Connected Vehicles: Solutions and Challenges

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***Abstract*—Providing various wireless connectivity for vehicles enables the communication between vehicles and their internal and external environments. Such a connected vehicle solution is expected to be the next frontier for automotive revolution and the key to the evolution to next generation intelligent transportation systems. Moreover, connected vehicles are also the building blocks of emerging Internet of Vehicles (IoV). Extensive research activities and numerous industrial initiatives have paved the way for the coming era of connected vehicles. In this paper, we focus on wireless technologies and potential challenges to provide vehicle-to-x connectivity. In particular, we discuss the challenges and review the state-of-the-art wireless solutions for vehicle-to-sensor, vehicle-to-vehicle, vehicle-to-Internet, and vehicle-to-road infrastructure connectivity. We also identify future research issues for building connected vehicles.**

***Index Terms*—Connected vehicles, Internet of Vehicles, intra-vehicle wireless sensor networks, vehicular networks, intelligent transportation systems.**

I. Introduction

As an indispensable part of modern life, motor vehicles have continued to evolve since they were invented in the Second Industrial Revolution. Nowadays, people expect more than vehicle quality and reliability. With the rapid development of information and communication technologies (ICT), equipping automobiles with wireless communication capabilities is expected to be the next frontier for automotive revolution. Connected vehicles on the go are proactive, cooperative, well-informed, and coordinated, and will pave the way for supporting various applications for road safety (e.g., collision detection, lane change warning, and cooperative merging), smart and green transportation (e.g., traffic signal control, intelligent traffic scheduling, and fleet management), location dependent services (e.g., point of interest and route optimization), and in-vehicle Internet access. The market of connected vehicles is booming, and according to a recent business report, the global market is expected to reach USD 131.9 billion by 2019 [1]. Academia and the automotive industry are responding promptly by exploring reliable and efficient connectivity solutions.

There are two immediate driving forces of bringing wireless connectivity to vehicles. The first one is the urgent need to improve efficiency and safety of road transportation systems. Growing urbanization yields an increasing population of vehicles in large cities, which is responsible for traffic congestion and the consequences in terms of huge economic cost and environmental problems. It is reported that the cost of extra travel time and fuel due to congestion in 498 U.S. urban areas was already USD 121 billion in 2011, and CO_2 produced during congestion was 56 billion pounds, compared to USD 24 billion and 10 billion pounds in 1982, respectively [2]. Connected vehicle solutions are very promising to alleviate traffic congestions via intelligent traffic control and management [3], as well as to improve the road safety via on-board advanced warning and driving assistance systems [4]. The second one is the ever-increasing mobile data demand of users on road. In recent years, the demand for high-speed mobile Internet services has increased dramatically. People in their own cars expect to have the same connectivity as they have at home and at work. Connecting vehicles to the Internet can be envisioned not only to meet the mobile data demand [5], but also enrich safety-related applications, such as online diagnosis [6], and intelligent anti-theft and tracking [7], in which the servers can be on the Internet cloud. Internet-integrated vehicles have hit the road, and it is predicted that the percentage of Internet-integrated vehicle services will jump from 10% today to 90% by 2020 [8]. In addition, government mandate has put the connected vehicle revolution on the fast track. The European Commission proposed to implement a mandatory "eCall" system in cars from 2015, by which cars can automatically establish a telephone link for emergency services in case of a collision [9]. Not surprisingly, the U.S. Department of Transportation's (DOT) National Highway Traffic Safety Administration (NHTSA) recently announced that it will start taking steps to enable communications between light vehicles [10].

Connected vehicles refer to the wireless connectivity enabled vehicles that can communicate with their internal and external environments, i.e., supporting the interactions of V2S (vehicle-to-sensor on-board), V2V (vehicle-to-vehicle), V2R (vehicle-to-road infrastructure), and V2I (vehicle-to-Internet), as shown in Fig. 1. These interactions, establishing a multiple levels of data pipeline to in-vehicle information systems, enhance the situational awareness of vehicles and provide motorist/passengers with an information-rich travel environment. Further, connected vehicles are considered as the building blocks of the emerging Internet of Vehicles (IoV), a dynamic mobile communication system that features gathering, sharing, processing, computing, and secure release of information and enables the evolution to next generation Intelligent Transportation Systems (ITS) [11]. The development and deployment of fully connected vehicles requires a combination of various off-the-shelf and emerging technologies, and great uncertainty remains as to the feasibility of each technology. In this paper, we focus on the wireless technologies and present an overview of industrial and academic advances for establishing vehicle-to-x (V2X) connectivity. The pros and cons of each option are presented to demonstrate its feasibility. We also discuss the

