



VEHICULAR CONNECTIVITY: C-V2X & 5G

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Executive Summary

Cellular-Vehicle-to-Everything (C-V2X) is at the forefront of digital transformation with operating spectrum allocated by the Federal Communications Commission (FCC), devices prepared by 5G Automotive Association (5GAA) members, and commercial launches announced by both car OEMs and road operators. This momentum also exists in other regions, including in Asia and Europe. As C-V2X and mobile networks move into the 5G era, there will be new services supported with the new communication modes and new business opportunities available. Previous discussions and whitepapers focused mainly on basic safety related services, but this whitepaper highlights the more advanced set of services beyond basic safety, and aspects of end-to-end realization.

5GAA identified a new list of services as examples that illustrate the needs of communication requirements and intelligent transportation system (ITS) infrastructures. The review concluded that Vehicle-to-Infrastructure (V2I), which can deliver immediate benefits regardless of C-V2X penetration rate, is suitable for these new services. There are different ways to realize the V2I services with novel approaches of deploying Roadside Units (RSUs), including mobile RSUs, distributed RSUs, and virtual RSUs. Also, the combined use of Edge Computing together with the PC5 capability for device-to-device communication to realize the V2I services is reviewed. Vehicle-to-Network (V2N) mode uses the 5G mobile network as a complementary tool to assist the V2I with delivering some end-to-end services, and provides an alternative solution for non-delay-critical services in V2I.

More spectrum needs to be allocated in the ITS bands to support these advanced set of services. The analysis based on the review of the above services concludes that 40 MHz more spectrum needs to be allocated in ITS bands with better unlicensed out-of-band emissions (OOBE) protections.

Additional deployment considerations revealed that new business opportunities for automotive OEMs and Mobile Network Operators provide even more than devices and basic connectivity; new business models involve improving social and brand recognition, offering dedicated network slice services, and open platforms allowing 3rd party integrations.

Security is another important deployment aspect reviewed in this white paper. Proper certificate management framework, misbehavior detection, and a reporting system are identified as the most important components to ensure the successful ITS deployment.

Additionally, this whitepaper reviews the new technology developments on C-V2X in 3GPP. These new developments provide automotive OEMs, mobile operators, and third-party application developers with a comprehensive understanding of requirements and considerations for the deployment of smart transportation services using 5G C-V2X technology.

1. Overview and Societal Importance of C-V2X

1.1 State of regulation, technology, trials, and deployments

C-V2X was developed by the telecommunications industry specifically for transportation safety applications and further standardized at the application layer by automotive and transportation stakeholders, and is rapidly gaining global mindshare. C-V2X is supported by a group of standards families:

- *LTE based C-V2X, as specified in 3GPP Release 14 (published in 2017), and Release 15 (published in 2018). [1]*
- *5G and NR based C-V2X, as specified in 3GPP Rel-16 (published in 2020) and with continuing evolution with further releases. [2]*
- *Applications and protocols developed by SAE. [3]*

C-V2X supports two modes of communications: direct (PC5/Sidelink) and mobile network based (Uu). The direct mode of C-V2X does not require that cellular networks offer data communication service, although end-to-end use cases can be complemented by mobile networks. This is currently adopted by the automotive industry, and provides an improved message delivery mechanism for Vehicle-to-Vehicle (V2V), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Infrastructure (V2I) applications to improve road safety and traffic efficiencies in the harmonized 5.9GHz ITS band. Cellular network connectivity (Uu mode of C-V2X)—often referred as Vehicle-to-Network (V2N)—is commonly used for telematics services. It first debuted in automotive applications in 1996, and has steadily increased across vehicle makes and models. Over the last few telematics design-cycles, automakers have increased communication technology adoption, and are rapidly moving to achieve 100 percent attach rates. This will offer connected vehicles a variety of use cases ranging from automotive crash notification (ACN), concierge services, firmware updates, connected infotainment, traffic and road condition updates, and remote supervisory control.

The two modes of C-V2X synergize in an integrated form, like in the same chipsets and platforms. This allows automakers to plan their new products with unified technology trajectories for improved performance and functionality as well as strong cost benefits. The complementary nature of each mode of communication can deliver a richer experience for end-to-end use cases by leveraging both local short-range and long-range connectivity. Additionally, vehicles can utilize the network to assist the scheduling of direct mode C-V2X for better radio resource efficiency when within coverage.

Infrastructure owner-operators and mobile network operators recognize comparable synergy as the infrastructure ecosystem features high-density 5G network deployment. Operators can integrate the functionality required for V2I applications with 5G infrastructure. Alternatively, RSUs deployed to improve road safety can include the necessary functionality to support 5G network infrastructure build-out and densification and yield win-win opportunities for public-private partnerships.



The FCC recently issued a Report & Order [4] assigning the upper 30 MHz of the 5.9 GHz ITS band to C-V2X technology that gives the C-V2X industry the green light to deploy C-V2X Roadside Units (RSU) and Onboard Units (OBU). This allows C-V2X to replace an earlier direct communication radio technology based on IEEE 802.11p, which dates to 1999 as a derivative of IEEE 802.11a Wi-Fi specifications. The Report & Order provides technology certainty but also reduces the allocated spectrum for V2X from 75 MHz to 30 MHz. 5G Americas has requested that the FCC allocate 40 MHz of additional mid-band spectrum to support advanced C-V2X capabilities and use cases [5]. In the meantime, C-V2X will deliver significant safety benefits with the 30 MHz spectrum allocation that are crucial for transportation stakeholder communities.

The global and vigorous ecosystem supporting C-V2X is reflected in the highly active 5G Automotive Association (5GAA) [6]. 5GAA has grown to over 130 members in four short years that represent leaders in both automotive and telecommunications industries. The telecom industry's commitment to delivering improved vehicle safety with advanced technology is a popular catalyst throughout the world for automakers to embrace a radio technology like C-V2X. The initial V2I use cases for traffic signal preemption and transit priority also promote C-V2X adoption. These use cases improve response times for emergency vehicles and enhance efficiency for public transportation and the movement of goods, respectively. In the same vein, V2I can help improve emissions by keeping vehicles moving efficiently and reducing sudden acceleration or idling which supports our collective commitment to sustainability. Imagine a future where vehicles are not only fully aware of their surroundings but can also see around corners to predict potential accidents; drivers would witness vehicles evolving to seamlessly communicate with each other and virtually everything around them. C-V2X technology will usher in

new levels of safety and connectivity, and bring vehicles even closer to autonomy—all while creating a diverse ecosystem that will drive the future of smart transportation.

There are multiple, active, C-V2X technology projects that focus on various use cases in the United States. For example, the U.S. Department of Transportation (USDOT) announced a \$9.9M award for the Smart Intersection project led by University of Michigan Transportation Research Institute (UMTRI) that will be matched by the project participants. [7] This UMTRI project is deploying a network of more than 20 smart intersections throughout the city, and a fleet of vehicles that communicate via C-V2X technology. The Smart Intersection project paved the way for a National Connected and Automated Vehicles (CAV) Deployment project with the pivotal integration of C-V2X.

Additionally, a shift in the U.S. market is emerging; Ford plans on introducing C-V2X in new vehicles beginning in 2022 (subject to a favorable regulatory environment), and Audi of America has recently announced early deployment of C-V2X on roadways in conjunction with the Virginia Department of Transportation and with American Tower Corporation that will provide advanced wireless infrastructure. [8] These C-V2X use cases are compelling because they enhance Audi's Traffic Light Information (TLI) service by warning impending red-light violations when traversing signalized intersections. They also improve work zone safety for Vulnerable Road Users (VRU), such as maintenance personnel, using vests equipped with C-V2X technology. Blue Bird, Fulton Co. Schools and Audi, Applied Information are also collaborating on connected vehicle deployment to boost school bus and school zone safety. [9]

In 2020 automakers including GM, Ford, Nissan, and Hyundai concluded a year-long test of C-V2X on the roads as part of a significant Crash Avoidance Metrics Partners LLP (CAMP) effort [10] that validated the feasibility of deploying C-V2X technology. Given C-V2X's momentum,

an abundance of products has emerged, including C-V2X RSUs, dual-radio DSRC/C-V2X RSUs, and C-V2X aftermarket On Board Units (OBUs). Additionally, Tier 1 automotive suppliers have introduced and are readying OBU solutions for factory design-in by OEMs.

There is also strong global momentum for C-V2X in regions like Asia and Europe. China is the first country to have a national strategy for the Internet of Vehicles (IoV); its automakers are already launching vehicles with this critical technology. After issuing the "Smart Vehicles Innovation Development Strategy" in February 2020, China began mass producing smart vehicles equipped with C-V2X technology. Nearly 90 cities have already partnered with local wireless network operators, deploying tens of thousands of roadside units (RSUs) to demonstrate intelligent highways and urban intelligent networked roads. In anticipation of LTE-V2X commercialization, China formed a special committee charged with managing the overall direction for the IoV, including market readiness and the development of core technical standards for the access layer, network layer, message layer, and security. The Ministry of Industry and Information Technology also issued the "Administrative Regulations on the Use of 5905-5925 MHz Spectrum for Direct Connected Communication on the Internet of Vehicles", which established dedicated C-V2X spectrum with a total bandwidth of 20 MHz. The Ministry of Industry and Information Technology and related standards committees have initiated planning for 5G-related standards and spectrum. The China Society of Automotive Engineers (C-SAE) hosts annual events to promote interoperability testing among auto OEMs, chipset vendors, module vendors, and application developers. The China New Car Assessment Program (C-NCAP) evaluates vehicles for safety and plans to introduce C-V2X as part of its rating system by 2024.

China's C-V2X developments have a phased rollout allowing for continuous improvements, starting from cellular connectivity for new vehicles, and

the direct mode of C-V2X between vehicles and roadside infrastructure, with 5G C-V2X planned for advance autonomous driving and intelligent transportation in the future.

Beyond China and the U.S., there is also positive progress for C-V2X in other parts of the world. For instance, Japan is targeting 2023 for a 5.9GHz allocation for designated ITS use. Korea, Brazil, and others are developing go-to-market plans, given their commitments to safety, and they are actively observing the recent market traction and global trends.

In Europe, a July 2020 ETSI C-V2X plugtest achieved an interoperability success rate of 94%, having seen ETSI publish EN 303 613 earlier in the year [11] that defines the use of C-V2X as an approved access layer technology for ITS devices in vehicles and roadside infrastructure. Additionally, a few important projects funded by different agencies demonstrated the feasibility and performance of C-V2X:

- *ConVeX (Connected Vehicle (V2X) of Tomorrow) [12], funded by BMVI (Bundesministerium für Verkehr und digitale Infrastruktur - Federal Ministry of Transport and Digital Infrastructure) Germany, was the first project worldwide to set-up a testbed to demonstrate the technical and economic feasibility of various C-V2X communication links, like direct V2V, V2I, and long-distance V2N communication.*
- *CONCORDA project [13], a consortium of 26 partners funded by EU CEF (Connecting Europe Facility), is conducting tests at different sites in 5 different countries in Europe—namely France, Spain, Belgium, The Netherlands, and Germany—at 6 different locations. The tests focus on connected and automated driving as well as high density truck platooning using different ITS technologies including C-V2X. The project strives to demonstrate interoperability across test sites to demonstrate interoperability across technologies, system architectures, services, and*

implementations.

