

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

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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, as well as a plethora of advanced applications. Realizing this grand vision requires a significantly enhanced vehicle-to-everything (V2X) communication network which should be extremely intelligent and capable of concurrently supporting hyper-fast, ultra-reliable, 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 will play an instrumental role for advanced vehicular communication and networking. To this end, we provide an overview on the recent advances of machine learning in 6G vehicular networks. To stimulate future research in this area, we discuss the strength, open challenges, maturity, and enhancing areas of these technologies.

Index Terms—6G-V2X, Intelligent reflective surfaces, Tactile-V2X, Brain-controlled vehicle, THz communications, Blockchain, Quantum, RF-VLC V2X, Machine learning, UAV/Satellite-assisted V2X, NOMA, Federated learning.

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I. INTRODUCTION

In recent years, vehicle-to-everything (V2X) communication has attracted significant research interest by both academia and industry. As a key enabler for intelligent transportation systems (ITS), 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, as well as a plethora of advanced applications.

Attempts to enable these applications are built upon the existing V2X communication technologies, such as dedicated short-range communication (DSRC) and cellular-V2X (C-V2X) [3]. DSRC is a wireless communication technology dedicated to automotive and ITS applications. For decades, DSRC has been 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 the 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) [4]. In March 2017, 3GPP Release 14 proposed using an LTE network for 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 the cellular network infrastructure [5]. The main focus of Release 14 is to deliver data transport services for fundamental road safety services such as cooperative awareness messages (CAM), basic safety messages (BSM), or decentralized environmental notification messages (DENM).

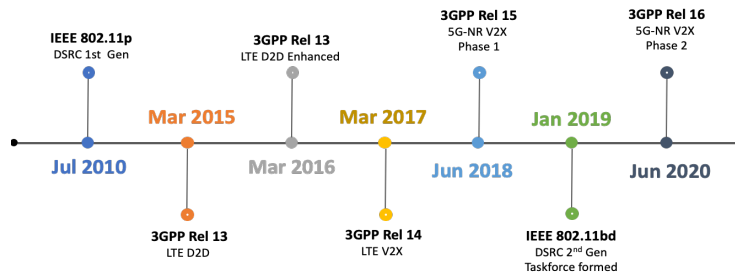


Fig. 1: Evolution of V2X communications.

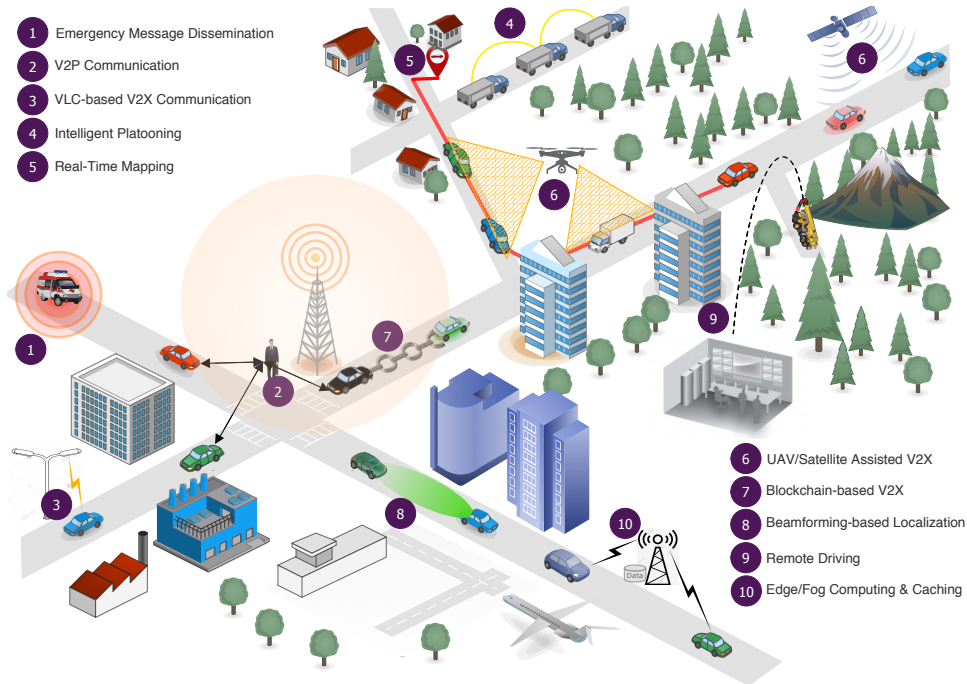


Fig. 2: Overview of V2X communications.