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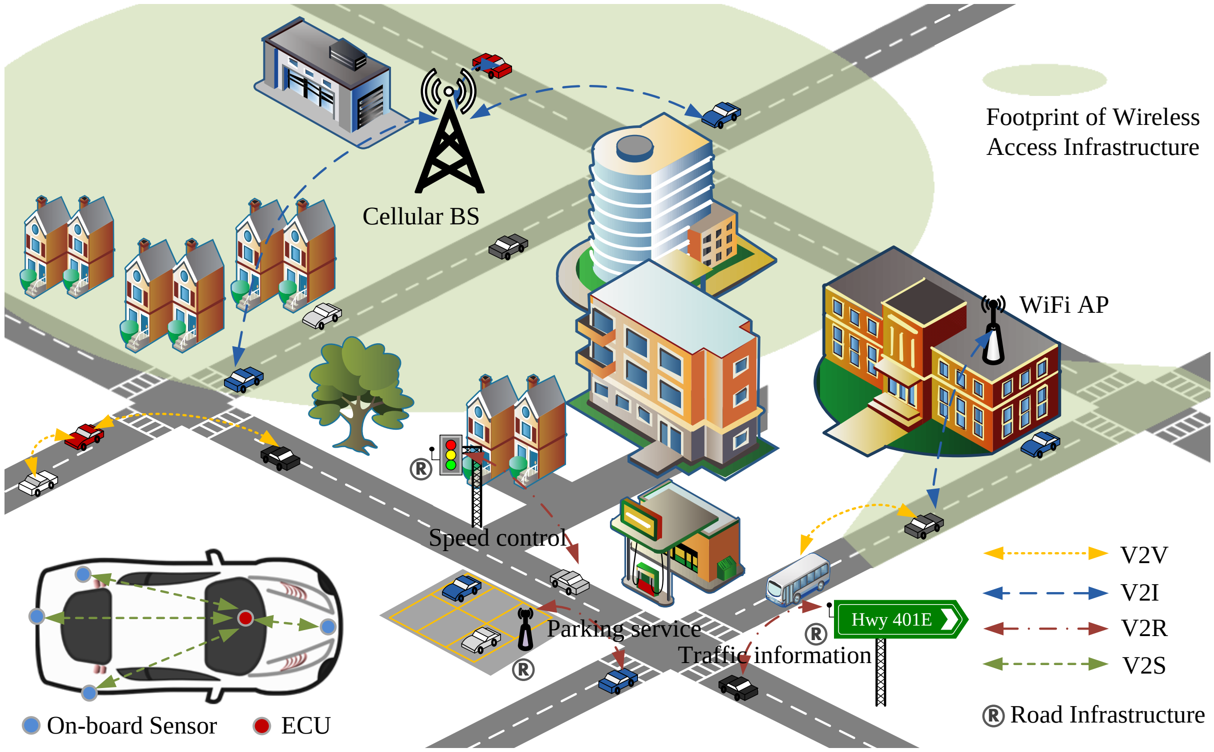

Fig. 1. Overview of Connected Vehicles

potential challenges and identify research issues in building vehicular connectivity. Our goal is to further promote the importance and research activities in the field of connected vehicles. The literature [12] and [13] serve as similar goal, but with different focus.

The remainder of the paper is organized as follows. Section II discusses the challenges and existing/potential solutions to intra-vehicle connectivity. Section III focuses on inter-vehicle connectivity. The V2I and V2R connectivity solutions are presented in Section IV and Section V, respectively. Section VI discusses further challenges and provides concluding remarks.

II. Intra-vehicle Connectivity

With increasing intelligence, modern vehicles are equipped with more and more sensors, such as sensors for detecting road conditions and driver's fatigue, sensors for monitoring tire pressure and water temperature in the cooling system, and advanced sensors for autonomous control. The number of sensors is forecasted to reach as many as 200 per vehicle by 2020 [14]. Such a big quantity of sensing elements are required to report event-driven or time-driven messages to the electrical control units (ECU) [15] and receive feedback if necessary. To do so, an intra-vehicle communication network should be carefully designed. Wired solutions [16], [17], such as Controller Area Network (CAN) protocol, FlexRay, and TTEthernet, require cable connections between ECU and sensors. Cables and other accessories nowadays can add significant weight (up to 50 kg) to the vehicle mass [12]. Moreover, the installation and maintenance of aftermarket sensors (providing add-on functions) are inconvenient by using cable connection. Recent advances in wireless sensor communication and networking technologies have paved the way for an intriguing alternative, where ECU and sensors are composed of an intra-vehicle wireless sensor network, leading to a significant reduction of deployment cost and complexity. There exist multiple candidate wireless technologies to build intra-vehicle wireless sensor networks, and the feasibility of different wireless options to in-vehicle environments has been a research focus.

A. Characteristics and Challenges

Different from generic wireless sensor networks, intra-vehicle wireless sensor networks show unique characteristics that provide the space for optimization.

- Sensors are stationary so that the network topology does not change over time;
- Sensors are typically connected to ECU through one hop, which yields a simple star-topology; and
- There is no energy constraint for sensors having wired connection to the vehicle power system.

In spite of favorable factors, the design and deployment of intra-vehicle wireless sensor networks are still challenging: (i) the intra-vehicle communication environment is harsh due to severe scattering in a very limited space and often none-line-of-sight. This is the major reason for extensive effort to characterize the intra-vehicle wireless channels [18], [19]; (ii) data transmissions require low latency and high reliability to satisfy the stringent requirement of real-time intra-vehicle control system; (iii) interference from neighboring vehicles in a highly densed urban scenario may not be negligible; and (iv) security is critical to protect the in-vehicle network and control system from malicious attacks [20]. In face of these challenges, the intra-vehicle wireless sensor network has become a research focus in the area of intelligent vehicle systems, and the following wireless technologies have been investigated extensively in the literature.

