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# 6G for Vehicle-to-Everything (V2X) Communications: Enabling Technologies, Challenges, and Opportunities

*This article provides a comprehensive overview of the scientific and technological advances that have the capability to shape future 6G vehicle-to-everything (6G-V2X) communications.*

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**ABSTRACT** | We are on the cusp of a new era of connected autonomous vehicles with unprecedented user experiences, tremendously improved road safety and air quality, highly diverse transportation environments and use cases, and a plethora of advanced applications. Realizing this grand vision requires a significantly enhanced vehicle-to-everything (V2X) communication network that should be extremely intelligent and capable of concurrently supporting hyperfast, ultrareliable, and low-latency massive information exchange. It is anticipated that the sixth-generation (6G) communication systems will fulfill these requirements of the next-generation V2X. In this article, we outline a series of key enabling technologies from a range of domains, such as new materials, algorithms, and system architectures. Aiming for truly intelligent transportation systems, we envision that machine learning (ML) will play an instrumental role in advanced vehicular communication and networking. To this end, we provide an overview of the recent advances of ML in 6G vehicular networks. To stimulate future research in this area, we discuss the strength, open challenges, maturity, and enhancing areas of these technologies.

**KEYWORDS** | Blockchain; brain-controlled vehicle (BCV); federated learning; intelligent reflective surfaces (IRSs); machine learning (ML); nonorthogonal multiple access (NOMA); quantum; radio frequency (RF)-visible light communication (VLC) vehicle-to-everything (V2X); sixth-generation (6G)-V2X; tactile-V2X; terahertz (THz)

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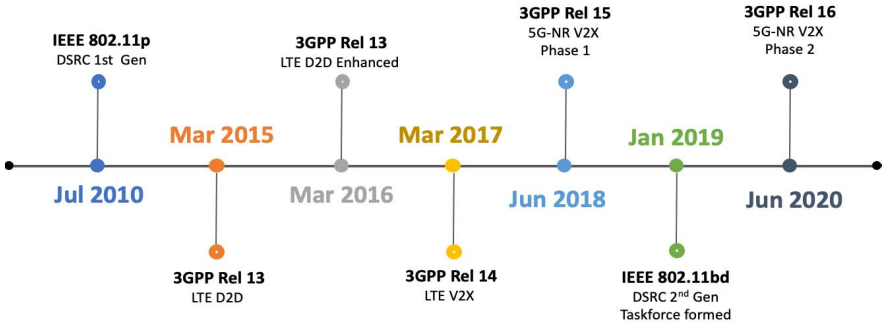


**Fig. 1.** ***Evolution of V2X communications.***

communications; unmanned-aerial-vehicle (UAV)/satellite-assisted V2X.

## I. INTRODUCTION

In recent years, vehicle-to-everything (V2X) communication has attracted significant research interest from both academia and industry. As a key enabler for intelligent transportation systems (ITSs), V2X encompasses a broad range of wireless technologies, including vehicle-to-vehicle (V2V) communications, vehicle-to-infrastructure (V2I) communications, and vehicle-to-pedestrian (V2P) communications, as well as communications with vulnerable road users (VRUs) and with cloud networks (V2N) [1]. The grand vision is that V2X communications, supported by the sixth generation (6G) of wireless systems [2], will be an instrumental element of future connected autonomous vehicles. Furthermore, V2X communications will bring far-reaching and transformative benefits, such as unprecedented user experience, tremendously improved road safety and air quality, diverse transportation applications and use cases, and a plethora of advanced applications.

So far, there have been two main technologies for V2X communications: 1) dedicated short-range communication (DSRC)-based vehicular network and 2) the cellular-based vehicular network [3]. Standards laying the foundation of DSRC include IEEE 802.11p for Wireless Access in Vehicular Environments (WAVE) and IEEE 1609.1.4 for resource management, security, network service, and multichannel operation [4]. For many years, DSRC was the only technology for V2X communication. In dense and high-mobility environments, however, DSRC suffers from major drawbacks, such as limited coverage, low data rate, limited quality-of-service (QoS) guarantees, and unbounded channel access delay. Leveraging standard cellular technologies, 3GPP has been developing a cellular vehicular communications standard, known as C-V2X. C-V2X enables every vehicle to communicate with different entities of a V2X network (such as V2V, V2I, V2P, and V2N) [5]. In March 2017, 3GPP Release 14 proposed LTE V2X communication with two air interfaces: a wide area network LTE interface (LTE-Uu) and a direct communications interface (PC5, also known as LTE side-link). The LTE-Uu is responsible for vehicle-to-network (V2N) communication, while the LTE side-link is responsible for V2V and V2I communications, which may operate without support from cellular network infrastructure [6]. The main focus of Release 14 is to deliver data transport services for fundamental road safety services, such as cooperative awareness messages (CAMs), basic safety messages (BSMs), or decentralized environmental notification messages (DENMs).

In Release 15 (announced in 2018), 5G New Radio (5G NR) V2X technology was introduced to support advanced V2X services, such as vehicle platooning, advanced driver assistance, remote driving, and extended sensors [7], [8]. In addition, the performance of the PC5 interface has been enhanced in Release 15 (known as LTE-eV2X) in terms of higher reliability (employing transmit diversity), lower latency (with the aid of resource selection window reduction), and higher data rates (using carrier aggregation and higher order modulation, e.g., 64-QAM) while retaining backward compatibility with Release 14 LTE-V2X. In 2020, 3GPP announced the second phase of 5G NR in Release 16, which aims at bringing enhanced ultrareliable low-latency communication (URLLC) and higher throughput. Note that 3GPP is currently working on Release 17, which aims to provide architectural enhancements to support advanced V2X services. The evolution of V2X communications is summarized in Fig. 1.

From an industry standpoint, there has been a major debate on which V2X technology should be adopted. Government regulations and public acceptance are two additional major factors that affect the real rollout of V2X technologies. Take the United States (U.S.) as an example, during the Obama administration, a mandate was proposed by the National Highway Traffic Safety Administration to support DSRC in all new vehicles, but no progress has been made during the Trump administration. Although Europe and Japan are in favor of DSRC, C-V2X has received tremendous support from the U.S. and China, mainly driven by large telecommunication companies, such as Qualcomm and Huawei, respectively. As a result, automakers may need to investigate and accommodate different V2X technologies according to their market shares in different jurisdictions and the interworking of both DSRC and C-V2X [9]. For instance, although Toyota was the first global automaker to sell connected vehicles equipped with DSRC technology, it is also testing C-V2X in China, and both DSRC and C-V2X in Australia [10]. In 2019,

Volkswagen, a German motor vehicle manufacturer, made a move to fully embrace DSRC [11], while Ford in the U.S. plans to enable all of its new vehicles to be able to "Talk and Listen" by 2022 through 5G NR-based C-V2X [12]. Road safety and traffic efficiency are two important aspects of public acceptance. Albeit autonomous vehicles have been actively studied and tested by companies such as Tesla, Uber, Waymo, and Toyota, the safety of driverless cars remains of utmost concern for the public, especially after the pedestrian death caused by a self-driving Uber car in 2018 and the Tesla car crash in 2021. Therefore, it is pressing for V2X to evolve to facilitate advanced orchestrations of communication, sensing, learning, and decision-making.

### A. Contribution and Organization

The main contribution of this article is a comprehensive overview of the scientific and technological advances that have the capability to shape future 6G-V2X communications. In contrast to the survey in [13], which focuses on the evolution of the two major V2X technologies (i.e., DSRC/802.11p-based V2X and C-V2X), as well as big-data-driven Internet-of-Vehicle (IoV) and cloud-based IoV, we take a forward-looking and inclusive approach from various perspectives (such as new materials, algorithms, and system structures), aiming to stimulate many forthcoming research activities for 6G-V2X and beyond. We also emphasize that the instrumental role machine learning (ML) will play for advanced use cases in future vehicular communication networking.

This article is organized as follows. We start our discourse in Section II with a high-level overview of 6G-V2X communications. Revolutionary 6G-V2X technologies, such as brain–vehicle interfacing, tactile communication, and terahertz (THz) communications, will be introduced in Section III. In Section IV, we present major 6G-V2X technologies (e.g., integrated localization and communications (ILACs), satellite/unmanned-aerial-vehicle (UAV)-aided V2X, and integrated computing) that have evolved over recent years and are going through further enhancements. The recent advances in ML for 6G vehicular networks are summarized in Section V. Finally, conclusions are drawn in Section VI.

## II. OVERVIEW OF 6G-V2X COMMUNICATIONS

This section first discusses why 6G-V2X is necessary and then summarizes key technologies that will enable 6G-V2X.

### A. Why 6G-V2X?

Although 5G-NR V2X offers improved performance with advanced services, its improved performance is achieved through investing more in spectral and hardware resources while inheriting the underlying mechanisms and system architectures of LTE-based V2X [14]. Meanwhile, it is anticipated that the number of autonomous vehicles will grow rapidly in the future due to urbanization, increased living standards, and technological advancements. This will drive explosive growth of communications devices and digital applications to enable intelligent autonomous vehicles. In addition, the rising demand for many emerging services in autonomous vehicles ranging from 3-D displays that offer more depth and more natural viewing experience and free-floating, to holographic control display systems, to immersive entertainment, and to improved in-car infotainment, will bring forth new communication challenges to the V2X network [14]–[18]. All these advances will drastically push the capacity limits of existing wireless networks, posing new scientific and technical challenges for vehicular networks in terms of data rate, latency, coverage, spectral/energy/cost efficiency, intelligence level, networking, and security, among others.