In Release 15 (announced in 2019), 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 [6], [7]. In addition, the performance of 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. Note that 3GPP has recently announced the second phase of 5G NR in Release 16, which aims at bringing enhanced ultra reliable low latency communication (URLLC) and higher throughput. The evolution of V2X communications is summarized in 26 Fig. 1.

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 [8]. 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 an 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 3D displays that offer more depth and more natural viewing experience and free-floating, to holographic control display systems, to immersive entertainment, to improved in-car infotainment, will bring forth new communication challenges to the V2X network [8]–[12]. 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

TABLE I: An Overview of Key 6G-V2X Technologies

| Category | Technology | Strength | Open Challenges | Maturity | Enhancing Areas |
|---------------------|--|--|---|----------|----------------------------|
| Revolutionary Tech. | Programmable V2X Environment | <ul style="list-style-type: none"> Intelligent V2X environments; Effective mitigation of path loss, shadowing, multipath and Doppler effect | <ul style="list-style-type: none"> Reflection optimization Channel estimation in highly dynamic V2X environment | ★☆☆ | PHY layer |
| | Tactile Communications | <ul style="list-style-type: none"> Real-time transmission of haptic information Enhanced vehicle platooning and remote driving | <ul style="list-style-type: none"> Simultaneous requirements for high rates, ultra-low latency, and high reliability in high mobility environments Suitable codecs and efficient reconstruction for the haptic data | ★☆☆ | Haptic interactions |
| | Quantum Computing | <ul style="list-style-type: none"> Superior computational capability Enhanced security | <ul style="list-style-type: none"> Design of quantum devices Security architecture, characterization of entanglement distribution | ★☆☆ | Computing & security |
| | Brain-Vehicle Interfacing | <ul style="list-style-type: none"> Enables brain controlled connected vehicles Managing uncertainties | <ul style="list-style-type: none"> Scalability of brain-controlled vehicles Comprehensive real-world testing | ★☆☆ | Driving experience |
| | Blockchain | <ul style="list-style-type: none"> Highly distributed Significantly enhanced security | <ul style="list-style-type: none"> Algorithm design for ultra-low latency application Increasing throughput and scalability | ★★☆ | Security |
| | THz Communications | <ul style="list-style-type: none"> Extremely high throughput Higher spectrum | <ul style="list-style-type: none"> Design of transceiver architectures Propagation measurement and channel modeling | ★☆☆ | PHY layer |
| | ML-aided V2X Design | <ul style="list-style-type: none"> Suitable for highly adaptive and complex V2X environments Performance enhancement | <ul style="list-style-type: none"> Performing effective training in highly dynamic environments Processing big-data in real-time | ★★☆ | PHY & MAC layers, Security |
| Evolving Tech. | Hybrid RF-VLC V2X | <ul style="list-style-type: none"> Ultra-high data rates Low setup cost | <ul style="list-style-type: none"> Inter-compatibility between VLC and RF Interference management | ★★★ | PHY & MAC layers |
| | Multiple Radio Access Technologies | <ul style="list-style-type: none"> Inherent benefits of sub-6 GHz, mmWave and/or THz for long communication range Hyper-high data throughput | <ul style="list-style-type: none"> Dynamic configurations meet different QoS requirements Beam and interference management | ★★☆ | PHY & MAC layers |
| | Non-orthogonal Multiple Access (NOMA) | <ul style="list-style-type: none"> Massive connectivity Ultra-low latency | <ul style="list-style-type: none"> Cross-layer optimization for grant-free NOMA Adaptive NOMA and OMA | ★★☆ | PHY & MAC layers |
| | New Multicarrier Scheme | <ul style="list-style-type: none"> Significantly enhanced resilience to Doppler Higher spectrum- and power-efficiencies | <ul style="list-style-type: none"> Backwards-compatibility with LTE and 5G NR Scalable multicarrier schemes in highly dynamic vehicular environments | ★★☆ | PHY layer |
| | Advanced Resource Allocation | <ul style="list-style-type: none"> Cross-layer resource allocation Context and situation awareness | <ul style="list-style-type: none"> Efficient and scalable deployments Distributed intelligent solutions | ★★☆ | PHY & MAC layers |
| | Integrated Localization and Communications | <ul style="list-style-type: none"> Enhanced localization Secured localization | <ul style="list-style-type: none"> Unified design of transceivers Optimal waveform design | ★★☆ | Positioning |
| | Satellite/UAV Aided V2X | <ul style="list-style-type: none"> Extra wide coverage Flexible aerial base-station | <ul style="list-style-type: none"> Energy-efficient computation & transmission Robust reception in high mobility environments | ★★☆ | PHY & MAC layers |
| | Integrated Computing | <ul style="list-style-type: none"> Faster computing and enhanced security Low operational cost | <ul style="list-style-type: none"> Integration of cloud, edge, and fog computing Heterogeneous design to support different data sources | ★★★ | Computing |
| | Integrated Control and Communications | <ul style="list-style-type: none"> Control-communications co-design Enhanced platooning | <ul style="list-style-type: none"> Derivation of fundamental limits Understanding of control and wireless networks interaction | ★★☆ | Control |

