TV White Space Enabled Connected Vehicle Networks: Challenges and Solutions

Haibo Zhou, Ning Zhang, Yuanguo Bi, Quan Yu, Xuemin (Sherman) Shen, Dan Shan, and Fan Bai

Abstract

Connected vehicle technology provides many potential benefits on the road such as safety applications, effective traffic management, and mobile Internet access. In order to mitigate the resulting high spectrum demands and provide vehicular connectivity with wider communication range, higher transmission rate, and lower data transfer cost, in this article, we exploit the abundant TV white space with superior propagation characteristics and building penetration performance. We first present the application scenarios exploiting TV white space in heterogeneous connected vehicular communication networks, and discuss white space channel availability and characteristics for vehicular communications. We then propose TV white space geolocation database based vehicular communication architectures for vehicle-to-infrastructure (V2I) communications and vehicle-to-vehicle (V2V) communications. Finally, we highlight the key technical challenges and pinpoint future research directions toward exploiting TV white space for vehicular communication networks.

Introduction

With the advances in communication and information technologies, wireless connectivity enabled vehicles to communicate with various infrastructures, devices, and participants for tailor-made vehicle services, and are referred to as connected vehicles [1]. Connected vehicles have been envisioned to provide enabling technologies to improve road safety, provide in-vehicle entertainment, enhance transportation efficiency, and improve the driving experience. In recent years, as passengers and drivers expect more cloud services, location based services, and automotive telematics, there is a phenomenal increase in the number of connected vehicles. According to the market research report from BI Intelligence released in 2015, 75 percent of cars shipped globally by 2020 will be built with the necessary hardware and software to support Internet access on the road. While research on connected vehicle networks has recently achieved tremendous progress, and there is already a staggering level of in-vehicle connectivity compared to just a decade ago, academia and the automotive industry still need to response promptly to the current challenges presented by connected vehicle networks.

The first major challenge is how to solve the spectrum-scarcity problem. Although the Federal Communications Commission (FCC) has allocated 75 MHz bandwidth at the 5.9 GHz spectrum band for dedicated short-range communications (DSRC) to support both vehicle-to-infrastructure (V2I) communications and vehicle-to-vehicle (V2V) communications, the ever increasing need to provide vehicles with high bandwidth and robust connectivity creates a huge demand for wireless spectrum. To solve this problem, it is essential to explore new spectrum, including both licensed and unlicensed spectrum for dynamic and flexible utilization [2]. Thanks to the decision of the FCC in the United States and the Office of Communications (Ofcom) in the United Kingdom to allocate abundant VHF/UHF spectrum (512–698 MHz in the United States and 470–790 MHz in Europe) for unlicensed users, which is referred to as TV white space with excellent propagation characteristics for wide-area transmissions. TV white space enabled connected vehicle networks would open the door for a promising solution to address the challenge of continued growth of mobile data in connected vehicle services [3].

The second major challenge is how to provide wide-coverage, high-rate, yet cost-effective wireless connectivity to vehicular users. Leveraging traditional wireless technologies, e.g., cellular technologies (3G, LTE-A, etc.,) or satellite networks, vehicular users can enjoy Internet access services with long-range network coverage on the go. In addition to the growing mobile data challenge discussed above, cellular technologies are also facing significant challenges in handling high mobility environments to enhance quality of experience (QoE) due to delay spread and Doppler effect [4, 5]. Drive-thru Internet is a potential alternative to cellular-based vehicle networking [6]. However, drive-thru Internet only provides vehicular users with intermittent and transitory connectivity, resulting in a limited amount of data within the coverage time of drive-thru Internet. Hence, drive-thru Internet would be ill-suited to support popular vehicular multimedia applications [7].

As mentioned above, the propagation characteristics of TV white space, the combination of the low cost of the abundant unlicensed white space spectrum and its long communication range, make it a good match for the needs of vehicular communications, i.e., wide-coverage, high-rate, yet cost-effective connectivity. In this article, we focus on TV white space enabled connected vehicle networks. We first introduce the comprehensive heterogeneous connected vehicle network scenario for connected vehicular communications. As the mandated use of geolocation databases can completely eliminate the need of sensing for TV white space channels, it has been well verified to be an effective means to dynamically manage the TV white space spectrum. To better understand connected vehicular communications over TV white space, we discuss the channel availabil-

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ity and main characteristics of TV white space in a geolocation database for dynamic vehicular utilization. After that, based on the IEEE 802.11af standard, we propose TV white space geolocation database assisted vehicular communication architectures for both V2I communications and V2V communications. We then discuss key technical challenges and research directions for connected vehicle networks by leveraging the TV white space geolocation database, including efficient TV whitespace networking for VANET, dynamic vehicular access over TV white space, and cost-effective vehicular TV white space offloading. Lastly we close the article with conclusions.

