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Abstract

5G is driving numerous improvements in vehicular communication realm. Cooperative communications advancements in V2X (Vehicular-to-Everything) are bolstering the autonomous driving paradigm. For connectivity between V2X nodes, 5G provides a short-range direct communication mode (PC5) and a long-range mode (Uu). Conventional vehicular networks employ unintelligent static wireless vehicular communication technology which is inefficient. In this study, hybrid 5G C-V2X is investigated, and an autonomous and intelligent technology selection algorithm has been proposed. The algorithm uses the information from the received C-ITS (Cooperative Intelligent Transport Systems) CAM (Cooperative Awareness Message) messages to calculate KPIs (Key Performance Indicators) and collect statistics (distance and one-way end-to-end latency) to be used as an input for the decision tree for selecting the appropriate technology (PC5 or Uu) for the next scheduled C-ITS message transmission. The performance evaluation of the intelligent hybrid C-V2X algorithm in our V2X test setup showcases considerable gains in terms of one-way end-to-end latency over the conventional static technology usage. Moreover, the considered hybrid communication mechanism provides automatic switching between PC5 and Uu if one of the technologies is unavailable or saturated. This enhances the safety and efficiency in applications such as vehicle platooning and autonomous driving. To conclude, this study provides several recommendations for various V2X stakeholders for strengthening the hybrid C-V2X communications.

Keywords: Hybrid, 5G, C-V2X, PC5, Uu, teleoperation, cooperative, communication, CAMINO, testbed, latency, V2V, V2I, cellular.

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EXECUTIVE SUMMARY

Traffic dynamics in V2X scenario change every moment due to the dynamically changing wireless and physical environment. Huge amount of data is generated and exchanged among various types of C-ITS nodes every second. According to global statistics, the compound annual growth rate stands at staggering 17.1% as far as connected car market is concerned. The global connected car market is expected to exceed $225 billion by 2025 [1]. This sizeable market growth is driven by 5G connectivity. Multiple short-range (C-V2X PC5, IEEE 802.11p based ITS-G5) and long-range (C-V2X Uu) technologies exist for communication between V2X nodes. Currently, a wireless vehicular communication technology is selected statically for information exchange among different road users. Moreover, any decision making on a central cloud server is far from optimal in a rapidly varying traffic and network scenarios. In this regard, one solution fits all scheme is inappropriate. Hence the need for an intelligent real-time statistics-driven technology selection decision making for wireless vehicular communication at every V2X node is crucial for optimizing V2X communications. In C-ITS, all V2X nodes receive periodic CAMs from nearby nodes. These CAM receptions have been exploited in determining certain network statistics like distance which is based on the GPS (Global Positioning System) information, and one-way end-to-end latency (based on transmission and reception timestamps of C-ITS messages). With this information, based on the generated decision tree for various C-ITS messages like CAM, DENM (Decentralized Environmental Notification Message), and IVIM (In-Vehicle Information Message), an intelligent decision is made on the use of specific C-V2X technology (PC5 or Uu). With this intelligent decision, it is ensured that the selected technology will provide optimal coverage and one-way end-to-end latency. Other statistics such as vehicle speed and C-ITS message frequency are also considered in the algorithm to pre-empt the successful reception of C-ITS messages. Specifically for the platooning use case, this algorithm can enhance the V2X communication within the vehicles of a platoon. V2X service providers can get a heads-up from such an intelligent mechanism and potentially can work on adding such/more advanced intelligent V2X technology selection mechanisms in their V2X systems. Also, MNOs (Mobile Network Operators) can learn in terms of efficient resource allocation and reducing the extra burden on long-range when more gains can be achieved via short-range communication. This study lays the foundations for the next generation real-time statistics-driven connectivity, in turn enhancing the safety and efficiency of future vehicular networks.

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ABBREVIATIONS

3GPP	Third Generation Partnership Project
ADAS	Advanced Driver Assistance Systems
CAM	Cooperative Awareness Message
CAV	Connected Autonomous Vehicles
CCAM	Cooperative, Connected & Automated Mobility
C-ITS	Cooperative Intelligent Transport System
COTS	Commercial Off the Shelf
CSMA/CA	Carrier-Sense Multiple Access with Collision Avoidance
D2D	Device-to-Device
DENM	Decentralized Environment Notification Message
DSRC	Dedicated Short Range Communication
DUST	Distributed Uniform Streaming
ETSI	European Telecommunications Standards Institute
GLOSA	Green Light Optimal Speed Advisory
GNSS	Global Navigation Satellite System
I2V	Infrastructure-to-Vehicle
IEEE	Institute of Electrical & Electronics Engineers
IP	Internet Protocol
IVIM	Infrastructure to Vehicle Information Message
KPI	Key Performance Indicator
LIDAR	Light Detection and Ranging
LR	Long Range
LTE	Long Term Evolution
MAPEM	MAP Extended Message
MEC	Multi-Access Edge Computing
MNO	Mobile Network Operators
N2V	Network to Vehicle
NCM	NR Sidelink Communication Manager
NR	New Radio
OBU	On-Board Unit
OEM	Original Equipment Manufacturer
RADAR	Radio Detection and Ranging
RSU	Roadside Unit
SCM	Sidelink Communication Manager
SDR	Software-Defined Radio
SPAT	Signal Phase and Timing Message

SPATEM	Signal Phase and Timing Extended Message
SPS	Semi Persistent Scheduling
SR	Short Range
SREM	Signal Request Extended Message
SSEM	Signal request Status Extended Message
V2I	Vehicle-to-Infrastructure
V2I2V	Vehicle to Infrastructure to Vehicle
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle to Everything
VCC	Vehicular Cloud Computing
VEC	Vehicular Edge Computing
VRU	Vulnerable Road User

1 INTRODUCTION

With the advancements in 3GPP (Third Generation Partnership Project) based cellular communications in the last decade, V2X communication is becoming a reality, based on the environment in which they operate, these communications can take various forms, such as V2V (Vehicle to Vehicle), V2I (Vehicle to Infrastructure), V2P (Vehicle to Pedestrian) and V2N (Vehicle to Network) as depicted by the C-ITS landscape [2] in Figure 1. Connected, autonomous and teleoperated vehicles are changing the dynamics of the vehicular communications. Currently, it is believed that approximately 95% of all road traffic accidents in the European Union are caused by human errors [3]. CAVs (Connected Autonomous Vehicles), teleoperation and platooning have the potential to greatly enhance various aspects of our daily lives. They have the potential to increase road safety by reducing the likelihood of human error. Additionally, these vehicles can also improve traffic efficiency by better managing the flow of vehicles on the roads and reducing the fuel consumption.

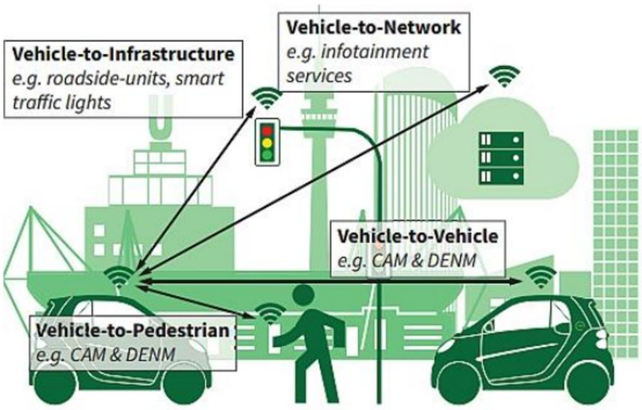


Figure 1: The C-ITS Landscape.

The use of CAVs, teleoperation and platooning are expected to lead to a significant reduction in accidents and fatalities on the roads. This is largely because these technologies are designed to be much safer for everyone. For example, vehicles in a platoon are equipped with a number of sensors and systems that allow them to detect potential hazards on the road, such as other vehicles, pedestrians, and obstacles. They can also communicate with other vehicles and infrastructure, such as traffic lights and road signs, to better coordinate traffic flow and avoid potential collisions. In addition to improving road safety, these technologies also enhance traffic efficiency. By better managing the flow of vehicles on the roads, these vehicles can help to reduce traffic congestion and improve overall traffic flow. For example, connected vehicles can communicate with each other and with infrastructure to share information about traffic conditions and potential hazards, allowing drivers to make more informed decisions about their routes and driving behaviour. As such, there is a growing need for continued research and development in this area, as well as for policies and regulations that can help to support the widespread adoption of these vehicles. By doing so, we can create a safer, more efficient, and more sustainable transportation system for all.

The term “Hybrid vehicular communication” refers to the use of a combination of communication technologies and protocols to facilitate communication between vehicles and their surrounding infrastructure. This approach leverages both dedicated short-range communication (C-V2X based PC5, IEEE 802.11p based ITS-G5) and cellular networks (4G/5G) to provide reliable and efficient communication between vehicles, as well as with roadside infrastructure such as traffic lights, toll booths etc. Hybrid vehicular communication offers numerous benefits, including improved safety through the sharing of real-time information about road conditions and potential hazards, as well as enhanced traffic management and reduced congestion. Additionally, hybrid vehicular communication can facilitate the platooning use case by enabling vehicles to communicate with each other and the surrounding infrastructure in real-time or with considerably reduced latencies.

Overall, hybrid vehicular communication is a promising solution that has the potential to revolutionize the way we think about transportation and mobility in the future.

In a hybrid V2X communication, based on the network statistics calculated from the received C-ITS messages from other V2X nodes, an advanced wireless vehicular communication technology selection decision can be made for optimizing the data communication between V2X nodes. Such a decision-making capability on the V2X node is crucial and can help in reducing the network latency, optimally use the wireless resources and enhancing the overall safety on the roads. However, until now, technology selection for transmission of C-ITS messages is static and does not consider any performance KPIs. Hence, in this deliverable, an intelligent algorithm for hybrid C-V2X communications is presented, implemented, and tested on a real life V2X testbed that is described in the later sections. Contrary to a vehicle making intelligent decisions, considerable latency can be incurred if vehicular communication data is first sent to a central cloud server where the decision on a technology is made and communicated back via the network to the respective V2X node. This puts extra load on the backhaul. Moreover, as reports predict exponential increase in intelligent/autonomous vehicles on the roads in the coming years, the current network can face high loads which specifically can have implications for latency critical applications. In use cases such as platooning, this intelligent decision making can reduce the latency, in turn enriching the cooperative communication among different road users.