- *5G CARMEN (5G for Connected and Automated Road Mobility in European Union) [14], a consortium of 25 partners (a 5G PPP project funded by European Horizon 2020 for research, technological development, and demonstration) is focused on 600 km Munich-Bologna corridor spanning 3 countries. The project combines direct short range and V2I communications with long range V2N communications using different technologies using 5G NR, C-V2X, and secure multi-domain cross-border service orchestration.*

Additionally, the European Union has launched several innovation projects that focus on cross-EU member border transportation management. These projects include:

- *5GCroCo [15] which tests harmonized solutions for cooperative, connected and automated mobility along Europe supporting cross-border traffic.*
- *5GMOBIX [16] which focuses on cross border service continuity with use cases such as Platooning.*
- *5G-ROUTES [17] which addresses cross-border service continuity for multi-modal transport including road, rail, and sea ferries.*
- *SHOW [18] which is a project that covers autonomous driving public transport in Sweden (Kista) and Germany (Aachen) with cooperative (V2V) fade-in and fade-out at on-demand bus stops and dashboard.*

Several OBU and RSU manufacturers, as well as other auto ecosystem participants, have developed solutions with C-V2X technology for European operations, and have obtained Radio Equipment Directive (RED) certification [56] to prepare for European deployment. ANAS, the largest road operator in Italy, announced that the Smart Road project [19] will create 3000 km of intelligent roads in Italy with an investment of 1B euros. Within the Smart Road project, ANAS

plans substantial C-V2X infrastructure deployment spanning multiple roads across Italy that will test connected car use-cases.

The activities at home and abroad point to the quick realization of C-V2X based Intelligent Transportation. A wide range of safety and advanced applications can be delivered with the outstanding performance of C-V2X and validation by vigorous engineering tests and real-world trials.

1.2 C-V2X performance

Enhanced road safety is the basic requirement driving most, if not all, innovations in the automotive world. Reliable and timely radio performance are uncompromisable for any solution introduced on our roads. 5GAA has conducted extensive and objective tests comparing the two available radio technologies: DSRC, using IEEE 802.11p (DSRC in the U.S. and ITS-G5 in Europe), and C-V2X, using 3GPP Release 14 Sidelink. Over the last decade, functional and performance tests were conducted at CAMP to evaluate the two radio technologies.

Under closely monitored conditions, field tests were conducted under both ideal and adversarial environmental conditions. The tests were conducted using a packet length of 193 bytes for basic safety messages transmitted on ITS band (channel 184) with bandwidth of 10 MHz. The detailed test report from 5GAA [20] elaborates on the test set up, conditions, parameters, and results. It also examined the overall C-V2X performance in comparison to DSRC, synthesized key reliability and link margin performance metrics, and shared the findings of the near-far problem for C-V2X. C-V2X clearly demonstrated superior performance and reliability compared to DSRC.

These tests were designed to represent real-world traffic conditions for non-line-of-sight (NLOS) static and moving obstructions, including background noise and interference. C-V2X showed significant range (link margin) advantage over DSRC, which translates to enhanced safety for drivers and vulnerable

road users (VRU). Systematic tests modeling path loss with and without background noise were conducted to assess communication reliability between transmitting and receiving vehicles at various signal strengths. C-V2X showed significant reliability advantage over DSRC. In real road scenarios obstructions (buildings, hills, and other blocking vehicles) can create dead spots or areas of very low received signal strength. Consider a car transmitting an Intersection Movement Assist (IMA) or Left Turn Assist (LTA) signal to a receiving vehicle on a hilly road: low signal strength can affect the receiving vehicle's ability to get the signal on time, potentially leading to a collision. However, with superior link performance C-V2X can alleviate the condition of poor signal strength.

Additionally, the ConVex project demonstrated that C-V2X Sidelink communication can be sustained at relative speeds of 437 km/h (the speed was limited by traffic, not C-V2X technology). Range in urban "blind" intersection settings was demonstrated to be greater than 140m, proving that C-V2X can successfully support key basic safety applications. The detailed final report of the project is available in ConVex's "Final Report on Field Test and Evaluation" [21].

Several OBU and RSU manufacturers, as well as other auto ecosystem participants, have developed solutions with C-V2X technology that are publicly available on the market and listed by 5GAA [22].

5G envisions a world united with a common, unifying connectivity fabric supporting various devices across diverse deployments and spectrum bands. C-V2X continues to be a key focus area of the innovation to support such a vision. While C-V2X in 3GPP Release 14 provided the reliability and performance for basic safety messages, the C-V2X extension in 3GPP Release 16+ builds on the strong foundation of the core 5G technologies to bring higher throughput, lower latency, and reliable group communication, for advanced V2X applications. It is noteworthy that

vehicles equipped with Release 16 based 5G C-V2X technology will also support C-V2X Sidelink from Release 14/15 for basic safety applications.

3GPP Release 16 introduced reliable multicast communication for the C-V2X Sidelink with both managed groupcast and connection-less groupcast mode. The connectionless groupcast is enabled by key foundational innovations, such as utilizing distance as a new paradigm in the physical layer, and addressing application-specific communication using NACKs. Using distance as a dimension helps to achieve uniform communication range for both LOS and NLOS scenarios. With this new 5G C-V2X connection-less groupcast mode, groups can form on-the-fly for exchanging messages with little to no overhead for group formation and dismantling. The superior reliability, extended range, low latency, and NLOS capabilities of 5G C-V2X allows it to support advanced safety use cases at higher vehicle speeds (~500kmph) and challenging road and traffic conditions. 5G C-V2X Sidelink includes advanced positioning technology which comes specifically handy in poor GNSS reception areas such as a tunnel or a parking garage. Vehicles can continue to reliably communicate using 5G C-V2X Sidelink for safe driving.

Besides the performance and feature enhancements to the Sidelink, 5G C-V2X brought additional enhancements to the Uu connectivity to better serve the advanced network based V2X applications, which requires high reliability and service guarantee. These new features include:

- *QoS Sustainability analytics for C-V2X application servers, as defined in 3GPP TS 23.287 [23]. This feature is also known as "Predictive QoS", which allows the network to estimate and decide whether a desired QoS requirement can be fulfilled in a target region before the service commences. Additionally, it also provides advance notification to the application servers if a QoS level change is expected in a*

target area. This allows the V2X application layer to determine and adjust its operation strategy accordingly to avoid service interruptions. In future developments in 3GPP, Artificial Intelligence and Machine Learning are also considered to unlock further utilization of the MNO network for C-V2X use cases.

- *Support of Alternative QoS Requirements from C-V2X application servers, as defined in 3GPP TS 23.287 [23] and TS 23.501 [24]. This feature allows the V2X application layer to indicate multiple levels of QoS requirements to the 5G C-V2X system, so that the system may adapt the QoS levels according to the radio conditions without incurring extra negotiations at the application layer. It can achieve much faster reactions at the 5G system and better utilization of the network resources.*
- *Standardized V2X Slice/Service Type (SST), as defined in 3GPP TS 23.501 [24]. The definition of the standardized V2X SST allows a consistent cross MNO control of the service provisioning for V2X even in the roaming case. GSM Association has defined an E2E network slicing architecture [25] describing how such different parties can collaborate to deliver the required performance (delay, reliability, for the V2X service).*

The innovations in 5G C-V2X set the stage well for an enhanced autonomous driving experience, faster and efficient traveling, and reduced carbon emissions in addition to enhanced road safety for everyone. Together with the stable and reliable LTE C-V2X (3GPP Release 14/15) that is tested and proven suitable for basic safety, the 5G C-V2X provides vendors a two-stage development structure that allows efficient and flexible support for current and future applications while facilitating a clear forward evolution path.

1.3 Intelligent transportation with C-V2X

Today's technology advancements shape tomorrow's smart transportation. Technology advances in cellular communication have ushered in a new era of ubiquitous connectivity. Smart transportation revolves around disseminating information of the transportation network from an underlying network of sensors, infrastructure, and communication devices to build operating solutions and services for an intelligent transport system (ITS): an ITS which is safe, efficient, inclusive, and serves the societal needs of modern living. The ITS rubric is broad, and solutions are needed across the board—from connectivity and telematics to in-vehicle compute, which are key to autonomous vehicles. Road owners and users alike benefit from unparalleled set of tools for personal mobility, safety, and environment-friendly transportation services, up to and including automated driving.

ITS empowers its users with meaningful information, facilitating a wide range of services from pre-trip planning and en route information, to advanced road safety services and enhanced automated driving. While such applications bring obvious benefits to road users, they also provide actionable insight to private entities such as transportation planners working alongside government agencies on optimal operations strategies. Transportation planners can use the information to project travel demand. The demand information can help to determine optimal deployment of transportation infrastructure, advanced public transit services, and placement of ITS-enabled transportation pricing and demand management systems such as electronic toll collection or variable parking fees. Planners can also benefit from insights into arterial road usage, traffic conditions, and congestion reports in shaping our neighborhoods and reducing greenhouse gas emissions.

According to the World Health Organization approximately 1.35 million people lose their lives each year to road traffic crashes, and more than half of all road fatalities are among vulnerable road users such as pedestrians, bike riders, and motorcyclists. In a smart transportation system, it is crucial that vehicles reliably communicate not only with each other, but also with the road infrastructure. The traffic management center (TMC) that oversees overall traffic control of the city or region can be hosted in a central cloud that harnesses the information from a wide distribution of edge clouds located throughout the city. Vehicular networks are highly dynamic, so it is essential for edge servers to be located closer to the relevant environment to provide local analytics, context, and faster processing.

Ultimately, V2I communication is imperative for a comprehensively integrated ITS to complement the growing network of connected vehicles exchanging information, and greatly improve road safety, in addition to significant economic benefits for all stakeholders. By granting roadside access to MNOs, transportation planners and road operators can share the cost of equipping our roads with infrastructure nodes (RSUs). At the same time, MNOs can benefit from obtaining roadside access for additional small cells installation to expand their cellular coverage. Public-private partnerships can go a long way in creating smart transportation solutions that are economically feasible and sustainable.

To support an ITS of connected vehicles, roads, and infrastructure, it is necessary that cloud services are invoked to provide efficient application, content, and service management. Additionally, the car-to-cloud platform can enable on-demand soft SKU configuration and over-the-air software updates, making feature licensing and device management scalable. Such enhancements enable a wide range of possibilities for multi-tiered streaming, location-based, and personalization experiences and services for users.

According to the National Highway Traffic Safety Administration, about 90% of motor vehicle crashes can be attributed at least in part to human error. Automotive companies and Tier 1 OEMs have genuine opportunities to lead with autonomous or self-driving vehicles to drastically reduce human error led

accidents for increased road safety. A system approach of building an autonomy stack greatly leverages the AI capabilities and would be a key step towards safe autonomy.

The proliferation of smartphones has contributed immensely to the rising expectations of enhanced personal mobility choices. There is a strong connection between personal mobility and economic mobility. This is where mobility-on-demand, such as bus rapid transit and various other shared ride services, has the potential to revolutionize transportation systems by maximizing automation opportunities by providing personal mobility services that are safer, affordable, reliable, and available to all.

The 5G C-V2X technology, with both Sidelink and Uu based communication, is expected to greatly enhance autonomous driving through perception sharing, path planning, real-time local updates, and coordinated driving. These features facilitate the next generation of ITS solutions for multiple autonomous driving applications (fleet management systems, advanced driver assistance systems, mobility, and parking services), and greatly reduce emissions. The core of the smart transportation vision revolves around an integrated communication and transportation network that promotes several societal benefits, and shapes a new era of advanced road safety, enhanced personal mobility, and environmental sustainability.

Peachtree Corners—home to one of the nation’s most advanced smart city ecosystems—further reinforces 5G C-V2X capabilities by deploying C-V2X solutions [26] that primarily focus on roadside infrastructure, traffic management, and road safety. They aim to enable future smart connected solutions deployed across the community and to bring the region to the forefront in the development of next generation Internet of Things (IoT) technologies. As a part of the program, the city will work with Commsignia to feature RSUs equipped with C-V2X. Utility vehicles equipped with C-V2X solutions will also be utilized to demonstrate V2I direct communications. The implementation of C-V2X within the smart city environment not only demonstrates the benefits of C-V2X communications in a real-world setting at scale, but also showcases C-V2X’s critical safety communication capabilities needed to meet the evolving needs of transportation as well.