TV Whitespace Enabled Connected Vehicle Networks

In this section, we present the TV white space enabled connected vehicle network, including a system model, application scenario, and channel availability and characteristics by leveraging the TV white space geolocation database.

System Model and Application Scenario

We investigate a comprehensive heterogeneous vehicular network (HVN) scenario for connected vehicular communications, in which connected vehicles can support a variety of customized vehicle services by exploiting different means of vehicular communications. As shown in Fig. 1, the TV white space network coexists with the cellular network in HVN, and two types of connected vehicular communication models by leveraging TV white space are supported, i.e., V2I communications and V2V communications.

Specifically, for the TV white space enabled V2I communications, we consider the IEEE 802.11af standard based vehicular Internet access infrastructure, referred to as WhiteFi. WhiteFi supports various Internet-based vehicular services, e.g., vehicular content distribution ranging from multi-media file download to road traffic data reports to location-aware vehicular advertisements. To leverage WhiteFi for V2I communications, the major elements in an IEEE 802.11af network are the geolocation database and registered location secure server (RLSS). The detailed presentation of the WhiteFi architecture for V2I communications will be introduced later in the article. For TV white space enabled V2V communications, a base station is connected with an RLSS, which can reserve a TV white space channel from the RLSS for dynamic vehicular utilization. The abundant TV white space spectrum resource can be available for feeding a number of bandwidth-hungry V2V communication applications, e.g., V2V live video streaming in vehicular social networks. In addition, TV white space with excellent propagation characteristic is especially suited for long-distance streaming to moving vehicles, and supporting various road safety related on-board applications with reduced multi-hop transmission delay and vehicular service quality guarantees [8, 9].

Channel Availability and Characteristics

Geolocation database assisted dynamic TV whitespace sharing is a promising paradigm to alleviate spectrum scarcity in vehicular communications. We present the TV white space data collection in the Waterloo region (seen in Fig. 2a) to show the channel availability from the geolocation database pilot hosted by Spectrum Bridge. As shown in Figs. 2b and 2c, the TV white space geolocation database supports three categories of unlicensed TV white space devices based on the transmission power limitation, including fixed devices (36 dBm), mode-II devices (20 dBm), and mode-I devices (16 dBm). Mode-II and mode-I devices are also referred to as portable devices. We can empirically present two unique characteristics of TV white space in the geolocation database as follows:

- A "power-spectrum tradeoff" phenomenon is observed, i.e., with the decrease of transmission power, there will be more available channels in the designated locations of TV white space devices. Specifically, the number of available fixed and portable devices in the designated data collection location in Waterloo region are 10 and 21, respectively.
- The availability of TV white space is difficult to model in a generic way, which is with spatial change over the scale of a few kilometers. As shown in Fig. 2a, the spatial change range of the availability of TV white space is about 2 kilometers in the data collection locations of the Waterloo region.

Furthermore, Table 1 shows the detailed technology and parameter comparisons among LTE, DSRC/WAVE, and the IEEE 802.11af/802.22 standards, which demonstrates that the low cost of abundant unlicensed white space spectrum can meet the needs of vehicular communications for wide-coverage, high-rate, yet cost-effective connectivity. However, the distinct characteristics of TV white space would challenge typical vehicular utilization in terms of TV white space networking, dynamic vehicular access, TV white space offloading, etc. For example, from Figs. 2b and 2c, there are tens of available TV white space channels in the designated location, and it is particularly important to consider the power-specific parameter when optimizing the TV white space

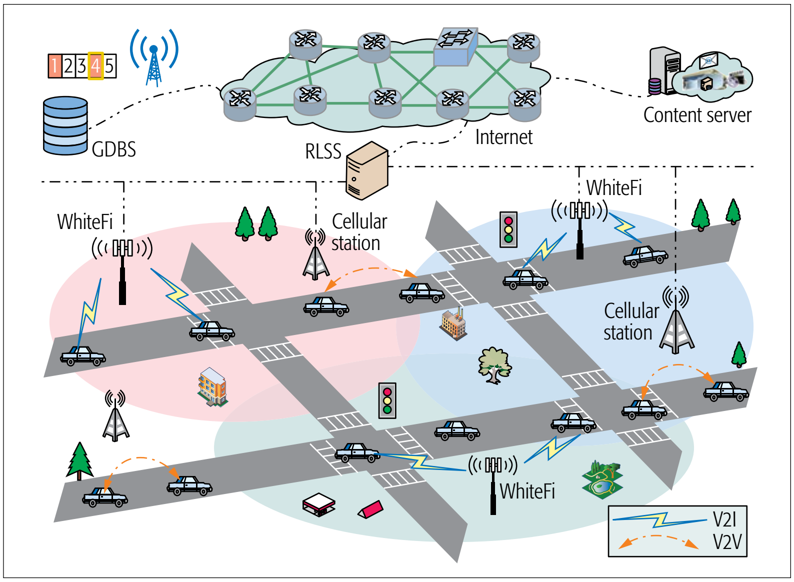

FIGURE 1. A comprehensive heterogeneous vehicular networks scenario for connected vehicular communications.