with ITS has 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 non-terrestrial communication networks such as satellite and unmanned-aerial-vehicle (UAV) communication networks. This will enable genuinely intelligent and ubiquitous V2X systems with significantly enhanced reliability and security, extremely higher data rates (e.g., Tbps), massive and hyper-fast wireless access (i.e., down to sub-milliseconds with billions of communications devices connected), as well as much smarter, longer, and greener (energy-efficient) three-dimensional (3D) 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 machine learning (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 [8].

B. An Overview of 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 are 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 enhance the communication QoS particularly in some blind corners which 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 ultra-high data rates, low setup cost, low power consumption, and enhanced security.

There are 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 the subsequent sections. 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 I. 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 communications 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, terahertz (THz) communications will enable ultra high data rates never experienced before.

C. Contribution and Organization

The main contribution of this paper is a comprehensive overview of the scientific and technological advances that have the capability to shape the 6G vehicle-to-everything (6G-V2X) communications. Revolutionary 6G-V2X technologies such as brain-vehicle interfacing, tactile communications, and terahertz communications, will be introduced in Section II. In Section III, we present major 6G-V2X technologies (e.g., integrated localization and communications, satellite/UAV aided V2X, integrated computing, etc) that have evolved over recent years and are going through further enhancements. The recent advances in machine learning for 6G vehicular networks are summarized in Section IV. Finally, conclusions are drawn in Section V.

II. 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.

A. Programmable V2X Environment

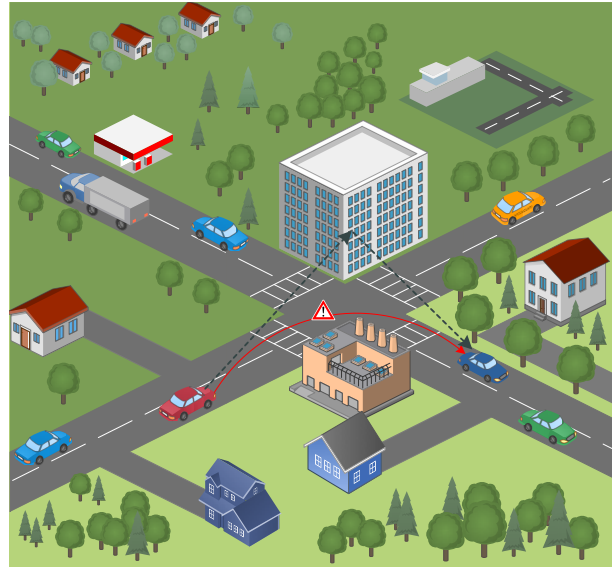


Fig. 3: Intelligent reflecting surface at intersection.

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 doubly selective channel (i.e., time-and-frequency selective) which widely appears in vehicular communication systems due to the mobility of 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, LTE and 5G NR-based V2X systems are configured with large subcarrier spacing as well as dense pilot placement. However, this may result in a considerably reduced spectral efficiency, not to mention very complex signal processing algorithms at the receiver.