B. State-of-the-art Alternatives

Bluetooth: Bluetooth is a short-range wireless technology based on the IEEE 802.15.1 standard and operating in the industrial, scientific and medical (ISM) frequency band (2.4 GHz). It allows the communication between portable devices at a data rate up to 3 Mbps, and is highly commercialized for consumer electronics [21]. The Bluetooth devices are common in current automobiles, such as the Bluetooth headset and rearview mirror. However, the Bluetooth transmission requires a high power level so that it might not be viable for battery-driven sensors in vehicles [12]. Moreover, due to the poor scalability, a Bluetooth network can only support eight active devices (seven slave devices and one master device) [22].

ZigBee: One option for enabling the V2S connectivity is through the use of ZigBee technology, which is based on the IEEE 802.15.4 standard and operates on the ISM radio spectrum (868 MHz, 915 MHz, and 2.4 GHz) [28]. As the first attempt to evaluate ZigBee performance in an in-vehicle environment, research in [29] reports the results of packet transmission experiments using ZigBee sensor nodes within a car under various scenarios (considering different sensor locations and ON/OFF status of the vehicle engine). This study demonstrates that ZigBee is a viable and promising solution for implementing an intra-vehicle wireless sensor network. ZigBee is low-cost and can provide an acceptable data rate (250 Kbps in 2.4 GHz frequency band). As stated in [29], however, the challenge of implementing ZigBee sensors is to combat the engine noise and interference from Bluetooth devices. In [30], the performance of ZigBee intra-vehicle sensor networks is thoroughly studied in the presence of Bluetooth interference, based on a realistic channel model. Data latency of in-vehicle sensor applications is an important network design consideration. To meet the hard latency requirements, [31] derives necessary design parameters of medium access control (MAC) protocol based on a star topology. A thorough analysis of transmission latency of using ZigBee is conducted in [15]. In addition, engineering issues, such as the interactions with the existing CAN backbone, are also discussed in [15].

RFID: The feasibility of using the radio-frequency identification (RFID) technology for building intra-vehicle sensor networks is studied in [25] and [32]. The rationale of the considered passive RFID solution is that each sensor is equipped with an RFID tag and a reader connected to the ECU periodically retrieves the sensed data by sending an energizing pulse to each tag. Extensive experiments have been conducted in these two studies for understanding the capabilities and limitations of RFID technology, including the wireless channel characteristics between the reader and RFID tags at different locations, packet reception rate, and maximum packet delay. The passive RFID solution has obvious advantages: low cost and no power supply to RFID tags. Moreover, the experiments show promising results in terms of the coherence bandwidth and the transmission reliability. These studies also identify two major challenges: (i) connection outage due to large power loss at some locations; and (ii) difficulty to guarantee the critical data transmission due to collisions among simultaneous transmissions. The suggested solution to address challenge (i) is to use advanced antennas or the active RFID technology [33] (additional wires to vehicle battery are required); and for the second challenge, efficient and reliable MAC protocols [34] should be developed for the RFID sensor network.

Ultra-Wideband: Ultra-wideband (UWB) refers to radio technology that operates in the 3.1–10.6 GHz frequency band (an astonishing bandwidth of 7.5 GHz) and can support short range communications at a data rate up to 480 Mbps and at a very low energy level [12]. UWB systems have a number of unique advantages, such as resistance to severe wireless channel fading and shadowing, high time domain resolution suitable for localization and tracking applications, low cost, and low processing complexity [35]. UWB has been adopted as a key physical (PHY) layer technology in the ECMA-368 standard specified by the WiMedia Alliance [26]. For intra-vehicle scenarios, extensive research [36]–[44] has demonstrated the feasibility of UWB technology for satisfying the stringent reliability and energy requirement of on-board sensor networks. The design and implementation of an intra-vehicle UWB communication testbed is reported in [36]. The testbed is built to transmit automotive speed data from four wheel speed sensors to the ECU. The measurement result shows a high data delivery reliability. Most of the existing works [37]–[43] aim at proposing appropriate channel models which can capture the propagation characteristics of in-vehicle environments. These studies focus on different parts of the vehicle, including passenger compartment [37], [41], engine compartment [38], [40], trunk [39], and locations beneath the chassis [40], [42], [43], as the channel statistics are quite different from location to location. Recent measurement study [43] also models small-scale fading within the vehicle which has not been considered before. Given an underlying wireless model, how to define the most suitable transmission techniques at PHY layer is a critical issue for UWB-based intra-vehicle sensor networks. [44] is the first attempt to investigate optimal power control, rate adaptation, and scheduling in this regard.