2. Use Cases & Connectivity Requirements

2.1 C-V2X services

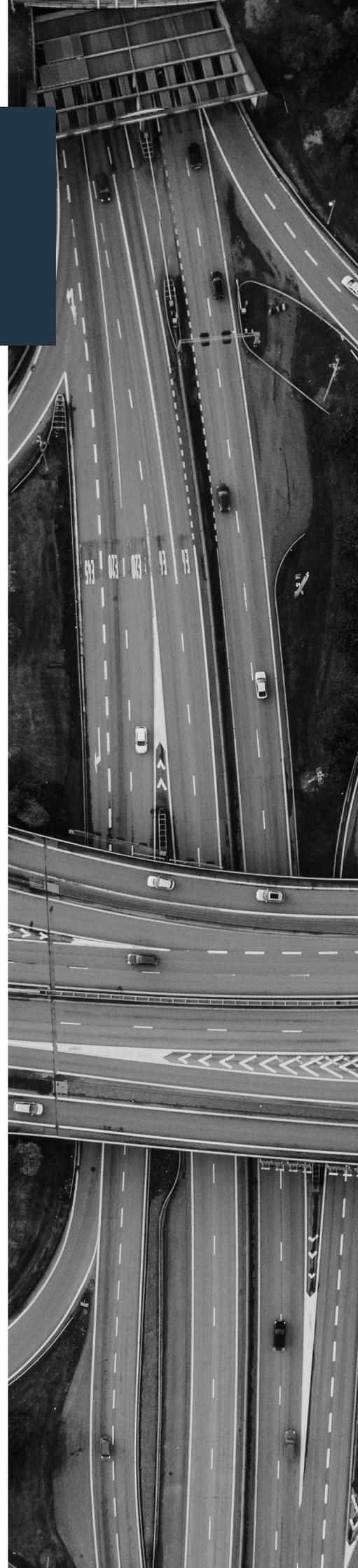
C-V2X is designed to be compatible with existing V2X framework to support all the existing V2X applications defined by application standards groups (Society of Automotive Engineers [SAE]). The 3GPP-defined C-V2X stack allows transparent delivery of various message formats like those defined by IEEE 1609.3. This allows existing V2X applications to be easily ported to a C-V2X platform. On the other hand, C-V2X—especially the 5G NR-based C-V2X—provides additional enhancements to better serve the V2X applications. For example, the QoS guarantee, the connection-less groupcast and secure unicast mechanism, allow new V2X services development.

Besides the Sidelink communication, which is suitable for the V2V and V2I type of services, C-V2X brings the Uu mode of communication that enables the V2N services. This allows multiple V2X applications—especially those that are not safety and time critical—to be reimagined, and even supported over different access modes at the same time (depending on deployment scenarios). With the deployment of 5G Ultra-Reliable Low Latency Communication (URLLC) systems, vehicles can receive broadcasted traffic alerts about upcoming traffic congestion or accidents. Cooperative information can also be exchanged among vehicles or road infrastructure (such as traffic lights) to improve road safety. V2N can also facilitate other applications for entertainment or convenience. For example, road users can download updated maps or stream video from a data center. Another function of the V2N is to connect vehicles with one another and to augment other modes of communication like V2V, V2I, and V2P. V2N systems can also help pedestrians prevent potential accidents by sending safety alerts to vehicles and pedestrians in various dangerous situations. For example, a vehicle driving through a red light or a pedestrian crossing an intersection.

C-V2X was also designed to be friendly to Vulnerable Road User (VRU) groups, including pedestrians and bikers. There are inherent features that allow such devices to operate with power saving options. Additionally, 3GPP is also working on new features for 5G C-V2X: Sidelink Discontinuous Reception (SL-DRX) allow the UE to be in sleep mode except for a predefined reception window to further reduce the power consumption of VRU devices. This makes many previously challenging V2P use cases feasible.

Collision avoidance related safety applications have long been studied in the V2X standards community for V2V type of communication, such as:

- *Forward Collision Warning*
- *Emergency Electronic Brake Lights*
- *Do Not Pass Warning*
- *Left Turn Assist*
- *Intersection Movement Assist*
- *Blind Spot Warning/Lane Change Warning*
- *Emergency Vehicle Alert*



With 5G C-V2X technology in mind, 5GAA has identified a group of new V2X applications and their service level requirements [27]. In Table 2.1, a list of selected service examples from 5GAA's "C-V2X Use Cases Volume II: Examples and Service Level Requirements" were presented with corresponding service requirements and the recommended C-V2X communication mode to fulfill the requirements. [27]

The V2I and V2N architecture used to support these services are further discussed in Section 2.2 and 2.3, respectively.

2.2 ITS infrastructure

The more immediate V2X opportunities come from V2I use cases which can materialize as soon as a single C-V2X-equipped vehicle can interact with roadside infrastructure. The ITS infrastructure with V2I support can support use cases that benefits the drivers, such as:

- *Traffic Signal Preemption*
- *Transit Priority*
- *Red Light Violation Warning*
- *Signal Phase and Timing (SPaT)/Map information*
- *Work Zone Warning, School Zone Warning*
- *Speed Limit Warning: Reduced Speed Zone Warning, Curve Speed Warning*
- *Spot Weather Information Warning*
- *Stop Sign Gap Assist*
- *Stop Sign Violation Warning*
- *Railroad Crossing Violation Warning*
- *Oversize Vehicle Warning*

The C-V2X based V2I is ready for deployment. Specifically:

- *C-V2X roadside units (RSUs) are already commercially available. [22]*
- *The NEMA TS 10, which is a RSU standard, is also close to completion. This standard will allow road operators to deploy uniformly performing C-V2X RSUs.*

There are also rapid developments in different fronts to enable the deployment of the ITS infrastructure. For example:

- *C-V2X is on track to receive certification from the OmniAir Consortium, which is a participant in the USDOT Next Generation Certification Program for Connected Vehicles. In the recent OmniAir Global Plugfest [28], OmniAir completed bench conformance, interoperability, security, and field testing for over 20 C-V2X and DSRC radio devices.*
- *Multiple State DOTs and local agencies including Virginia, California, Georgia, Arlington, Hawaii and 5GAA events have showcased successful C-V2X early deployments while many other road operators have active requests for proposals (RFP) to deploy C-V2X. The Federal Highway Administration has awarded an Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) grant to the Hawaii DOT [29] to implement C-V2X to make roads safer and an ITS vision of the future.*

C-V2X uses the spectrum efficiently and effectively for these early applications. 5G Americas looks forward to the FCC providing additional spectrum for the advanced safety use cases that will enable a further transformation in connected and automated vehicles through rich sensor sharing, coordinated driving, and higher situational awareness [5].

2.3 C-V2X and public mobile networks

2.3.1 RSU with mobile network connection as backhaul

The RSU can have two roles in the ITS infrastructure. In communication with the vehicles, it uses the Sidelink mode of the C-V2X communication. To simultaneously provide information for the Sidelink communication, or handle

the messages received over the PC5 link, it may also operate as a normal UE (as defined by 3GPP systems) to access a back end V2X application server deep in the network.

For example, having an RSU deployed on the traffic light that uses the Uu as the backhaul link to obtain the Signal Phase and Timing (SPaT)/Map information from a traffic management centers (TMC), and using the Sidelink to distribute the information to the vehicle requesting for it. Additionally, the Work Zone Warning, School Zone Warning service can make use of such Uu based backhaul for the RSU so that temporary RSUs can be set up any time at a site when necessary. This can greatly improve the road safety and reduce overhead for the work procedures.

Mobile operators can take part in the C-V2X eco-system by offering reliable cellular connectivity for the RSU device. Special Service Level Agreements (SLA) can be arranged to offer the RSU devices subscriptions specially designed for its use so the RSUs can obtain prioritized access and guaranteed QoS. In this sense, RSUs can be viewed as a new type of IoT devices.

Typically, ITS use cases with RSUs revolve around short range communication based V2I using dedicated physical RSUs. However, an innovative approach emerged utilizing C-V2X based on existing 4G and 5G wireless networks provided by the mobile network operator without deploying any new physical infrastructure, ultimately creating virtual RSUs. A trial involving a new platform based on a standard interface, enabling multi-OEM, multi-agency implementation was conducted in Australia to demonstrate this approach. Use cases included Slow/Stopped vehicle warnings, in-vehicle speed advisories, red-light violation warnings, emergency electronic brake lights, and right turn assist/pedestrian warnings. Those use cases were demonstrated on a 4G network where the observed latency was <50 ms at 95% of the trials. [30] This revolutionizes the industry's ITS ecosystem, accelerates

Table 2.1 C-V2X service examples and recommended communication modes

Service Types	Example use cases	End-to-end latency (ms)	Reliability	Data rate	Recommended C-V2X mode
Safety	Cooperative Traffic Gap	50 ms	99.9%	2 Mbps	V2V
Safety	Interactive VRU crossing	100 ms	99.9%	64 Kbps	V2P
Vehicle Operation management	Software Update of Reconfigurable radio system	Delay tolerant (hours)	99%	200MB (delay tolerant)	V2N
Convenience	Automated Valet Parking (incl. authentication, proof of localization, wake up)	500 ms	99%	16 kbps	V2I
Convenience	Awareness confirmation	20 ms	99.9%	40 kbps	V2V, V2N
Convenience	Cooperative Curbside management	100 – 5000 ms	99.0%	Few kbps	V2P, V2I, V2N
Convenience	Cooperative Lateral Parking	10 – 100 ms	99.9%	27 Mbps	V2V
Convenience	In-vehicle entertainment	20 ms	99%	Up to 250 Mbps	V2N
Convenience	Obstructed view assist	50 ms	99%	5 Mbps	V2I, V2V
Autonomous Driving	Cooperative Lane merge	20 ms	99.9%	12 kbps	V2V
Autonomous Driving	Cooperative Maneuvers of AV for emergency situations	10 ms	95%	48 kbps	V2V
Autonomous Driving	Coordinated, cooperative driving maneuver	20 ms (each for 4 round trips)	99.9%	64 Mbps (system level)	V2V
Autonomous Driving	Vehicle Platoon in steady state	50 ms	99.0%	24 kbps	V2V
Autonomous Driving	Automated Intersection crossing	10 ms	99.9999%	~ 64 kbps	V2I
Autonomous Driving	HD Map Collecting and sharing	100 ms	99%	16 Mbps	V2N, V2I
Autonomous Driving	Infrastructure Assisted Environment perception	100 ms	99.99%	4 – 80 Mbps	V2I, V2N
Autonomous Driving	Infrastructure-based tele-operated driving	50 ms	99.999%	400 kbps	V2I, V2N
Autonomous Driving	Tele-operated Driving (ToD)	100 ms (UL); 20 ms (DL)	99.999%	36 Mbps (UL); 400 kbps (DL)	V2N
Autonomous Driving	Autonomous vehicle disengagement report	10 min	99.99%	26.7 Mbps	V2N
Traffic efficiency and society	Bus lane sharing request/revocation	200 ms	99%	40 kbps	V2I, V2N
Traffic efficiency and society	Continuous traffic flow via green light coordination	100 ms	95%	20 kbps	V2I, V2N
Traffic efficiency and society	Group start	10 ms	99.999%	20 kbps	V2I

the deployment of road safety solutions which unleashes the potential to explore new use cases, and makes the solutions extremely scalable and economical. Virtual RSUs with no physical infrastructure reduce costs and time to-market (TTM) for all these solutions, which is an unmatched advantage. Where the business cases for physical RSUs are not viable due to low populations, traffic requirements, or physical restrictions/regulations preventing the deployment of the RSU, an approach like this can play a key role to widen support for RSU and related use cases.

2.3.2 RSU with 5G distributed RAN architecture

3GPP has defined RAN disaggregation architecture [31] [32] [33] that allows a base station to be split into Central Unit (CU), Distributed Unit (DU), and Radio Unit (RU). This split offers more flexible deployment options, and centralization of common functions; it greatly reduces the complexity of deploying and managing base stations or radio networks. Furthermore, it allows the split of the control plane and user plane entities, which provides further options for deployments. Standardized disaggregation interfaces are defined and published by the Small Cell Forum [34] and O-RAN [35] to define the lower layer split (at the MAC and PHY layer, for example).