More recently a disruptive communication technique called intelligent reflective surfaces (IRSs) 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 [13] 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 multi-path 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 [14], [15]. As such, vehicles located in perpendicular streets may not communicate with each other very well, which could result in significant degradation of V2V communication performance. To mitigate this issue, IRSs 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 scenario is illustrated in Fig. 3. It is interesting to point out that IRS can be employed for mitigation of the Doppler effect and multi-path fading as well, making IRS an appealing research direction for significantly enhanced V2X communication in 6G. 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. Quantum Computing Aided V2X

6G-V2X is expected to support more spectrum, a very large number of densely connected vehicles, a wider range of applications, higher complexity in the processed signals, and more stringent requirements in terms of reliability, latency, and power efficiency compared to 5G-based V2X. In order to meet these requirements, 6G-V2X networks require significant computational resources than are currently available. Those resources are necessary in order to perform many computationally intensive tasks in a hyper fast manner. The advent of quantum computing promises a radically enhanced computational dimension to wireless communication, supporting the ultra-fast execution of highly complex algorithms, in particular signal processing tasks which cannot be carried out in a real-time manner with traditional computing resources. 6G-V2X equipped with quantum computing will be able to perform extremely complex and currently time-consuming algorithms to significantly enhance V2X services. For example, the implementation of advanced machine learning algorithms which 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 [10], [16].

In addition to the superior computational ability, quantum computing offers enhanced security in wireless

communications. Note that security in V2X communications is significantly more important than traditional communications since, for example, security breach in autonomous vehicles 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 [8], 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 to detect any malicious eavesdropping attempt.

Although quantum computing can be a promising technology for 6G-V2X from different aspects, much more research is needed to exploit and implement the benefits of quantum computing in V2X communication. For example, current quantum computer chips can only operate at extremely low temperature (close to zero Kelvin), which makes them usable only in vehicular infrastructure. To use them in the vehicles, significant research is needed on the thermal stability of quantum computer chips. Other fundamental challenges include development of large-scale quantum computing, design of quantum security architectures, and characterization of entanglement distribution.

C. Tactile Communications in V2X

Tactile communication is a revolutionary technology, which enables a paradigm shift from the current digital content-oriented communications to a steer/control-oriented communications by allowing real-time transmission of haptic or olfactory information (i.e., touch, smell, motion, vibration, surface texture) [17]. Integrating human sensual information, tactile communication in 6G-V2X is expected to provide a truly immersive experience for on-board vehicle users [18]. In addition to traditional applications of multimedia communications (e.g., on-board meetings/demonstrations, 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.

While tactile communication has enormous potential, the progress in this area is still in its infancy and many problems remain open. 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. 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 [19], 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 (HRLLC) 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 design of application-specific control and communication protocols, development of human-to-machine interfaces for wireless haptic interactions, and design of suitable haptic codecs to capture and represent the haptic data, and exact reconstruction of received haptic data.

D. 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. While this may be quite a futuristic scenario, for people with disabilities, BCVs offer great potential for improved independence by providing an alternative interface for them to control vehicles. Brain activity signals can be translated into motion commands to the vehicle through the use of a brain-computer interface. 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 [20]. By keeping humans in the loop, BCV is also 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 ultra-high reliability, ultra-low latency, and ultra-high data rate communication and ultra-high speed computation. For example, a coarse estimation of the whole brain recording demand is about 100 Gbps [21], the transmission of which is not supported by the existing wireless technologies. However, through full-phased brain-vehicle interfacing and machine learning techniques, 6G-V2X must enable learning and adapting the behaviour of human drivers.

Recently, research has demonstrated the feasibility of BCV. For example, authors in [22] and [23] 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 [21]. Moreover, extensive real-world experiments are required to demonstrate the effectiveness of BCVs, as most of the existing works on BCV has been verified through simulation only.

E. 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 ultra-resilient security to deal with potential malicious attacks or jamming, whilst multimedia data services may require only lightweight security due to the 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 de-centralized 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 [24]. Through the inherent 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 [25], [26]. Moreover, the characteristics of blockchains are of interest for 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 [27].

While several attempts have been made to realize blockchain-based communication network [24], a straightforward adoption of an existing blockchain technology is not suitable for V2X communication scenario due to its dynamic network characteristics and real-time data processing requirement. 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 ultra-low 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.