60 GHz Millimeter Wave: Communications at 60 GHz band, often referred to as millimeter-wave (mmWave) communications, pave another way for building intra-vehicle connectivity. Operating in the frequency band between 57 and 64 GHz, mmWave communications can support multi-Gbps wireless connections in a short range for bandwidth-intensive multimedia applications [45]. mmWave-based PHY layer has been specified in the IEEE 802.15.3c [46] and the IEEE 802.11ad [47]. There has been increasing research interest in applying mmWave communication technology to multimedia transmission in the intra-vehicle environment, such as high definition video transmission for seat-monitor in the vehicle. As the propagation loss becomes more serious in 60 GHz frequency band, the first and foremost is to gain a better understanding of propagation characteristics inside the vehicle. Propagation measurement campaigns have been performed in [48]–[51], to investigate the small-scale parameters [48]–[50],

TABLE I
SUMMARY OF FEATURES OF EXISTING ALTERNATIVES

Wireless solution	Bluetooth [23]	ZigBee [24]	Passive RFID [25]	UWB [26]	60 GHz mmWave [27]
Frequency Band	2.4 GHz	868 MHz, 915 MHz, 2.4 GHz	915 MHz	3.1–10.6 GHz	57–64 GHz
Data Rate	1, 2, 3 Mbps	20–250 kbps	$<$ 4 Mbps	53.3–480 Mbps	$>$ 1 Gbps
TX Power	1, 2.5, 100 mw	$<$ 1 mw	0	1mw/Mbps	10 mw
MAC Protocol	TDMA	CSMA/CA	EPCglobal	CSMA/CA &TDMA	CSMA/CA &TDMA
Modulation	GFSK (1 Mbps) $\pi/4$-DQPSK (2 Mbps) 8DPSK (3 Mbps)	BPSK (868 MHz) BPSK (915 MHz) O-QPSK (2.4 GHz)	BPSK	MB-OFDM	Single carrier, OFDM
Application	Multimedia	Monitoring/Control	Monitoring/Control	Multimedia	Multimedia

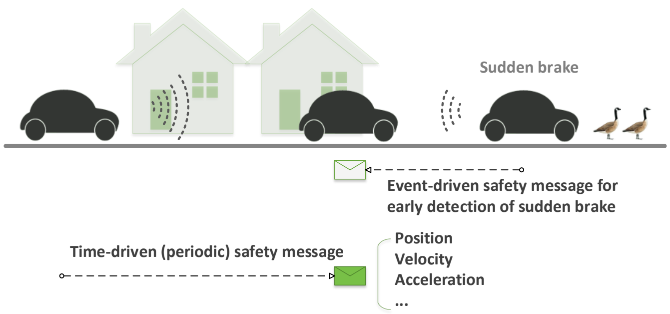

Fig. 2. Example of safety applications based on V2V communications.

the large-scale parameters [50], and the impact of passenger and antenna location [49], [51]. The results show that mmWave is a promising wireless solution for intra-vehicle multimedia transmissions. A summary of features of existing V2S solutions is shown in Table I.

III. INTER-VEHICLE CONNECTIVITY

It is widely believed that the advances of inter-vehicle communications will reshape the future of road transportation systems, where inter-connected vehicles are no longer information-isolated islands. By means of inter-vehicle communications or V2V communications, information generated by the vehicle-borne computer, control system, on-board sensors or passengers can be effectively disseminated among vehicles in proximity, or to vehicles multiple hops away in a vehicular ad hoc network (VANET). Without the assistance of any built infrastructure, a variety of active road safety applications (e.g., collision detection, lane changing warning, and cooperative merging) [52] and infotainment applications (e.g., interactive gaming, and file and other valuable information sharing) [53] are enabled by inter-vehicle wireless links.

A. *Characteristics and Challenges*

VANETs have attracted extensive research attentions for many years, and how to establish efficient and reliable wireless links between vehicles is a major research focus.

The most cumbersome challenge is to combat the harsh communication environment. In urban scenarios, the line-of-sight (LOS) path of V2V communication is often blocked by buildings at intersections. While on a highway, the trucks on a communication path may introduce significant signal attenuation and packet loss [54]. Field tests in [55] demonstrate that multi-path fading, shadowing, and Doppler effects due to high vehicle mobility and the complex urban environment will lead to severe wireless loss, and with a large scale of vehicles transmitting simultaneously, the mutual interference plays an important role as well. Accurate modeling of the propagation environment is premier to design reliable V2V communication systems. [56] presents an overview of the state of the art of the vehicular channel measurements. It is noteworthy that there is a lack of unified channel model that can be applied for all scenarios (e.g., urban, rural, and highway), and the existing channel models, only for a specific scenario, have their own merits and deficiencies. [56] also provides suggestions for V2V communication systems based on the channel characterization. For example, the adoption of multiple antennas would enhance the communication reliability.

From a network perspective, compared to typical low-velocity nomadic mobile communication systems, VANETs also present unique characteristics that have a significant impact on inter-vehicle connectivity.

- The network topology changes frequently and very fast due to high vehicle mobility and different movement trajectory of each vehicle;
- Due to the high dynamics of network topology and limited range of V2V communication, frequent network partitioning can occur, resulting in data flow disconnections; and
- Surrounding obstacles (e.g., buildings and trucks) can lead to an intermittent link to a mobile vehicle.

In addition to the technical challenges, the following features can benefit inter-vehicle communications: (i) the vehicle mobility is map-restricted and can be predicted in a certain time interval to a certain degree; (ii) there is no power constraint on communications and each vehicle can have relatively powerful processing capability; and (iii) with the aid of Global Positioning System (GPS), vehicles can locate themselves with an error up to a few meters.