The hybrid approach of C-V2X communication enables low latency communication for safety-critical messages, such as collision avoidance warnings, emergency braking, and road hazard notifications. Such messages require immediate response and quick action to prevent accidents or reducing the impact of a potential collision. By reducing the latency of these messages, hybrid C-V2X communication can improve the overall safety of the road environment. Another critical advantage of C-V2X communication is its reliability and scalability in a scenario where many V2X nodes want to transmit at the same time. The hybrid approach of C-V2X communication also ensures that the communication remains robust even in areas with poor cellular coverage, where short-range communication can be used as a backup.

The scope of this deliverable is only the 5G C-V2X communications (PC5 and Uu) so IEEE 802.11p based ITS-G5 is not considered in technical analysis and the proposed algorithm. The deliverable report first sheds some light on short-range and long-range V2X communication in section 2. Different types of C-ITS messages along with their ETSI (European Telecommunications Standards Institute) standardization and 3GPP C-V2X standardization are discussed in section 3 and 4, respectively. The proposed intelligent hybrid C-V2X algorithm is presented in detail in section 5. IMEC’s V2X testbed and a proof-of-concept on top of it are shown in section 6 and 7, respectively. Numerous recommendations for V2X stakeholders such as MNOs and V2X service providers are presented in section 8, whereas the deliverable report is wrapped up with conclusions in section 9.

2 SHORT-RANGE AND LONG-RANGE COMMUNICATION

V2X systems allow vehicles to communicate with each other and with roadside infrastructure, providing real-time information about traffic conditions, potential hazards, and more. There are two main types of V2X communication: short-range (direct) and long-range cellular. V2X technology classification [4] is shown in Figure 2. In this section, the characteristics, benefits, and challenges of each type of communication are explored.

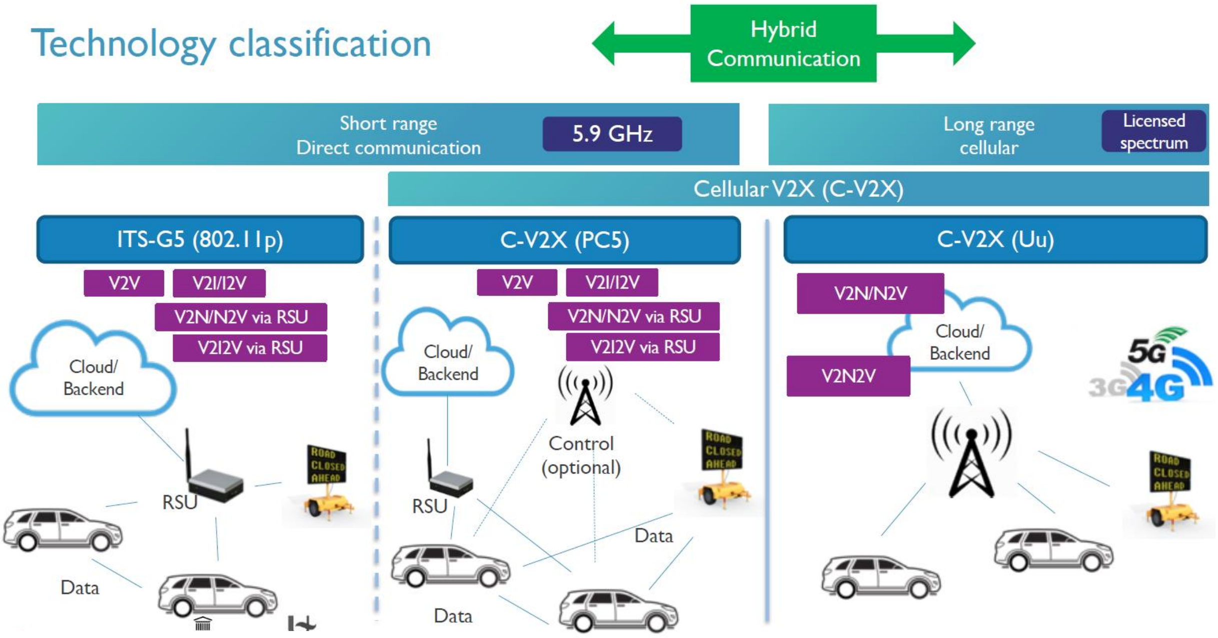


Figure 2: V2X technology classification.

2.1 Short-Range direct V2X Communication

Over the past decade, two wireless communication technologies have emerged to facilitate direct data exchange within dedicated spectrum. The initial protocol, based on IEEE 802.11p, comprises separate ITS protocol stacks in Europe and the U.S., known as ITS-G5 and DSRC (Dedicated Short Range Communication), respectively. The second technology is C-V2X PC5, also known as C-V2X Sidelink, which is based on cellular networks. The communication range for these short-range wireless vehicular communication technologies is a few hundred meters. They operate in the 5.9 GHz unlicensed frequency band and provide low-latency communication that is well-suited for safety-critical applications.

ITS-G5 and DSRC are built on top of the 802.11p standard and utilize CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) to access the wireless medium. According to CSMA/CA, each station checks if the wireless channel is available before transmitting. If the channel is busy, the station performs a random backoff before checking the channel again. However, in highly dense environments where multiple clients contend for access to the wireless medium, the medium access time and packet transmission latency may increase due to the CSMA/CA mechanism. On the other hand, C-V2X PC5, being a newer technology, offers two operating modes: mode 3 and mode 4 [5]. In mode 3, ITS stations can directly exchange messages, with the base station responsible for resource scheduling. In mode 4, ITS stations autonomously schedule their resources using sensing-based SPS (Semi Persistent Scheduling). With SPS, each station schedules its own resource blocks for transmissions, spreading them out in time to minimize collisions with other transmissions on the same subcarriers [6]. However, in dense environments, scalability issues can impact latency as multiple users may select the same resources, leading to transmission collisions.

Short-range direct V2X communication has many benefits. For example, it can improve safety by providing real-time warnings about potential hazards, such as accidents, road closures, or weather events. It can also optimize traffic flow by coordinating with traffic signals and other infrastructure. Short-range direct V2X can also provide information about parking availability and guide drivers to available spaces, reducing congestion and emissions. However, there are also challenges to implementing short-range direct V2X communication. For example, it requires significant infrastructure investment to install the necessary roadside units and other equipment. There are also concerns about cybersecurity and privacy, as short-range direct V2X communication involves the sharing of sensitive information between vehicles and infrastructure [7]. Finally, there are interoperability issues, as different regions and countries may adopt different communication standards.

2.2 Long-Range V2X Communication

Long-range V2X communication uses cellular networks, such as 4G or 5G, to communicate between vehicles and infrastructure over longer distances. Unlike short-range direct V2X, which is designed mainly for safety-critical applications, long-range V2X is mainly intended to provide a broader range of services, such as hight throughput data transfer and streaming, infotainment, navigation, and remote vehicle management. Long-range V2X communication has many benefits. For example, it can provide real-time traffic information, such as congestion and road closures, over much wider areas than short-range direct V2X. It can also enable new services, such as remote driving, remote vehicle diagnostics, software updates, and over-the-air services. Additionally, long-range V2X can, similar to short-range direct V2X, support vehicle platooning, where a group of vehicles travel closely together to improve fuel efficiency. However, there are also challenges to implementing long-range V2X communication. For example, it requires a reliable and robust cellular network, which may not be available in all areas. It also requires advanced security measures to protect against cyber threats. Additionally, long-range V2X communication may be subject to latency and bandwidth limitations, which can affect the quality and reliability of the service. Also, if the cells or the network is loaded with traffic from other users, it negatively impacts the performance as QoS provision may not be guaranteed. This issue could be resolved once 5G network slicing gets available. Network slicing in 5G is a network architecture that allows for the simultaneous existence of multiple virtualized and independent logical networks on a shared physical network infrastructure. Each network slice represents a distinct and self-contained end-to-end network that is customized to meet the specific QoS demands of a particular application like V2X.

Short-range direct and long-range V2X communication both have their own characteristics, benefits, and challenges. Both are important for enabling ADAS (Advanced Driver Assistance Systems), C-ITS, autonomous driving, and hybrid C-V2X communication. Short-range direct V2X is well-suited for safety-critical applications, such as collision avoidance and emergency warnings, but might require significant infrastructure investments. Long-range V2X, on the other hand, is intended to provide a broader range of services, such as infotainment and remote vehicle management, but requires a reliable and robust cellular network and is subject to latency and bandwidth limitations. Overall, both types of V2X communication have the potential to improve safety, efficiency, and mobility in transportation systems. However, their successful deployment depends on a range of factors, including technological readiness, regulatory frameworks, cost, and public acceptance.

3 C-ITS MESSAGES AND ETSI STANDARDS

C-ITS messages are a set of standardized messages used in C-ITS to enable communication between vehicles, infrastructure, and other road users. These messages are designed to improve traffic safety, efficiency, and sustainability by providing real-time information and services to drivers and other road users. C-ITS messages are transmitted using various wireless technologies such as ITS-G5, C-V2X PC5 and C-V2X Uu. The ETSI has defined the standards for C-ITS messages, which are widely adopted by automotive and transportation industry stakeholders worldwide. Some of these messages are as follows:

- **CAM (**Cooperative Awareness Message**)** is a standardized message that allows vehicles to share their state and kinematic data with other vehicles and infrastructure. CAM messages are transmitted periodically, enabling vehicles to receive and process information about the surrounding traffic and road conditions. The CAM message includes data such as vehicle speed, heading, position, and acceleration, and can also include vehicle identification and safety-related information. The CAM standard is defined in ETSI TS 102 637-1 [8] and is a fundamental building block of C-ITS.