F. Terahertz-assisted V2X networks

THz communication, which operates at terahertz bands (0.1-10 THz), is envisioned as a promising approach to alleviate increasingly congested spectrum [10], [28] at lower frequencies. Leveraging the availability of ultra-wide bandwidth, THz communication will be able to provide transmission rates ranging from hundreds of Gbps to several Tbps. Such an extremely high throughput will enable a plethora of new V2X application scenarios such as ultra-fast 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

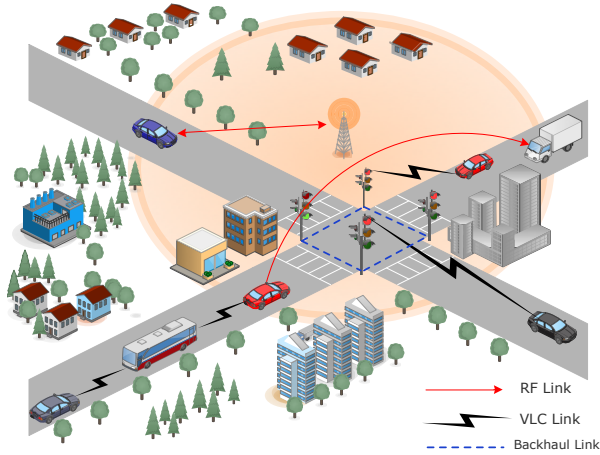


Fig. 4: Hybrid RF-VLC-based V2X communications.

be used in on-board 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 [29]) can be potential solutions to extend the coverage of TH-based V2X communications.

III. 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 [30], [31]. One alternative approach may be the combination of RF and visible light communication (VLC)-based V2X

communications, where along with radio waves, visible light can be used as a medium of communication in vehicular networks. The ultra-high data rate (potentially up to 100 Gbps) achieved by light emitting diode (LED) or laser diode (LD)-based VLC [32] and its inherent features (such as low power consumption, enhanced security, and anti-electromagnetic 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 pre-installed 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 [28]. 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 [33]. 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) of 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 [14].

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 as well as 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 [34], [35]. 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 Non-orthogonal Multiple Access (NOMA)

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 orthogonal multiple access (OMA) schemes, NOMA allows multiple users to utilize time and frequency resources concurrently for both random access and multiplexing [36], [37]. There are two main types of NOMA: power-domain NOMA [38], [39] and code-domain NOMA [40], [41], such as sparse-code multiple access (SCMA) [42]–[44] and resource spread multiple access [45], 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 ultra-low latency massive connectivity whilst 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 for 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 [46]. 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 which 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., Tbps

data rates, billions of connected devices, sub-milliseconds of access latency). The rich frequency resources at mmWave and THz bands can provide larger bandwidth (e.g., multi-Gigabits and 10s GHz 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 modelling 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 [19]. It is foreseen that multi-radio access technologies with sub-6 GHz, mmWave and/or THz will be needed to work together in future 6G-V2X networks [47]. For example, while mmWave and THz radios will provide extra bandwidth and capacity to 6G-V2X networks, but sub-6 GHz radios are critical for the enabling of long communication ranges and connectivity stability.

There are a number of challenges to be addressed for efficient usage of multi-radio 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 in high moving speeds. Communication between two vehicles over a mmWave link including the physical channel and communications of mmWave for V2V has been studied [48]. 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 multi-radio 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 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 [29].

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 [49]–[51]. However, there are several major challenges for RRM in 6G-V2X networks. As previously mentioned, 6G-V2X networks will very likely need

multi-radio 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 [52]–[54]. 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 multi-radio 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 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 cross-layer design of RRM solutions. For instance, in [55], we showed how one could use such smart multi-radio 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 multi-radios that are able to dynamically allocate resource blocks (RBs) and power should be designed following the hybrid RRM framework. Reinforcement learning could be applied to design such intelligent solutions. More discussion on the ML-based resource allocation will be presented in section IV.

E. New Multicarrier Scheme

6G should provide ultra-reliable high-rate V2X communications in high mobility environments. Connected vehicles and high-speed trains, moving at speeds of 1000 km/h or even higher, will communicate with each other and the surroundings including various sensors, infrastructure nodes (e.g., roadside units, base stations, robots), satellites, and the internet cloud. Innovation is needed to deal with the notorious Doppler effect as well as the resultant doubly selective channels (i.e., rapidly time-varying and frequency-selective channels) [56]. In both LTE and 5G

NR, orthogonal frequency-division multiplexing (OFDM) and its variants are adopted for high-rate transmissions [57], [58]. Nevertheless, OFDM is very sensitive to the Doppler effect which may destroy the multi-carrier orthogonality and result in increased amounts of inter-carrier interference and inter-symbol interference. To overcome this drawback, some advanced multicarrier waveforms [59] may be excellent candidates to 6G V2X. A promising multicarrier waveform is filter-bank multicarrier (FBMC) which enjoys tight spectrum containment as well as 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 [60].