The academia, industry, and government institutions have initiated numerous activities in the area of VANETs. An overview of the current and past major related projects in the USA, Japan, and Europe can be seen in [57]. The standards and standardization process of VANETs are given in [58], [59]. There have been significant research efforts in the past decade for the development of VANETs, including comprehensive surveys (e.g., [57] and [60]). Within the scope of this paper, we only review the options of wireless technology for enabling inter-vehicle communications.

B. DSRC/WAVE

Dedicated Short-Range Communications (DSRC) is a key enabling wireless technology for both V2V and V2R communications. The U.S. Federal Communication Commission (FCC) has allocated 75 MHz bandwidth at 5.9 GHz spectrum band for DSRC. The dedicated bandwidth is further divided into seven channels to support safety and non-safety services simultaneously. The specifications of DSRC are in the IEEE Standard for Wireless Access in Vehicular Environments (WAVE), including the IEEE 802.11p for PHY and MAC layers and the IEEE 1609 family for upper layers. Many automotive and ICT manufacturers, academia, and governments have responded positively and are actively working in collaboration to bring this promising technology to fruition. There have been extensive research efforts from academia to characterize communication properties of DSRC [55], [61]–[65], and to enhance DSRC performance both in the PHY layer and MAC layer [66]–[69].

PHY Layer: DSRC PHY layer adopts almost the same Orthogonal Frequency Division Multiplexing (OFDM) modulation as the IEEE 802.11a/g standard and is able to support a data rate of 3–27 Mbps on a 10 MHz channel [58]. Though simulation [61], empirical study [62], and measurement campaigns [55], [63], the performance of DSRC PHY layer has been well understood. Although several research works have demonstrated that DSRC PHY layer is adequate to support safety message delivery, many challenges remain, such as (i) reliable communication is not guaranteed especially when the LOS path is obstructed or the delay spread of wireless channel is too large [64]; (ii) cross-channel interference introduces performance penalty when two adjacent channels are operated simultaneously [58]; and (iii) a gray-zone phenomenon is particularly observed in [63], i.e., the behavior of intermittent loss rate during the transmission. To well fit the vehicular environment, DSRC PHY layer is required to keep evolving. More challenges in this evolution are discussed in [64], such as the difficulty in estimating the channel condition accurately. Some guidelines for OFDM system design in the DSRC PHY layer are also given in [56], such as a suggestion of a modified pilot pattern to reduce receiver complexity.

MAC Layer: Dissemination of safety messages, either time-driven (periodic) or event-driven (as shown in Fig. 2), is mostly based on one-hop broadcast, i.e., distributing the same safety message to all the nodes within the communication range, and requires low latency and high reliability, e.g., the dissemination of emergency braking message. However, based on the legacy IEEE 802.11 distributed coordination function (DCF), the current version of DSRC MAC is contention-based and thereby does not support efficient and reliable broadcast services. Specifically, the poor performance of the DSRC MAC in supporting safety applications is mainly due to the high collision probability of the broadcasted packets. For unicast communications using DSRC MAC, the collision probability of two or more transmissions is reduced by the adoption of a two-way handshaking mechanism, i.e., request-to-send/clear-to-send (RTS/CTS), before the actual data is transmitted. However, the RTS/CTS mechanism and the acknowledgement from data recipients (ACK) are not implemented for broadcast services. As time division multiple access (TDMA) is capable of controlling channel access more precisely, by which the vehicle only needs to listen and broadcast during the acquired time slot, many alternatives have been proposed to guarantee the quality of service (QoS) of safety and other real-time applications in highly densed vehicular scenarios based on TDMA, such as the MAC protocols proposed in [66]–[69].

TABLE II
COMPARISON OF DSRC AND DSA [70] SYSTEM PARAMETERS

Parameter	DSRC	DSA
Frequency Band	5.850–5.925 GHz	476–494MHz
Channel Bandwidth	10 MHz	1 MHz
Data Rate	3–27 Mbps	1 Mbps
Modulation	BPSK, QPSK, 16QAM and 64QAM	GMSK
TX Power	33 dBm	16 dBm
MAC Protocol	CSMA/CA-based	Simplified CSMA/CA

C. Dynamic Spectrum Access

In spite of the DSRC spectrum, V2V communications still face the problem of spectrum scarcity due to the following reasons: (i) the ever-increasing infotainment applications, such as high-quality video streaming, require a large amount of spectrum resource, and thereby the QoS is difficult to satisfy merely by the dedicated bandwidth; and (ii) in urban environments, the spectrum scarcity is more severe due to high vehicle density, especially in some places where the vehicle density is much higher than normal [71], [72]. Numerical study [73] has reported the limitation of the dedicated spectrum in supporting the increasing demand of V2V applications.

Due to recent advances in cognitive radio, dynamic spectrum access (DSA) is becoming a possible complementary technology for DSRC. DSA allows vehicles to communicate opportunistically on spatially and/or temporally vacant licensed spectrum for other communication systems [74]. The feasibility of using TV white space for V2V communications has been demonstrated in [70], [75], [76] recently. TV white space refers to unused television spectrum between 54 MHz and 698 MHz, and provides superior propagation and building penetration compared to the DSRC frequency band [77]. It is noteworthy that the IEEE has standardized the IEEE 802.11af [78] and the IEEE 802.22 [79] based on DSA on TV white space for wireless local area network (WLAN) and wireless regional area network (WRAN), respectively.