- The **DENM (**Decentralized Environment Notification Message**)** is another standardized message that enables vehicles and infrastructure to share information about environmental hazards or abnormal traffic situations. DENM messages are triggered by events such as accidents, road closures, or weather conditions and provide real-time information to vehicles in the vicinity. DENM messages can also be used to broadcast information about traffic signal changes, speed limits, or parking availability. The DENM standard is defined in ETSI TS 102 637-3 [9] and is designed to complement the CAM message.

- The **IVIM (**Infrastructure to Vehicle Information Message) is a standardized message that provides drivers with personalized information and services. IVIM messages are tailored to the driver's preferences and can include information such as traffic updates, weather forecasts, or recommended routes. IVIM messages are transmitted from a cloud-based service to the vehicle's infotainment system and can be displayed on the dashboard or read aloud using text-to-speech technology.

- The **SPaT** (Signal Phase and Timing) message is a key component of the C-ITS ecosystem, providing vehicles with real-time information about the current and upcoming traffic signal phases and timing at intersections, as in ETSI 103 191-3 [10]. By sharing this information with vehicles, the SPaT message enables a range of traffic management and safety applications, such as GLOSA (Green Light Optimal Speed Advisory) and intersection collision warning. GLOSA helps drivers to optimize their speed and reduce delays by providing them with the optimal speed to travel to reach the next green light without stopping, while intersection collision warning alerts drivers when they are at risk of colliding with another vehicle at an intersection. Overall, the SPaT message helps to improve traffic flow, reduce delays, and enhance safety at intersections, making our roads more efficient and safer for everyone.

- The **SPATEM** (Signal Phase And Timing Extended Message) is an advanced version of the SPaT message that provides even more detailed and accurate information about the traffic signal phases and timing at intersections. The message includes additional information such as the geometry of the intersection, the lane configuration, and the location of the signal heads, which helps to improve the accuracy and reliability of signal prediction for vehicles equipped with C-ITS technology. The SPATEM message is an important tool for traffic management and safety applications, such as GLOSA and intersection collision warning. By providing vehicles with more precise and comprehensive information about traffic signals, the SPATEM message can help to reduce congestion, improve safety, and enhance the overall driving experience.

- **MAPEM** (MAP Extended Message) is a C-ITS message that provides vehicles with high-definition, real-time maps of the road network, including lane-level information, speed limits, and road geometry. These maps are essential for the safe and efficient operation of automated vehicles, which rely on accurate and up-to-date maps to navigate the road network. The MAPEM message is designed to support a range of automated driving applications, such as lane departure warning, automated lane changing, and automated parking. By providing vehicles with more detailed and accurate maps, the MAPEM message can help to improve the safety, efficiency, and overall performance of automated driving systems, paving the way for a more connected, autonomous, and sustainable future.

- **SREM** (Signal Request and Emergency Message) is a C-ITS message that allows drivers to request green traffic lights or send emergency messages to traffic management centres. The message is generated by the vehicle and sent to the traffic management centre using the C-ITS technology. The SREM message can be used to request priority at traffic lights or inform the traffic management centre of an emergency, such as a breakdown, accident, or medical emergency. The message also includes information about the location and direction of the vehicle, as well as other relevant details. The SREM message is particularly useful for improving the efficiency and safety of the road network, as it helps to reduce congestion, improve response times, and prioritize emergency services. By using the SREM message, drivers and traffic management centres can work together to ensure a safer, more efficient, and reliable transportation system.

- **SSEM** (Signal Status and Phase Timing Message) is a C-ITS message that provides drivers with real-time information about traffic signal timings and status. The message is generated by traffic signal controllers and shared with vehicles using the C-ITS technology. The SSEM message can include information about signal timings, such as the time remaining before a red light, as well as signal status, such as whether the signal is malfunctioning or undergoing maintenance. The message is particularly useful for improving the efficiency of the road network, as it helps drivers to anticipate signal changes and adjust their speed, accordingly, reducing the likelihood of accidents and traffic congestion. By sharing SSEM messages with drivers, the C-ITS technology can help to improve the overall driving experience and support the development of smarter and more efficient transportation systems.

The IVIM, MAPEM, SPATEM, SREM and SSEM are defined in ETSI TS 103 301 [11]. For simplicity purposes, considering the teleoperation and platooning use case, only the most relevant C-ITS messages such as CAM, DENM and IVIM are considered in this study.

4 C-V2X IN 3GPP STANDARDIZATION AND USE CASES

C-V2X (both long- and short-range) is a key enabler of connected and automated driving and has been the subject of extensive standardization work by 3GPP. 3GPP is a collaborative standardization organization that brings together telecommunications standards' organizations from around the world. The group's work focuses on the development of standards for cellular networks, including the 5G standard. As part of its work, 3GPP has developed a series of specifications for C-V2X that outline how the technology should work and how it should be deployed. One of the key benefits of C-V2X is its ability to support a wide range of use cases. For example, it can be used for vehicle-to-vehicle communication to enable cooperative driving, teleoperation, and enhanced safety. It can also be used for vehicle-to-infrastructure communication to enable traffic management and improving the efficiency of transportation systems. Additionally, it can be used for vehicle-to-pedestrian communication to improve the safety of vulnerable road users.

To support these use cases, 3GPP has developed a range of specifications for C-V2X that cover everything from the physical layer to the application layer. These specifications define how C-V2X should be implemented, what frequencies it should use, and how it should be integrated with existing cellular networks. One of the key features of C-V2X is its ability to operate in both the 5.9 GHz ITS spectrum (for short range direct) and the cellular spectrum (for long range). This is known as dual-mode operation and allows C-V2X to use short-range PC5 sidelink or long-range via cellular interface, whichever is most appropriate for a given use case. Another important aspect of C-V2X standardization is interoperability. To ensure that C-V2X devices from different manufacturers can communicate with each other, 3GPP has developed a range of test specifications and conformance tests. These tests ensure that devices meet a common set of standards and are capable of interoperating with other C-V2X devices. Overall, the standardization of C-V2X by 3GPP is a key enabler of connected and automated driving. By providing a common set of standards for C-V2X, 3GPP is helping to ensure that the technology can be deployed at scale and that it will work effectively across different networks and devices. As such, it is an important step towards the realization of a safer, more efficient, and more connected transportation system.

3GPP Release 14 introduced C-V2X PC5 technology, which uses LTE (Long Term Evolution) networks for the V2V and V2I communication. The focus of Release 14 was on sidelink communications, which allows direct communication between vehicles without the need for a cellular network. This mode of communication is also known as D2D (Device-to-Device) communication. The release defined two modes of sidelink communication: autonomous and network controlled, as in Figure 3: LTE C-V2X mode 3 and mode 4. [12]. In autonomous mode, devices are responsible for performing all the necessary operations to establish and maintain a sidelink connection, also known as LTE sidelink mode 4. In network-controlled mode, also known as LTE sidelink mode 3, a network entity named SCM (Sidelink Communication Manager) is responsible for managing sidelink resources and establishing sidelink connections between devices.

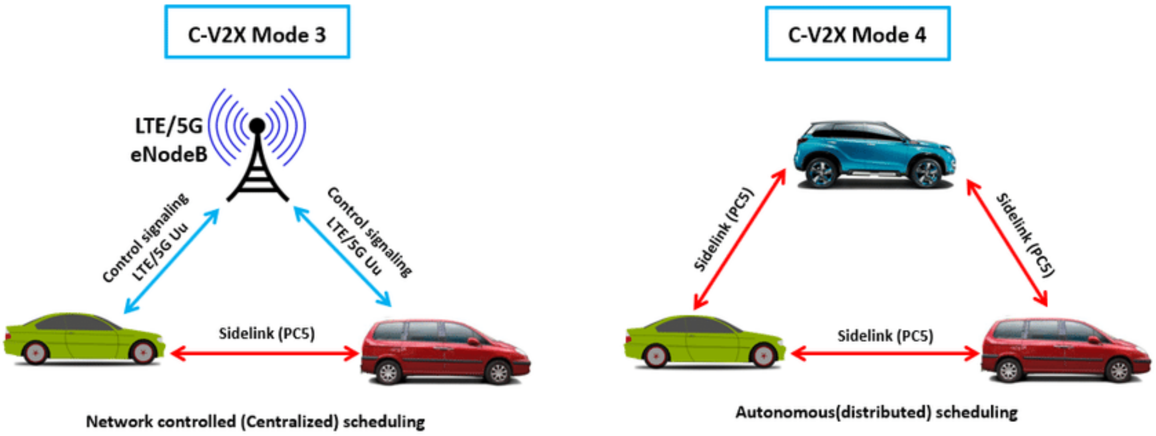


Figure 3: LTE C-V2X mode 3 and mode 4.

Release 16 introduced several enhancements to C-V2X technology. One of the most significant enhancements is the introduction of 5G New NR (New Radio) sidelink, which allows direct communication between vehicles using 5G networks. The release defines two modes of 5G NR sidelink communication: Mode 1 and Mode 2, as shown in Figure 4 [13], which are the counterparts to modes 3 and 4 in LTE V2X. Mode 2 is based on the same principles as in Release 14 autonomous sidelink communication, where devices are responsible for performing all the necessary operations to establish and maintain a sidelink connection. Mode 1, on the other hand, is based on network-controlled sidelink communication, where a network entity, called the 5G NCM (NR Sidelink Communication Manager), is responsible for managing sidelink resources and establishing sidelink connections between devices.