With this vision in mind, 5G NR-based V2X networks may be unable to meet such a wide range of requirements and use cases. Moreover, while the concepts associated with ITS have been studied for many years, legacy V2X communication systems can only provide limited intelligence. Therefore, a significant paradigm shift away from traditional communication networks to more versatile and diversified network approaches is needed. It is anticipated that such a transformation will start from the recently proposed 6G wireless communication network, which aims to combine terrestrial and several nonterrestrial communication networks, such as satellite and UAV communication networks. This will enable genuinely intelligent and ubiquitous V2X systems with significantly enhanced reliability and security, extremely high data rates (e.g., terabits per seconds), and massive and hyperfast wireless access (i.e., down to submilliseconds with billions of communications devices connected), as well as much smarter, longer, and greener (energy-efficient) 3-D communication coverage [2]. Because of the extremely heterogeneous network composition, diverse communication scenarios, and stringent service requirements, new techniques are needed to enable adaptive learning and intelligent decision-making in future V2X networks. It is foreseen that 6G will work in conjunction with ML not only to unfold the full capability of the radio signals by evolving to intelligent and autonomous radios but also to bring a series of new features, such as enhanced context-awareness, self-aggregation, adaptive coordination, and self-configuration [14].

### B. Key 6G-V2X Technologies

To achieve the aforementioned ambitious goals, 6G will require the integration of a range of disruptive technologies, including more robust and efficient air interfaces, resource allocation, decision-making, and computing. Fig. 2 illustrates such a 6G-V2X system where a range of vehicular communication technologies is adopted to serve various advanced use cases. For example, UAVs and low Earth orbit satellites can support V2X systems with significantly enlarged and seamless coverage, helping to

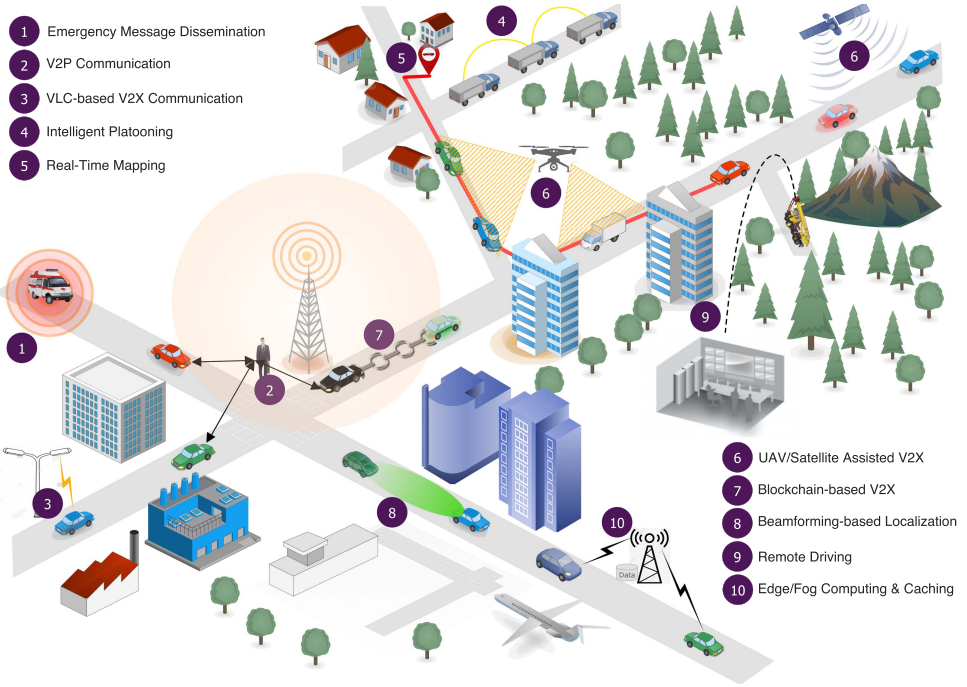


**Fig. 2.** ***Overview of V2X communications.***

enhance the communication QoS, particularly in certain blind spots that might exist in traditional terrestrial communication systems. Edge/fog computing and caching will help V2X communication devices achieve faster computation, optimized decisions, and longer battery life. Visible light communication (VLC)-aided V2X communications will operate along with traditional RF-based communications to achieve ultrahigh data rates, low setup cost, low power consumption, and enhanced security.

There is a range of key technologies that we believe will enable the future vision of 6G-V2X as an intelligent, autonomous, user-driven connectivity and service platform for ITS. We will introduce these technologies in the following with more detail in Sections III–V. We classify these technologies into two categories: *revolutionary* V2X technologies and *evolutionary* V2X technologies. Strength, open challenges, maturity, and enhancing areas of these technologies are summarized in Table 1. First, we consider technology areas, such as intelligent reflective surfaces (IRSs), a range of new ML techniques, and brain–vehicle interfacing as key enablers (from the perspectives of new materials, algorithms, and neuroscience, respectively) for more intelligent V2X, which will further enhance and revolutionize evolving V2X technologies. Tactile communication will provide drivers and passengers with an unprecedented travel experience in the future by exchanging sensory information, such as haptics anytime and anywhere. Emerging quantum computing technology will endow 6G-V2X systems with superior computational capabilities, while we will also see significantly enhanced security along with the use of blockchain technologies. Furthermore, THz communications will enable ultrahigh data rates never experienced before.

Here, the various technologies listed in Table 1 may interact with each other to deliver an unprecedented driving experience, especially for fully autonomous vehicles. First, many gigabits per second data rates can be enabled via millimeter-wave communication, VLC, and THz communications, whereas ultralow latency and reliable information exchange can be supported by multiple radio access technologies, new multicarrier scheme, and advanced resource allocation. For massive and ubiquitous vehicular access, nonorthogonal multiple access (NOMA) and satellite-/UAV-aided V2X are two promising wireless paradigms. In addition, integrated sensing, localization, and communication will contribute to cm-level positioning and cm/s-level velocity estimation accuracy; artificial intelligence and brain–vehicle interfacing will lead to augmented awareness of both the complex physical and electromagnetic environments.

For example, NOMA has been employed in [19] to support low-latency tactile internet for autonomous vehicles thanks to its enabling of massive connectivity and, thus, faster random access. In NOMA-based V2X, data security is a real issue as one user's decoding often involves the decoding of other users. Such an issue may be addressed by utilizing blockchain for secured networking, as reported in [20]. On the other hand, the low-latency nature of NOMA may help tackle the slow access problem in blockchain-based V2X networking, imposed by the inherent algorithm in attaining consensus among decentralized entities, such as vehicles and infrastructure. Also, to realize both the orthogonal multiple access (OMA) and sparse-code multiple access (SCMA) [21] (one of the typical code-domain NOMA schemes [22]) according to the requirements of specific V2X use cases, a highly flexible

**Table 1** Overview of Key 6G-V2X Technologies

| Category | Technology | Strength | Open Challenges | Maturity | Enhancing Areas |
|---|---|---|---|---|---|
| Revolutionary Tech. | Programmable V2X Environment | • Intelligent V2X environments;<br>• Effective mitigation of path loss, shadowing, multipath and Doppler effect | • Reflection optimization<br>• Channel estimation in highly dynamic V2X environment | ★☆☆ | PHY layer, safety |
| | Tactile Communication | • Real-time transmission of haptic information<br>• Enhanced vehicle platooning and remote driving | • Simultaneous requirements for high rates, ultra-low latency, and high reliability in high mobility environments<br>• Suitable codecs and efficient reconstruction for the haptic data | ★☆☆ | Haptic interactions, remote driving |
| | Quantum Computing | • Superior computational capability<br>• Enhanced security | • Design of quantum devices<br>• Security architecture, characterization of entanglement distribution | ★☆☆ | Computing & security |
| | Brain-Vehicle Interfacing | • Enables brain controlled connected vehicles<br>• Managing uncertainties | • Scalability of brain-controlled vehicles<br>• Comprehensive real-world testing | ★☆☆ | Driving experience, disabled people driving |
| | Blockchain | • Highly distributed<br>• Significantly enhanced security | • Algorithm design for ultra-low latency application<br>• Increasing throughput and scalability | ★★☆ | Security, safety, EV charging efficiency |
| | THz Communications | • Extremely high throughput<br>• Higher spectrum | • Design of transceiver architectures<br>• Propagation measurement and channel modeling | ★☆☆ | PHY layer, intra-vehicle communication |
| | ML-aided V2X Design | • Suitable for highly adaptive and complex V2X environments<br>• Performance enhancement | • Performing effective training in highly dynamic environments<br>• Processing big-data in real-time | ★★☆ | PHY & MAC layers, Security, self driving vehicle |
| Evolving Tech. | Hybrid RF-VLC V2X | • Ultra-high data rates<br>• Low setup cost | • Inter-compatibility between VLC and RF<br>• Interference management | ★★★ | PHY & MAC layers |
| | Multiple Radio Access Technologies | • Inherent benefits of sub-6 GHz, mmWave and/or THz for long communication range<br>• Hyper-high data throughput | • Dynamic configurations meet different QoS requirements<br>• Beam and interference management | ★★☆ | PHY & MAC layers |
| | Non-orthogonal Multiple Access (NOMA) | • Massive connectivity<br>• Ultra-low latency | • Cross-layer optimization for grant-free NOMA<br>• Adaptive NOMA and OMA | ★★☆ | PHY & MAC layers |
| | New Multicarrier Scheme | • Significantly enhanced resilience to Doppler<br>• Higher spectrum- and power-efficiencies | • Backwards-compatibility with LTE and 5G NR<br>• Scalable multicarrier schemes in highly dynamic vehicular environments | ★★☆ | PHY layer |
| | Advanced Resource Allocation | • Cross-layer resource allocation<br>• Context and situation awareness | • Efficient and scalable deployments<br>• Distributed intelligent solutions | ★★☆ | PHY & MAC layers |
| | Integrated Sensing, Localization and Communications | • Higher spectral efficiency<br>• Lower hardware cost<br>• Improved situational awareness | • Unified design of transceivers<br>• New signal processing algorithms<br>• Optimal waveform design | ★★☆ | PHY layer, positioning, parking efficiency |
| | Satellite/UAV Aided V2X | • Extra wide coverage<br>• Flexible aerial base-station | • Energy-efficient computation & transmission<br>• Robust reception in high mobility environments | ★★☆ | PHY & MAC layers, accident/hazard monitoring |
| | Integrated Computing | • Faster computing and enhanced security<br>• Low operational cost | • Integration of cloud, edge, and fog computing<br>• Heterogeneous design to support different data sources | ★★★ | Computing, efficient navigation |
| | Integrated Control and Communications | • Control-communications co-design<br>• Enhanced platooning | • Derivation of fundamental limits<br>• Understanding of control and wireless networks interaction | ★★☆ | Control, vehicle platooning |

and scalable multicarrier system is preferred. The selection of a new multicarrier waveform for OMA or SCMA and with respect to different QoS requirements (e.g., mobility, spectral efficiency, and error rate performance) is of strong interest for reliable, ubiquitous, fast, and efficient wireless access in 6G V2X. Enhanced integrated sensing, localization, and communication for autonomous vehicles may also be carried out with the aid of IRS and THz mapping [23]–[25].