The first measurement campaign of V2V cognitive communication between two moving vehicles over TV white space is reported in [75], followed by [76] and [70] where multi-hop inter-vehicle communications are considered. The implemented DSA system consists of three subsystems: the

TABLE III
SUMMARY OF INDUSTRIAL SOLUTIONS

Manufacturer	Solution	Type of Solution	Featured Application	Additional Payment
BMW	ConnectedDrive	Built-in	Mobile office and WiFi hotspot	Subscribed
Audi	Audi Connect	Built-in	Google Earth	Subscribed
Ford	SYNC	Brought-in	Audible text messaging	No
Toyota	Touch 2	Brought-in	Application Suite	No
Volvo	Apple CarPlay	Brought-in	App Store and Siri voice control	No
GM	OnStar	Brought-in	Emergency and Security	Subscribed

two-layer control channel subsystem, the multi-hop data communication subsystem, and the spectrum sensing and channel switching subsystem. The system parameters compared to DSRC system are given in Table II. In terms of the availability of TV spectrum, a general geo-location database approach is proposed in [80] to create a spectral map of available channels in a given geographical area. Preliminary results from [70], [75], [76], [80] have demonstrated a great potential of DSA over TV white space to solve the expected spectrum shortage, for example, to meet the communication need for a platoon of vehicles on a highway. This is the first step towards a heterogeneous spectrum for inter-vehicle communications. Technical challenges remain, such as the design of efficient MAC protocol with QoS provisioning for both safety and infotainment applications.

IV. V2I CONNECTIVITY

Internet connectivity is becoming a must-have feature of modern vehicles. The industry has responded promptly by using off-the-shelf technologies, aiming to build a huge mass market of Internet-connected cars, whereas the academia focuses on the development of optimal solutions to enable connections between vehicles and the Internet. Wireless access technologies play a vital role in delivering the Internet services to vehicle users. Cellular and WiFi are two promising candidates. The cellular networks, such as 3G and 4G-LTE, can provide reliable and ubiquitous access services. The feasibility of using low-cost roadside WiFi access point (AP) for outdoor Internet access at vehicular mobility has also been demonstrated in [81]. We first review the up-to-date status of industrial progress, and then discuss research issues towards efficient and robust V2I connectivity.

A. Industrial Solutions

Earliest concepts of Internet-enabled vehicles were proposed in 1990s in the literature, such as "the Internet multimedia on wheels" [82], "web on wheels" [83], and "the network vehicle" [84]. Nowadays, Internet-integrated vehicle is no longer conceptual due to numerous initiatives in the automotive, telecommunications, and consumer electronics industry. Existing solutions connect vehicles to the Internet through widely deployed cellular network infrastructure, and can be divided into two categories, i.e., brought-in and built-in, advocated by different automobile manufacturers.

Brought-in Connectivity: The brought-in option caters to 3G/4G mobile users who prefer tethering their own smart phone to the car. The most popular tethering technology, namely *MirrorLink*, is powered by Car Connectivity Consortium (CCC) [85], an organization calling leading automobile (e.g., Volkswagen and Toyota) and ICT manufacturers (e.g., Sony and Nokia) together to create a phone-centric car connectivity solution. By using MirrorLink, a device interoperability standard in essence, the motorist/passengers in a vehicle can connect the phone to the vehicle infotainment system via wires (e.g., USB) or wirelessly (e.g., WiFi or Bluetooth), so that the vehicle gains immediate access to the Internet and some duplicate functions of smart phones. MirrorLink-enabled vehicle infotainment systems are already in the market, such as Toyota Touch 2 [86]. For iPhone users, especially, Apple recently released CarPlay [87] as a standard of tethering iPhone to cars. In addition to smart phones, Internet connectivity can also be brought in the vehicle by aftermarket devices, such as GM OnStar [88]. OnStar uses a built-in cell phone to communicate with the outside world, and provides subscription-based services, such as voice calls, emergency services, and Internet access. The advantage of aftermarket devices is that the vehicle does not need to have an pre-embedded infotainment system.

Built-in Connectivity: Built-in option integrates cellular service in the on-board infotainment system. The Internet connection relies on the built-in cellular module, rather than smart phones of motorist/passengers. For example, through built-in cellular communications, BMW ConnectedDrive [89] combines various elements from online applications, driver assistance, call center services, and solutions to providing Internet connection for in-vehicle mobile devices. Audi connect [90] is another example of built-in solution. Especially, by using the state-of-the-art cellular technology, the concept of LTE connected car is emerging, which is to connect the cars to the Internet through the 4G-LTE cellular network. Compared to the 3G cellular service, LTE can offer ultra-high speed, high-bandwidth connectivity, and lower cost. NG connected program is conceived and founded by Alcatel-Lucent to lead the research and development of LTE connected cars [91]. Verizon Wireless recently has also aggressively pursued its LTE-connected-car strategy to power future automotive telematics applications. The best way to enable Internet connectivity in vehicles is still in debate. Built-in options could provide motorist/passengers with stronger connections and customized services compared to brought-in options. The limitation is that the cellular connectivity cannot evolve once it is embedded. A summery of a few cellular-based industrial solutions is shown in Table III.