Similarly, the RSUs can be also disaggregated and deployed in a distributed manner. For example, the radio panels can be placed at a different location from the MAC layer of the RSU, especially in case of larger coverage areas. It is also possible to place the PDCP and RRC layer of the RSU in a centralized location (close to the 5G system CU site) while placing multiple distributed RSU “DUs” at roadsides closer to the vehicles, like on the traffic light.

Such distributed RSU deployment brings both technical and operational benefits. Having a centralized logical upper layer could allow the same RSU to serve much wider areas and reduce the potential service transitions. For example, the vehicles can be served by the same RSU along a few kilometers of road. This effectively increases the V2I service range and allows additional new V2I services to be developed. It can be especially useful for unicast based applications because the connection and IP address can be preserved across the different RSU “DUs” so that the vehicle can have a longer uninterrupted session with a V2X application server.

The distributed RSU deployment can also significantly reduce the cost of ownership for the ITS infrastructure operators. As C-V2X technology evolves, the ITS infrastructure operators can choose to upgrade the system based on needed upgrades. For example, they can perform a simple software upgrades of the RSU “CUs” to gain new functions based on latest standards, or they can upgrade certain part of the RSU “DUs”, without affecting the ongoing operation of the rest of the RSU.

The RSU disaggregation shares the similar splitting options as that of the 5G RAN system, and the distributed RSU components (RSU “CU” or RSU “DU”) can collocate with the disaggregated 5G RAN entities. For example, the RSU “DU” can be placed at the same cell site as that of the gNB DU. Therefore, the backhaul link for the gNB DU can be also shared by the RSU “DU” to connect it to the RSU “CU” which might be collocated with the gNB “CU”. This is especially useful for cases where the backhaul link is also wireless (IAB deployments).

Given the collocation, the RSU may also be able to assist the 5G RAN operations. For example, the RSU could obtain V2X information (location, speed, direction, of a vehicle UE) from its Sidelink (PC5) interface which could be useful to assist the 5G gNB to manage corresponding operations (beamforming) that serve the same vehicle UE’s Uu connection.

2.3.3 Direct connectivity to vehicle via 5G PLMN

A V2N system supports the direct connectivity between vehicles and a cellular network through the Uu interface. The system architecture defined by 3GPP TS 23.287 [23] is shown in Figure 2.1. As can be seen, existing network functions (NFs) of the 5GS architecture can adequately support the C-V2X communication without introducing new NF. Instead, new C-V2X functionalities have been incorporated into the existing NFs. UEs in the architecture can include vehicles, VRU devices, or RSU devices. 3GPP reports the C-V2X capability (Uu or PC5) to the 5G Core (5GC) over N1 and/or from V2X Application Server over the V1. Meanwhile, C-V2X operation parameters are sent from the 5GC to UEs over N1. The Policy Control Function (PCF) provides the UEs with authorization and policy parameters for V2X communication over PC5 and Uu. The PCF also provides the AMF with necessary parameters as part of the UE context to configure and manage V2X communications. These parameters are retrieved from a Unified Data Repository (UDR). The Network Repository Function (NRF) helps other NFs choose the appropriate PCF based on corresponding C-V2X capabilities. The V2X Application Server has the functionalities needed for the following:

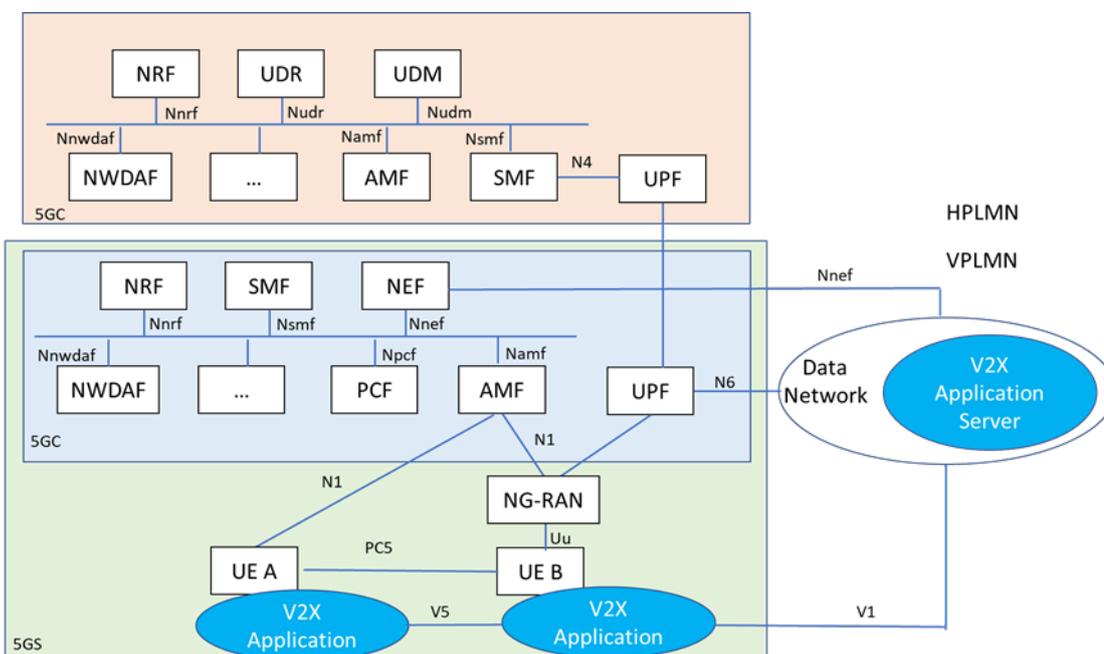
- *Provisioning of the UEs and/or the 5GC with the necessary parameters to perform V2X communication over the PC5 or Uu*
- *Requesting 5GC services*
- *Receiving uplink data and delivering data to the other UEs*

The interworking between a 5G System (5GS) V2X and 4G LTE V2X does not require new interfaces at the architecture level and does not impact existing network function entities in the 4G Evolved Packet Core (EPC) and 5GC.

Many V2N use cases have been specified by both 3GPP and 5GAA. 5GAA combines the use cases defined by 3GPP and new use cases, which are categorized into the following groups [27]:

- *Vehicle operations and management*
- *Autonomous driving*
- *Traffic efficiency and environmental friendliness*
- *Convenience and in-vehicle entertainment*
- *Society and community*

Figure 2.1 5G System Architecture for V2X Applications over PC5 and Uu



For vehicle operations and management, V2N can be used to update the software, monitor the health of the vehicles, send alerts when maintenance or service is required, and enable tele-operated driving or automated valet parking. When an autonomous vehicle detects the need for remote support it will share all the camera and sensor data (from RADAR or LIDAR sensors) to provide the remote driver with adequate perception of the environment. The remote driver can then provide appropriate instructions to help the autonomous vehicle resolve the issues.

To facilitate autonomous driving, vehicles can be equipped with cameras, LIDAR, or other sensors to collect information about their surroundings and share the information with a cloud map server. The server will then process the collected information and dynamically update the local map with more accurate information before sending it back to the vehicles.

A series of traffic lights can be dynamically coordinated by a central data center to allow continuous traffic flow over several intersections in one main direction to improve traffic efficiency and reduce congestion.

In addition to improving safety on the road, V2N can also be deployed to provide other services. For entertainment, HD video streaming or online gaming can be accessed from a data center or content delivery network (CDN). In an ambulance or other emergency response vehicle, a patient's telemetry data, images or video can be shared between paramedics and doctors in the hospital for timelier patient care.

Compared to V2V, the end-to-end latency is higher in a V2N system. Therefore, it is more suitable for use cases that do not have very tight latency requirements.

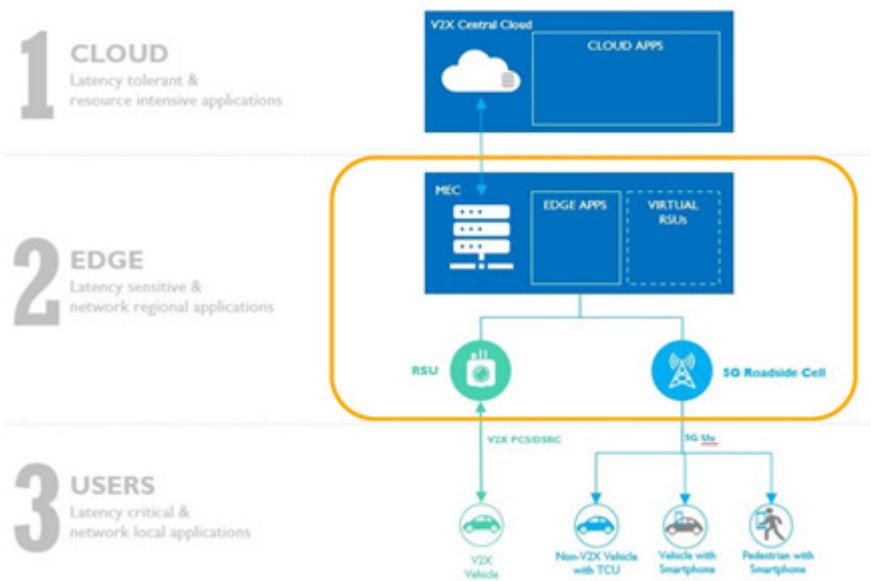
2.3.4 PC5 and edge computing for end-to-end service delivery

2.3.4.1 Multi-Access Edge Computing for C-V2X services

As shown in the previous sections, the ITS infrastructure-based services can be realized with V2I using RSUs and PC5 connection with the Uu and 5G system complementing connectivity. However, as the services and applications go beyond basic safety and toward overall smart transportation, (including autonomous driving) the siloed V2X data model becomes insufficient. Most of the decisions or information required for vehicular service realization depends on the environment or information around the vehicle. To realize flexible and innovative end-to-end services with various data from other V2X (and non-V2X) sources, it is preferable to ensure enhancements to the ITS infrastructure that enable the cross-platform information integration. Multi-access Edge Computing (MEC), formerly known as mobile edge computing, can help bring processing power near the vehicle to meet ultra-low-latency requirements, and to reduce network traffic towards a centralized datacenter.

MEC is a type of cloud-computing located near the edge of the network. It helps to offer various end-to-end services based on the bandwidth and/or latency requirements needed for various applications. The roadside edge network infrastructure can provide vehicular services (over PC5) by aggregating various road-side sensors and data processing via an Edge Computing platform. This can adapt the CPU and storage resources to handle the large volumes of data to and from the vehicles or RSUs based on the service requirements. [36] Furthermore, the MEC deployment can use a hierarchical architecture (shown in Figure 2.4) using gateways and roadside units to further reduce the latency and processing load of the overall network [36].

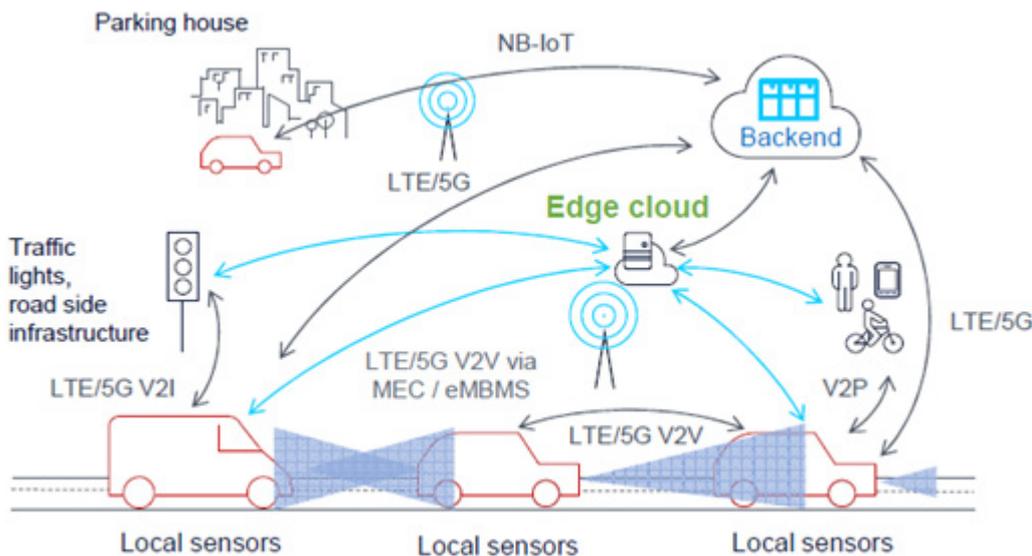
Figure 2.2 Hierarchical architecture of MEC for C-V2X service



Operators or MEC providers can open the edge cloud and services to authorized third parties that will enable rapid development and adaptation of applications and services for vehicular services, mobile subscribers and other vertical market segments. MEC will enable applications and services to be hosted ‘on top’ of the mobile network elements (above the network layer) that can be accessed via various methodologies including PC5 as shown in the figure 2.3. [37]

MEC uniquely allows software applications to tap into local content and real-time information about local-access network conditions. For example, Edge Computing can provide various vehicular services over the PC5 or Uu interface to provide High-Definition real-time maps, real-time traffic monitoring/alerts, and various entertainment content. MEC services can provide help in autonomous driving scenarios by providing access and alerts based on observed/detected road hazards and predictions based on local computing (such as weather condition-based or camera detection-based alerts, pedestrian crossing, and more).