In addition, enhanced vehicular message dissemination is also expected to transform the future of electric vehicles (EVs), which are the automotive industry's response to address fossil fuel depletion and environmental pollution [26]. It is anticipated that 6G V2X will significantly improve both the driving efficiency and battery efficiency of EVs. As the road conditions and the best routes are predictable, optimized driving modes for EVs can be applied for battery and travel time-saving [27], [28]. With 6G V2X, the EV battery status can be better monitored and configured through cloud-based computation or ML [29], [30]. EV charging times can also be optimized as 6G V2X can guide an EV to find the most convenient charging stations at different periods of a day/season. In this case, the nearest charging station may not be the best as there might be many EVs queuing for charging, and also the driving time to that charging station may be longer during peak-hour periods. Fig. 3 illustrates the connection between different technologies and three important aspects of 6G-V2X, namely, communication, computing, and security.

## III. REVOLUTIONARY TECHNOLOGIES FOR 6G-V2X

In this section, we introduce some of the promising revolutionary technologies with the potential to be used in 6G-V2X.

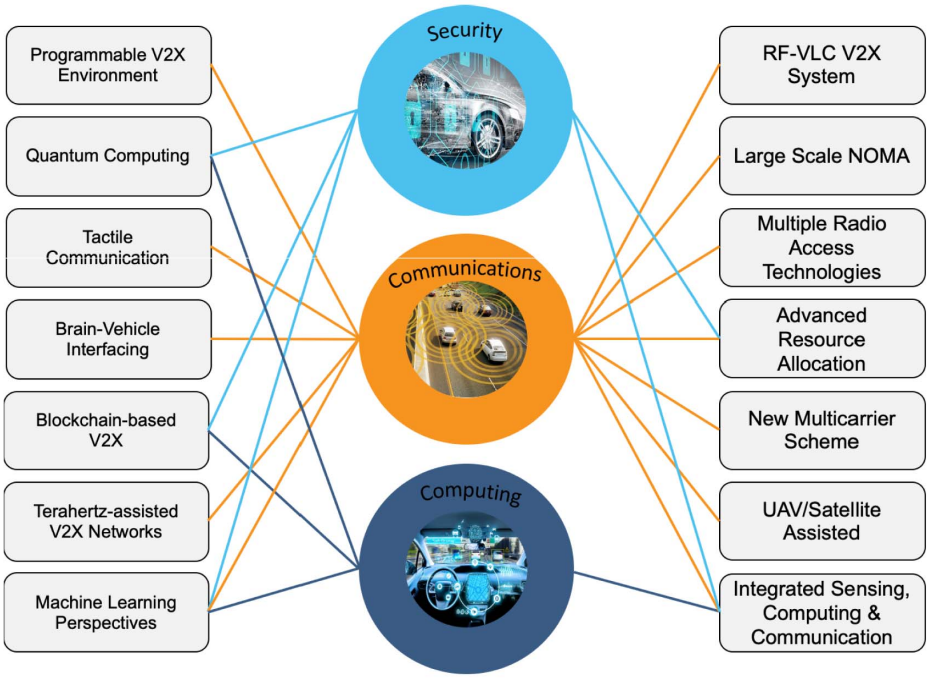


**Fig. 3.** ***Connection between different technologies and three important aspects of 6G-V2X, namely, communication, computing, and security.***

## A. Programmable V2X Environment

In conventional communication theory, wireless channels are regarded as a destructive and adversarial entity, yielding distorted received signals, causing excessive training overhead, yet having limited channel capacity. One of the most destructive wireless channels is called a doubly selective channel (i.e., time-and-frequency selective), which widely appears in vehicular communication systems due to the mobility of the transmitter and/or receiver. Furthermore, V2X communication signals may experience significant shadowing effects due to high-rise buildings in urban areas or hills and major vegetation in rural environments. To achieve robust information flow in high-mobility channels, LTE- and 5G NR-based V2X systems are configured with large subcarrier spacing[1] as well as dense pilot placement. However, this may result in considerably reduced spectral efficiency, not to mention very complex signal processing algorithms at the receiver.

More recently, a disruptive communication technique called IRSs [31], [32] has attracted increased attention, aiming at creating a smart radio environment by customizing the propagation of radio wavefronts. Specifically, IRSs are man-made programmable metasurfaces (consisting of a vast amount of tiny and passive antenna elements with reconfigurable processing networks), which can effectively control the phase, amplitude, frequency, and even polarization of the incident wireless signals to overcome the negative effects of natural wireless propagation. As such, IRSs allow the environment itself to be considered as an element of the communication system, whose operation can be optimized to enable higher rates, enlarged coverage, and uninterrupted connectivity. The recent work in [33] shows that sufficiently large IRSs can outperform traditional relay-aided systems in terms of throughput while allowing nearly passive implementation with reduced complexity.

6G-V2X can take advantage of IRS in coverage-limited scenarios (e.g., V2X communications operating at millimeter-wave (mmWave) or THz bands) or unfavorable propagation conditions (e.g., non-line-of-sight communication links). In such scenarios, the use of an IRS can enhance the vehicular channel conditions by introducing enhanced multipath propagation, which will result in larger transmission coverage. An out-of-coverage traffic intersection is an ideal use case scenario for using an IRS because the V2V communication links may be blocked by buildings and other obstructions. Measurements have shown that the strength of the received V2V signal power reduces quickly over distance away from the intersection due to such blockages [34], [35]. As such, vehicles located on perpendicular streets may not communicate with each other very well, which could result in significant degradation of V2V communication performance. To mitigate this issue, IRS may be installed on the surfaces of buildings around the intersection. The communication coverage of transmitting vehicles in the perpendicular streets can, thus, be enhanced by fine-tuning the reflecting elements of IRS. An IRS-assisted vehicular communication

[1]A relatively large subcarrier spacing is needed in high-mobility channels due to the frequency dispersion incurred by the Doppler spread, or the V2X communication system could suffer from a substantial increase of intercarrier interference, which, in turn, leads to drastic deterioration of the error rate performance. Such a phenomenon has been highlighted in [3] where NR V2X with a subcarrier spacing of 60 kHz enjoys considerable gains at high velocities (280 and 500 km/h) compared to that with a subcarrier spacing of 15 kHz.

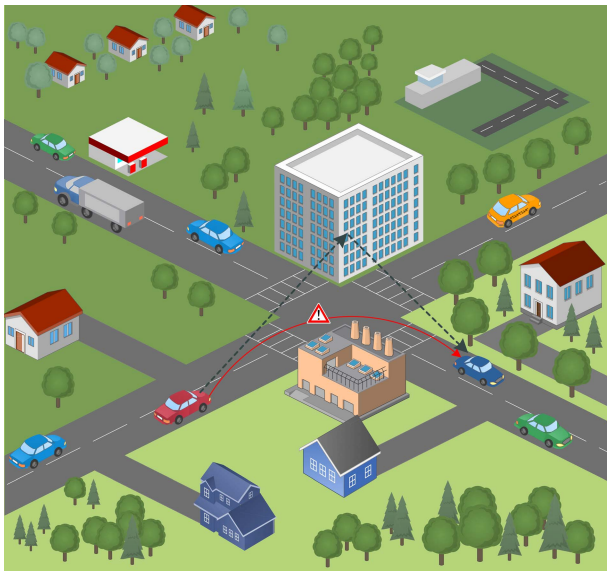

**Fig. 4.** *Intelligent reflecting surface at the intersection.*

scenario is illustrated in Fig. 4. It is interesting to point out that IRS can be employed for mitigation/suppression of the Doppler effect and multipath fading, making IRS an appealing research direction for significantly enhanced V2X communication in 6G. Specifically, recent work [36] has shown that: 1) the rapid fluctuations in the received signal strength due to the Doppler effect can be effectively reduced by using real-time tunable IRS and 2) for more general propagation environments with several interacting objects, even a few real-time tunable IRS can remarkably reduce the Doppler spread and the deep fades in the received signal. For a high-mobility wireless channel, a Doppler mitigation method by novel transmission protocol and real-time phase control of IRS has been developed in [37]. To efficiently integrate with 6G-V2X, IRS needs to overcome some fundamental challenges, such as reflection optimization, optimal placement of IRS, channel estimation in a highly dynamic vehicular environment, and adaptation to different spectrum ranges.

## B. Tactile Communication in V2X

Tactile communication is a revolutionary technology, which enables a paradigm shift from the current digital content-oriented communications to steer/control-oriented communications by allowing real-time transmission of haptic or sensual information (i.e., touch, motion, vibration, and surface texture) [38]. By integrating human sensual information, tactile communication in 6G-V2X is expected to provide a truly immersive experience for onboard vehicle users [39]. In addition to traditional applications of multimedia communications (e.g., onboard meetings/demonstrations and infotainment), tactile communication will enhance vehicular specific applications, such as remote driving, vehicle platooning, and driver training by enabling fast and reliable transfer of sensor data along with the haptic information related to driving experience and trajectories. Several haptic-based warning signals (e.g., waking up drowsy drivers or catching distracted drivers' attention) have been developed and tested for automotive applications to improve driving safety [40]–[42]. On the other hand, tactile-based V2X can be extremely helpful to VRUs by providing them with appropriate haptic signals that will enhance their safety and activity. For instance, Cespedes *et al.* [43] used haptic signals to combine cycling with cooperative driving while supporting cyclists moving in a platoon. The authors observed that the proposed system enhanced cycling behavior without negatively impacting concentration levels.