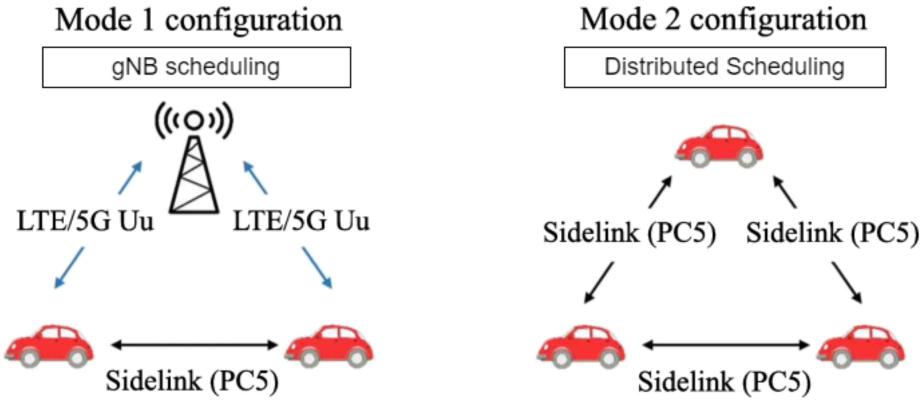
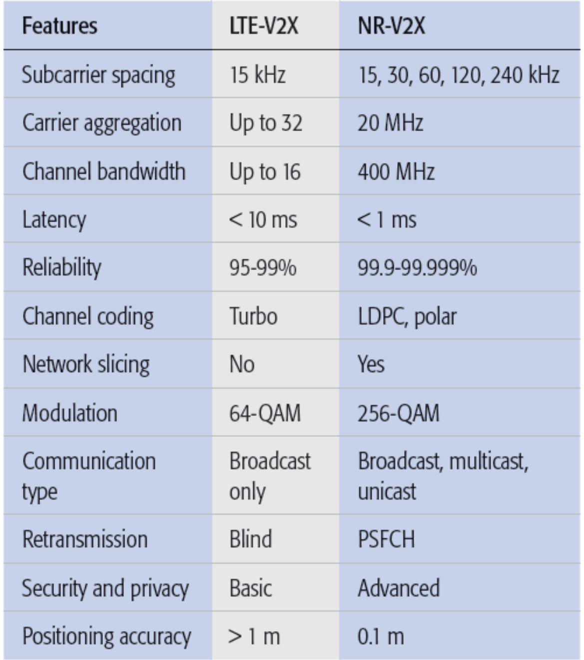


Figure 4: NR C-V2X mode 1 and mode 2.

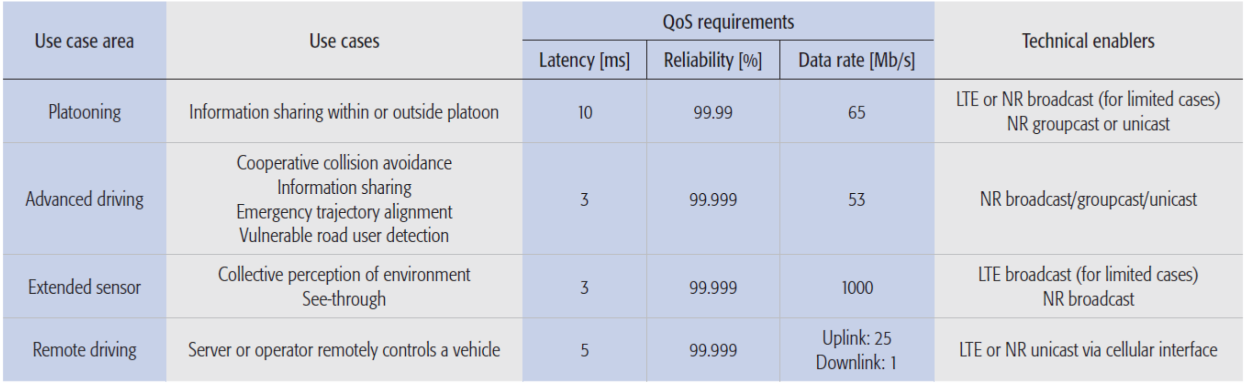
Release 16 also introduced enhancements to the network-controlled mode of sidelink communication defined in Release 14. These enhancements include improved resource allocation mechanisms, better support for multi-hop communication, and the ability to use 5G NR-V2X sidelink as a backup for LTE-V2X sidelink. Release 16 based sidelink also added support of unicast next to the multicast communication, which was missing in release 14 based sidelink. However, Release 16 Sidelink equipment is not yet available in the market. Figure 5 highlights the major differences in features of LTE-V2X sidelink and NR-V2X sidelink [14].



Features	LTE-V2X	NR-V2X
Subcarrier spacing	15 kHz	15, 30, 60, 120, 240 kHz
Carrier aggregation	Up to 32	20 MHz
Channel bandwidth	Up to 16	400 MHz
Latency	< 10 ms	< 1 ms
Reliability	95-99%	99.9-99.999%
Channel coding	Turbo	LDPC, polar
Network slicing	No	Yes
Modulation	64-QAM	256-QAM
Communication type	Broadcast only	Broadcast, multicast, unicast
Retransmission	Blind	PSFCH
Security and privacy	Basic	Advanced
Positioning accuracy	> 1 m	0.1 m

Figure 5: Comparison between LTE-V2X Sidelink and NR-V2X Sidelink [14].

The success of 5G NR, in practical terms, is largely dependent on its ability to meet the demands of specific services and advanced use cases. The main goal of the NR-V2X standard is to support use cases with ultra-high reliability, ultra-low latency, precise positioning, and high throughput requirements that may not be achievable by LTE-V2X. For this, both short-range direct and long-range NR-V2X can be used depending on the use case. NR-V2X is not designed to replace LTE-V2X services but rather to complement them with advanced services. While LTE-V2X is focused on basic safety services, NR-V2X can be used for advanced safety services and cooperative and connected autonomous driving. Figure 6 shows the QoS requirements (end-to-end latency, reliability, data rate) and technical enablers for various NR-V2X use cases [15], whereas the end-to-end latency and reliability requirements for advanced NR-V2X use cases have been highlighted in Figure 7 [14]. For this study, only broadcast (one-to-all) communication is considered which means that a V2X node can send a message to all other V2X nodes in the vicinity.



Use case area	Use cases	QoS requirements			Technical enablers
		Latency [ms]	Reliability [%]	Data rate [Mb/s]	
Platooning	Information sharing within or outside platoon	10	99.99	65	LTE or NR broadcast (for limited cases) NR groupcast or unicast
Advanced driving	Cooperative collision avoidance Information sharing Emergency trajectory alignment Vulnerable road user detection	3	99.999	53	NR broadcast/groupcast/unicast
Extended sensor	Collective perception of environment See-through	3	99.999	1000	LTE broadcast (for limited cases) NR broadcast
Remote driving	Server or operator remotely controls a vehicle	5	99.999	Uplink: 25 Downlink: 1	LTE or NR unicast via cellular interface

Figure 6: Requirements and the potential technologies for the V2X use cases considered in 3GPP [15].

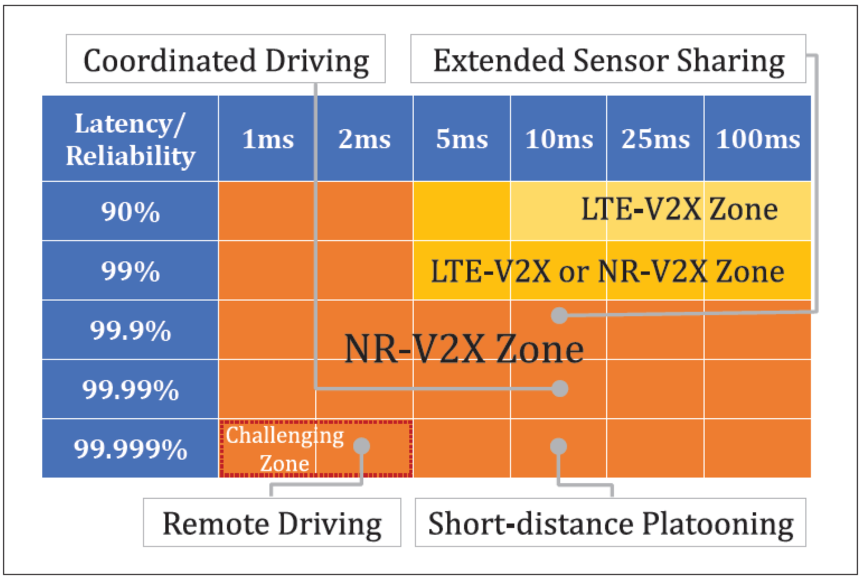


Figure 7: End-to-end latency and reliability requirements for advanced NR-V2X use cases [14].

It can be observed from Figure 7 that remote driving is the most challenging use case with 99.999% reliability requirement and that too with less than five milliseconds latency constraint. Such a stringent requirement calls for intelligent decision making at the C-ITS node itself. The following use cases are among the target services that may be supported by NR-V2X:

- **Vehicle platooning** refers to a group of vehicles traveling together in the same direction and at short inter-vehicle distances. To dynamically form and maintain platoon operations, all vehicles need to receive periodic data, such as direction, speed, and intentions, from the leading vehicle.

- **Trajectory sharing and coordinated driving** is a use case that involves sharing the trajectory and intention of each vehicle to enable fast but safe manoeuvres. The planned movements of surrounding vehicles are known, and the exchange of intention and sensor data ensures more predictable and coordinated autonomous driving.

- **Extended sensor sharing** enables the exchange of raw or processed data collected through local sensors or live video images among vehicles, roadside units, devices of pedestrians, and V2X application servers. The vehicles can increase their perception of their environment beyond what their own sensors can detect and have a broader and more holistic view of the local situation.

- **Remote driving** involves a remote driver, or a cloud based V2X application taking control of the vehicle. This use case is particularly useful in scenarios where driving vehicles in dangerous environments, public transportation, logistics, or incapacitated persons are involved.