Recently, orthogonal time-frequency-space (OTFS) has emerged as an effective multi-carrier scheme by spreading each information symbol over a two dimensional (2D) orthogonal basis function spanning across the time-frequency domain [61]–[63]. In principle, OTFS is capable of converting a time-varying multipath channel into a relatively static delay-Doppler image of the constituent reflectors. The 2D basis function in OTFS, called discrete symplectic Fourier transform (DSFT), is essentially an 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 ultra-reliable 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 [64]. Particularly, in a highly dense vehicular environment, UAVs can cooperate with the static network infrastructures nodes (i.e., base stations) in managing the wireless network to enhance the user experience. Because of their nearly unrestricted 3D movement, UAV can offer a number of unique V2X applications as a flying agent, such as: a) providing an advance road accident report prior to the arrival of rescue team, b) monitoring traffic violations to assist law enforcement agencies, and c) broadcasting warning about road hazards that occurred in an area not pre-equipped with an RSU [65]. Despite significant advancements in UAV technology, there exist several challenges in the area of UAV-enabled V2X system. For example, it is highly challenging to maintain reliable and high-speed wireless communication between UAVs and ground vehicles, as 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 [66]. Several other key challenges include safety and regulations, seamless integration with existing networks, and 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. 5. 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, multi-beam satellites [67] 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 which enjoy constant signal envelopes such as continuous phase modulation (CPM) [68]. A drawback of conventional CPM is that it may not be suitable to support high-rate communication as OFDM does [69]. 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 [70], [71]. It is noted that PMH is capable of achieving the highest power efficiency, while having the advantage of approaching the capacity of Gaussian inputs. 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 their 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 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

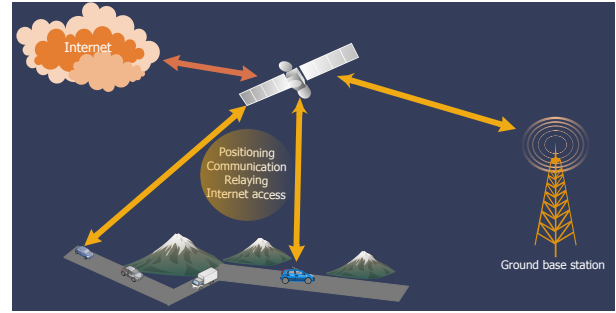


Fig. 5: Satellite-assisted V2X communications.

end users. On the other hand, fog computing has multiple interconnected layers and could interact with the distant cloud and edge nodes [12]. 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 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. 6. 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.

An 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 at close proximity to the locations where the data is generated, while together with the cloud, fog can support more sophisticated applications such as data analysis, pattern recognition, and behavior prediction [12]. Moreover, it has been demonstrated that network coding [72] 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 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 optimising computing resources.

H. Integrated Localization and Communication

Acquiring precise location information of a vehicle in real-time is becoming indispensable, not only to explore endless opportunities of location-based services but also to explore advanced V2X applications such as real-time

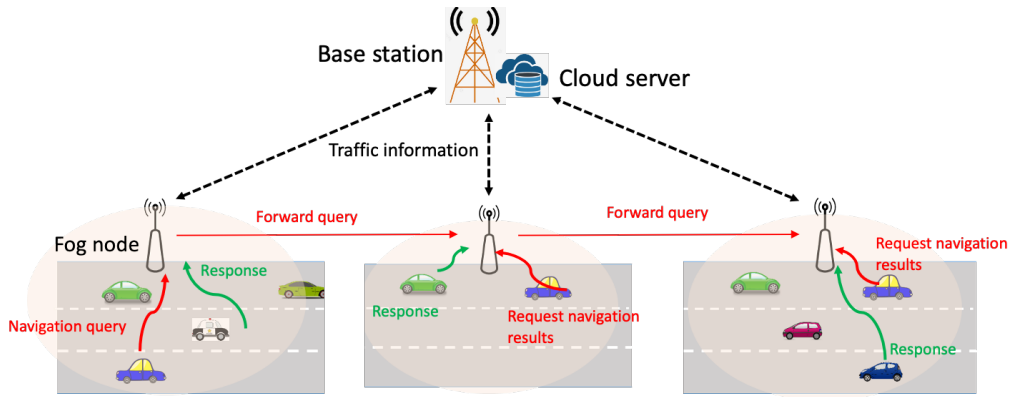


Fig. 6: Fog node assisted traffic navigation.

