Unveiling the Road Ahead: Assessing the Landscape of C-V2X Technology and Its Journey to 6G Networks

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***Abstract*—This paper examines the advancements in Vehicle-to-Everything (V2X) communication, focusing on the integration of Long-Term Evolution (LTE) and 5G cellular technologies to enhance vehicular networks. The study evaluates the benefits and challenges of LTE-based V2X communications, comparing them with dedicated short-range communication (DSRC) systems, and explores the emerging role of 5G New Radio (NR) in improving latency, reliability, and coverage. Additionally, the potential of 6G networks to further revolutionize V2X communications through advanced technologies such as terahertz communication, intelligent reflective surfaces, and quantum computing is discussed. The incorporation of edge and fog computing is highlighted for its ability to provide low-latency, high-reliability services by processing data closer to the source. Moreover, the use of unmanned aerial vehicles (UAVs) and satellites is explored for enhancing V2X coverage, especially in remote areas, offering solutions for communication blind spots and extending network capabilities.**

***Index Terms*—dedicated short-range communication (DSRC), Vehicle-to-Everything (V2X), Long-Term Evolution (LTE), terahertz (THz), unmanned aerial vehicles (UAVs)**

I. INTRODUCTION

Advancements in Vehicle-to-Everything (V2X) communications are pivotal for improving transportation safety and efficiency, encompassing Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Pedestrian (V2P) interactions. Initially reliant on dedicated short-range communication (DSRC) systems, V2X is now transitioning to cellular technologies like Long-Term Evolution (LTE), which offer better coverage and support for high vehicle mobility. The 3rd Generation Partnership Project (3GPP) is developing LTE-based V2X services to enhance road safety and traffic flow. The introduction of 5G New Radio (NR) further advances V2X capabilities by addressing latency and reliability issues, though challenges such as handover complexities and channel interference remain. Looking ahead, 6G networks are poised to revolutionize V2X communication with technologies like terahertz communication, intelligent reflective surfaces, and quantum computing. This paper explores the integration of LTE, 5G, and future 6G technologies in V2X communication, highlighting the roles of unmanned aerial vehicles (UAVs), satellites, and edge and fog computing in enhancing V2X networks. The purpose is to provide readers with a brief overview of the future of vehicular communication.

II. LTE IN C-V2X: CHALLENGES AND ADVANTAGES

Cellular technologies like long-term evolution (LTE) provide extensive coverage and robust support for high vehicle mobility and density within a cell. This potential has interested organizations like the 3rd Generation Partnership Project (3GPP) to explore LTE's usability for V2X communications. Currently, 3GPP is actively developing cellular-based V2X services to offer a range of V2X capabilities [1].

A proposed solution, LTE-Cellular-Based V2X, offers a systematic and integrated approach for vehicular applications, featuring two transmission modes: network-assisted communication and autonomous direct communication. LTE-Cellular-Based V2X solutions cater to public transport security needs by offering essential features such as low latency, high reliability, and compatibility with high-speed movement. These attributes play a pivotal role in promoting road safety, optimizing traffic flow, and facilitating the development of connected autonomous driving technologies. Compared to IEEE 802.11p, LTE-Cellular-Based V2X leverages LTE's strengths, including centralized scheduling for network-assisted communication and decentralized autonomous resource selection for direct communication. This approach ensures reliable communication between vehicles with varying performance requirements and enables efficient utilization of LTE infrastructure [2] .

In [2] there where simulations made that indicate that LTE-Cellular-Based V2X performs better than DSRC in both freeway and urban environments, with network-assisted communication achieving higher packet reception rates (PRR) and reliability than autonomous direct communication [2]. C-V2X technology also excels DSRC in several aspects, such as data rate, latency, mobility support, communication range, handling of congested traffic, and minimizing adjacent channel interference. LTE-V2X, built on LTE, offers essential traffic safety services by enabling the exchange of status information like location, direction, and speed among vehicles, pedestrians, and infrastructure. However, the existing LTE physical layer has limitations, particularly at high vehicle speeds and high carrier frequencies, due to the Doppler effect, which affects carriers and reduces channel estimation accuracy. Current LTE physical layers can handle frequency offsets up to 1 kHz, but offsets between adjacent cell terminals can exceed 2.2 kHz, necessitating an improved physical layer structure. To tackle these challenges, the 3rd Generation Partnership Project (3GPP) proposes improvements such as a 1 ms subframe, reducing the interval between reference signals, and strategically placing four reference signal symbols to improve performance. Techniques for estimating high-frequency offsets by comparing phases within a reference signal symbol are being developed. Additionally, a new frame structure with 10 subframes of 1 ms each, featuring two slots per subframe and a variable subcarrier interval of 15 kHz, allows for more efficient scheduling and improved data rates [3].