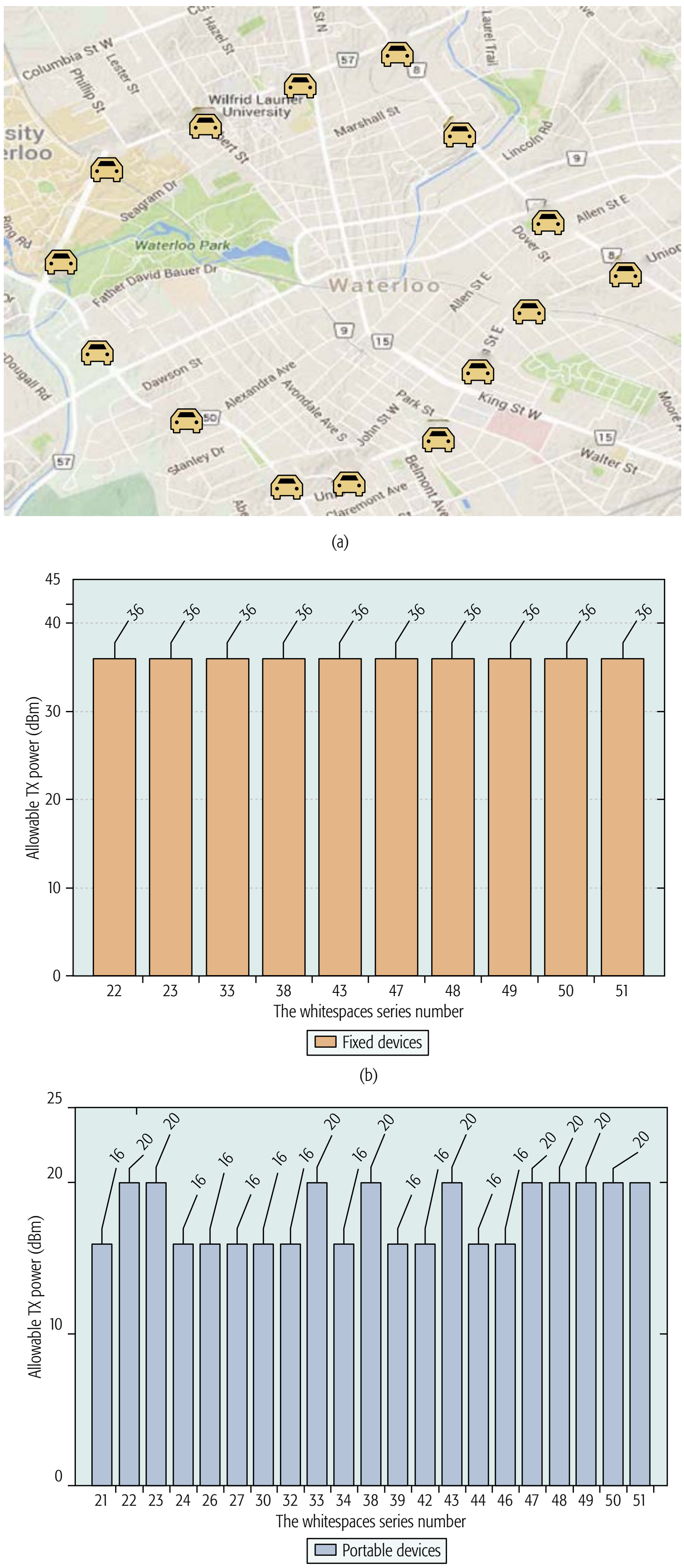

FIGURE 2. The channel distribution of real-world TV white space in geolocation database: a) the location of TV white space data collection; b) the available TV white space for fixed devices; and c) the available TV white space for portable devices.

network capacity and scheduling the TV white space channels among different vehicular users with acceptable computational complexity. Additionally, the spatial change of available TV white space is with a scale of a few kilometers, and it is more likely that many vehicular users would have the same channel selection set in a wide-coverage range, which will aggravate co-channel and adjacent channel interference, especially in a high mobility vehicular environment. Consequently, frequency agility feature for fast channel switching and power control must be considered in the vehicular access protocol design and vehicular TV white space offloading applications [10]. To discuss the challenges of vehicular utilization by considering the distinct characteristics of TV white space from the geolocation database in detail, we will discuss how to address those challenges later.