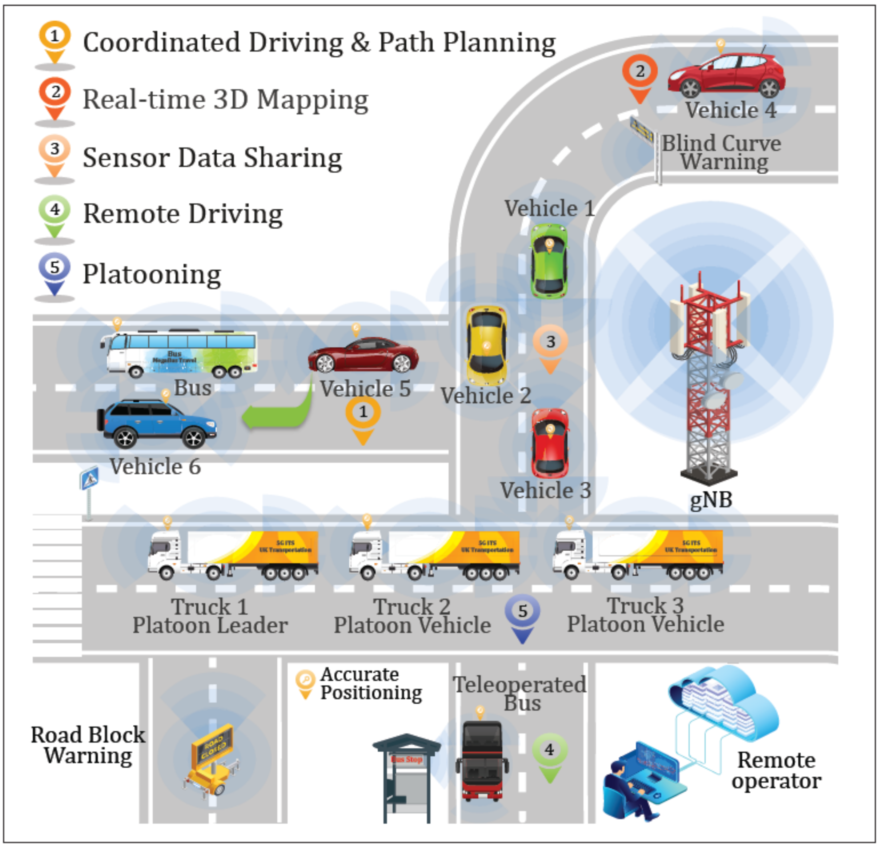


Figure 8: Advanced use cases and services of NR-V2X [14].

Different advanced NR-V2X use cases can be observed in a real road environment in Figure 8 [14]. All these use case requirements are expected to be fulfilled with 5G (and beyond) C-V2X communications. In summary, NR-V2X is designed to complement LTE-V2X services with advanced use cases that require ultra-high reliability, ultra-low latency, precise positioning, and high throughput requirements While both 3GPP Release 14 and Release 16 focus on C-V2X technology, Release 16 introduces several significant enhancements, including the introduction of 5G NR sidelink communication. These enhancements improve the reliability and efficiency of C-V2X communication and pave the way for the deployment of advanced V2X services, such as teleoperation and platooning i.e., the main use cases considered in the 5G-Blueprint Project.

5 HIGH THROUGHPUT DATA CONNECTIONS

To ensure a secure and safe experience while remotely operating a vehicle using a mobile connection, it is essential to have an exceptionally fast and low-latency connection between the vehicle and the driver. Additionally, the connection should possess high throughput capabilities to facilitate smooth and responsive communication between the two. Having a high-capacity connection is crucial for transmitting both control signals and the video stream(s) captured by the vehicle's camera system, which the driver views on their screen. It is essential to achieve a high-resolution transmission without noticeable delays or excessive packet loss. To accomplish this, a substantial bandwidth is of utmost importance. The data to be shared from the vehicle to the teleoperator is not limited to the video streams, but also other vehicle sensor data like LiDAR (Light Detection and Ranging) or RADAR (Radio Detection and Ranging). The sensors present in future automated vehicles are already producing gigabytes of data per second. To enable these vehicles to be more connected and cooperative, it is crucial for 5G or even upcoming 6G networks to offer ample bandwidth. This is necessary to accommodate the increased data requirements and ensure seamless communication among the vehicles. This is specifically important for use cases such as teleoperation and platooning because the safe manoeuvring of the whole platoon and remote driving depends on the reliable high throughput connections. As in Figure 9, remote driver is usually connected with the core network using a high bandwidth wired link (usually a fibre optic cable), whereas the teleoperated vehicle is connected with the serving 5G base station using the long-range high throughput Uu link.

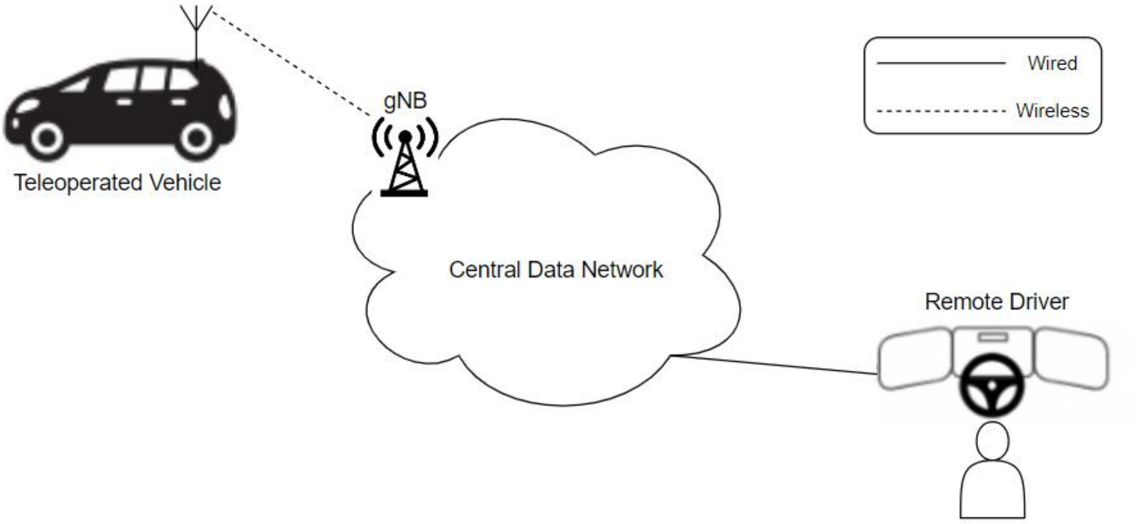


Figure 9: Teleoperation scenario with one vehicle and one remote station.

The proposed algorithm in this study switches between short-range and long-range C-V2X for broadcasting basic C-ITS messages, in short, the low throughput connections. Considering their purpose in the intelligent transport systems, these messages are always broadcasted, and they facilitate in cooperative driving. Contrary to it, the flow-based high throughput connection for remote driving is always a unicast link with a dedicated IP (Internet Protocol) address. To strengthen the teleoperation link, having standardized SLAs (Service Level Agreements) with the respective network providers would be required, which can accelerate the shift towards remote driving.

6 C-ITS LONG-RANGE MESSAGE EXCHANGE VIA UU USING GEOCASTING

Contrary to the direct short-range message exchange between V2X nodes, long-range message exchange requires additional mechanisms and configurations. A broker-centric architecture for cellular-based V2X communication with dedicated C-ITS servers on the internet is presented in [16] which is open and scalable. MQTT (Message Queueing Telemetry Transport) is a messaging transport protocol based on a Client-Server model with a publish/subscribe pattern. It is known for its lightweight, open, and easy-to-implement design, making it suitable for various scenarios, including long-range C-ITS message exchange via Uu using geocasting in V2X communications. This allows V2X nodes to only receive messages that are of interest for them. MQTT protocol operates over TCP/IP or other reliable network protocols, ensuring ordered, lossless, and bi-directional connections. Overall, MQTT's versatile features make it a reliable and efficient choice for various communication needs, especially in resource-constrained environments where efficiency is paramount. The content of MQTT messages adheres to SAE standards [17]. These standards define various message types, including but not limited to CAM, DENM, IVIM, MAP, and SPaT, depending on the specific service being provided. Similarly, an AMQP-based alternative broker-centric architecture called the Interchange has been developed in the NordicWay project [27], and later on adopted in the C-Roads specifications on hybrid C-ITS [28], and in the 5GAA V2X Application Layer Reference Architecture [29].

The design of the geocasting solution relies heavily on the topic structure within the central broker. Intrinsic geocasting occurs when information is broadcasted through short-range wireless communication, typically within a reception range of 300 to 1000 meters, depending on local conditions. However, when utilizing internet-based communication via cellular networks, a specific geocasting solution is necessary to maintain scalability. If a system were to incorporate data from all major European cities and broadcast all SPaT messages, as is the case with short-range communication, the resulting data stream would become unmanageably large. Geocasting aims to ensure that only messages relevant to the receiver's location are forwarded.

There are several solutions for geocasting. A tiling concept, as introduced in [18], is one of the geocasting solution where there is no requirement for users to transmit CAM data along with their location. In this approach, a vehicle registers once without relying on CAM data and receives the boundaries of its current map-tile. When the vehicle exits the tile, it contacts the server again to obtain new coordinates. Despite the possibility of a broker attempting to track an end-user, this task becomes nearly impossible due to the use of pseudonyms. Pseudonyms are smartly changed every time a new tile is requested, ensuring a high level of user privacy, especially in a system with numerous users. Another advantage of not utilizing CAM data is the avoidance of additional user-identifying information such as vehicle dimensions. Users automatically receive only the relevant data pertaining to their specific tile. Moreover, this solution exhibits excellent computational scalability, as the broker simply needs to consult the list of subscribed clients when forwarding a message, reaching them individually. As the internet supports unicast messages only, a cellular-based solution would require more communication bandwidth compared to short-range communication. However, this drawback can be minimized through efficient tile planning. No complex geographic calculations are needed for each message. For data sources with a fixed dissemination area like MAP data, a simple table can be used to determine to which tiles they should publish. The primary limitation is that the dissemination is confined to a combination of square tiles, which may result in a slightly larger dissemination area than initially intended.