TABLE IV
SUMMARY OF REAL-WORLD MEASUREMENT RESULTS

Measurement	Scenario	Connection Time	Maximum Rate	Data Transfer in One Drive-Thru
[92]	Highway	9s at 80 km/h	TCP: 4.5 Mbps UDP: 5 Mbps	TCP: 6 MB at 80 km/h, 1.5 MB at 180 Km/h TCP: 8.8 MB at 80 km/h, 2.7 MB at 180 Km/h
[93]	Highway	N/A	15 Mbps	Maximum 110 MB
[94]	Traffic free road	217s at 8 km/h 13.7s at 120 km/h	TCP: 5.5 Mbps UDP: 3.5 Mbps	92 MB at 8 km/h, 6.5 MB at 120 km/h
[95]	Highway	58s	TCP: 27 Mbps	Median 32 MB
[81]	Urban	13s	240 kbps	Median 216 KB
[96]	Urban	N/A	86 kbps	Median 32 MB

B. Drive-Thru Internet

As a popular wireless broadband access technology, WiFi, operating on the unlicensed spectrum, offers the "last-hundred-meter" backhaul connectivity to private or public Internet users. With millions of hotspots deployed all over the world, WiFi can be a complementary solution to vehicular Internet access with low cost. Recent research has demonstrated the feasibility of WiFi for outdoor Internet access at vehicular mobility [81]. The built-in WiFi radio or WiFi-enabled mobile devices in the vehicle can access the Internet when the vehicle is moving in the coverage of WiFi hotspots, which is often referred to as the *drive-thru Internet* [92], as shown in Fig. 3. This kind of WiFi access is deployable to offer a low-cost data pipe for vehicle users, and recent advances in Passpoint/Hotspot 2.0 make WiFi more competitive to provide secure connectivity and seamless roaming [97]. Moreover, with the increasing deployment of the urban-scale WiFi network (e.g., Google WiFi in the city of Mountain View), there would be a rapid growth in drive-thru Internet connectivity.

Characteristics and Challenges*:* Unlike an indoor WiFi network which only serves stationary or slow-moving users, unique characteristics of drive-thru Internet impose many challenges on reliable and robust Internet access. First of all, high vehicle mobility yields a very short connection time to the WiFi AP, e.g., only several tens of seconds, which greatly limits the amount of data transferred in one connection. For example, the overall connectivity range to a roadside AP is around 500–600 meters, corresponding to a connection time of 18–21 seconds for a vehicle moving at 120 km/h [92]. Moreover, time spent in WiFi association, authentication, and IP configuration before actual data transfer is not negligible. Secondly, V2I communications also suffer from high wireless loss due to the channel fading and shadowing [56]. Thirdly, the WiFi protocol stack is not a specific design for a high mobility environment.

Real-World Measurement*:* There have been a number of real-world measurements in the literature based on diverse testbed experiments to characterize and evaluate the performance of the drive-thru Internet. In [92] and [93], the drive-thru Internet based on the IEEE 802.11b and 802.11g is evaluated respectively in a planned highway scenario where two APs are closely deployed. Different vehicle speeds (80, 120, and 180 km/h) and different transport layer protocols (UDP and TCP) are considered. A very important observation is that the drive-thru Internet has a three-phase (*entry*, *production*, and *exit*) characteristic. In the entry and exit phases, vehicles

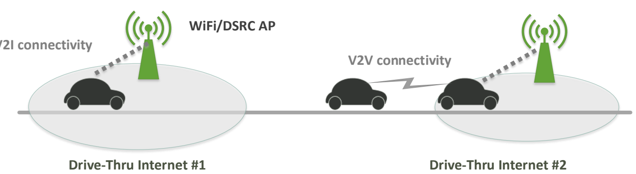

Fig. 3. An illustration of drive-thru Internet.

gain less throughput than when in production phase due to such as the weak signal, connection establishment delay, and rate overestimation. To investigate the impact of backhaul capability on drive-thru Internet, a measurement is conducted in [94] on a traffic free road where the interference from other vehicles does not exist. It is evidenced that the performance of the drive-thru Internet suffers a lot from the limitation of the backhaul network. For example, with a 1 Mbps bandwidth backhaul capability, the data volume transferred within a drive-thru reduces from 92 MB to 25 MB. Moreover, a backhaul connection with 100 ms one-way delay significantly degrades the performance of web services due to the time penalty of HTTP requests and responses. The problems that may cause the performance degradation of the drive-thru Internet are thoroughly discussed in [95]. Experiments in [81] and [96] are conducted for large-scale urban scenarios with multiple vehicles. The data sets used in the experiments are collected from the city of Boston with in situ open WiFi APs. It is shown that in [81] with a fixed 1 Mbps data rate, vehicles can gain a median upload throughput of 240 Kbps and a median one-drive-thru uploaded data volume of 216 KB. In addition, the average connection and inter-connection time are shown to be 13 seconds and 75 seconds, respectively. The experiment in [96] shows a long-term throughput of 86 kbps averaged over both connection and inter-connection periods. A summary of real-world measurement results is shown in Table IV.