While LTE-V2X faces significant challenges, particularly in physical layer design and frequency offset management, ongoing advancements and proposed solutions promise to enhance its capability, reliability, and efficiency, paving the way for more robust and scalable vehicular communication systems [3].

III. Introduction to 5G

Cellular-based V2X operates in three modes Cellular V2X, which interacts with base stations (BS), cellular-assisted V2V, in which vehicles communicate with each other via BS's, and unassisted V2V, where communication happens without relying directly on BS's [4]. While LTE-based communication was gathering a lot of interest and appreciation, the fascination with C-V2X communications only increased with the emergence of the fifth generation of cellular communications, 5G NR, as part of 3GPP Release 15 in 2019 [5].

This led to the initiation of the 5G Communication Automotive Research and Innovation (5GCAR) project, a joint undertaking involving the automotive industry, mobile communications sector, and academia. Prioritizing driving safety and efficiency, the project aimed to tackle critical challenges such as latency minimization, reliability enhancement, interoperability across various radio technologies, accommodating extensive connectivity demands, and fortifying vehicular communication security [4].

Recent studies scrutinizing the enhancements introduced by 5G NR have showcased exemplary performance outcomes in controlled environments underscoring the technology's significant promise [6], [7]. In [8], data was gathered from cellular routers fitted with and without 5G NR on a vehicle. Specific test conditions indicated a sizable improvement in latency in the 5G NR option, which was due to the NR enhancements [9]. However, it has been observed that neither 5G NR nor 4G LTE can minimize latency enough to meet the requisite standards in various applications, ranging from VRU warnings to different levels of autonomous driving. Furthermore, while 5G NR deployments show some latency improvement, their reliability isn't as strong as the 4G LTE options.

IV. Challenges of 5G

One of the features of 5G is that the network has many macro, micro, and nano cells. So, as the cell size decreases, we can increase the network capacity. However, the problem with this is that, when the user is in motion, the handover between cells is becoming increasingly difficult because it is a huge load on the network. Also, handover involves many parameters that are difficult to map. One solution to this is to have dual connectivity, where the vehicle is simultaneously connected to two BS's [10]. Another idea would be to have a multi-access manager on vehicles to predict and oversee handovers and ensure no loss of connectivity in vehicles in motion between areas of different coverage [11].

Massive MIMO involves using multiple antennas at the BS to cope with the increase in demand. However, it is very difficult to obtain channel state information to prevent interference and increase gain. Additionally, in vehicular communications, where most users are in a constant state of motion, the length of the pilot is very low because of the short coherence time [12]. This implies that the reuse distance of the pilot between cells is much less. So, there will be interference when users are at the borders of two cells. In [13], it is proposed to use transmit diversity and quadrature phase shift keying (QPSK) when the channel is bad and to use spatial multiplexing and 64 quadrature amplitude multiplexing (QAM) when the channel is good. This helps improve the gain in different scenarios.

Millimeter wave (mm Wave) communications in 5G V2X offer high data rates between vehicles and roadside infrastructure but are susceptible to shadowing. This shadowing restricts their performance to mostly line-of-sight (LoS) connections in the range of a few hundred meters. One way to overcome this would be to have BS's very close to one another which would do very well in terms of increasing the range since the signals can be handed over via multiple BS's.

Vehicular positioning is another aspect of C-V2X that is increasingly important. Adding on to the fact that mm waves have a short range, they also need at least 3-4 BS's to accurately indicate position. However, researchers in [14] improved vehicular positioning by using just 1 BS depending on multipath propagation. Also, another way to improve positioning is through the novel use of two Kalman filters, which improve positioning based on the different angles of arrival and departure and the already existing kinematic readings from the vehicle [15].

Vehicular Cloud Computing (VCC) provides cloud services for vehicular communications by processing data from sensors on and around a vehicle. However, the amount of incoming data is very high and needs high computational power to be analysed. Therefore, vehicular fog computing (VFC) was developed to handle this issue. Many fogs (taxis or buses) that already have cellular connectivity are deployed as nodes which host services to users in their vicinity, that in turn reduces latency [16]. The mobility of these nodes helps cater to a wide audience, and in case of overload on the fog, processing can easily be shared with nearby fogs. This is also very useful in vehicular crowdsensing where data specific to a particular region is collected during dire situations.