Figure 2.3 Applicability of Edge Cloud for C-V2X services



2.3.4.2 MEC standards and relevance to V2X use cases

There is an initiative for the key standards bodies/groups to harmonize the standards for edge computing [38], including:

- *ETSI ISG MEC: ETSI ISG MEC created an open and standardized IT service environment that allows third-party (both edge-unaware and edge-aware) applications to be hosted at the edge of the mobile network, and that can expose network and context information. It specified a common and extensible application enablement framework for delivering services, (specific service-related APIs for information exposure and programmability) as well as management, orchestration, and mobility related APIs.*
- *3GPP SA6: Defines an architecture (EDGEAPP) for enabling Edge Applications, particularly through the specification of an enabling layer to facilitate communication between application clients and applications deployed at the edge. The architecture also enables the CAPIF (Common API Framework) to be leveraged as a standardized means of providing and accessing APIs in the Edge Cloud.*
- *3GPP SA2: Defines the architecture for mobile core networks (including 5G). It also provides the means for applications to provision traffic steering rules.*
- *3GPP SA5: Oversees management and charging aspects of 3GPP networks.*
- *GSMA: Works to specify requirements and end-to-end high-level architecture for a unified Operator Platform that can help operators to make their assets and capabilities consistently available to the developers and the enterprise segment across networks and national boundaries.*
- *5GAA: Defines requirements and implementation recommendations for Cellular V2X applications using Multi-access Edge Computing as per ETSI ISG MEC specifications.*

Table 2.2. V2X use cases and the relevance for MEC

Group	Use cases	Description	Relevance for MEC
Safety	Intersection Movement Assist	Warn driver of collision risk through an intersection.	High
Convenience	Software Updates	Deliver and Manage Automotive Software Updates and vehicle telematics	Mid
Advanced Driving Assistance	Real-Time Situational Awareness & High-Definition Maps	Alert driver of Host Vehicle (HV) moving forward of hazard (icy) road conditions in front.	High
	See-Through	Driver of Host Vehicle that signals an intention to pass a Remote Vehicle (RV) using the oncoming traffic lane is provided a video stream showing the view in front of the RV.	High
	Cooperative Lane Change (CLC) of Automated Vehicles	Driver of Host Vehicle (HV) signals an intention to change the lane with at least one Remote Vehicle (RV) in the target lane in the vicinity of the HV.	High
VRU	Vulnerable Road User Discovery	Detects and Warns drivers of VRUs in the vicinity.	High

The 5GAA categorizes a comprehensive list of connected vehicle applications, categorized in four main groups of use cases [37]:

- (i) *Safety*,
- (ii) *Convenience*,
- (iii) *Advanced Driving Assistance and*,
- (iv) *Vulnerable Road User (VRU)*

Of the above groups, several use cases have significant relevance to MEC as listed in table 2.2 [37].

From the user experience perspective, the edge computing helps to provide a safe and immersive driving experience.

2.3.4.3 Challenges and impact

The growing number of automated vehicles and various infrastructure sensors for aiding vehicular services for fully automated driving and safety suggests that a large amount of data processing and sensor information data will get exchanged between vehicles and infrastructure over PC5 and Uu interfaces. Subsequently, this calls for massive computation and storage requirements which may not be handled in the vehicle due to limited power and resources on vehicles. Instead, these functionalities can be offloaded to the MEC which can handle it in a cost effective and real-time basis.

It is equally important for vehicular services over the PC5 interface to access critical safety and real-time processing of sensor signal from various infrastructure and RSUs. MEC can act as a coordinating anchor for various V2X services.

In the multi-operator scenario, the end-to-end latency is challenged because the peering points between operators are typically located in central cloud location. With MEC acting as a central anchor or peering point for multiple access (for operators, application developers, automakers), it can realize many vehicular end-to-end services with appropriate latency and without choking the central/core network nodes.

With the synergy of MEC interface standardization, distributed computing, and adoption of fully automated driving, the needs for high throughput and low latency communication over the PC5 interface will reach new highs. MEC will play a key role in realizing the V2X end-to-end services in the coming future.

2.4 Services using the additional ITS spectrum

Among the service examples identified by 5GAA [27], many of the V2V and V2I related services require additional ITS spectrum to operate, including those that require the support of higher data rate and reliabilities. To ensure the performance requirements, only safety related applications should be used over the allocated 30 MHz spectrum in the 5.9 GHz band. Therefore, advanced application categories (sensor sharing, platooning, and coordinated driving) should use the additional ITS spectrum when it becomes available.

Specifically, service examples in section 2.1, like Autonomous Driving and Traffic efficiency, would require additional ITS spectrum to be deployed. For example, the Cooperative Lateral Parking service would require a 27 Mbps data rate, and the coordinated, cooperative driving maneuver service would even go above 64 Mbps over the Sidelink for the V2V communications.

Services are expected to be best served with the 5G NR V2X technology instead of the LTE V2X technology due to the corresponding QoS requirements. 5G NR V2X provides groupcast and unicast support in addition to higher modulation rates that are suitable for these advanced services.

2.5 Services outside of ITS spectrum

Section 2.1 identifies some suitable services for V2N services aside from those previously discussed. These are the V2X services that can be offered outside of the ITS spectrum. When the Uu interface is used for these services, the licensed spectrum owned

by mobile operator would be utilized for the V2X services. This requires the C-V2X device having a subscription with the mobile operator. Based on that subscription, the mobile operator can determine the exact spectrum and corresponding radio resources to be used for such services.

There are two different types of considerations regarding offering V2N services. In the first case, this presents a great opportunity for the mobile operators to expand into new market areas with opportunities to replace V2I with the V2N model. This is made possible with the large deployment of cloud and edge computing platforms in the mobile network. In areas of good network coverage (urban or highly populated areas) it can match the delay performance of V2I.

In the second case, there may be unexpected impacts from the other services sharing the same network since the mobile network is not strictly dedicated to the V2X service. For example, there may be network congestions or service quality drops. Because of the larger coverage areas of the mobile network base stations, it has less opportunity to achieve spatial spectrum reuse like in the V2I case. Two RSUs located several hundred meters apart can operate Sidelink on the same channel without interfering each other. This would not be possible with the mobile network base stations in the V2N case; it could be possible that some of the service cannot be sustained using V2N (when too many devices are trying to access the network). There may be other situations (coverage holes) that can have negative impacts on the V2N performances. Some 5G System enhancements like network slicing or RAN slicing could mitigate certain aspects of the problem, but not fully eliminate it. Mobile operators' liability concerns when offering the V2N services expect that most of the V2X service used over V2N would relate to information sharing and complement other V2X services offered via V2V or V2I.

3. C-V2X Spectrum Requirements

The FCC's November 2020 Report and Order allocates 30 MHz in the 5.9 GHz band (5895 to 5925 MHz) for C-V2X operations. [4] Although this allows for basic safety V2X application support, it lacks sufficiency to support the myriad advanced V2X applications discussed in the previous sections. 5G Americas' response to the FCC FNPRM explains the need for at least 40 MHz additional mid-band spectrum for advanced C-V2X capabilities to take advantage of 5G-based advanced C-V2X and future wireless technology developments. [5]

An ITS America study reviewed spectrums needed for basic and advanced V2X technologies for different categories of applications. [39] Notably, advanced V2X applications (including those that rely on collective perception messages [CPM]), maneuver coordination messages (MCM), and personal safety messages (PSM) will likely require additional spectrum beyond the current 30 MHz allocation in the United States. Similarly, 5GAA has specified the different use cases and example service level requirements (SLRs) that covered advanced applications demanding higher throughput and reliability (HD Map collecting and sharing, Infrastructure assisted environment perception, etc.). [40]

In addition to the need for 40 MHz of spectrum for advanced C-V2X applications, another spectrum issue to consider is the potential interface avoidance from other technologies. In the FCC allocation, the new U-NII-4 unlicensed band out-of-band emissions (OOBE) may create interference with C-V2X communication if they are too high, particularly from outdoor operations. [5] 5G Americas requested that the FCC set U-NII-4 OOBE from fixed outdoor access points to a maximum of -27dBm/MHz at the 5895 MHz edge to guarantee the performance of C-V2X in the allocated bands. Client-to-client and mobile hotspot use of the U-NII-4 band must be denied because there is insufficient isolation to protect C-V2X On Board Unit receivers.

Given that C-V2X supports two modes of communication (Uu and PC5), 3GPP also defined the possible concurrent operation combinations of the two interfaces in 3GPP TS 38.101 [41] and TS 36.101. [42] Specifically, the Sidelink and Uu can operate concurrently with the following combinations:

- *NR and/or LTE Sidelink (n47) + NR Uu (licensed bands)*
- *NR and/or LTE Sidelink (n47) + LTE Uu (licensed bands)*

Such concurrent operation allows a C-V2X unit to combine different categories of V2X applications at the same time to deliver an end-to-end service. For example, using Sidelink for time critical and safety critical low latency V2V applications, and using Uu for delay tolerant V2N applications. Examples of the V2N services are listed in section 2.1. The spectrum needs and recommendations for the Uu access for these V2N services were provided in 5GAA studies. [43]



4. Deployment Considerations

4.1 Business Model for C-V2X

4.1.1 Business Models for Automotive OEMs

The addition of C-V2X to the automotive ecosystem reveals numerous possibilities for new business models that will affect many industry stakeholders. The adoption of C-V2X by the automotive industry remains in a preliminary phase, so is challenging to predict the full extent of its influence, especially given the wide range of use cases outlined in section 2. Broadly speaking, C-V2X business models include monetization opportunities for automotive OEMs and MNOs.

Historically, the automotive industry had been divided over the communications technology used for V2X applications. This division has served as a barrier to consensus adoption for either technology, hindering advancement and development within the industry. As C-V2X gains traction in the industry, along with the FCC's recent Report and Order, C-V2X will be the core communications protocol for C-V2X direct communications in the 5.9 GHz ITS spectrum band. This should ensure that C-V2X is even more widely adopted by automotive OEMs and suppliers, prevent further fragmentation, and enable the benefits of scale for the automotive industry.

A focus on C-V2X by automotive OEMs, suppliers, and communications service providers will only accelerate development and innovation with concentration on research, resources, and C-V2X. The ways that C-V2X can be used to meet industry needs can be more comfortably explored with the knowledge and certainty that it will be used in the 5.9 GHz band. Consensus on C-V2X and adoption by all industry players will also realize economies of scale, and drive down component prices that lead to additional widespread adoption across all lines of vehicles. That widespread adoption of a common communication protocol, and the interaction between as many vehicles and infrastructure points as possible will always be critical for fully realizing the benefits of V2X mentioned in Section 1.