TV White Space Geolocation Database-based Vehicular Communication Architectures

Motivated by various demands of vehicular applications over TV white space, in this section, we present two types of TV white space geolocation database based vehicular communication architectures: the V2I communication architecture and the V2V communication architecture.

Vehicle-to-Infrastructure Communication Architecture

Database-assisted TV white space networking is a promising paradigm for efficient vehicular access and can alleviate spectrum scarcity through centralized control of a geolocation database residing in the cloud. To provide wide-coverage, high-rate, and cost-effective wireless connectivity, and in particular, convenient and fast Internet access for in-motion vehicular users, we propose location-dependent TV white space networking for V2I communications by leveraging the TV white space geolocation database. Based on the IEEE 802.11af standard, as shown in Fig. 3a, the TV white space enabled vehicle-to-infrastructure communication architecture is composed of the geolocation data base server (GDBS), registered location secure server (RLSS), and WhiteFi nodes. Specifically, as shown in Fig. 4a, GDBS can perform the local vacant TV white space channel query to a small number of WhiteFi nodes via the Internet, which stores the necessary information for WhiteFi node deployment in different geographic locations to fulfill regulatory requirements. The information for any unlicensed vehicles includes:

- The list of available TV white space channels
- The transmission constraints (e.g., maximum transmission power) on each channel in the list
- The qualities of TV white space channels.

RLSS needs to interact with the geolocation database periodically for information updates of its associated WhiteFi nodes, e.g., mobile traffic status and available white space channels. The interaction period for updating the TV white space information (called the frame) is subject to regulatory constraint, e.g., 15-minutes for the latest Ofcom rule. In addition, RLSS can dynamically coordinate optimal TV white space spectrum sharing among different WhiteFi nodes, including TV white space channel and power assignment for co-channel and adjacent channel interference avoidance. RLSS can be considered as the implementation entity for planning the TV white space spectrum and distributing the permitted operation parameters to WhiteFi nodes. By leveraging the centralized scheduling scheme, WhiteFi nodes can provide Internet-based long-range broadband access for various vehicular applications within the coverage of associated WhiteFi nodes.

Vehicle-to-Vehicle Communication Architecture

To enable high-rate and reliable vehicular connectivity in a scalable and cost-effective manner, as shown in Fig. 3b, we propose a cellular-assisted long-range TV white space access architecture for V2V communications, which can be regarded as an opportunistic device-to-device (D2D) communication approach to enhance QoE requirements of vehicular users and traffic congestion in vehicular networks [11]. Specifically, as shown in Fig. 4b, we assume that a base station is connected with an RLSS, and can periodically broadcast the cellular-wide white space availability to vehicular users within its coverage. Due to the high vehicular transmission cost using cellular bands, the cellular link is only performed as the control link for opportunistic TV white space utilization in V2V communications. The cellular station will update real-time vehicular location and resource demand information once one vehicle enters its coverage range. Through local white space data query in the geolocation database, RLSS will obtain the cellular-wide available white space information in the form of a white space map (WSM). If one vehicle would like to apply the available TV white space channels in the current location, a distributed channel/power selection scheme can be leveraged for adaptive white space access. Different from dynamic vehicular access in V2I communications, mobile vehicular users are only allowed to transmit at much lower power, no more than 100 mW compared to the V2I infrastructures that are allowed to up to 4 W. This difference in allowable transmitter power is to prevent mobile devices from causing harmful interference to the primary incumbents and to vehicles using the same white space.

Metric \ Standard	LTE	DSRC/WAVE	IEEE 802.11af/IEEE 802.22
System capacity	High	Medium	High
Mobility support	≤ 350 km/h	≤ 190 km/h	≤ 114 km/h
Coverage range	≥ 5 km	500 ~ 1000 m	1 km (802.11af); 17 ~ 33 km (802.22)
Channel bandwidth	1.4, 3, 5, 10, 15, 20 (MHz)	10 (MHz)	6 (MHz)
Data rate	≤ 300 Mb/s	3–27 Mb/s	420 Mb/s (four bonded channels)
Cost issue	High	Low	Low

TABLE 1. Technologies and parameters comparison.

Additionally, the distributed white space channel and power selection scheme is scalable and can be compatible with the current DSRC standard. In this sense, database-assisted V2V communications by utilizing the TV white space is a typical example of a cloud-enabled virtualized network.

Key Technical Challenges and Research Directions

In this section, by fully considering the characteristics of the TV white space channel for typical vehicular utilization, we highlight key technical challenges and pinpoint future research directions to exploit TV white space for connected vehicle networks, i.e., efficient TV whitespace networking for VANET, dynamic vehicular access over TV white space, and cost-effective vehicular TV white space offloading.