Despite tactile communication's immense potential, there are still many challenges. For example, tactile communication requires extremely high-speed and extremely low-latency communication to ensure reliable and real-time exchange of large volumes of haptic information [19]. These stringent connectivity constraints are very difficult to meet in high-mobility vehicular environments. This is because they require higher frequencies (e.g., mmWave or even THz) to meet their data demand. However, those higher frequencies are not very reliable, particularly in mobile environments. For example, in [44], we showed that, even in an indoor environment, THz networks may not be able to provide highly reliable high-rate communications. This, in turn, motivates research to develop a new breed of services called highly reliable high rate low-latency communications (HRLLCs) that can provide a combination of traditional 5G services (e.g., enhanced mobile broadband (eMBB) services that ignore reliability and URLLC services that ignore rate). Apart from the above challenges, tactile communication poses several fundamental challenges, including the design of application-specific control and communication protocols, the development of human-to-machine interfaces for wireless haptic interactions, and the design of suitable haptic codecs to capture and represent the haptic data and exact reconstruction of received haptic data.

## C. Brain–Vehicle Interfacing

In a brain-controlled vehicle (BCV), the vehicle is controlled by the human mind rather than any physical interaction of the human with the vehicle. For people with disabilities, BCV may offer great potential for improved independence by providing an alternative interface for them to control vehicles [45]. On the other hand, brain–vehicle interfacing may lead to an improvement in manual driving by predicting a driver's actions and detecting discomfort [46]. Although the current vision is for fully automated vehicles, the adaptability of humans will play an irreplaceable role in managing the uncertainties and complexity of autonomous driving [47]. By keeping humans in the loop, a BCV is expected to mitigate the limitations of autonomous driving in challenging and

uncertain environments, such as rural and unstructured areas. Current wireless communication (e.g., 5G) and computation technologies are not able to realize BCV as services related to brain–machine interactions will require simultaneously ultrahigh reliability, ultralow latency, and ultrahigh data rate communication and ultrahigh-speed computation. For example, a coarse estimation of the whole brain recording demand is about 100 Gb/s [48], the transmission of which is not supported by existing wireless technologies. However, through full-phased brain–vehicle interfacing and ML techniques, 6G-V2X must support the learning and adapt to the behavior of human drivers.

Recently, the feasibility of BCV has been demonstrated in academia (e.g., [49] and [50]) and by the car industry (e.g., [45] and [46]). Bi *et al.* [49] and Fan *et al.* [50] have shown a brain–computer interface-based vehicle destination selection system. Although successfully tested under different conditions, the currently designed BCV is not a scalable solution since this would require a wireless connection to support brain–machine interactions with high coverage, availability, speed, and low latency to provide reliability and safety for the end-users. THz communications can be a potential solution to enable high-throughput and low-latency brain–vehicle interfacing. Fundamentally different performance metrics [e.g., quality of physical experience (QoPE)] need to be introduced and quantified to capture the physiological characteristics and then map into the conventional wireless QoS metrics [48]. Moreover, extensive real-world experiments are required to demonstrate the effectiveness of BCVs, as most of the existing works on BCVs have been verified through simulation only.

### D. Blockchain-Based V2X

The widespread deployment of V2X networks very much relies on significantly enhanced security for large-scale vehicular message dissemination and authentication. The consideration for this imposes new constraints for resource allocation in V2X networks. For example, mission-critical messages should have ultraresilient security to deal with potential malicious attacks or jamming, while multimedia data services may require only lightweight security due to a large amount of data. These two types of security requirements lead to different frame structures, routing/relaying strategies, and power/spectrum allocation approaches. 6G-V2X can adopt a blockchain system that is viewed as a disruptive technology for secured decentralized transactions involving multiple parties. Compared to traditional security and privacy techniques, the use of blockchain can provide a wide range of enhanced security and privacy services without requiring any third parties [51]. Through the inherently distributed ledger technology of blockchain, 6G-V2X communication can perform distributed security management, offloading certain tasks with mobile cloud/edge/fog computing, and content caching. A blockchain-based security solution (e.g., smart contract or consensus mechanism) in 6G-V2X is expected to not only allow verification of the authenticity of a message but also preserve the privacy of the sender [52], [53]. Moreover, the characteristics of blockchains are of interest for the management of unlicensed spectrum, which allows different users to share the same spectrum. 6G-V2X may also utilize a blockchain-based spectrum sharing approach, which has the potential to provide secure, smarter, low-cost, and highly efficient decentralized spectrum sharing [54].

While several attempts have been made to realize a blockchain-based communication network [51], a straightforward adoption of existing blockchain technology is not suitable for a V2X communication scenario due to its dynamic network characteristics and real-time data processing requirements. Despite blockchain's great potential in enabling enhanced security and network management, the technology itself suffers from high latency, and hence, new blockchain algorithms with ultralow latency need to be developed before they can be applied to 6G-V2X. Limited throughput and scalability of current blockchain technology are also major open problems that require a thorough investigation.

### E. Terahertz-Assisted V2X Networks

THz communication, which operates at THz bands (0.1–10 THz), is envisioned as a promising approach to alleviate increasingly congested spectrum [16], [55] at lower frequencies. Leveraging the availability of ultrawide bandwidth, THz communication will be able to provide transmission rates ranging from hundreds of gigabits per second to several terabits per second. Such an extremely high throughput will enable a plethora of new V2X application scenarios, such as ultrafast massive data transfer between vehicles and haptic communications. Since THz communication is able to provide fiber-like data rates without the need for wires between multiple devices at a distance of a few meters, it may also be used in onboard use cases, such as the BCV scenario, where extremely high throughput and low-latency wireless communication is required.

While the THz spectrum brings a number of unique benefits, there are many major challenges to be addressed, such as transceiver architectures, materials, antenna design, propagation measurement, channel modeling, and new waveforms. In particular, it is essential to characterize and understand THz radio propagation in different V2X scenarios, such as highway, urban, and in-vehicle. One of the main challenges in THz-assisted 6G-V2X will be the effective use of traditional cellular and new THz bands. As such, suitable dynamic resource scheduling is required to exploit their unique benefits. For example, while THz communication offers very high data rates, it is only suitable for short-range V2X communications. In this case, resources may be allocated in THz bands to those transmitters with receivers within a short range. Note that appropriately designed relaying or IRS techniques (as done in [56]) can be potential solutions to extend the coverage of TH-based V2X communications.

### F. Quantum Computing-Aided V2X

Quantum computing is considered one of the revolutionary technologies for generic 6G wireless communications in a number of seminal works (e.g., [14], [16], [54], [57], and [58]). However, the development of practical quantum computing and communication systems is in its infancy, and practical solutions may be quite some time off. Therefore, as mentioned in [2], quantum computing and communications may potentially play a role toward the end of the 6G development or even beyond for 6G+ technologies. Nevertheless, once some form of quantum computing is available for 6G communications, it can be expected to make its way into V2X applications as well.

If available, we can envision that quantum computing will offer enhanced security in V2X communications. Note that security in V2X communications is significantly more important than in traditional communications since, for example, a security breach in an autonomous vehicle can cause fatal accidents. As the wireless spectrum is shared between vehicles and other types of cellular users (e.g., pedestrians), V2X communications may be vulnerable to malicious attacks, and traditional encryption strategies may not be adequate. Quantum computing has the inherent security feature of quantum entanglement that cannot be cloned or accessed without tampering with it [14], making it an appropriate technology to enhance 6G-V2X communications security. Moreover, quantum domain security is based on the quantum key distribution (QKD) framework that allows detecting any malicious eavesdropping attempt. For example, the use of quantum federated learning to securely execute learning tasks among vehicles can be an important use case [59].

In addition to the enhanced security feature, the advent of quantum computing promises a radically enhanced computational capability offering to significantly enhance and optimize 6G-V2X services through the fast execution of extremely complex and currently time-consuming optimization algorithms. For example, the implementation of advanced ML algorithms that require big data processing and massive training (e.g., finding an optimum geographic route with multiple objectives) is a very challenging task. In such scenarios, traditional computing often sacrifices optimality, while quantum computing can efficiently achieve optimality with reduced complexity [16], [60].

Although quantum computing is seen as a promising technology, much more research is required to turn it into a widely usable technology in order to exploit its potential. For example, current quantum computer chips can only operate at extremely low temperatures (close to zero Kelvin), which makes them at best only usable on the vehicular infrastructure side. To use them in vehicles, significant research is needed on the thermal stability of quantum computer chips. Other fundamental challenges include the development of large-scale quantum computing, the design of quantum security architectures, and the characterization of entanglement distribution.

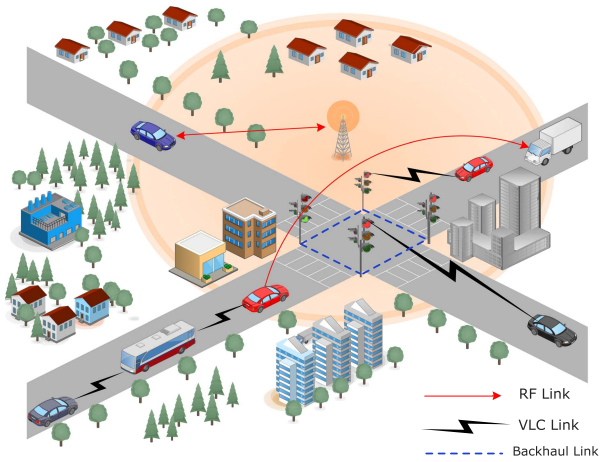


**Fig. 5.** *Hybrid RF-VLC-based V2X communications.*

## IV. EVOLUTIONARY TECHNOLOGIES FOR 6G-V2X

In this section, we present a range of technologies that may be classified as evolutionary. While they have reached a certain maturity due to extensive research, testing, and deployment in the past, significant further development and trials are needed to adapt them to meet the new challenges and requirements in 6G-V2X.