In the context of pan-European C-ITS applications, the tile system's efficiency is taken to the next level in the standard. Instead of exchanging the coordinates of tile edges between the vehicle and the broker, the vehicle acquires its own location using the Google XYZ standard [19]. This location serves as the basis for the vehicle's requests to the broker, enabling any system to determine the relevant geographic tiles for its current position. Figure 10 illustrates this concept, depicting the level 1 tiles on the left, where the world is divided into four squares at the first level. At level 2, each level 1 tile is further divided into four squares. On the right side of the figure, level 18 tiles are displayed. Due to the Mercator projection used for the map, the tile size varies with latitude. Tiles become smaller as you move closer to the poles. In the case of ITS applications, level 18 strikes a good balance, providing sufficient granularity to avoid receiving irrelevant messages while minimizing the frequency of tile subscription updates. This results in a quadtree structure, where a tile is repeatedly divided into four equal parts, with the smallest tile size being 65m in Oulu, located in northern Finland at 65 degrees latitude. At the equator, the tile size is 154m.

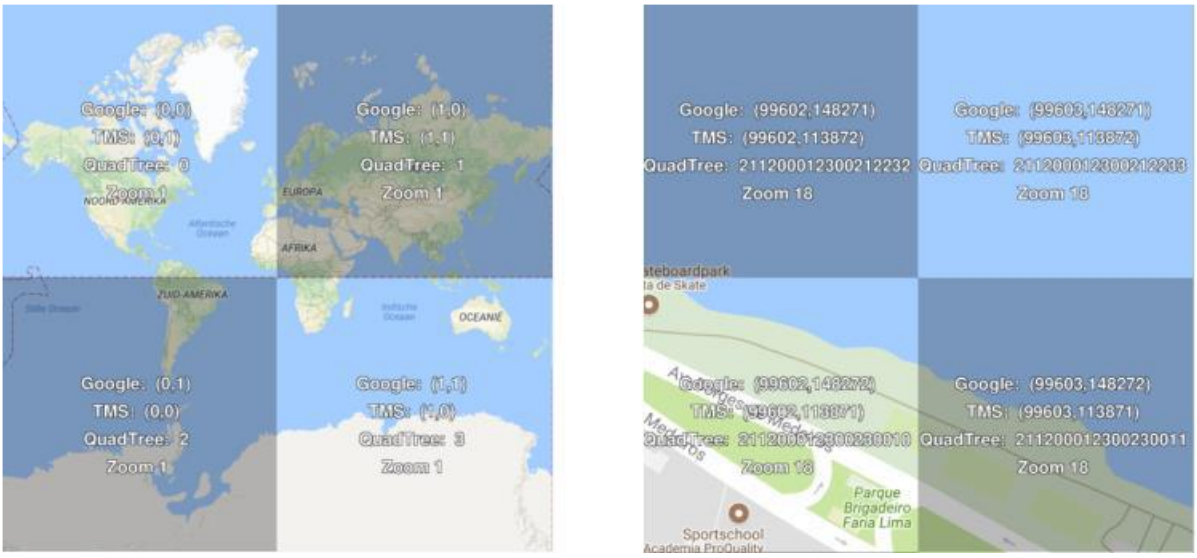


Figure 10: Tiling concept, with zoom level 1 example on the left and zoom level 18 on the right. Image acquired using [19].

7 AN INTELLIGENT HYBRID C-V2X ALGORITHM

In this section, an intelligent hybrid 5G C-V2X technology selection algorithm is presented for transmission of CAM, DENM & IVIM. For this, a decision tree has been generated to facilitate the intelligent technology selection based on a set of inputs as further described is this section. The proposed algorithm assumes that all V2X nodes support C-ITS services and transmit periodic CAM messages. These assumptions ensure real time statistics-driven decision making on all V2X nodes. It is important to mention that short-range will only be considered for low throughput data transfer of certain C-ITS messages. In contrary, the high throughput connections like infotainment and remote driving using video streaming use long-range Uu link, as described in Section 5. The inputs that every C-ITS node considers before selecting a specific technology for any C-ITS message transmission are summarized below in Table 1: Inputs considered for Intelligent hybrid C-V2X algorithm.

Algorithm Input	Possible options
Type of C-ITS node	Vehicle, RSU, VRU, Network
C-ITS message to send	CAM, DENM, IVIM
CAM reception status	Yes, no
CAM reception technology	PC5, Uu, or both
Average E2E latency of CAM receptions via PC5	Averaged over a 10 second sliding window
Average E2E latency of CAM receptions via Uu	Averaged over a 10 second sliding window
Distance of CAM receptions via Uu	95th percentile value over a 10 second sliding window
Vehicle speed	>100 Km/h or <=100 Km/h
Dense network traffic (received > 1000 CAMs/s)	Dense, not dense

Table 1: Inputs considered for Intelligent hybrid C-V2X algorithm.

The proposed algorithm first checks the type of C-ITS node, on which V2X wireless communication technology selection decision is to be taken. Then, the type of C-ITS message (CAM, DENM, IVIM etc.) to be transmitted is determined. The complete decision tree is broken down into smaller parts for better visualization and clear understanding. Numbered tags at the end of Figure 11 are used to identify the respective decision tree branches. The numbered tag 1 branch is explained in detail in this Section, whereas, on the similar lines, tag 2 and tag 3 branches are shown in Appendix A.

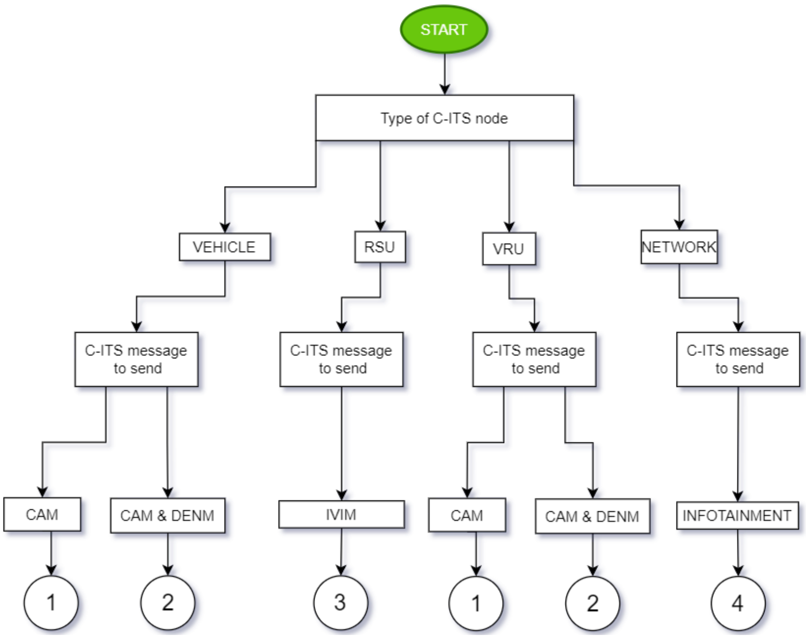


Figure 11: Decision tree for intelligent hybrid C-V2X communications (part 1).

Initially, the decision tree for transmitting CAM transmission is presented (tag 1), as in Figure *12*. Firstly, it is checked if CAM(s) from other V2X stations are being received on the C-ITS node or not. If no CAMs are received, statistics-driven decision cannot be made. In this scenario, CAMs are sent via both PC5 and Uu links in an attempt to maximize the chances of CAM reception in the vicinity of the V2X node by one of the technologies, or both, in the absence of statistics-driven decision making. If CAMs are received, it is checked if receptions are from both, PC5 and Uu. After this check, the two different branches of the decision tree are followed, as further explained.

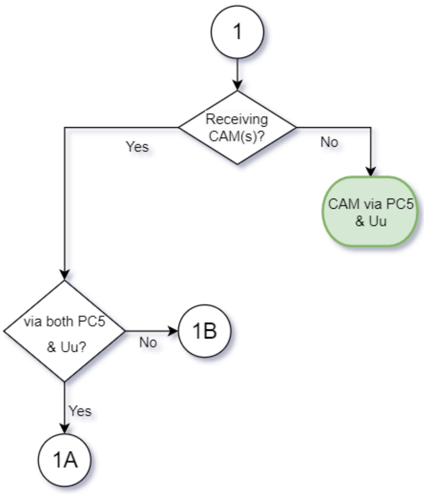


Figure 12: Decision tree for intelligent hybrid C-V2X communications (part 2).