C-V2X will benefit automotive OEMs by allowing access to standardized communications protocols that will serve as the developmental building blocks for new features and services that could be monetized according to consumer demand. For example, convenience features or services that improve efficiencies for consumers on a continuous basis could be developed with focus on attracting additional subscription revenues. Seamless integration of new features or services with in-vehicle technology will likely be required to win over consumers with a compelling value proposition that cannot be freely replicated on a smartphone. Such integration will only be facilitated by widespread adoption of C-V2X and reductions in the cost of components.

Automotive OEMs can also translate the safety improvements offered by C-V2X into increased vehicles sales, higher margins, or additional revenue streams. By making adoption of C-V2X technology and safety applications an integral part of their brand positioning and marketing efforts, automotive OEMs can appeal to the premium that consumers place on vehicle safety. According to a 2021 consumer study by Deloitte, safety features were the most important factors when consumers considered their next vehicle purchase with 43% of surveyed



U.S. consumers reporting that increased vehicle connectivity would be beneficial. [44] The proliferation of new safety features such as blind spot monitoring, collision warning and avoidance, lane departure warning, and rear cross traffic alerts demonstrates the diffusion of safety technology. As adoption of C-V2X grows, consumers will become accustomed to C-V2X and value its benefits when considering their next car purchase.

In addition, the presence of C-V2X capabilities could be factored into future vehicle safety ratings. For example, the National Highway Traffic Safety Administration (NHTSA) currently evaluates vehicle safety as part of its New Car Assessment Program (NCAP) to determine how vehicles perform in various crash tests. The NCAP has started to include the advanced driver assistance system (ADAS) in its 2021 model evaluation testing. Furthermore, NHTSA has also announced that the C-V2X technology may be considered in future updates to the NCAP to further increase automotive OEMs sales and differentiate their brands. [53]

Autonomous vehicles are thought to represent a transformation from traditional vehicle ownership models to mobility-as-a-service business models in the future automotive ecosystem (at least in more densely populated areas). This evolution of the automotive ecosystem will leverage the performance and advantages of

C-V2X in the transition to more fully autonomous vehicles. The adoption of C-V2X will significantly assist the development of autonomous vehicles by complementing the in-vehicle sensors and cameras that provide knowledge of the dynamic environment in proximity to the vehicle. The combination of direct communication with nearby vehicles, infrastructure, vulnerable road users, and connectivity with cellular networks will offer more comprehensive situational awareness. C-V2X will also support autonomous vehicles as they encounter difficult situations and are forced to disengage. In these situations, tele-operated driving via C-V2X will allow remote operators to overcome these challenges—a fallback that may even be required by regulations in some locations. While significant development work is still required for autonomous vehicles to become commonplace, C-V2X will remain a core building block for that vision.

4.1.2 Business Models for MNOs

MNOs can utilize new business models to interact with the automotive industry to ensure that C-V2X services reach their full potential. Network slicing will likely be a key component allowing MNOs to consistently meet the diverse requirements of automotive OEMs that span safety, convenience, and efficiency use cases. The goal of network slicing is to allow MNOs to operate multiple

logical networks, or “slices,” using their common infrastructure to serve multiple customers while simultaneously isolating the network slices to ensure specific SLAs. Figure 4.1 from 3GPP shows a high-level view of network slicing: two automotive network slices, and one network slice for mobile phones. [45] Network slicing provides distinct advantages over dedicated network solutions regarding increased flexibility and lower costs. Offering different “slices” of the mobile network based on specific service requirements of the end customer also gives MNOs the power to differentiate pricing and better monetize the full extent of their network capabilities. For example, a network slice targeting safety-related use cases with low latency and high reliability could provide higher value to the end user than a high latency and lower reliability slice for convenience use cases.

In addition to network slicing, MNOs can offer a unique set of tools that will enhance the automotive industry’s C-V2X service utility. Rather than providing complete services or product solutions, these tools will likely serve as the foundations of advanced V2X services required by the automotive industry and offer additional monetization pathways for MNOs.

Edge computing is a significant tool that can reduce latency for C-V2X use cases requiring computation by relocating those computations closer to the end user rather than existing

Figure 4.1 High-level view of potential network slicing deployments

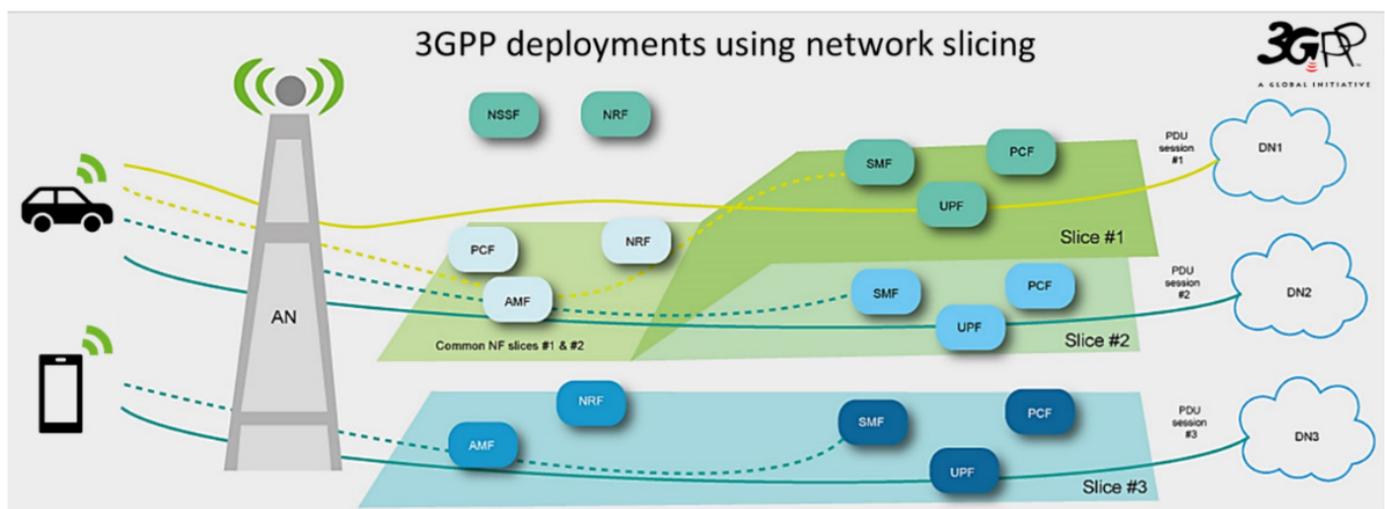
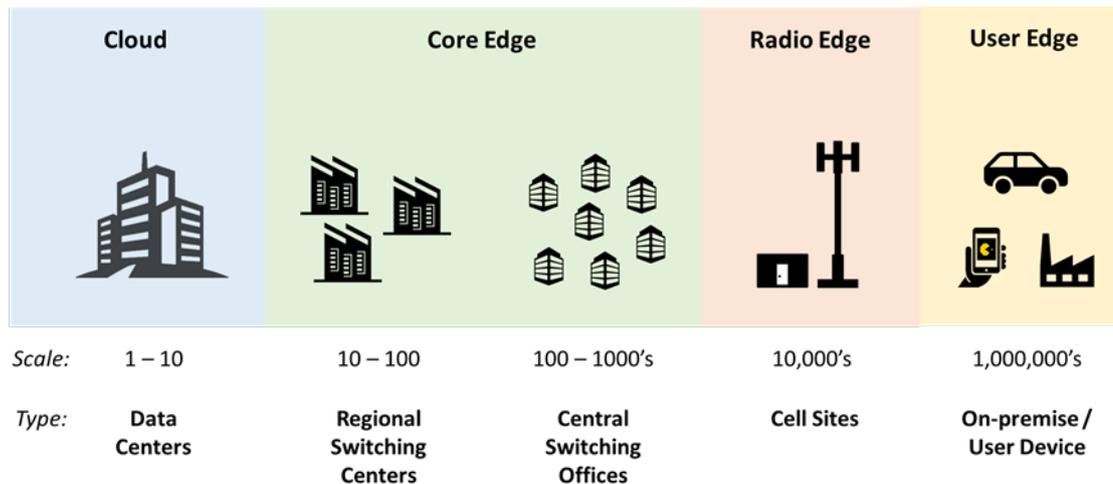


Figure 4.2 Different layers of edge computing from possible points of presence provide unique benefits but are implemented at different scales and costs



in a distant public cloud data center. Additionally, edge computing allows for the pooling and coordination of data at the local or even regional levels for analysis and actionable intelligence for C-V2X services. By keeping the computational resources within the confines of their own networks, MNOs are also able to achieve greater control and improve service level reliability.

MNOs' existing nationwide infrastructure portfolio offers numerous points of presence that could be utilized for edge computing, as shown in Figure 4.2 from 5G Americas whitepaper, "5G Services Innovation". Notably, switching offices could offer edge computing services to the automotive industry. Infrastructure at the "Core Edge" level offers a beneficial tradeoff between a sufficient distribution of available sites to ensure computing resources are located close to the end users while also maintaining a scale that balances the economic costs with the provided benefits. In contrast, the economic costs of providing edge computing services at tens of thousands of radio access network (RAN) sites, or the "Radio Edge," would likely be cost-prohibitive for today's C-V2X use cases. For truly delay-stringent matters where each millisecond matters, the computation would be done at the User Edge, within the vehicle subsystems and chipsets.

Another tool offered by MNOs is Predictive Quality of Service

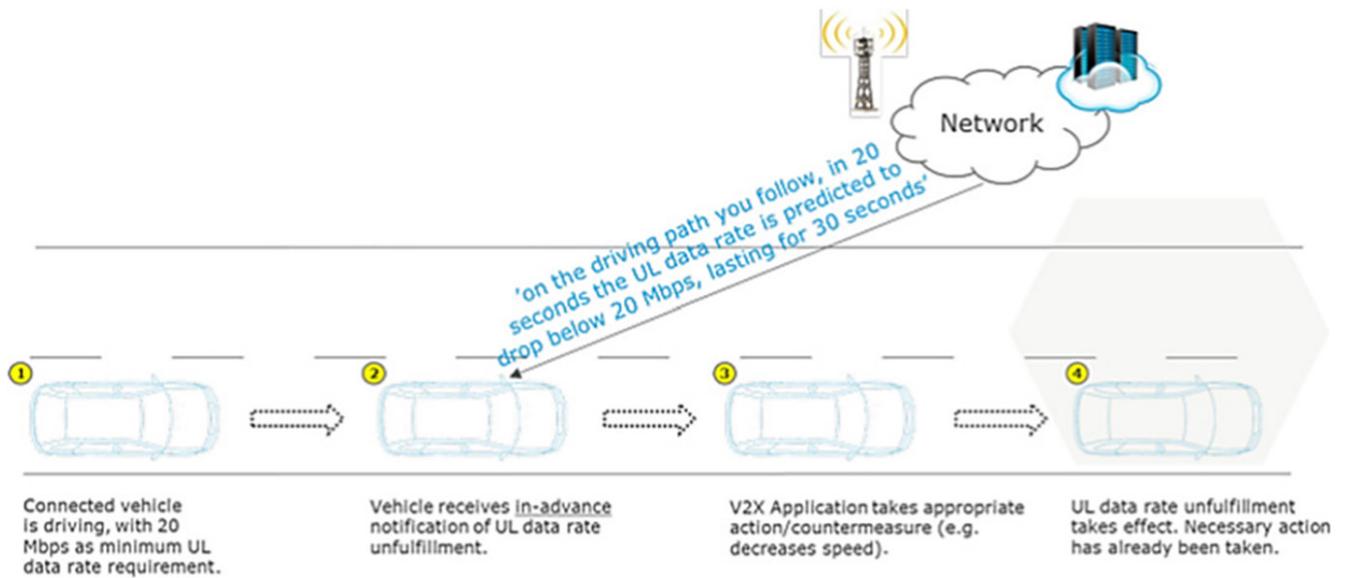
(PQoS). PQoS is needed due to the complex/non-deterministic nature of mobile networks and road traffic conditions. While MNOs make their best effort to provide consistent network experiences and high reliability, total consistency is rarely obtainable in practical application. This is important for vehicles that rely on connectivity with a mobile network for the functionality of various C-V2X use cases. The vehicle needs to confirm that the desired level of mobile network connectivity is feasible throughout the future route for a variety of reasons. Knowledge of this ahead of time would allow the vehicle to react proactively and prepare accordingly, including altering transmission of data or even modifying its route. Figure 4.3 from 5GAA depicts potential PQoS utilization by a C-V2X application for proactive action and mitigation for the impact of reduced mobile network performance. [46] By making PQoS information available, MNOs can deliver an important tool that automotive OEMs and suppliers can utilize to more effectively implement C-V2X services. MEC architectures can also be utilized to provide on-demand notification messages about the predicted QoS based on current network KPIs.