Efficient TV White Space Networking for VANET

Geolocation database assisted TV whitespace networks can provide wide-coverage, high-rate, and cost-effective vehicular connectivity by deploying an infrastructure-based TV white space sharing framework. However, as shown in Fig. 5, there

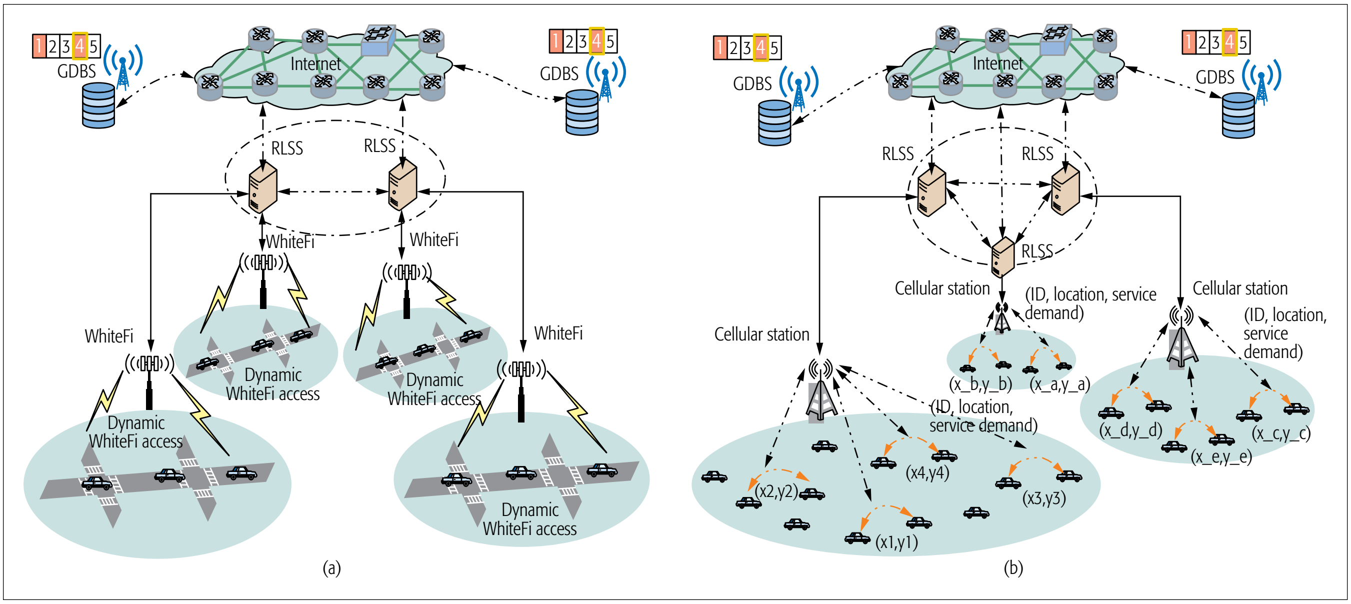

FIGURE 3. The connected vehicular communication architecture by leveraging TV white space: a) vehicle-to-Infrastructure communication architecture; b) vehicle-to-vehicle communication architecture.