3D mapping for building an accurate environment model. In addition, accurate location information enhances the performance of the wireless communication system. It is anticipated that 6G will bring a new feature called integrated localization and communication (ILAC) into the wireless communication network [11]. In this new paradigm, leveraging ultra massive MIMO, mmWave technologies, and UAV/satellite networks, centimeter-level localization accuracy is expected. 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 [73], location information has been used in cognitive radios and for network optimization applications, whereas in [74], [75] resource allocation utilizing location information has been proposed for a multi-user and multi-cell system. A comprehensive survey can be found in [76] on location-aware communication across various layers of the protocol stack. In [77]–[81], 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 [11]. Optimal waveform design with ultra-high spectral efficiency is another challenge for ILCA, which can be solved through effective spectrum sharing techniques. 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* [82]–[84], 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 [85]–[87] or control centric [88]–[90]. 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 the 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. There are only a few works have been reported in the literature such as [91], [92], 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 analysing integrated control and communication design [93]. 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.

IV. KEY MACHINE LEARNING PERSPECTIVES

Recent advances in ML research with the availability of large datasets and storage, and high computational power [94] have enabled various novel technologies such as self-driving vehicles and voice assistants [95]. In view of this background, ML has become increasingly indispensable and instrumental towards a highly autonomous and intelligent operation of tomorrow's 6G vehicular networks [96].

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, accurate channel estimation, etc.) are unlikely [94]. Since ML is capable of extracting the characteristics and identifying (even certain deeply hidden) relationships between input and output data, it can be adopted as a powerful tool in aforementioned scenarios where traditional communication system design may suffer from model mismatches. Additionally, the data-driven nature of ML can help inferences and predictions about channel dynamics, user behaviour, network traffic, application requirements and security threats, thus leading to better resource provisioning and improved network operation [94].

In this section, we describe the potential applications of ML in future 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 the 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. 7.

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.

Due to a potentially high mobility, the large Doppler spread may cause extremely fast channel fading which prevents accurate channel estimation. Although linear minimum mean square error (LMMSE) estimation produces optimal performance for linear and stationary channel environments [97], 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 [98]. From this point of view, ML is envisaged to help improve channel estimation in future 6G-V2X networks. In [99]–[101], deep learning has been adopted to optimize the channel estimation through the training of neural networks. However, due to long training period and large training data, the learning based channel estimation in [99]–[101] includes offline training. In this case, the potential mismatch between the real channels and the channels considered in the training phases could result in performance degradation [95]. 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 which 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 [102] and [103] 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 [103] and [104] 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 [95]. For instance, ML-based enhanced adaptive coding and modulation (ACM) is likely for significantly reduced communication latency as well as improved robustness [105], [106]. 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 [107].

B. ML for Improved Radio Resource Management

Radio resource allocation, as a classical problem in wireless networks [108], has received tremendous research attention in the past years. Although numerous radio resource allocation approaches (e.g., based on 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 [109]. Here again, ML based approaches offer promise as an efficient tool for data-driven decisions to enhance vehicular network performance [110]. For example, in [111], the prediction capability of ML is adopted to facilitate rapid response to dynamic change of traffic loads. Their proposed ML-based approach is able to predict the