V. 6G : Vision for future V2X communication

Although 5G-NR V2X delivers enhanced performances and advanced services by investing more in spectral and hardware resources while retaining the fundamental mechanisms and system architectures inherited from LTE-based V2X, the projected rapid growth of autonomous vehicles, fueled by urbanization and technological advancements, is expected to result in an upsurge of communication devices and digital applications to support intelligent vehicle systems. The emergence of services like advanced displays, holographic control systems, and immersive entertainment, as depicted in Fig. 1, will pose new challenges for V2X networks, including issues related to data rate, latency, coverage, and security [17], [18]. Traditional 5G NR-based V2X networks may struggle to meet these diverse requirements, necessitating a paradigm shift towards more versatile 6G wireless communication networks.

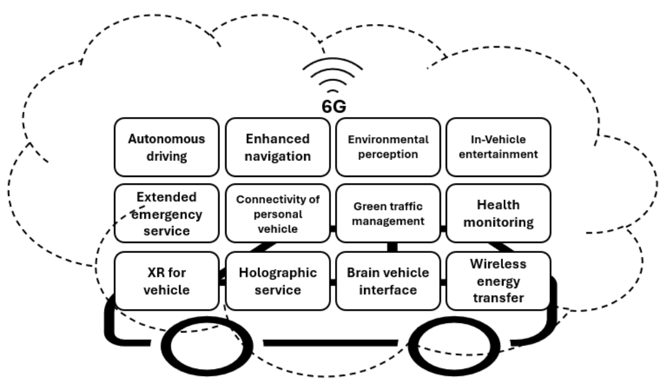

Fig. 1. Evolutionary 6G vehicular applications.

The key features and capabilities of 6G networks for V2X communication encompass a range of disruptive technologies set to transform the landscape of intelligent transportation systems. These networks will integrate robust and efficient air interfaces, resource allocation mechanisms, decision-making frameworks, and advanced computing architectures.

Notably, the incorporation of unmanned aerial vehicles (UAV) and low Earth orbit satellites into V2X systems will substantially enhance coverage, particularly in areas traditionally afflicted by communication blind spots. The wide-area coverage capability of UAVs can serve as aerial radio access points within the 6G-V2X network. They offer various services to vehicular users, including relaying, caching, and computing [19].

In highly congested vehicular environments, such as those displayed in Fig. 2, UAVs can communicate with BS's to optimize wireless network management and improve the user experience. The unrestricted 3-D mobility of UAVs can serve as aerial agents in various V2X applications. These applications include delivering advanced road accident reports before rescue teams arrive, monitoring traffic violations to aid law enforcement agencies, and broadcasting warnings about road hazards in areas without pre-equipped Roadside Units (RSUs) [20].

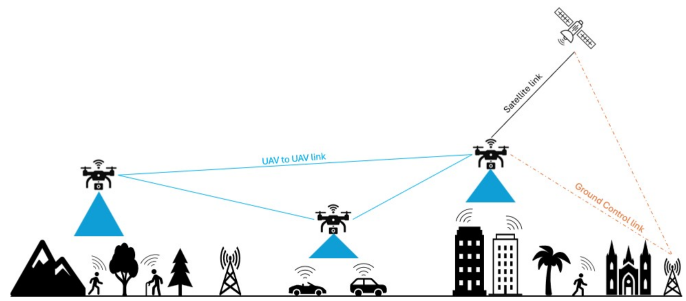

Fig. 2. UAV and satellite application scenarios.

Satellites present an alternative aerial communication platform for 6G-V2X. In existing V2X standards, satellites are solely employed for localization purposes. Notably, the data rates of satellite communication have seen a substantial rise in recent years, where one example is multibeam satellites [21]. These satellites enhance wireless data rates, making satellite communication a viable option for 6G-V2X to facilitate communication between vehicles and remote data servers in scenarios where terrestrial coverage is unavailable, and they can also undertake computing and network management tasks. However, achieving satellite-assisted V2X communications requires thorough investigation to accurately model channel characteristics between satellites and high-mobility vehicles.

Edge and fog computing, coupled with caching techniques, will empower V2X communication devices to execute computations swiftly, optimize decision processes, and extend battery life.

While cloud computing has found extensive applications in vehicular networks, it may not fully address the strict latency requirements of many V2X applications when used alone. A newly introduced paradigm, edge or fog computing, offers faster distributed computing and enhanced security at a lower operational cost. Edge computing functions independently, processes data on nodes located in close proximity to end users. In contrast, fog computing comprises multiple interconnected layers that can interact with distant cloud and edge nodes [18].

6G is set to offer more user-aware, scalable, and low-latency services for vehicles by utilizing computing resources at edge or fog nodes situated at the network's edge. Complex algorithms within the V2X network can be swiftly solved in real-time by offloading intricate computational tasks to these edge or fog nodes. An example of fog computing's utility lies in real-time navigation under traffic conditions. For instance, fog computing can facilitate navigation-based real-time traffic updates, as depicted in Fig. 3. Here, a vehicle's navigation query is directed to the nearest fog node, which then relays it to the destination fog node using a hop-by-hop relaying mechanism. Each fog node in the relay chain collects real-time traffic information within its coverage area. Subsequently, the originating fog node computes the optimal vehicle path based on the traffic reports recieved from other fog nodes [22].