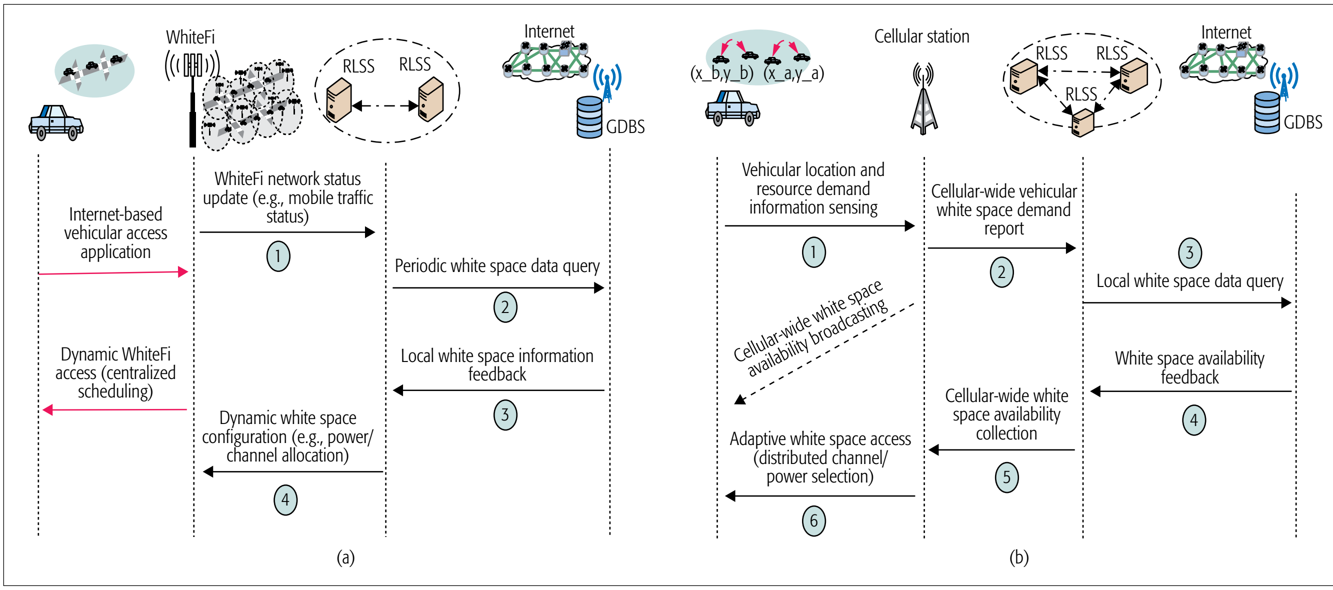

FIGURE 4. The connected vehicular communication procedure by leveraging TV white space: a) vehicle-to-Infrastructure communication procedure; b) vehicle-to-vehicle communication procedure.

are two main crucial technical challenges for efficient white space sharing in infrastructure-based TV white space networks:
- How to optimally deploy TV white space infrastructures for the best TV white space utilization and well matched vehicular access demand on the road [12].
- How to allocate the available TV white space channels to reduce co-channel and adjacent channel interference and maximize TV white space network capacity [13].

For the first problem, the availability of TV white space spectrum is with spatial-temporal variation, and the vehicular traffic changes over time and location as well. The prediction and learning technologies based TV white space and vehicular traffic data analysis can be utilized to establish statistic models of both TV white space spectrum availability/distribution in the geolocation database and the arrival vehicular services demand.

For the second problem, the global combinatorial optimization theory can be helpful to achieve optimal TV white space network capacity considering the co-channel and adjacent channel interference reducing/avoiding. We can denote the feasible M-channel and joint channel-power configuration for WhiteFi n by $(c_n, p_n(c_n))^M$, $n = \{1, 2, \ldots N\}$. Denote $\mathbb{T}^M = (c_1^M, c_2^M, \ldots, c_n^M)$ and $\mathbb{P}^M = (p_1^M, p_2^M, \ldots, p_n^M)$ as the M-channel configuration profile and transmission power configuration profile on the selected channels, respectively, which forms a joint channel-power selection set for all the N WhiteFi nodes, denoted by $\Upsilon^M = (\mathbb{T}, \mathbb{P}^M)$. Based on the calculation of the Shannon capacity $\mathbf{E}_n(\Upsilon^M)$ of WhiteFi n, the optimal channel/power selection profile $(\Upsilon^M)^* = ((\mathbb{T}^M)^*\} (\mathbb{P}^M)^*)$ for the maximized network-wide throughput can be formulated as

$$(\Upsilon^M)^* \triangleq \underset{\Upsilon^M \in \mathcal{J} \triangleq \prod_{m=1}^{N} \mathcal{J}_m^M}{\arg\max} \sum\nolimits_{n \in N} \mathbf{E}_n(\Upsilon^M) \quad (1)$$

where $\prod_{m=1}^{N} \mathcal{J}_m{}^M$ is denoted as the multi-channel and joint channel-power selection profile of all N WhiteFi over the discrete solution space $\mathcal{J}$.

Considering a potentially large number of deployed WhiteFi nodes and channel-power combination sets in discrete solution space $\mathcal{J}$, the number of feasible schedules increases considerably, and therefore choosing the appropriate schedule becomes computationally more challenging. Basically, some distributed approximated approaches, e.g., distributed Markov approximation, has been verified to achieve almost the equivalently optimal goal with acceptable computational complexity [14]. As shown in Figs. 6a and 6b, we can see that the distributed Markov approximation based approach can quickly reach the equilibrium, and the gap between the distributed Markov approximation approach and the optimal traversal solution is only about 0.17 percent, which indicates very little performance loss with the proposed Markov approximation in optimal white space planning.

Dynamic Vehicular Access over TV White Space

According to the FCC rules, and particularly the transmission power limitation, there are two types of vehicular access approaches for geolocation database assisted dynamic TV white space sharing: infrastructure based cellular type access, and short range WLAN like access. How to provide efficient vehicular access over TV white space considering vehicular mobility and vehicular application requirements is a key research issue [15].