If CAMs are received via both PC5 and Uu (tag 1A) as in Figure 13: Decision tree for intelligent hybrid C-V2X communications (part 3), average one-way end-to-end latencies of CAMs received via PC5, and Uu are calculated over a 10 second sliding window. For this to be accurate, synchronized clocks are needed between all the C-ITS nodes e.g., using GPS synchronization. Here, via a geocasting mechanism, it is made sure that messages received via Uu are filtered and only the relevant ones are used for the algorithm. The 95th percentile of the distance for CAMs received via Uu is also calculated by using the GPS coordinates included in the CAM messages. If the 95th percentile of the distance comes out to be less than 300 meters and both latency values are below 20 milliseconds, it means that still both PC5 and Uu are contender technologies for next scheduled CAM transmission. These values are derived based on studies [20], [21] of typical ranges and latencies. At this stage, if the C-ITS node is a vehicle, speed of the vehicle at that point in time is considered. If the vehicle speed is below 100 Km/h and the 95th percentile of the speed of other vehicles in the vicinity is also below 100 Km/h, it means that traffic dynamics do not change a lot, meaning that it is not necessary to enforce CAM transmission via Uu during the next technology selection decision. 100 Km/h check in Figure 13 will be true if either the vehicle speed itself is more than 100 Km/h or the 95th percentile of the speed of other vehicles is more than 100 Km/h, or both. A check has been placed on the network traffic density (received CAMs > 10000 in the sensing window) to adapt the algorithm with real-time scenario. If the network traffic is not dense, PC5 is selected for CAM transmission during the next technology selection decision. How frequent to make the technology selection decision is dependent on the traffic dynamics. For example, in an almost stationary situation like a traffic jam, the technology selection decision frequency can be reduced because traffic dynamics are highly likely to remain the same. Contrary to it, if the average vehicle speed is above a certain threshold, implying rapidly varying traffic dynamics, the technology selection decision frequency can be increased. If the network traffic is dense, the frequency of CAM transmissions is reduced (while satisfying the minimum and maximum frequency bounds based on ETSI standard i.e., 1 Hz to 10 Hz) and again PC5 is selected for CAM transmission during the next technology selection decision. If the speed of the vehicle is above 100 km/h or the 95th percentile of the speed of other vehicles in the vicinity is above 100 Km/h, or both, then the network traffic density is still considered but CAM is transmitted via both PC5 and Uu after the next technology selection decision, because the traffic dynamics might have changed a lot and transmissions made via PC5 might fail to reach all the road users in the vicinity.

If the 95th percentile of the distance of CAMs received via Uu is less than 300 meters but both latency values are greater than 20 milliseconds, it means that both the technologies are still the contenders for the next scheduled CAM transmission, but both channels are experiencing additional delays. In this scenario, CAM is transmitted via both PC5 and Uu but with a minimum CAM frequency to avoid further deteriorating the channels. If Uu distance (again 95th percentile) and latency is less than 300 meters and 20 milliseconds, respectively, but the latency for PC5 is greater than 20 milliseconds, next CAM is transmitted via Uu only to not further deteriorate the PC5 channel with unnecessary transmissions. Contrary to it, if latency via PC5 is less than 20 milliseconds but Uu latency is greater than 20 milliseconds, CAM is transmitted via PC5 after the next technology selection decision but with an additional check on traffic density so that CAM frequency can be modified, if needed. At last, irrespective of the latency values, if the 95th percentile of the distance of CAMs received via Uu is above 300 meters, only Uu is used for the next CAM transmission to reach all the relevant V2X nodes in the vicinity.

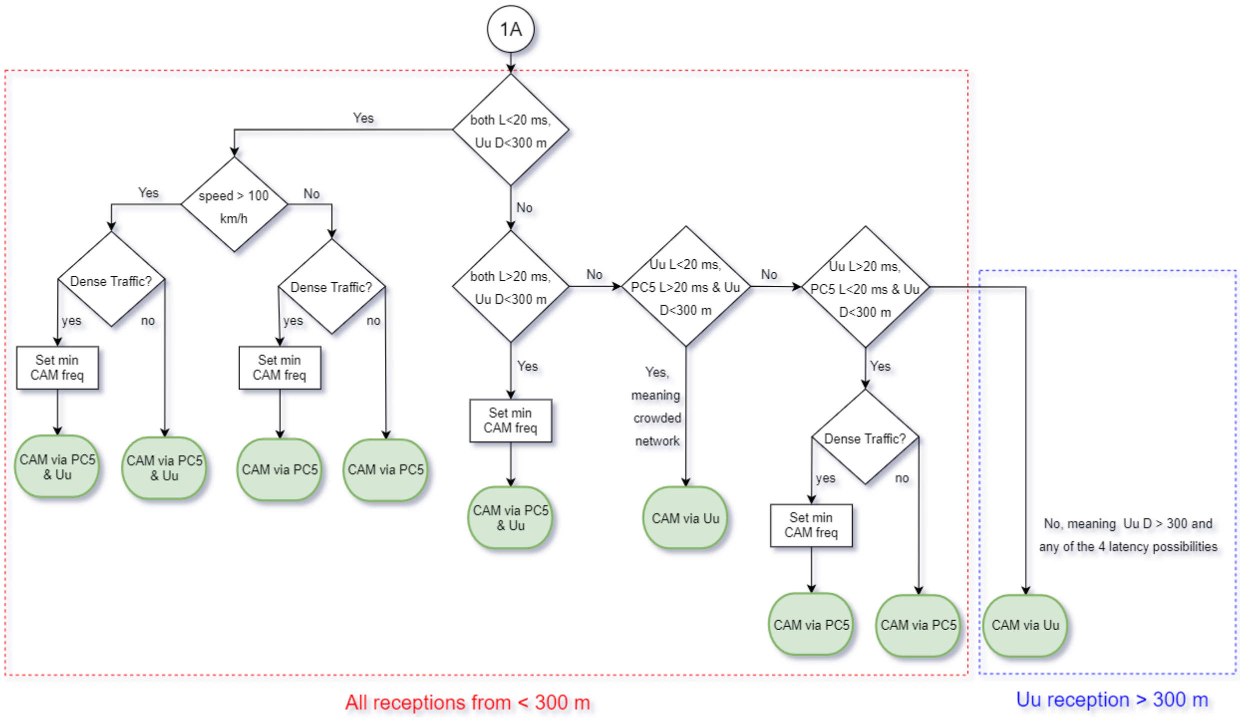


Figure 13: Decision tree for intelligent hybrid C-V2X communications (part 3).

Figure 14: Decision tree for intelligent hybrid C-V2X communications (part 4) shows the part of decision tree where CAMs are received only via PC5 or Uu (tag 1B). If CAM receptions are only via PC5, PC5 latency is checked. If it suffices the 20 milliseconds check, CAMs are scheduled via PC5 only but with an additional check on network traffic density, so that the CAM frequency can be modified to minimum if network traffic is dense. On the other hand, if the PC5 latency does not suffices the 20 milliseconds latency check, the CAM is transmitted via both PC5 and Uu after the next technology selection decision, and with the minimum CAM frequency. If CAM are received only via Uu, a check is placed on distance and the CAM is transmitted via Uu if the 95th percentile of the distance is greater than 300 meters. If not, it is checked if the latency of CAM receptions via Uu is less than 20 milliseconds or not. If yes, the CAM is sent via Uu only, after the next technology selection decision. If not, a further check is made on the network traffic density. If the traffic is not dense, the CAM is sent via both PC5 and Uu. Otherwise, if the traffic is dense, the CAM is sent via Uu only using minimum CAM frequency.

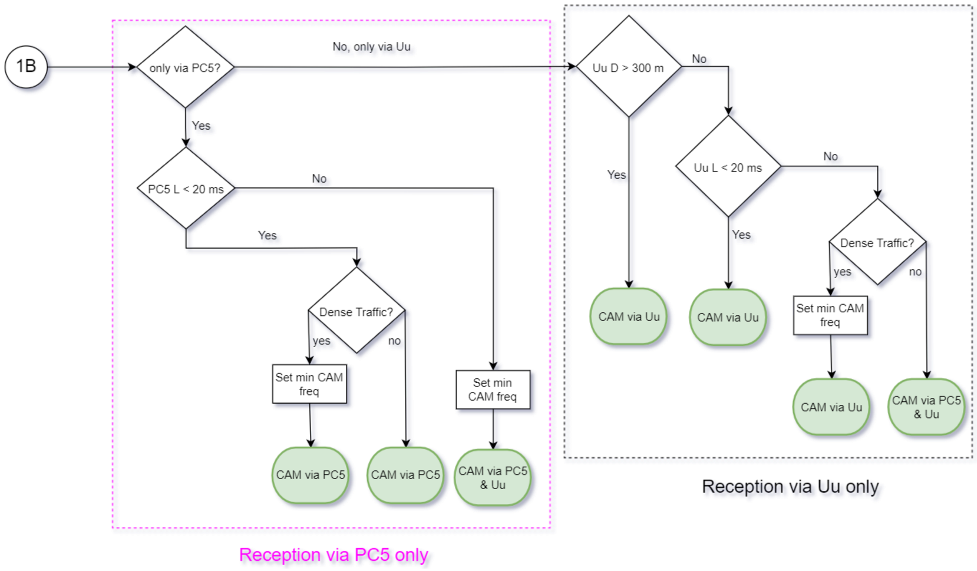


Figure 14: Decision tree for intelligent hybrid C-V2X communications (part 4).

Infotainment (numbered tag 4) is always sent over the long-range Uu link. Furthermore, video or other streaming data such as Lidar data that are very crucial for teleoperation use case are also sent via long-range Uu link.

This concludes the intelligent decision mechanism for selection of a short-range (PC5) or long-range (Uu) or both technologies when CAM messages are transmitted. In a similar way, in a scenario, where both CAM and DENM messages need to be transmitted (numbered tag 2), availability of different technologies can be helpful in making an informed decision. As the statistics for decision making are only calculated from the received CAMs (not DENM, IVIM or any other C-ITS message), all the checks and conditions remain the same. Only the final decision on transmitting CAM via PC5/Uu and DENM via PC5/Uu changes. More information is shown in appendix A. Also, for IVIM, generally the decision tree is the same except from the fact that the roadside units are stationary so a check on their speed is not required. However, a check is placed on the speeds of the other vehicles in the vicinity. If the 95th percentile of the speed of nearby vehicles on the road is above 100 Km/h, long-range Uu is also selected during the next technology selection decision for IVIM. For clarity purposes, the complete decision tree for the case of IVIM transmission is also shown in appendix A.

8 IMEC V2X TESTBED

In this section, the two state of the art IMEC V2X testbeds are discussed. The first one is a real-life Smart Highway testbed [22] that is developed by IMEC at key highway locations in Flanders (on the E313 highway near Antwerp) and it serves as a state-of-the-art C-ITS testing platform. The second one is a small-scale lab V2X test setup that is built specifically for the purposes of this study to test the intelligent V2X wireless vehicular communication technology selection algorithm. Some of the key details of the two testbeds are presented in the following subsections.