Improvement Strategy*:* Due to high vehicle speeds, intermittent links, and potential severe channel contentions, the throughput of per drive-thru is limited as observed in real-world tests. It fundamentally restricts the QoS of data applications. To improve the performance of drive-thru Internet, solutions in the literature include: (i) reducing connection establishment time [96]; (ii) improving transport protocols to deal with the intermittent connectivity and wireless transmission losses [96]; (iii) enhancing MAC protocols for high mobility [95], [96], [98]; (iv) designing efficient handoff schemes to deal with the frequent disruptions [5]; (v) using the multi-hop

V2V communication capability for relaying data traffic [99], as shown in Fig. 3; (vi) exploiting cooperation among vehicles [100], [101]; and (vii) optimal deployment of WiFi APs [102].

C. Towards Cost-Effective Solutions

Cellular-based access technologies play a vital role in providing reliable and ubiquitous Internet access to vehicles, however, with relatively high cost both in terms of capital expenditures (CAPEX) and operational expenditures (OPEX) (resulting in an expensive cellular service). Although Roadside WiFi network can be a deployable solution, the problem of such a drive-thru access is that in-vehicle users may have to tolerate intermittent connectivity so as to compromise the users' satisfaction on QoS. Therefore, there remains great uncertainty as to the cost effectiveness in applying the existing solutions to deliver Internet services to highly mobile vehicles. On the other hand, as the explosive growth of mobile data traffic have already congested today's cellular networks, off-the-shelf cellular infrastructures might not be able to support a huge number of connected vehicles; in spite of free open WiFi network, the carrier WiFi, i.e., deployed by carrier operators, is also expected to provide more robust and secure Internet access. As the deployment and operation cost of the wireless network infrastructure is a dominant factor in bringing Internet on wheels into reality, developing innovative cost-effective vehicular networking solution to enable high-quality vehicular Internet access is of great importance.

Research to this end is quite limited. A head-to-head comparison of the performance characteristics of a 3G network and a metro-scale commercial WiFi network is performed in [103], and a hybrid network design is suggested to enhance the network performance. Fundamental relations between network throughput and infrastructure cost (CAPEX and OPEX) are established in [104] for cellular deployment and WiFi-based deployment, respectively. The WiFi-based solution is suggested for providing a cost-effective data pipe to vehicles, however, without considering service delay and opportunistic communications among vehicles. In addition to the cost-performance issue of network infrastructure, WiFi offloading strategy is also a research focus, which is to offload cellular traffic through WiFi networks so that the cellular congestion can be alleviated and the usage cost of access service can be reduced for mobile users. The performance of offloading cellular traffic via drive-thru Internet remains unclear in the literature. Such an opportunistic WiFi offloading has unique features. (i) a relatively small amount of data can be delivered to a vehicle in each drive-thru, due to the short connection time with WiFi APs; and (ii) the offloading performance can be significantly improved if the data service can be deferred for a certain time, as vehicles with a high speed can have multiple drive-thru opportunities in a short future. The challenges and solutions of WiFi offloading in a vehicular environment are discussed in [105].

V. V2R Connectivity

V2R connectivity is critical to avoid or mitigate the effects of road accidents, and to enable the efficient management of ITS. DSRC/WAVE is considered a key technology to enable connections between vehicles and ITS infrastructure, such as traffic lights, street signs, and roadside sensors. Moreover, roadside infrastructures can also be commercial content providers, such as the roadside unit (RSU) broadcasting flyers of superstores [106]. RSU does not necessarily serve as Internet gateway as wireless infrastructures in V2I communications. Visible light communication (VLC), transmitting data by using light-emitting diodes (LEDs), has also been proposed for road-to-vehicle ITS applications, such as traffic light control at intersections [107]–[109]. As a key technology specified in the IEEE 802.15.7 standard, VLC can support a data rate up to 96 Mbps through fast modulation of LED light sources [110]. VLC is becoming an intriguing complement to DSRC for light-of-sight communication scenarios. To combat outdoor optical noises, however, advanced receiver is required, such as high-speed camera [107], [108], which may incur a high implementation cost. Compared to the mature IEEE 802.11-based technology, VLC is still in the introductory phase and substantial efforts are needed before it can be widely deployed for short-range ITS applications.

VI. Conclusion

In this paper, we have presented an overview of the state-of-the-art wireless solutions to vehicle-to-sensor, vehicle-to-vehicle, vehicle-to-Internet, and vehicle-to-road infrastructure connectivity. We have discussed the potential challenges and identified the space for future improvement. The biggest challenge for efficient and robust wireless connections is to combat the harsh communication environment inside and/or outside the vehicle. In addition, the significant research and development efforts are required to deal with the following issues.

- To enable various wireless connectivity, multiple radio interfaces have to be implemented, such as DSRC/WAVE, WiFi, and 3G/4G-LTE interfaces, which may incur a high cost and thereby impede the development of connected vehicles. A unified solution to provide V2X connectivity with low cost might be required;
- In-vehicle systems have stringent requirement on latency and reliability for control/monitoring purposes. The full adoption of V2S connectivity may not be feasible in the near future unless V2S connectivity can provide the same performance and reliability as the wired communication [43]; and
- Connected vehicle offers the driver a variety of information. However, research in [111] and [112] suggests an up limit on information provided to the driver. Excessive information increases the driver's workload and hence has a negative impact on safety. Therefore, the vehicle information system has to be appropriately designed for offering information to drivers.

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