### A. Hybrid RF-VLC V2X System

In 6G-V2X, it is expected that the vehicle and its occupants will be served at extraordinarily high data rates and with extremely low latency. However, this feature may not be feasible with standalone radio frequency (RF)-based V2X communication as conventional RF-based vehicular communication often suffers from high interference, large latency, and low packet delivery rates in highly dense scenarios [61], [62]. One alternative approach may be the combination of RF and VLC-based V2X communications, where, along with radio waves, visible light can be used as a medium of communication in vehicular networks. A hybrid RF-VLC-based V2X communication scenario is shown in Fig. 5. The ultrahigh data rate (potentially up to 100 Gb/s) achieved by light-emitting diode (LED) or laser diode (LD)-based VLC [63] and its inherent features (such as low power consumption, enhanced security, and antielectromagnetic interference) make VLC technology an ideal candidate for future ITS. Moreover, a VLC-based V2X communication system will require minimum setup cost as VLC-based V2X can be implemented by using the existing LEDs/LDs in vehicle headlights or preinstalled street/traffic lights.

In V2X networks, VLC can be mainly used in the following three scenarios: V2V communication through headlights/backlights, V2X communication through traffic lights, and V2X communication through street lights. Note that the traffic/street lights can be used to establish backhaul links with one another by using free-space coherent optical communications [55]. In addition to enhancing the

data rate, VLC can boost the performance of V2X networks by eliminating the limitations of traditional RF-based V2X communications. For example, in the presence of big vehicle shadowing, RF-based V2V communication suffers from severe packet drop due to high path-loss and packet collision [64]. In this scenario, the transmitting vehicle can communicate with the big vehicle through VLC, and then, the big vehicle can relay the messages to the vehicles in the shadow region. Similarly, using VLC, traffic/street lights can also be used in the urban intersections to relay the messages to facilitate communication between vehicles from perpendicular streets, where traditional RF-based V2V communication often suffers from severe packet loss. Note that, while RF-based solutions (e.g., big vehicle or roadside unit (RSU) relaying) to the above problems are studied in the literature, such solutions can cause severe interference in the high-density scenarios due to the RF-based re-transmissions [34].

Although extensive research has been carried out on VLC-based V2X communication in the past decade, VLC has not been included in the 5G-V2X standard. Several open issues still need to be solved for enabling hybrid RF-VLC V2X. These include interoperability between VLC and RF technologies, and deployment issues. In an outdoor environment, the performance of VLC degrades due to the interference caused by natural and artificial light sources. On the other hand, the received signal strength in VLC may dramatically vary due to the vehicles' mobility [65], [66]. Hence, ambient lighting-induced interference and mobility-induced channel variations need to be properly addressed before deploying VLC in 6G-V2X systems.

### B. Large-Scale Nonorthogonal Multiple Access

6G-V2X will require massive connectivity for timely, reliable, seamless, and ubiquitous exchange of V2X messages. This is to allow connected vehicles to constantly sense and interact with the environments for full situational awareness and, hence, considerably improved safety. A key enabling technology for 6G-V2X networks to meet these requirements is NOMA. Compared to traditional OMA schemes, NOMA allows multiple users to utilize time and frequency resources concurrently for both random access and multiplexing [67], [68]. There are two main types of NOMA: power-domain NOMA [69], [70] and code-domain NOMA [22], [71], such as SCMA [21], [72]–[74] and resource spread multiple access [75], in which multiple users are separated by different power levels and different codebooks/sequences, respectively. In recent years, NOMA has been proposed for grant-free access to achieve ultralow-latency massive connectivity while achieving superior spectrum efficiency.

As a matter of fact, NOMA can be a strong complement to other aforementioned 6G-V2X enabling technologies for use in both V2V and V2I communications. For example, NOMA can be used for distributed V2V autonomous scheduling, where connected vehicles need to contend with the random access control channel to reserve resources for data packet transmissions. In large-scale 6G-V2X networks, the control channel with traditional random access schemes may be saturated, leading to severe collisions on scheduling assignment packets and significant loss of data packet reliability. With the application of NOMA (e.g., SCMA) for control channels, collisions of scheduling packets can be significantly reduced, and the reliability of data packets can, thus, be improved. NOMA can also be applied in large-scale 6G-V2X networks to achieve efficient data packet transmission. This requires multiple communication modes, such as unicast and multicast, which have been added for V2X communications (in addition to broadcast) since Release 15. These multiple communication modes pave the way for the application of NOMA, where broadcast packets may be superimposed by unicast or multicast packets targeting very close neighboring vehicles [76]. In this scenario, power-domain NOMA, in which a large portion of transmit power is allocated to broadcast packets and the remaining for unicast or multicast packets, may be used.

Despite significant research efforts by both academia and industry, however, NOMA has not been adopted in 5G NR as no consensus has been achieved in 3GPP. While existing research works have been reported on the applications of NOMA to V2X networks, they are mainly focused on the V2I links and centralized resource allocation. Many problems of NOMA remain open. For example, how to efficiently coordinate and schedule different users for NOMA transmissions to co-exist with the current OMA (e.g., orthogonal frequency-division multiple access) communications? How to design a highly flexible and scalable NOMA scheme that can strike a balance between overloading factor, reliability, and user fairness? How to design practical and efficient large-scale NOMA for connected and autonomous vehicle (CAV) applications, especially in distributed V2V network scenarios?

### C. Exploration of Multiple Radio Access Technologies

Exploiting the higher frequency spectrum in the mmWave and THz range is vital to achieve the 6G KPIs (e.g., terabits per seconds data rates, billions of connected devices, and submilliseconds of access latency). The rich frequency resources at mmWave and THz bands can provide larger bandwidth (e.g., multigigabits and tens of gigahertz for mmWave and THz, respectively) than the one available at sub-6 GHz, which is highly congested in existing cellular systems. These rich frequency resources are needed to enable high data rates and low latency for 6G-V2X communications. Extensive research has been carried out studying infrastructure-based 5G mmWave communications, such as channel modeling and massive multiple-input–multiple-output (MIMO) beamforming. However, V2X communications in mmWave and THz frequency bands suffer from excessive propagation loss and susceptibility to blockage by obstacles such as vehicles and buildings. In addition, the much smaller cells

in mmWave and THz bands may significantly increase the frequencies of handovers. These problems make it challenging for mmWave and THz communication systems to provide the relevant QoSs needed for the expected advanced V2X applications [44]. It is foreseen that multiradio access technologies with sub-6 GHz, mmWave, and/or THz will be needed to work together in future 6G-V2X networks [77]. For example, while mmWave and THz radios will provide extra bandwidth and capacity to 6G-V2X networks, sub-6 GHz radios are critical for the enabling long communication ranges and connectivity stability.

There are a number of challenges to be addressed for efficient usage of multiradio access technologies. From the perspectives of mmWave and THz V2X communications, the excessive propagation loss and signal blockage necessitate the use of directional beamforming. The directional connectivity makes V2V operation with mmWave and/or THz radios very challenging for vehicles with high moving speeds. Communication between two vehicles over a mmWave link, including the physical channel and communications of mmWave for V2V, has been studied [78]. However, the challenges that mmWave and THz introduce at the MAC layer due to beamforming communications remain largely open for 6G V2V networks. Novel schemes for coordination and collaboration among these multiradio access technologies are needed in order to tackle MAC layer challenges, such as fast link configuration and beam management, contention-based channel access, sidelink autonomous scheduling, distributed congestion control, and interference management at the MAC layer. Moreover, the use of IRS combined with high frequencies is worthy of a close investigation as it has the potential to help alleviate some of those challenges, as shown in [56].

### D. Advanced Resource Allocation

Radio resource management (RRM) will play a crucial role in 6G-V2X networks, especially for providing the QoS required by advanced V2X applications. The base stations usually take the main responsibility for RRM in the current cellular V2X networks, which has been widely studied in the literature [79]–[81]. However, there are several major challenges for RRM in 6G-V2X networks. As previously mentioned, 6G-V2X networks will very likely need multiradio technologies to deliver the expected QoS. The resources of different technologies will need to be taken into account in the RRM decision-making. Solutions that smartly use the characteristics of different technologies (e.g., higher rate for mmWave and better reliability for sub-6 GHz) are needed. Moreover, most current RRM approaches in the literature use either fixed rules, analytical models, or supervised learning in relatively low-dimensional scenarios. However, existing 5G RRM research has mainly focused on infrastructure-based communications [82]–[84]. The expected problem dimensionality will significantly increase for 6G-V2X networks partly due to mmWave deployment and coexistence of multiple V2X use cases with additional direct V2V communications and autonomous resource control operational modes. Moreover, the fast-moving nature of V2X networks and the stringent QoS requirements that must be met to support advanced V2X use cases make the RRM problems more challenging.

In order to address the above challenges of supporting multiradio technologies and increased algorithm complexity, advanced resource allocation schemes are needed, which could be built with the support of context awareness and cross-layer design. A hybrid RRM framework can be created, in which both dedicated radio resources and a shared resource pool are allocated to the connected vehicles for V2V and V2I communications. The dedicated radio resources to the individual CAVs ensure that a basic but critical level of QoS is guaranteed for various CAV applications. The shared resource pools are then provided to flexibly accommodate the temporary loss of mmWave or THz connections and adapt to fast-changing network conditions. The allocation can be adjusted adaptively according to the QoS feedback and the context. Context awareness of the communication system and the driving environment could be pivotal for the cross-layer design of RRM solutions. For instance, in [85], we showed how one could use such smart multiradio solutions (at mmWave and sub-6 GHz) with context-awareness to provide a reliable video performance at high mobility. To deal with the very large action space and time complexity of RRM and QoS control problems, distributed intelligent solutions over multiradios that are able to dynamically allocate resource blocks (RBs) and power should be designed following the hybrid RRM framework. Reinforcement learning (RL) could be applied to design such intelligent solutions. More discussion on the ML-based resource allocation will be presented in Section V.