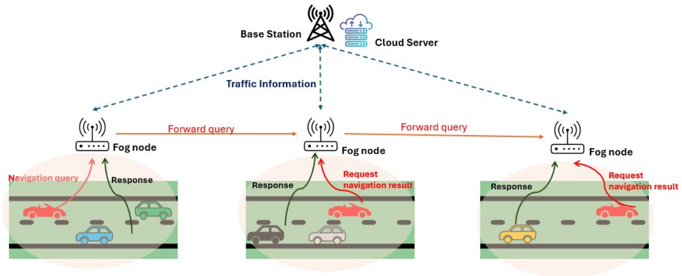

Fig. 3. Fog-node real-time navigation.

The integration of cloud, edge, and fog computing is essential in 6G-V2X to capitalize on the unique benefits of these computing technologies. Working alongside edge computing, fog computing can perform timely data processing, situation analysis, and decision-making in close proximity to data generation locations. Conversely, in tandem with the cloud, fog computing can support more sophisticated applications like data analysis, pattern recognition, and behavior prediction [18].

Terahertz (THz) communications emerge as a cornerstone, enabling gigabit-per-second data rates essential for realizing the ambitious goals of V2X communication in 6G networks. THz communication, operating within the THz bands (0.1–10 THz), is seen as a promising solution to alleviate the growing congestion in spectrum usage [23]. At lower frequencies, THz communication is set to revolutionize wireless transmission by capitalizing on ultrawide bandwidth availability. With transmission rates ranging from hundreds of gigabits per second to several terabits per second, THz communication offers unparalleled throughput, facilitating a multitude of innovative V2X applications such as ultrafast massive data transfer and haptic communications between vehicles. This fiber-like data transmission capability, without the need for physical wires over short distances, extends its utility to onboard scenarios like the brain-controlled vehicle (BCV) scenario, demanding extremely high throughput and low-latency wireless communication.

Revolutionary V2X technologies are on the horizon, including intelligent reflective surfaces (IRSs), novel machine learning (ML) algorithms, and brain vehicle interfacing, each poised to elevate V2X intelligence and sensory interaction to unprecedented levels. The emergence of quantum computing signals superior computational capabilities for 6G-V2X systems, also supported by enhanced security protocols potentially fortified by blockchain technologies.

The interconnected nature of these technologies promises to revolutionize the driving experience, particularly for fully autonomous vehicles. Through the convergence of millimeter-wave communication, VLC, and terahertz communications, multigigabit data rates will become achievable, complemented by ultralow latency and reliable information exchange facilitated by diverse radio access technologies and innovative resource allocation schemes. Technologies such as nonorthogonal multiple access (NOMA) and satellite-UAV-aided V2X stand as promising paradigms for massive and ubiquitous vehicular access. Integrated sensing, localization, and communication systems will pave the way for centimeter-level positioning accuracy and artificial intelligence-driven awareness of complex physical and electromagnetic environments [22]. Furthermore, enhanced vehicular message dissemination enabled by 6G V2X is set to redefine the future of electric vehicles, enhancing both driving and battery efficiency. Predictive road conditions and optimized driving modes will be facilitated, allowing for enhanced battery monitoring and configuration through cloud-based computation or machine learning algorithms. In essence, the fusion of these technologies exemplifies the transformative potential of 6G networks for V2X communication, paving the way for safer, more efficient, and interconnected transportation ecosystems.

VI. Conclusion

In conclusion, this paper has examined the advancements and challenges in V2X communication, focusing on the integration of LTE, 5G, and future 6G technologies. The transition from dedicated short-range communication (DSRC) to LTE-based V2X systems was discussed, highlighting both the benefits and challenges. LTE in C-V2X shows significant potential to enhance road safety and traffic flow through network-assisted and autonomous communication modes. The introduction of 5G NR further augments V2X capabilities by aiming to reduce latency and increase reliability, although issues such as handover complexities, channel interference, and shadowing in millimeter wave communications remain. Solutions like vehicular cloud computing and fog computing were explored to manage high data volumes and reduce latency.

Looking ahead, the vision for 6G networks in V2X communication encompasses disruptive technologies such as terahertz communication, intelligent reflective surfaces, and quantum computing. The integration of UAVs and satellites promises to extend coverage and address communication blind spots, while edge and fog computing ensure swift data processing and decision-making. The convergence of these technologies holds great promise for creating safer, more efficient, and interconnected transportation systems, paving the way for transformative V2X communication in the future.

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