For many C-V2X services and advanced driver assistance systems (ADAS), awareness of a vehicle's absolute position (latitude, longitude, and elevation) is critical

for determining a vehicle's precise location. The Global Navigation Satellite System (GNSS) is used by vehicles to obtain their absolute location, but its self-determined accuracy (~3-10m), is often insufficient for V2X use cases. Higher level accuracy (precise positioning) requires reference stations on Earth that are used to correct for the inherent atmospheric, satellite orbit, and timing errors. The reference stations can be used to calculate corrections to the GNSS signals that are received by vehicles to unlock more accurate location.

Real-Time Kinematic (RTK) is a precise location technique that can ideally achieve accuracy down to the cm-level. Precise Point Positioning - Real-Time Kinematic (PPP-RTK) is a related technique that can obtain accuracy of ~10cm over larger areas with fewer reference stations. [47] MNOs can play a key role in these location techniques by serving as a distribution channel for the vehicle's position corrections by utilizing either the user or control planes. 3GPP has already defined a standard supporting an Observation State Representation (OSR) format for RTK corrections in Release 15, while Release 16 includes support for a State Space Representation (SSR) format compatible with PPP-RTK that can be used in a control plane broadcast solution. [48] Release 16 also adds dedicated positioning reference signals (PRS) for

Figure 4.3 Example of a C-V2X application supported by predictive QoS.



5G network-based positioning using roundtrip time (RTT), angle of arrival/angle of departure (AOA/AOD), and time difference of arrival (TDOA) to obtain positioning independent of GNSS systems. [49] As the density of vehicles needing precise positioning grows, scalable and efficient precise positioning mechanisms based on common standards will be important for MNOs and the automotive ecosystem.

Finally, MNOs offer a critical piece of the puzzle for C-V2X service realization: cross-MNO support. With different automotive OEMs being supported by different MNOs and the additional flexibility provided by eSIM technology, there will be a critical need for V2N services to function across multiple MNOs. Cross-MNO support will ensure that the full benefits of C-V2X services are realized at the greatest scale possible. This is especially true for use cases requiring data pooling and information sharing that will benefit from the inclusion of all possible vehicles.

4.1.3 Business model for other players

The broad reach of C-V2X across the automotive ecosystem will also unleash new business models for industry players beyond automotive OEMs and mobile network operators.

V2I communication is one component of C-V2X that will draw in multiple parties to support new services. Interactive communication between vehicles and infrastructure (including traffic lights, roadways, parking locations, RSUs, and other intelligent transportation systems) will require involvement and cooperation from cities and municipalities to effectively manage traffic patterns, increase transport efficiencies, and improve safety. Integrated communication systems at the municipal level based on C-V2X could offer new monetization opportunities in exchange for these improvements. For example, dynamic toll road pricing and automatic parking fee collection could optimize revenue, while improved traffic efficiencies could reduce planned road infrastructure investments and maintenance costs.

An important C-V2X service consideration involving many industry players is how the platforms and systems that support cross-party operations will be set-up and integrated. It is evident that robust platforms will be needed to support the scale of operations to maximize the benefits with C-V2X's developing ecosystem. For example, municipalities would need platforms to manage C-V2X connected infrastructure and any third

party RSUs, and analyze the data flowing through the system to create actionable intelligence. In another example, certain V2N services would clearly benefit from intelligence shared across the set of MNOs supporting vehicles, infrastructure, and VRUs. There could also be a role for third party platforms in supporting MEC and cloud computing operations and contributing to effective C-V2X services. As C-V2X adoption grows and C-V2X services are implemented, the role of these platforms will continue to evolve and become more clearly defined.

4.2 End-to-end service realization examples with ITS infrastructure

C-V2X enabled use cases are emerging in the near future; safety and traffic efficiency use cases are now being deployed with C-V2X technology/products commercially available, and an understanding of vetted use cases. Additional safety services (collision avoidance capability, for example) will be realized as the C-V2X penetration rate increases. However, significant near-term benefits can be achieved from valuable V2I use cases that are possible once a single intersection and vehicle are enabled by installing an RSU and retrofitting a vehicle

with an aftermarket OBU. C-V2X is a valuable technology that is on a trajectory to improve vehicular safety and traffic efficiency. Possible realization of a few typical V2I services is discussed below.

For specialty vehicles in public fleets, Traffic Signal Preemption and Transit Priority (earlier green light, for example) are two compelling use cases currently being adopted. Examining both use cases offers rationale for early deployment of roadside infrastructure that supports their applications, and lays the foundation for other equipped vehicle interaction with the same roadside infrastructure for the other applications highlighted above.

For instance, a full “lights and siren emergency” is highly volatile for emergency responders and other road users, especially at a traffic signal-controlled intersection. Today’s legacy system, including infrared (IR), has helped emergency vehicles navigate roadways but requires line-of-sight for communications. Additionally, it only operates when emergency vehicles are in proximity to traffic signals. This results in less warning time for other motorists to react to the emergency vehicle in the intersection. However, using C-V2X for V2I communications to trigger Traffic Signal Preemption can provide more advanced planning for traffic signal timing; signal changes become less abrupt for other motorists when an emergency vehicle approaches a traffic signal-controlled intersection, and allow faster passage for emergency vehicles, which can ultimately improve outcomes of critical situations. Combining C-V2X direct communication emanating from emergency vehicles with the larger cellular network (V2N) coverage areas further improves traffic management by ensuring that intersections are cleared for swift passage in anticipation of the vehicle’s arrival.

Two additional benefits of C-V2X include:

- *Feedback from the traffic signal controller to the emergency vehicle confirming the status of the signal controller*
- *The ability for the emergency vehicle to send alerts to other vehicles (V2V) warning of its approach*

Emergency vehicles are often heard before seen, so incorporating information on its arrival and overlaying it onto a digital map can help increase awareness by other road users.

Transit Priority—which offers both an early green light as well as extending a green light phase—can help busses and other designated vehicles maintain their schedule by allowing them to re-enter traffic without having to wait in a line of vehicles (such as metered freeway onramps), and experience efficient passage through intersections. Transit Priority can help cities promote the use of public transit by offering more predictability and adherence to published schedules. Transit Priority can also reduce idle times of specialty trucks (garbage trucks, armored vehicles, etc.) to reduce emissions, and can help snowplows maintain momentum as they clear roads. There are numerous lifesaving qualities to improving Traffic Signal Preemption for emergency vehicles, and various economic and sustainability (greenhouse gas emission reduction) attributes to Transit Priority.

Freight transportation can also utilize Freight Signal Priority as a priority user to extend the green light phase so that heavy freight trucks can move through a traffic signal uninterrupted. This is especially valuable in uphill and downhill intersections where it can be difficult for trucks to accelerate from or brake for a red light. Freight Signal Priority can also help improve safety by reducing truck-related collisions at intersections which minimizes traffic congestion due to slowly accelerating trucks, reducing stop-and-go conditions that contribute to wear and tear on roads, reducing pollution, and cumulatively ensuring more predictable movement of goods. In addition to commercial benefits, Freight Signal Priority could offer revenue-generation opportunities. Both use cases require initial integration of an aftermarket OBU and installation of RSUs on

specific signal controllers along designated corridors and can be expanded as budgets permit.

The critical Red Light Violation Warning and SPaT/Map capability provided by infrastructure at an instrumented, signalized intersection when it interacts with a connected vehicle should also be considered. An application factoring in vehicle speed and acceleration profile, distance to the intersection, and SPaT/Map and intersection geometry information can help determine if the approaching vehicle will enter the intersection in violation of a traffic signal. If so, the application can alert the driver and help reduce red-light violations and collisions at signalized intersections. This alert/warning can be shared not only with drivers of offending vehicles, but also other drivers in the area.

Like the Red Light Violation Warning, other alerts/warnings, such as Work Zone Warning, School Zone Warning, Speed Limit Warnings (Reduced Speed Zone Warning and Curve Speed Warning), and Spot Weather Information Warning can improve safety across the board for many drivers, pedestrians, cyclists, and work crews.

Regarding non-signalized traffic intersections, the Stop Sign Gap Assist safety application can support vehicles entering an intersection where only the minor road has posted stop signs. The drivers on a minor road stopped at an intersection can understand the state of activities (major road, minor road, and median sensors) associated with that intersection by receiving a warning. Like the Red Light Violation Warning, the Stop Sign Violation Warning can alert the driver when the vehicle may violate a stop sign and reduce collisions. This alert/warning can be shared not only with drivers of offending vehicles, but also with other drivers in the area.

The Railroad Crossing Violation Warning mirrors the Red Light Violation Warning and can be used to avert a devastating collision, while the Oversize Vehicle Warning can help avert impact with bridges, overpasses, or tunnels.

Finally, once SPaT/Map is employed at a signalized intersection, other use cases emerge. Automated vehicles loaded with sensors—many of which are line-of-sight visual sensors (including radar, LiDAR, and cameras)—can benefit further by receiving SPaT/Map so they are able to travel through intersections without unexpected acceleration/braking to provide a more pleasant riding experience. SPaT/Map information also benefits larger fleets as it can provide red light-time-to-go foresight as well as eco approach and departure (information to drivers about traffic signal timing allows drivers to adapt their speed so they pass the signal on green or decrease speed to a stop in the most environmentally efficient way) to ensure efficient movement through signalized traffic intersections.

4.3 User equipment impacts and adoption life cycles

C-V2X deployment has emerged in certain regions and commercial products are available in the market. However, it is still an evolving technology with continual enhancements and new features based on 3GPP release timelines. The device life cycle of the C-V2X equipment differs widely from that of the traditional mobile communication devices (smart phones). According to Bureau of Transportation statistics, the average age of the vehicles on the road is more than 10 years, compared to a typical 2-3 year replacement cycle for smart phones. [50] Therefore, additional considerations and planning are required for the deployment and product design.

C-V2X equipment have different forms and sub-components. For example, the embedded equipment in a vehicle has hardware components difficult to change or upgrade; software and firmware components can be upgraded and changed when a network connection is available. Similarly, software upgrading for the smart phones (OTA software upgrading for the automotive platforms) is also becoming popular and is supported by the car-to-cloud ecosystem. [51]

Such software upgrading can solve some aspects of the technology evolution issue, like allowing new, hardware agnostic features to be introduced when necessary. Additionally, C-V2X technology has been designed to offer backward compatibility when new features are introduced. For example, 5G NR-based V2X can operate in parallel with LTE-based V2X, with device configuration dictating the appropriate technology based on V2X service types (PSID). Additionally, for the different features within a particular release, the device can be configured with the specific transmission profiles (Tx Profile) for a particular service. Such service-type-based feature management allows new services to be developed that utilize new features of C-V2X without affecting the existing services or operations.

Mobile network operators may play a big role in the C-V2X device management due to their extensive experience in managing mobile devices. Updating configuration and profiles can be automated through the existing device management platforms, or via the new 5G system-based UE policy control platform. Within the eco-system, there are also the non-embedded devices for different use cases, like VRUs, or after-market devices. These devices may be handled in the same manner as normal mobile devices if they have mobile subscriptions or handled by 3rd party vendors over-the-top. The C-V2X platform was also designed to allow the 3rd party to make use of the 5G system to manage the devices. If the device is under coverage of the mobile network (using 3GPP or non-3GPP access) it would have a way to be updated with the latest configurations to ensure optimal operations.

