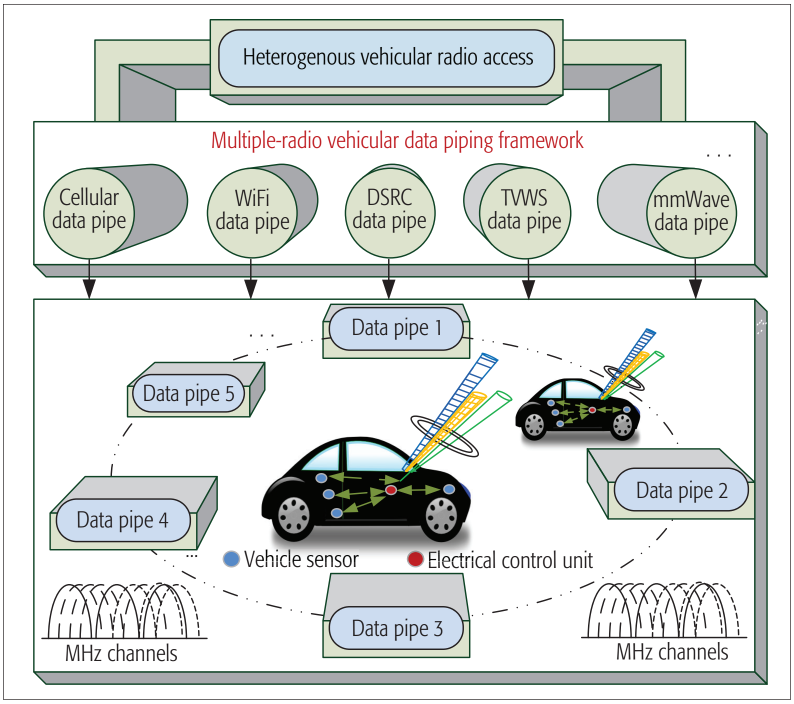

FIGURE 5. The multiple vehicular data pipe management framework for heterogenous radio resource sharing.

tualization of different licensed and unlicensed spectrum resources, services, and functions is presented. With virtualization technologies, heterogenous physical network resources and radio resources can be abstracted and sliced into virtual network resources with various functionalities, and shared by different vehicle users through isolating each other. The main challenge of virtualization technologies for software defined dynamic spectrum sharing is to enable dynamic slicing of vehicular networks and make specific physical network infrastructures capable of supporting a wider range of vehicular applications and different vehicular access requirements.

Efficient Interworking for Vehicular Spectrum Access

Due to the high vehicle mobility and opportunistic availability of spectrum resource, the services provided for vehicular users may be disrupted. To keep the continuity of vehicular services and improve the vehicular users' communication experience, as shown in Fig. 5, we propose a dynamic vehicular data pipe management framework for IE-driven efficient interworking among these data pipes. The dynamic vehicular data pipe management framework allows vehicular communications over heterogenous licensed and unlicensed spectrum bands, which is a feasible and effective solution for dynamic vehicular spectrum access. By fully taking advantage of the heterogeneity of wireless spectrum resource and the dynamics of vehicular spectrum sharing behavior, we can enable high data rate and reliable vehicular access and meet different vehicular application requirements in a cost-effective manner. However, the high relative vehicle speed and frequent changes of vehicular network topology will induce instability in vehicular connectivity and often result in unacceptable long handover latency and increased data loss for vehicular services, especially in time-critical vehicular application scenarios. To realize multiple-vehicle data pipe management and support seamless interworking among the licensed and unlicensed bands for optimal vehicular access, we have to carefully design the dynamic optimization mechanisms for the performance improvement of heterogeneous vehicular spectrum sharing and propose efficient interworking approaches for seamless and high-rate data flow among those licensed and unlicensed data pipes when multiple wireless access techniques coexist. Technically, coalition formation games have been widely applied in the dynamic optimization mechanisms and interworking approaches [6]. In addition, with the expected proliferation of vehicular terminal devices, efficient vehicular association with diverse QoS guarantees and dynamic reconfiguration of network resources are also very important in high-speed and high-density vehicular network environments.

Conclusion

In this article, we have investigated the dynamic sharing of both 5G spectrum and DSRC spectrum for better quality of vehicular communication experience. We have proposed an efficient spectrum sharing architecture and highlighted the key technical challenges. Finally, we have pinpointed future research directions. We hope this article sheds light on the dynamic sharing of 5G spectrum for vehicular ad hoc networks and promotes the advancement and development of vehicular communication technologies.

Acknowledgment

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