### E. New Multicarrier Scheme

6G should provide ultrareliable high-rate V2X communications in high-mobility environments. Connected vehicles and high-speed trains, moving at speeds of 1000 km/h or even higher [16], [54], will communicate with each other and the surroundings including various sensors, infrastructure nodes (e.g., RSUs, base stations, and robots), satellites, and the internet cloud. Such high speeds may lead to significantly reduced channel coherence time and as a result, the vehicular channel fading coefficients are rapidly time-varying. Considering the effects of large Doppler and multipath propagation, innovation is needed to cope with the increased interference seen by the receiver [86]. In both LTE and 5G NR, OFDM and its variants are adopted for high-rate transmissions [87], [88]. Nevertheless, OFDM is very sensitive to the Doppler effect, which may destroy the multicarrier orthogonality and result in increased amounts of intercarrier interference and intersymbol interference. To overcome this drawback, some

advanced multicarrier waveforms [89] may be excellent candidates for 6G V2X. A promising multicarrier waveform is filter-bank multicarrier (FBMC), which enjoys tight spectrum containment and relatively strong resilience to carrier frequency offsets and Doppler spreads. These advantages give FBMC a great potential for the support of a diverse range of modern use cases where flexible time–frequency allocations are highly demanded [90].

Recently, orthogonal time–frequency space (OTFS) has emerged as an effective multicarrier scheme by spreading each information symbol over a 2-D orthogonal basis function spanning across the time–frequency domain [91]–[93]. In principle, OTFS is capable of converting a time-varying multipath channel into a relatively static delay-Doppler image of the constituent reflectors. The 2-D basis function in OTFS, called discrete symplectic Fourier transform (DSFT), is essentially orthogonal precoding transform to harvest the diversity gain from time, frequency, and space domains. Thus, it would be interesting to investigate new multicarrier transforms with reference to OTFS for enhanced performance in high-mobility environments. Besides, the existing NOMA studies are mostly focused on its application for massive machine-type communications with low-mobility and low-rate transmissions. To provide ultrareliable high-rate massive connectivity (driven by augmented reality/virtual reality (AR/VR) and autonomous driving), it is also promising to study the integration of NOMA (e.g., SCMA) and OTFS (or its variants) to exploit the benefits of these two disruptive techniques.

### F. UAV-/Satellite-Assisted V2X

Due to the inherent property of wide-area coverage, UAVs can be used as aerial radio access points in the 6G-V2X network. UAVs can provide different types of services for vehicular users, such as relaying, caching, and computing [94]. Particularly, in a highly dense vehicular environment, UAVs can cooperate with the static network infrastructure nodes (i.e., base stations) in managing the wireless network to enhance the user experience. Because of their nearly unrestricted 3-D movement, UAVs can offer a number of unique V2X applications as a flying agents such as: 1) providing an advance road accident report prior to the arrival of a rescue team; 2) monitoring traffic violations to assist law enforcement agencies; and 3) broadcasting warning about road hazards that occurred in an area not preequipped with an RSU [95]. Despite significant advancements in UAV technology, there exist several challenges in the area of UAV-enabled V2X systems. For example, it is highly challenging to maintain reliable and high-speed wireless communication between UAVs and ground vehicles, as the mobility of both UAVs and ground vehicles will lead to highly dynamic channel characteristics. While line-of-sight links are expected for UAV-ground vehicle channels, systematic measurements and modeling of such channels are still ongoing [96].

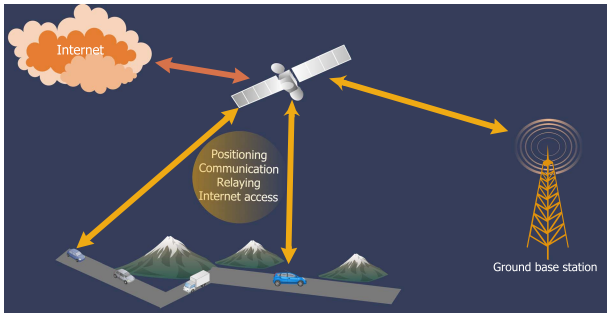


**Fig. 6.** ***Satellite-assisted V2X communications.***

Several other key challenges include safety and regulations, seamless integration with existing networks, and the limited battery life of UAVs.

Satellites are another potential aerial communication platform for 6G-V2X communications. An example of a satellite-assisted V2X communication system is illustrated in Fig. 6. In current V2X standards, satellites are currently only used for localization purposes. It is worth mentioning that the data rates of satellite communication have been increasing significantly in recent years. For example, multibeam satellites [97] have been widely adopted in satellite communication systems due to their capability to enhance wireless data rates. Thus, communication via satellite can be a potential technique for 6G-V2X to assist the communication between vehicle and remote data server in an out-of-terrestrial-coverage scenario. Similar to the UAV-based V2X communication, a satellite can also perform computing and network management tasks. To enable satellite-assisted V2X communications, an extensive investigation is required to accurately model the characteristics of the channels between satellites and high-mobility vehicles. It will also be challenging to integrate the different communication mechanisms (e.g., PHY or MAC layer transmission protocol) adopted in V2X and satellite communications.

From the PHY point of view, another key research problem is how to attain the highest power transmission efficiency for high-rate and long-range satellite communications. This may not be attained by OFDM due to its high peak-to-average power ratio (PAPR), which ultimately limits its maximum communication coverage. The time has come for the research community to rethink and revisit several traditional modulation schemes that enjoy constant signal envelopes, such as continuous phase modulation (CPM) [98]. A drawback of conventional CPM is that it may not be suitable to support high-rate communication as OFDM does [99]. Although MIMO could be a way to address this problem, CPM's continuous phase constraint prevents its straightforward integration with MIMO. Recently, a new phase modulation on the hypersphere (PMH) has been developed for load-modulated MIMO [100], [101]. It is noted that PMH is capable of

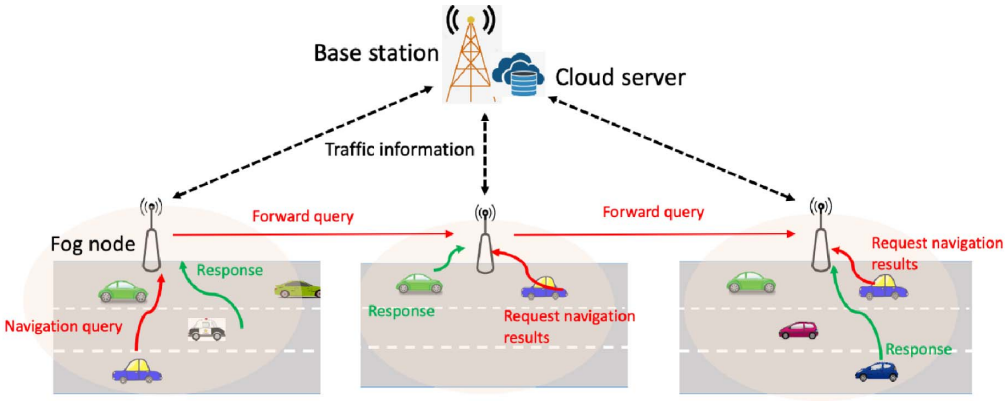


**Fig. 7.** *Fog node-assisted traffic navigation.*

achieving the highest power efficiency while having the advantage of approaching the capacity of Gaussian inputs. The application of PMH for satellite-aided long-distance V2X deserves a close investigation.

### G. Integrated Computing for V2X

Although cloud computing has been widely used in vehicular networks, on its own, cloud-based solutions may not be able to meet many of the very delay-sensitive applications of V2X networks. Edge/fog computing is a newly introduced paradigm, which enables faster distributed computing and better security at a low operational cost. Edge computing operates in a stand-alone mode, whereby the data processing is performed on the nodes that are close to the end users. On the other hand, fog computing has multiple interconnected layers and could interact with the distant cloud and edge nodes [18]. By leveraging computing resources at edge/fog nodes located at the edge of the network, 6G is expected to provide more user aware, scalable, and low-latency services for vehicles. Complex algorithms used in the V2X network can be solved in real time by offloading complex computational tasks to the edge/fog nodes. One of the use cases of fog computing can be navigation under real-time traffic conditions. For example, fog computing can be used to provide navigation-based real-time traffic conditions, as illustrated in Fig. 7. The navigation query generated by a vehicle can be sent to the nearest fog node and then relayed to the destination fog node by a hop-by-hop relaying mechanism, where each fog node in the hopping chain collects real-time traffic information in its coverage area. Upon receiving the traffic reports from the other fog nodes, the originated fog node computes the optimal path for the vehicle that generated the query.

Integration of cloud, edge, and fog computing is required in 6G-V2X to exploit the unique benefits of the computing technologies. For instance, together with the edge, fog can perform timely data processing, situation analysis, and decision-making in close proximity to the locations where the data are generated, while, together with the cloud, fog can support more sophisticated applications, such as data analysis, pattern recognition, and behavior prediction [18]. Moreover, it has been demonstrated that network coding [102] can be effectively used to trade abundant computing resources at the network edge for communication bandwidth and latency. 6G-V2X can exploit the inherent benefits of edge/fog computing and network coding by properly integrating these two techniques. While edge/fog computing provides a number of unique benefits for the V2X network, there exist some fundamental challenges and open problems, such as building an integrated computing architecture, handling security and privacy issues, managing handover, and optimizing computing resources.

### H. Integrated Sensing, Localization, and Communication

Attaining improved situational awareness for connected vehicles is dependent on not just rapid and reliable communication but also high-resolution sensing and high-accuracy localization (or positioning/mapping). While sensing helps extract key information (such as ranges, speeds, and moving directions) of vehicles, pedestrians, obstacles, and infrastructure, localization permits every vehicle to acquire its precise position, which is of utmost importance for the safe maneuvering of vehicles (especially autonomous vehicles). The improved situational awareness will, in turn, facilitate the exploration of endless opportunities for position-based services and advanced V2X applications, such as real-time 3-D mapping for building an accurate environment model. Like communication, both sensing and localization rely on electromagnetic radio waves to measure, track, and interact with the driving surroundings. Hence, it is worthy to explore the natural synergy of sensing, localization, and communication by observing the fact that they share similar signal processing operations (e.g., carrier modulation/demodulation and synchronization) and hardware implementation. Very recently, in the 6G research community, there has been

a strong voice to integrate these three into one converged RF system for higher spectrum and energy efficiencies, lower hardware cost/storage, and mutually enhanced functionalities [24], [25].