4.4 Eco-system (incl. 3rd party involvement)

Due to its 3GPP origin, C-V2X inherited not only the technology advantages of the cellular system but also the well-established eco-system of mobile communication networks. This includes the large number of device and network vendors, matured

testing and certification platforms, extensive distribution channels and device management systems. Besides these, the 5G compliant C-V2X system also offers interfaces to expand the eco-system.

The 5G C-V2X system allows two possible paths to integrate 3rd party operations. The first path is for the 5G C-V2X system to offer a manageable transportation service to the external operations. For example, beyond the normal data pipe, the 3rd party V2X Application Servers are allowed to manage the target service area, influence the data path selection for a certain set of services, and configure the UEs with preferred operation parameters.

Another path supported by the 5G C-V2X system is to expose the relevant operational information to the external parties so more advanced V2X applications can be developed. An example of the network analytics could provide indications of the QoS levels of a particular area so different V2X application communication strategy can be pre-planned.

There are also efforts in 3GPP SA WG6 to develop unified service layers (VAE [54] and SEAL [55]) to support the interaction with the application layers. This makes the integration of external services with the 5G C-V2X system even easier.

4.5 Security aspects

Many within the automotive industry believe that the widespread use of C-V2X could potentially save thousands of lives and prevent hundreds of thousands of collisions every year. C-V2X also offers automotive manufacturers and road operators a technology that enhances mobility, efficiency, and environmental sustainability. Hence, securely delivered C-V2X messages are taken very seriously. (Note: The following discussion focuses on the Sidelink aspect of C-V2X.)

With any form of communications technology, there is always the risk of cyberattacks. However, the success or failure of such attacks often depends on the quality of the communication system's implementation. C-V2X was created from the start with security and privacy in mind and was consciously designed to make it easy to implement securely.

There is a continuous back and forth when developing any communications system, particularly when a system like C-V2X has a direct impact on safety of life. The more a system can communicate, the more useful it is to the user; however, the risk of a malicious external actor using that communications capability to attack and exploit the system also grows. Two key technologies that help protect against this kind of attack are sandboxing and authentication.

Sandboxing has a variety of meanings, but in this context, it means deliberately limiting the types of data that will be accepted. The opposite of a sandboxed system is one that offers remote terminal access where an attacker can open a command prompt and subsequently run any command they like on the system. This kind of free-form access makes security design and testing very difficult because a defender needs to cover all possible ways the attacker might try to get access, while the attacker only needs to find a single avenue of attack.

C-V2X deliberately avoids this kind of "Wild West" approach to what can be sent and accepted. Instead, a series of applications are defined and specified in standards published by SAE, ETSI, CCSA, and other organizations (an "application" here does not mean a phone app—it refers to a specific set of messages that can be sent over the air, and a specific set of uses that can be made of those messages). Each different application is identified by an Application Identifier; this is called both a Provider Service Identifier (PSID) in the U.S., and an Intelligent Transportation Systems Application Identifier (ITS-AID) in the ETSI/ISO systems. When a message is sent, it is associated with an AID. When it is received, it is immediately associated with the application

for that AID. Essentially, within the C-V2X system, it is impossible to send the arbitrary commands that corrupt other systems; each message is for a specific application and will be processed by that application only, which preventing spillover to other applications or to other components within the vehicle.

Sandboxing is the first line of defense and key to preventing an attacker from using C-V2X to gain access to wider vehicle systems.

Authentication is widely used in C-V2X and throughout communications systems worldwide. For example, website authentication with a password, phone authentication with a thumbprint, or work system authentication (sometimes with a smartcard). In the V2X system, authentication has unique challenges and unique solutions:

- *Broadcast: The system is a broadcast, ad-hoc networking system. In principle, any users can communicate, but it is not realistic to set up a secure relationship in advance with all users in the system. Instead, C-V2X uses digital certificates to authenticate the broadcast messages. This is a well-known internet technology, though customized for C-V2X, that allows one party to trust another party's messages, even if the two parties have never communicated before. The customized certificate and message formats are specified in IEEE 1609.2, the development of which was led by Qualcomm Technologies and serves as the baseline standard for C-V2X security worldwide.*
- *Identity is not useful: Website authentication can utilize a user's identity to look up account details. In the C-V2X setting, a sender's identity is too hard to use; there are simply too many existing identities that change too rapidly. Instead, sender authentication uses the AID mentioned above, not the sender identity, to indicate what application activities the sender can carry out. This both authenticates the sender and helps sandbox the message. IEEE 1609.2 specifies this approach.*
- *Constrained channels: Although C-V2X has greater channel capacity than rival technologies, the total bandwidth available for V2X communications is still limited. IEEE 1609.2 uses a special compact form of cryptography called elliptic curve cryptography to keep sizes down.*

Authentication by the mechanisms of IEEE 1609.2 provides assurance to the receiver that the message came from a good sender; the sender is allowed to send the message for the application identified by the PSID/ITS-AID in the 1609.2 certificate (for example, a real car sending Basic Safety Messages) with working sensors by running a correct instance of the application instead of malware. Certification programs to ensure sender authentication are being actively developed and will be mandated in Europe and elsewhere. Certificates will be issued only to valid senders so receivers can trust incoming messages.

Another layer of protection is provided by misbehavior detection. Misbehavior detection can be thought of as plausibility checking on steroids; it is a process of confirming that every incoming message for an application is appropriate. If a message does not fit with sensor data, with other messages from the same sender, or with messages from other sensors, it can be rejected. This indicates that even if an attacker's goal is limited to misbehavior within the C-V2X system (to send messages that cause a driver to get an alert, disrupting them or potentially prompting them to take unnecessary action) they are severely limited in what they can send and hope the receiver will notice. ETSI is currently working on a standard for misbehavior detection and reporting, and a misbehavior detection specification is maintained by the U.S. Security Credential Management Systems (SCMS) Manager.

In principle, privacy concerns may seem invasive for potentially breaching and sharing personal information, but the system is designed from the ground up to make violating privacy difficult.

First, for normal end-user vehicles, messages do not contain any identifying information. As noted above, the certificates do not need to reveal users' identity; they only need to display user permissions. This is a point of strength for the system from a privacy perspective. If receivers do not require user identity to trust a message, they gain privacy benefits by simply omitting user identity.

Second, although messages are signed with a certificate which could potentially be used to track users (users are the only ones who own that certificate), the system protects against this kind of tracking by issuing multiple certificates to each car. In the U.S., no rules have been made about how many certificates to issue, but in Europe, the number is 60 to 100 per week. This means that a V2X sender can easily switch from one certificate to another as they go from one place to another, meaning that a tracker can only monitor them if the tracker is physically following the sender.

Potential concern that the certificate issuers (a Certificate Authority or CA) violate privacy because the certificate issuer knows which certificates have been sent to which vehicle. This would allow an insider at the CA to track a user, or worse, if there was a database breach at the CA, it would allow anyone with access to the database to track everyone who received certificates from that particular CA. The system design anticipates this; the certificate issuance uses multiple separated organizations and intuitively spreads the issuance information between them so there is no single database that can be breached and allow tracking.

Adding any access point to a system brings additional security considerations, and this is as true of C-V2X as of any other access point. However, unlike almost every other system with the cellular system itself being an honorable exception, C-V2X security has been considered from the very start of the process. The C-V2X system designers are security-conscious, and the implementers take security into consideration at every step of the way. Because of these critical factors, the C-V2X system is designed with security at the forefront.

Conclusion & Recommendations

Deployment recommendations

C-V2X technology has a bright future, and the deployment of the V2X services based on it has already started. Based on the previous discussions, a few aspects need to be taken into consideration in the deployments:

- *Spectrum: As discussed in section 3, there is a need to adopt necessary unlicensed OOB protections to ensure reliable C-V2X communications. Additionally, for the support of advanced V2X services, allocation of 40 MHz of additional mid-band spectrum for advanced 5G-based C-V2X applications is required.*
- *Deployment/business model: As discussed in sections 2 and 4, supporting multi-MNO and cross-MNO operation for end-to-end use cases is crucial. To build a healthy eco-system, opening the service exposure interfaces to allow 3rd party participation is important. Integration of the C-V2X with public mobile network could also bring much more new service and business opportunities.*
- *Security: As discussed in section 4.5, proper certificate management framework is required to avoid privacy violation. Misbehavior detection and reporting system would be necessary to present the attacks on the system.*

Future evolution path

C-V2X technology is evolving with new versions in the making by 3GPP. There are many exciting new features being studied and standardized in multiple working groups.

For example, power efficiency has been identified as an important feature for VRU devices. Therefore, 3GPP has included a power saving design in its Release 17 package which is expected to be completed by Q1 2022. This would greatly help the adoption of C-V2X technology in the mobile devices used by pedestrians or cyclists which have power limitations. Additionally, the Release 17 package also includes a new mechanism for efficient resources management, striving to better utilize the limited ITS spectrum.

Recently, 5GAA has also identified a list of new features that is important for ITS applications [52], including:

- *support of high accuracy Sidelink Positioning independent of mobile network or GNSS coverage, which allows advanced use cases to be supported in different coverage scenarios, (out-of-coverage or partial coverage, indoor, underground parking facilities, or long tunnels);*
- *co-existence of different V2X technologies, which allow LTE and NR V2X to operate in the same channel in regions with limited spectrum allocation, and co-exist with other non-3GPP ITS technologies in adjacent channels;*
- *support for carrier aggregation, which allows aggregating any available bandwidth for advanced applications;*
- *power saving for the Sidelink, which allows power efficient use of C-V2X technology in more advanced use cases that can be beneficial to both vehicle and VRU users;*
- *V2X traffic over 5G MBS system, which allows a more spectrum efficient delivery of V2X application over Uu;*
- *Vehicle mounted relays, which allows the vehicle to serve mobile devices inside or outside of the vehicle for better throughput and power efficiency;*
- *support of UE-to-UE Relays, which allows efficient extension of the C-V2X Sidelink coverage;*
- *support of higher spectrum bands operation for C-V2X, which allows the use of mmWave bands to reach higher data rates (> 1Gbps, for more advanced use cases);*
- *in-vehicle wireless communications, which allows convenient high throughput connections of in-vehicle devices.*

3GPP will consider these features in the scoping of Release-18 packages that is to be concluded by the end of 2021.

With all these technology advancements, more tools become available to develop an ITS system that is truly intelligent and beneficial to the society.

Acronyms

ACN: Automatic Crash Notification	PSID: Provider Service Identifier
CA: Certificate Authority	RSU: Roadside Unit
CAMP: Crash Avoidance Metrics Partners LLP	RU: Radio Unit
CDN: Content Delivery Network	SAE: Society of Automotive Engineers
C-SAE: China Society of Automotive Engineers	SCMS: Security Credential Management Systems
C-V2X: Cellular Vehicle-to-Everything	SEAL: Service Enabler Architecture Layer for Verticals
CU: Central Unit	SLA: Service Level Agreement
DSRC: Dedicated Short Range Communications	TLI: Traffic Light Information
DU: Distributed Unit	TMC: Traffic Management Center
EPC: Evolved Packet Core	TTM: Time to market
ETSI: European Telecommunications Standards Institute	UDR: Unified Data Repository
FCC: Federal Communications Commission	URLLC: Ultra-Reliable Low Latency Communication
IoT: Internet of things	USDOT: U.S. Department of Transportation
IoV: Internet of Vehicles	VAE: V2X Application Enabler
ITS: Intelligent Transportation System	VRU: Vulnerable Road User
ITS-AID: Intelligent Transportation Systems Application Identifier	V2I: Vehicle-to-Infrastructure
MNO: Mobile Network Operator	V2N: Vehicle-to-Network
MEC: Multi-access Edge Computing	V2P: Vehicle-to-Pedestrian
NF: Network Function	V2V: Vehicle-to-Vehicle
NLOS: Non-line-of-sight	3GPP: 3rd Generation Partnership Program
NRF: Network Repository Function	5GAA: 5G Automotive Association
OBU: Onboard Unit	5GC: 5G Core
OOBE: Out-of-band Emission	5GS: 5G System

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Acknowledgments

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