Cellular type vehicular access over TV white space can enable large-scale vehicular content distribution applications, e.g., location-aware advertising and Internet-based on-board vehicular services. Since the wide-coverage feature of TV white space network causes increased vehicular access congestion, to avoid Medium Access Control (MAC) performance deterioration due to contention, and especially to guarantee time-bounded vehicular access for many deadline-sensitive vehicular applications, centralized scheduling is preferred, i.e., a contention-free polling vehicular access method. It is worth mentioning that the predictable vehicular trajectory and drivers' motivation to report their locations for a better driving and Internet experience would greatly increase the benefits of centralized scheduling.

Short-range WLAN-like vehicular access over TV white space can enable microscopic and real-time vehicular applications, e.g., self-organized vehicular social networking. According to the introduced MAC principle in the newly released IEEE 802.11af standard, a hybrid coordination function (HCF) scheme is suggested, including the point coordinated function (PCF), through the services of the enhanced distributed coordinated function (EDCF) for medium sharing and access [3]. Due to the large-coverage feature of Wi-Fi-like TV white space deployment and high mobility of vehicular users, the widely revealed performance anomaly phenomenon in multi-rate 802.11 WLAN is even worse. To maximize the vehicular access throughput of all vehicular users, the vehicular user's driving location and user's requirements (the size of file transmission and transmitted task portion) should be jointly considered to form a vehicular access priority. According to priority setting, the amended EDCF for vehicular Internet access will optimize the MAC parameters, e.g., CWmin, CWmax, TXOPlimit, etc. The main purpose of the protocol design is to enable vehicles that are closer to the TV white space infrastructure and have fewer channel access numbers to access the medium first, to reach a fairness and throughput tradeoff optimization in the Wi-Fi like vehicular access over TV white space.

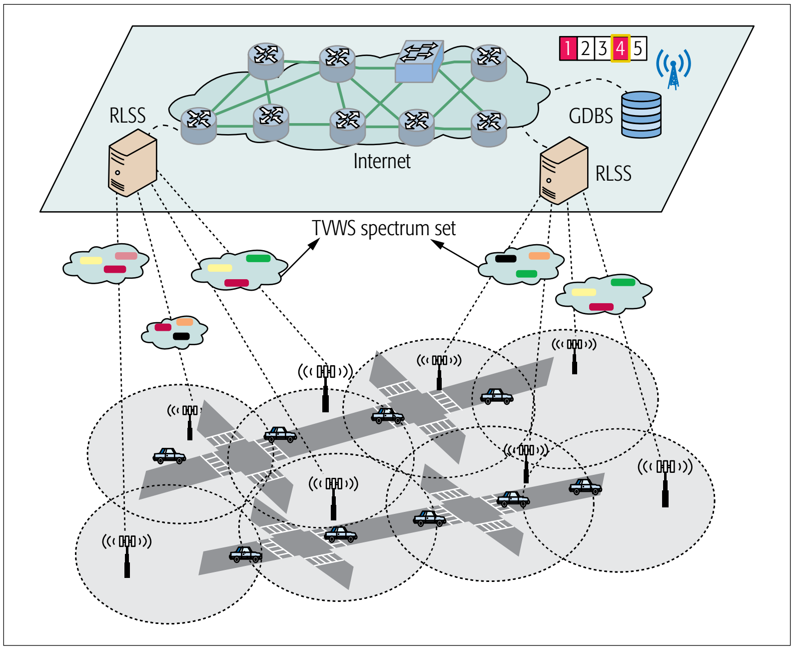

FIGURE 5. Dynamic spectrum planning in TV white space networks.

Cost-Effective Vehicular TV White Space Offloading

The combination of low cost of abundant unlicensed spectrum resource, high-speed transmission rate, and its wide-coverage communication ranges matches the needs of vehicular connectivity quite well, which provides a significant new opportunity to offload vehicular data traffic from cellular networks in a cost-effective way. However, dynamic TV white space availability with spatial-temporal variation, symmetric uplink/downlink transmit power constraints, high vehicular mobility, and severe vehicular access environments due to increased contention, would make TV white space enabled connected vehicular communication challenging. It is strategic to consider a more effective multi-tier offloading framework, in which cellular networks, DSA over TV white space, and WiFi networks can work coordinately to provide different levels of broadband access in terms of data rate and spectrum availability. Each vehicle can independently employ multiple data pipes for vehicular communications depending on the time and location, including the widely available high-speed data pipe over cellular band, the high data rate but limited-coverage data pipe over the ISM band, and the opportunistic data pipe over TV white space with a much larger coverage area and moderate data rate.