Among others, there have already been tremendous research attempts concerning the integration of sensing and communication (ISAC) [103] and ILAC [17]. ISAC, also known as a fusion of radar and communication (RadCom) [104] and dual-function RadCom (DFRC), has emerged recently as a disruptive design paradigm for 6G mobile networks with an important application for connected vehicles. For example, in [105], the preambles of the single-carrier 802.11ad system have been exploited to carry out long-range radar sensing in the 60-GHz unlicensed band. It is shown in [105] that a gigabits-per-second data rate is achieved simultaneously with cm-level range accuracy and cm/s-level velocity accuracy for a single-target scenario. An architecture for an OFDM-based RadCom system has been studied in [104] with unique advantages to the radar application, such as very high dynamic range, independence from the transmitted user data, the enabling of relative velocity estimation, and efficient implementation based on the fast Fourier transform.

Similar to the state-of-the-art of ISAC, centimeter-level localization accuracy is expected by leveraging ultramassive MIMO, mmWave technologies, and UAV/satellite networks. On the other hand, the vehicles' location information can assist wireless networks with a wide range of information such as location-aided channel state information, beam processing, routing, network design, operations, and optimization to effectively utilize network infrastructure and radio resources. Research has already started in this direction. In [106], location information has been used in cognitive radios and for network optimization applications, whereas, in [107] and [108], resource allocation utilizing location information has been proposed for a multiuser and multicell system. A comprehensive survey can be found in [109] on location-aware communication across various layers of the protocol stack. In [110]–[114], joint localization and data transmission have been studied for 5G networks using different beamforming schemes. A key challenge here is how to allocate the radio resources effectively between localization and communication while maintaining their QoS requirements. To tackle this problem, ML-based approaches can be used since ML can unfold the full capability of the radio resources intelligently [17]. In both ISAC and ILCA, optimal waveform design with ultrahigh spectral efficiency is another challenge, which can be solved through effective spectrum sharing techniques or by properly sharing one waveform. The unified design of transceivers also needs to be considered for the seamless integration of localization and communication.

### I. Integrated Control and Communication

Integrated communication and control will play a crucial role in 6G and could potentially help in improving advanced and autonomous V2X services. One of the use cases of integrated communication and control is *vehicle platooning* [115]–[117], where a group of vehicles travels closely together in a coordinated movement without any mechanical linkage. The key benefits of vehicle platooning include increased road capacity, a rise in fuel efficiency, and comfortable road trips. Each vehicle in the platoon must know its relative distance and velocity with its neighboring vehicles in vehicle platooning to coordinate their acceleration and deceleration. Most of the prior works in this direction are either communication-centric [118]–[120] or control-centric [121]–[123]. The former entirely abstracts the control mechanism, while the latter assumes that the performance of the communication networks is deterministic. However, such an assumption can impair the performance of the system. For example, if the exchange of information is delayed, which can be caused by the uncertainty of the wireless channel, the stable operation of the platoon will be jeopardized. Therefore, to enable autonomous platooning, integrated communication and control will play an important role. Few studies have been reported in the literature, such as [124] and [125], which jointly studied the communication and control systems in a V2X network, particularly for vehicle platooning. Although control and communication theories are well studied in the past, existing tools are not yet adequate for analyzing integrated control and communication design [126]. For example, the fundamental limits of wireless control in real-time applications (e.g., vehicle platooning) are still unknown. On the other hand, the tight interaction between vehicle control and wireless networks is not yet well-understood. Understanding this interaction will play an important role in the field of integrated communication-control design for autonomous vehicles.

## V. KEY MACHINE LEARNING PERSPECTIVES

Recent advances in ML research with the availability of large datasets and storage, and high computational power [127] have enabled various novel technologies, such as self-driving vehicles and voice assistants [128]. In view of this background, ML has become increasingly indispensable and instrumental toward highly autonomous and intelligent operation of tomorrow's 6G vehicular networks [129].

The design of traditional wireless communication systems heavily relies on model-based approaches in which various building blocks of communication systems are judiciously modeled based on analysis of measurement data. While these model-based approaches have demonstrated their successes in traditional communication system design, there may be some scenarios in 6G-V2X in which accurate modelings (e.g., interference model and accurate channel estimation) are unlikely [127]. Since ML is capable of extracting the characteristics and identifying (even certain deeply hidden) relationships between input

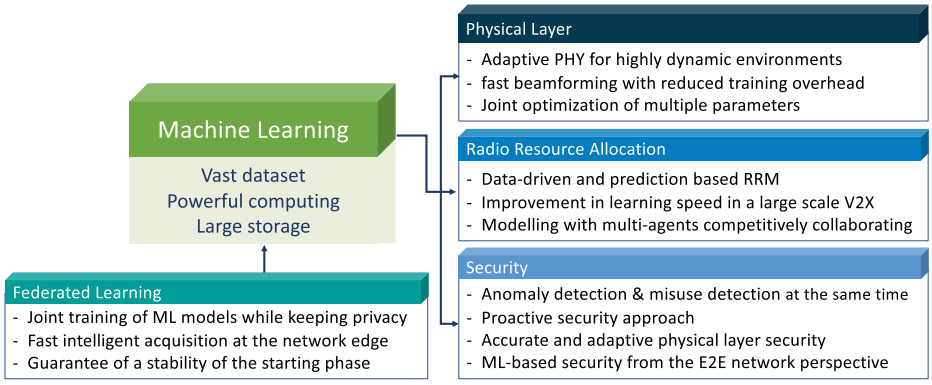


**Fig. 8.** ***Summary of potentials and open issues of ML for 6G-V2X.***

and output data, it can be adopted as a powerful tool in the aforementioned scenarios where traditional communication system design may suffer from model mismatches. In addition, the data-driven nature of ML can help inferences and predictions about channel dynamics, user behavior, network traffic, application requirements, and security threats, thus leading to better resource provisioning and improved network operation [127]. In addition to the key role that ML plays in improving road safety and driver experiences, the latest progress in ML techniques is advancing the realization of autonomous cars [130]. For instance, the data streams of the observed information from cameras, LiDARs, GPS units, and sensors can be processed, with which data-driven intelligent decision-making takes place through modular perception-planning-action or by end-to-end learning methods for autonomous driving [131]. As far as vision-based ML is concerned, multimodal reasoning by fusing camera frames and LiDAR scans is investigated in [132] for better object detection to help autonomous driving. While numerous ML-based smart driving applications are expected for future driving, we focus in this article on the network perspective and highlight the impact of ML in 6G-V2X networks. We discuss the grand vision, significant opportunities, and major challenges of ML with a key focus on the physical layer, radio resource allocation, and system security. In addition, we introduce federated learning, which is one of the most promising ML technologies. A summary of this section is shown in Fig. 8.

## A. ML for New Physical Layer

The vast range of data services in future V2X communications necessitates the judicious selection of coding, modulation, waveform, and multiple access schemes. In 6G-V2X, it is highly desirable to design an adaptive PHY, which can accommodate diverse use cases and the corresponding technological requirements.

The large Doppler spread may cause very rapid channel fading due to the high mobility, preventing accurate channel estimation. Although linear minimum mean square error (LMMSE) estimation produces optimal performance for linear and stationary channel environments [133], it may not be effective for complicated channel conditions, especially in highly dynamic environments. Moreover, since conventional methods generally estimate the channel state information first and then recover the transmit signals, excessive signal processing latency at the receiver may be incurred [134]. From this point of view, ML is envisaged to help improve channel estimation in future 6G-V2X networks. In [135]–[137], deep learning has been adopted to optimize the channel estimation through the training of neural networks. However, due to the long training period and large training data, the learning-based channel estimation in [135]–[137] includes off-line training. In this case, the potential mismatch between the real channels and the channels considered in the training phases could result in performance degradation [128]. How to carry out effective channel estimation/prediction in highly dynamic environments is a challenging and interesting research problem.

Furthermore, the design of channel codes, such as low-density parity-check (LDPC) or polar codes, for example, is usually handcrafted with a relatively simple channel model (e.g., Gaussian or Rayleigh). Such a handcrafted channel code may lead to compromised error correction capabilities when it is adopted over a high-mobility V2X environment. In such a scenario, a connected vehicle may experience a rapid variation of interference when it moves from one location to another at a high speed. Therefore, it is of strong interest to investigate how to efficiently generate channel code *on-the-fly* for more flexible rates, lengths, and structures that are well adaptive to the rapidly varying communication environments.

As mmWave communication is expected to be widely used in 6G-V2X, beamforming and massive MIMO technologies are desired to overcome the notorious high path loss problem. The works in [138] and [139] pointed out that the existing beamforming methods for vehicular communication networks suffer from the overload problem incurred by frequent switching. Adaptive beamforming in a vehicular communication scenario [139] and [140] is

possible, but frequent beam training may be needed. Thus, it is desirable to develop new approaches to help reduce frequent training and heavy overhead while guiding the design of intelligent ML-based beamforming.

The high heterogeneity and dynamics of vehicular networks will increase the complexity of the environment including the varying wireless channels. As discussed, in legacy communication systems, different blocks of the PHY layer are usually optimized independently for ease of design. Such a design paradigm may not be optimal when different QoS requirements (e.g., latency, reliability, spectrum and energy efficiencies, and implementation cost) have to be met, particularly over very complex vehicular channels. Different functional blocks at the PHY layer would need to be configured jointly and adaptively according to the dynamically varying environment [128]. For instance, ML-based enhanced adaptive coding and modulation (ACM) is likely to significantly reduced communication latency and improved robustness [141], [142]. ML can also be applied to jointly optimize multiple configurations. In this case, an ML-based joint optimization needs to be developed while taking into account the entire end-to-end physical layer architecture [143].