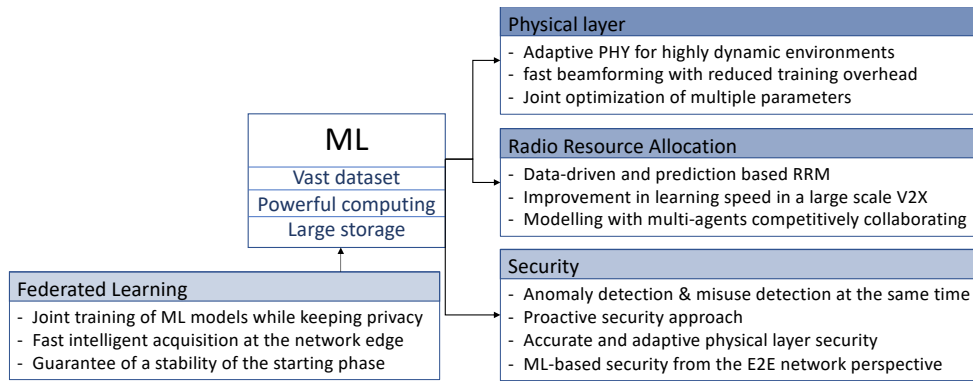


Fig. 7: Summary of potentials and open issues of ML for 6G-V2X

future traffic load (about bursty traffic patterns) and assign the available channel to certain links, thus helping avoid potential network congestion as well as rapid channel allocation.

The scarcity of qualified real datasets for vehicular networks is considered as a big challenge for the use of ML [112]. Reinforcement learning (RL) may be exploited when pre-labeled datasets are not available. For instance, in [113], RL is adopted for a vertical handoff strategy of V2I networks, in which RSUs, as learning agents, take into account of 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 behaviour, their proposed RL-based method can achieve rapid and accurate handoff to ensure seamless mobility management. In [114], RL is employed for a user association solution in heterogeneous vehicular networks (i.e., macro, pico and femto cells). It is shown that 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 [113] and [114], RL, which does not require prior knowledge of vehicular environment, is expected to attract increasing research attention compared to learning approaches requiring data sets obtained in advance (i.e., supervised and unsupervised learning).

To use RL for radio resource management 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 [115]. 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 for better ones for future adoption or to exploit those examined actions and adopt them. While exploration increases the flexibility of the agent to adapt in 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 [116]. 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 [117]. 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 reinforcement learning (DRL) has been investigated recently. In [118], multiple parameters of local observations, including channel information of V2V and V2I links and interference levels, are considered to manage the sub-band and power allocation issue. 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 [119].

It is worth mentioning that a single-agent learning framework is considered in prior art (e.g., see [118]), where each agent in the same network may take its action without collaborating with any of the others [120]. Such independent choice of actions could influence other agents' rewards, hindering the convergence of the learning process [121]. Thus, when ML is applied to a vehicular network with multiple agents, the challenge of competitive collaboration should be considered for effective multi-agent learning. As an example, in [122], the problem of joint channel assignment and power allocation in C-V2X networks is studied with multi-agent learning. When dealing with multi-agent RL, it is often meaningful to use game-theoretic tools [123] 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 [124]) could target a vehicular network. Given that, in a V2X system, private user information such as user identity or trajectory are exchanged over wireless link, the development of new user identification

and authentication scheme is of particular importance to maintain secure and legitimate access of data/services/systems [125].

ML can be adopted for detection and prevention of intrusions. In [126] and [127], 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 a supervised learning may be incapable of detecting novel/unknown attacks. In [128] and [129], unsupervised learning which is capable of clustering and does not require labeled data, is considered for real-time detection. Specifically, an intrusion detection by using K-means clustering is proposed for vehicular networks in [128]. To deal with attacks which can dynamically in real time, anomaly detection using unsupervised learning is studied in [129]. 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 cost. However, in a 6G-V2X network where the communication resources are relatively abundant, proactive exploration-based security approaches are expected to be useful for enhanced security level [96]. For example, in [130], a proactive anomaly detection approach is adopted to connected cars for cyber-threat 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 [131]. In this regard, one can complement standard cryptographic approaches with physical layer security (PLS) solutions [132]. 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 which follow each other either on a deserted road or at an 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 [133]. ML may be employed in the latter case to dynamically decide the required security level as well as 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 [134].

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 [135] to ensure overall secure communications [136].

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 environment 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 to the training of ML models, has attracted extensive research interests for enhanced wireless networks [137]–[140].

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 reinforcement learning models are more likely to be used, a scalable federated reinforcement learning 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 reinforcement learning 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 inter-connectivity between the vehicles. The vehicles may be out of communication range with the base stations or other vehicles which 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 [138], 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.

V. CONCLUSIONS

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. Further, we have provided an overview of recent advances on applications of machine learning in 6G vehicular networks, which is widely regarded as a key to pave the way towards truly intelligent transportation systems. For each enabling technology, we have highlighted and discussed the major advances, the most pressing challenges as well as 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 towards the practical design, testing and deployment of these technologies.

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