Considering the heavy vehicular traffic case and channel contention nature of the distribut-

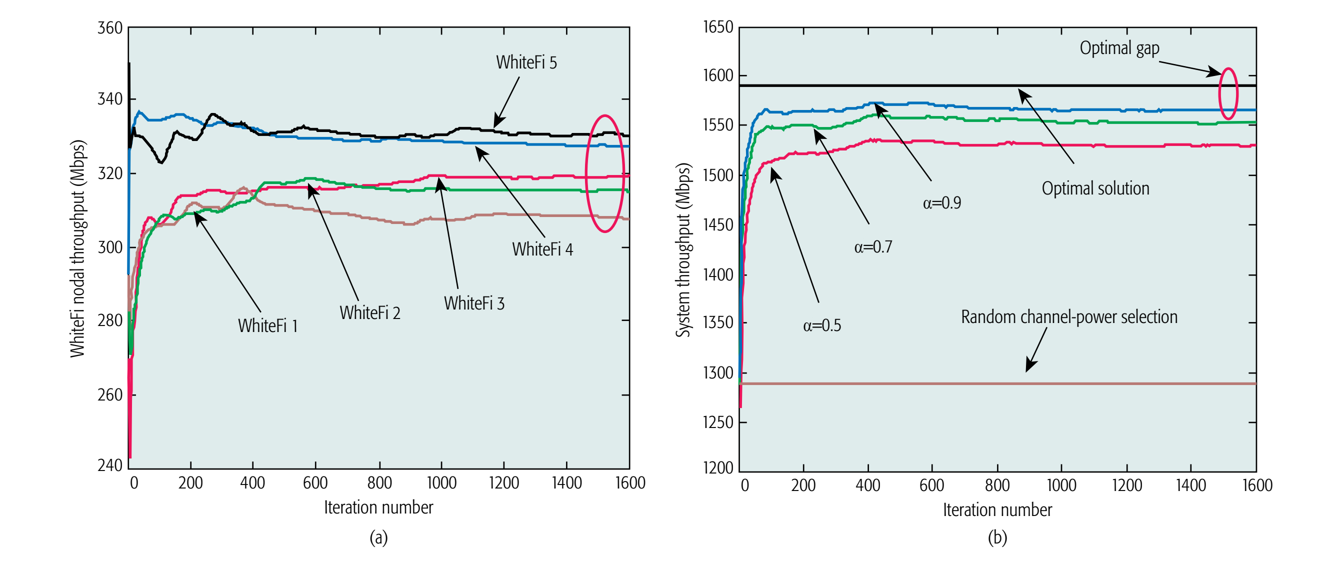

FIGURE 6. Distributed Markov approximation based dynamic TV white space planning: a) the average WhiteFi nodal throughput with 2-frequency configuration; b) the average WhiteFi network throughput with 10 nodes and single-frequency configuration.

To effectively offload cellular networks for vehicular applications through adaptive data piping in a multi-tier offloading framework, the noncooperative game approach can be leveraged to make adaptive data pipe selection and improve vehicular communication performance.

ed coordinated function (DCF), the ISM band based data pipe can sometimes severely suffer from performance deterioration. In addition, local white spaces availability is spatial-temporal varied. Therefore, it is highly motivated to guide a number of vehicles to dynamically share the same set of white space channels by utilizing white space data pipes in the V2V communications throughput optimization. To effectively offload cellular networks for vehicular applications through adaptive data piping in a multi-tier offloading framework, the noncooperative game approach can be leveraged to make adaptive data pipe selection and improve vehicular communication performance. Denote A_d and A_w as the vehicular user set using the ISM band based data pipe and the white space based data pipe, respectively. Taking into account vehicle mobility, user preferences and requirements, and network operation policies from the service providers, the vehicular selection strategy set can be denoted by $\mathcal{M}_j$ of vehicle j, i.e.,

$$Mj = \left\{ \eth^{j}_{A_w}, \eth^{j}_{A_d} \right\}, j \in \mathcal{N}.$$

We can formulate the adaptive data pipe selection process as follows:

$$\max_{a_j \in M_j} \mathbb{U}_j\left(a_j, a_{-j}\right) = \begin{cases} \mathbb{E}^{j}_{A_d}, j \in A_d \\ \mathbb{E}^{j}_{A_w}, j \in A_w \end{cases}, j \in \mathcal{N} \quad (2)$$

where $\mathbb{U}_j(a_j, a_{-j})$ is the utility function of vehicle j with data pipe selection strategy a_j, and $\mathbb{E}^j_{Ad}$ and $\mathbb{E}^j_{Aw}$ are the potential utilities by employing the two types of data pipes, respectively.

Conclusion

In this article, we have introduced various vehicular application scenarios in heterogenous connected vehicle networks, and empirically presented the unique characteristics of TV white space in the geolocation database. Moreover, we have proposed two types of TV white space geolocation database based vehicular communication architectures for both V2I communications and V2V communications. Lastly, we have highlighted key technical challenges and pinpointed future research directions in this regard. We believe that this study will shed light on TV white space enabled connected vehicle networks and promote the advance and development of future connected vehicles.

Acknowledgment

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