### B. ML for Improved Radio Resource Management

Radio resource allocation, as a classical problem in wireless networks [144], has received tremendous research attention in the past years. Although numerous radio resource allocation approaches (e.g., based on the greedy algorithm, game theory, and optimization) have been investigated, investigations on RRM are needed to satisfy certain new features of 6G-V2X networks, such as high mobility, heterogeneous structure, and various types of QoS requirements.

First, the mobility of vehicles leads to fast handovers over the links, leading to frequent resource allocation. While the channel quality and network topology may vary continuously, conventional resource allocation approaches would potentially need to be rerun for every small change, incurring huge overhead [145]. Here again, ML-based approaches offer promise as an efficient tool for data-driven decisions to enhance vehicular network performance [146]. For example, in [147], the prediction capability of ML is adopted to facilitate rapid response to dynamic changes in traffic loads. Their proposed ML-based approach is able to predict the future traffic load (about bursty traffic patterns) and assign the available channel to certain links, thus helping avoid potential network congestion and rapid channel allocation.

The scarcity of qualified real datasets for vehicular networks is considered a big challenge for the use of ML [148]. RL may be exploited when prelabeled datasets are not available. For instance, in [149], RL is adopted for a vertical handoff strategy of V2I networks, in which RSUs, as learning agents, take into account the information from vehicles (i.e., average received signal strength, vehicle velocity, and the data type), as well as traffic load for optimal handoff decisions. Without prior knowledge of handoff behavior, their proposed RL-based method can achieve rapid and accurate handoff to ensure seamless mobility management. In [150], RL is employed for a user association solution in heterogeneous vehicular networks (i.e., macrocells, picocells, and femtocells). It is shown that a high data rate with load balancing is attainable by learning an enhanced association policy based on the data of traffic loads and the pilot signal strengths received at vehicles. As indicated in [149] and [150], RL, which does not require prior knowledge of the vehicular environment, is expected to attract increasing research attention compared to learning approaches requiring datasets obtained in advance (i.e., supervised and unsupervised learning).

To use RL for RRM problems, it is imperative to seek RL solutions that can quickly converge. In this regard, one of the major challenges in RL is the so-called exploration and exploitation dilemma [151]. Specifically, an RL agent has to decide between exploration or exploitation, i.e., whether to explore the unknown states and try new actions in search of better ones for future adoption or to exploit those examined actions and adopt them. While exploration increases the flexibility of the agent to adapt to a dynamic environment at the expense of a possible degradation in the agent's learning accuracy, exploitation drives the agent's learning process to local optimal solutions [152]. When resource allocation problems are modeled with the large state/action space, finding a good tradeoff between exploration and exploitation is indispensable in order to improve computational time and convergence speed [153]. For a large-scale network with multiple vehicles, the state and action space in RL may grow very large. In this case, it is likely that a large number of states are not frequently visited, and therefore, a much longer time would be required for convergence.

To alleviate this problem, deep RL (DRL) has been investigated recently. In [154], multiple parameters of local observations, including channel information of V2V and V2I links and interference levels, are considered to manage the subband and power allocation issues. With their problem modeled with a large state/action space, DRL is adopted to extract the mapping relationship between the local observations and the resource allocation-and-scheduling solution. Moreover, DRL is particularly effective in dealing with the high complexity of joint optimization problems that often arise when dealing with wireless V2X resource allocation [155].

It is worth mentioning that a single-agent learning framework is considered in prior art (e.g., see [154]), where each agent in the same network may take its action without collaborating with any of the others [156]. Such independent choice of actions could influence other agents' rewards, hindering the convergence of the learning process [157]. Thus, when ML is applied to a vehicular network with multiple agents, the challenge of competitive collaboration should be considered for effective multiagent

learning. As an example, in [158], the problem of joint channel assignment and power allocation in C-V2X networks is studied with multiagent learning. When dealing with multiagent RL, it is often meaningful to use game-theoretic tools [159] to provide fundamental and rigorous analysis of the RL process.

### C. ML for Security Management

The integration of diverse connectivity and the stringent data provision of services for 6G-V2X will exacerbate the security challenges. While 6G-V2X aims at providing seamless connectivity between infrastructural nodes and vehicles, the broadcast nature of vehicular communication makes it susceptible to malicious attacks. Various types of malicious attacks (e.g., authentication and authorized attacks, and data forgery and distributions [160]) could target a vehicular network. Given that, in a V2X system, private user information, such as user identity or trajectory, is exchanged over wireless link, the development of new user identification and authentication scheme is of particular importance to maintain secure and legitimate access to data/services/systems [161].

ML can be adopted for the detection and prevention of intrusions. In [162] and [163], supervised learning with classification capability is proposed as an effective mean to identify vehicles' abnormal behavior. It is noted that the training and detection process relies on existing labeled data, and therefore, such supervised learning may be incapable of detecting novel/unknown attacks. In [164] and [165], unsupervised learning that is capable of clustering and does not require labeled data is considered for real-time detection. Specifically, intrusion detection by using K-means clustering is proposed for vehicular networks in [164]. To deal with attacks that can dynamically in real time, anomaly detection using unsupervised learning is studied in [165]. However, since these approaches consider either misuse detection or anomaly detection, they may not be effective in a real scenario where known and unknown attacks can take place at the same time. In addition, reactive detection is mainly considered in the existing detection approaches to save communication costs. However, in a 6G-V2X network where the communication resources are relatively abundant, proactive exploration-based security approaches are expected to be useful for the enhanced security level [129]. For example, in [166], a proactive anomaly detection approach is adopted to connected cars for cyberthreat prevention.

Security issues in wireless communication are usually managed in the upper layers of the protocol stack using cryptographic-based methods. However, the management and exchange of secret keys will be challenging in heterogeneous and dynamic V2X networks in which vehicles may randomly access or leave the network at any time [167]. In this regard, one can complement standard cryptographic approaches with physical layer security (PLS) solutions [168]. While PLS techniques exploit the randomness and the physical characteristics of wireless channels to thwart eavesdropping, these methods can be sensitive to channel modeling accuracy. Due to the high mobility and consequently the channel variations in a V2X scenario, ML can be useful for accurate channel estimation and tracking, which may benefit the design of more effective PLS-based techniques. Furthermore, depending on the scenarios and services, different security levels are expected. For example, consider two vehicles that follow each other either on a deserted road or at a busy intersection. Due to the vehicles' movement, the latter has a higher amount of factors, which may affect the decision-making, resulting in stringent security requirements [169]. ML may be employed in the latter case to dynamically decide the required security level and the most appropriate PLS solution.

ML can also be used to design better control and communication mechanisms that can prevent data injection attacks on vehicular networks, in general, and vehicular platoons, in particular, as shown in [170].

When ML is adopted to improve the security, ML-based solution needs to be validated with respect to the end-to-end network performance. As already mentioned, ML can be used in functional modules in multiple layers of the networks. Thus, the use of ML should be synchronized across the network [171] to ensure overall secure communications [172].

### D. Federated Learning for 6G-V2X

A critical issue for efficient applications of ML is the training of ML models, which may be used at the base stations or in the vehicles. The training of large ML models in remote clouds is an obvious solution but could be time-consuming. One problem is that the fast-changing vehicular network and communication conditions may lead to a slow response to environmental changes, thus resulting in degraded performance. Furthermore, most training samples are generated at the network edges, such as base stations and vehicles, and hence, the cost and latency of transferring such data to a remote cloud could be very high. Against this background, local training of ML models is a desirable solution in 6G-V2X networks. As each base station or vehicle may hold only a small number of training samples, joint training of ML models with shared training samples is a potential way to improve ML model accuracy and generalization of performance. However, a major concern for the joint training is privacy, in which base stations and vehicles may not want to compromise by sharing training samples. Federated learning, emerged in recent years to address the privacy and communication overhead issues associated with the training of ML models, has attracted extensive research interest for enhanced wireless networks [173]–[176].

Deemed to be an excellent ML approach for more efficient 6G-V2X networks, there are several technical challenges to be tackled for effective applications of federated

learning. In the existing research works on federated learning of wireless networks, supervised learning is mainly considered. As RL models are more likely to be used, a scalable federated RL framework, which can cover many different 6G-V2X use cases, is needed. In addition, since many V2X applications are mission-critical, it is often not possible to allow federated RL to learn from scratch to avoid an unstable phase at the beginning of the learning process. Another challenge of federated learning involving vehicles is the short interconnectivity between the vehicles. The vehicles may be out of communication range with the base stations or other vehicles that are involved in the federated learning. Hence, the vehicles may need to participate in federated learning, while they are parked. Finally, the impact of the wireless channel on the federated learning performance deserves a deeper investigation. As shown in [174], wireless errors and delays can affect the accuracy of federated learning. This effect can be further exacerbated in a mobile V2X network due to the high-speed mobility of the vehicles and the dynamics of the channel. Further research on the joint design of wireless and learning mechanisms for V2X is needed.

## VI. CONCLUSION

In this article, we have identified a number of key enabling technologies and revolutionary elements of next-generation 6G-V2X networks by unfolding their potential features and advantages that are far beyond the capabilities of 5G. Furthermore, we have provided an overview of recent advances in applications of ML in 6G vehicular networks, which is widely regarded as a key to pave the way toward truly ITSs. For each enabling technology, we have highlighted and discussed the major advances, the most pressing challenges, and the potential opportunities. We expect this article to provide academic and industry professionals with key insight into 6G-based next-generation V2X, which, in turn, will stimulate more research with innovative solutions toward the practical design, testing, and deployment of these technologies. ■

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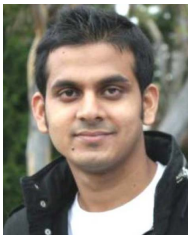

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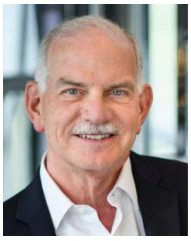

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