8.1 Smart Highway Testbed

To assess the performance of different C-V2X technologies, including short-range C-V2X PC5 mode 4, IEEE 802.11p based ITS-G5 and long-range 4G C-V2X Uu, the Smart Highway testbed can be utilized. Specifically focusing on C-V2X PC5, only mode 4 can be considered since mode 3 equipment is not yet available in the market. It comprises eight RSUs (Road-Side Units) equipped with MEC (Multi-Access Edge Computing) capabilities and two OBUs (On-Board Units) that can be integrated into vehicles. Seven RSUs are strategically placed along the E313 highway, as illustrated in Figure 15, while one is set up in a controlled lab environment for safe testing of implemented services and tools before deployment on the highway.

Figure 15: Locations of the RSUs deployed along the E313 highway.

The Smart Highway testbed offers a unique opportunity for comprehensive experimental analysis, enabling the exploration of both existing and future technologies using COTS (Commercial Off the Shelf) and SDR (Software Defined Radio) equipment. It provides an ideal environment for research and experimentation, accommodating various V2X technologies with different ranges. Researchers and experimenters can leverage real hardware in non-deterministic conditions, encompassing factors such as varying vehicle speeds, dynamic vehicle types, weather conditions, and traffic densities. Figure 16 depicts the roadside infrastructure and the vehicle which serves as OBU. These RSU and OBU nodes are used for evaluating V2X wireless communication technologies, allowing us to do comparative analysis.

Figure 16: Vehicle and roadside infrastructure at the highway.

8.1.1 V2X on board Units

To facilitate communication between vehicles, roadside infrastructure, and cloud services, the Smart Highway utilizes OBUs that can be mounted on vehicles. The OBU architecture is divided into two separate units. The first unit is installed inside the vehicle and includes the processing component for Lidar (such as the Nvidia Jetson computer board), the power system, and modules for in-vehicle sensor processing, such as CAN processing. The second unit is mounted on the vehicle's roof and is connected to the in-vehicle OBU through Ethernet and power connections. The roof unit comprises all the necessary hardware for V2X communication, V2X processing, SDR equipment, and a GNSS (Global Navigation Satellite System) device. The communication modules' antennas are also positioned on the vehicle's roof. An overview of the OBU architecture is depicted in Figure 17.

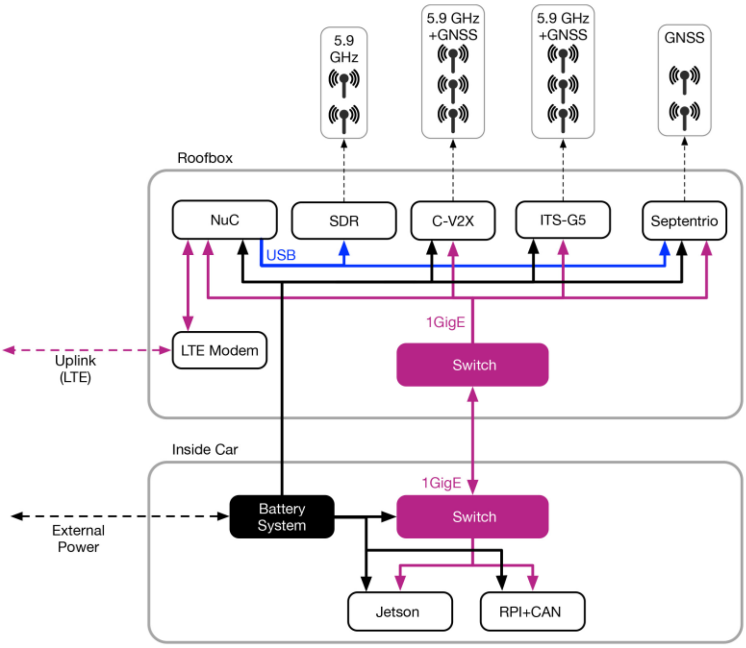


Figure 17: Overview of the OBU architecture.

8.1.2 Roadside Infrastructure

The equipment deployed alongside the road to support C-ITS services and enable connected, cooperative, and autonomous functionalities is referred to as the roadside ITS subsystem, commonly known as RSU (Road-Side Unit). RSUs facilitate the exchange of data messages between vehicles and infrastructure using both short- and long-range communication technologies. They can also act as routers, forwarding data between vehicles (V2I2V), RSUs, or the central ITS subsystem (V2N/N2V) via various backhauling technologies, such as optical fibre or wireless connections. RSUs may incorporate different types of sensors, such as cameras, Lidar, traffic lights, and environmental sensors (e.g., fog sensors), which can be seamlessly integrated into the C-ITS system. Each RSU within the Smart Highway testbed comprises V2X wireless communication modules, processing hardware for local computations, a GNSS device, and SDR equipment. Furthermore, it includes modules necessary for conducting experiments on the RSU and enabling remote management and recovery. An overview of the RSU architecture is illustrated in Figure 18.

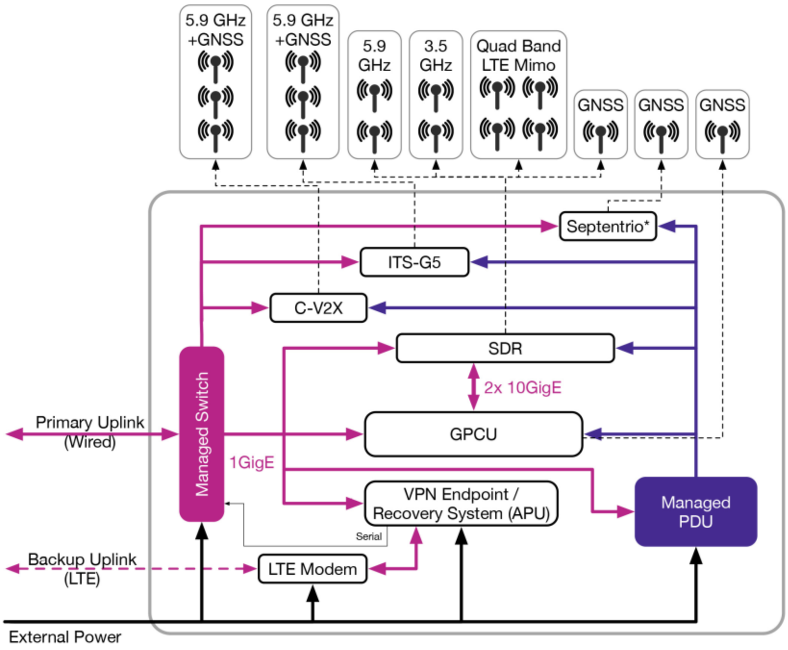


Figure 18: Overview of the RSU architecture.

The CAMINO framework serves as the central system for managing V2X communication technologies and services in the Smart Highway testbed. It can integrate with both current and future short and long-range V2X technologies such as ITS-G5, C-V2X PC5, and C-V2X Uu (5G/4G), as well as vehicle or roadside infrastructure sensors, actuators, HMIs, and third-party service providers. CAMINO supports standardized C-ITS services that can be triggered dynamically and can also be extended in a modular way to accommodate future or customized C-ITS services. The framework, as in Figure 19 allows for flexible message transmission via one or multiple V2X technologies, increasing transmission capacity and reliability. It is compatible with various ITS devices and offers logging capabilities for evaluating performance. The CAMINO-Core, which is the framework's heart, manages data flows between northbound and southbound interfaces, integrates with different V2X wireless technologies through transceiver classes, and interconnects with sensors, actuators, third-party services, and HMIs through the DUST (Distributed Uniform Streaming) open-source framework [23]. The CAMINO-Core also manages the facility layer of the ITS stack, supports several C-ITS standardized and custom services, and provides logging services.

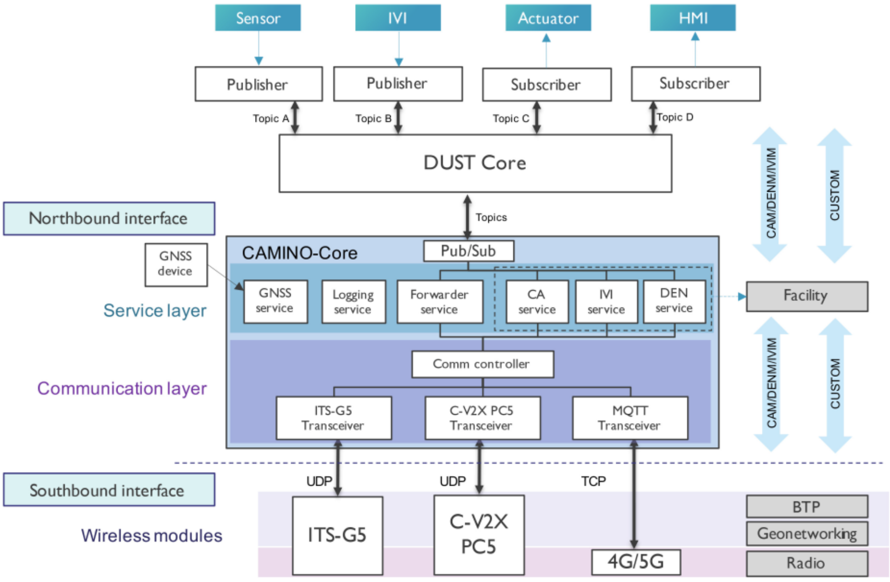


Figure 19: Overall CAMINO framework architecture.

8.2 Lab V2X test Setup

This is a lab built small-scale V2X test setup that is created in the scope of this task aiming to study the hybrid C-V2X communications and to allow us to perform various tests as described in the next proof-of-concept section. Under the scope of this study, only C-V2X PC5 and NR Uu capabilities have been integrated as depicted in the network diagram in Figure 20.

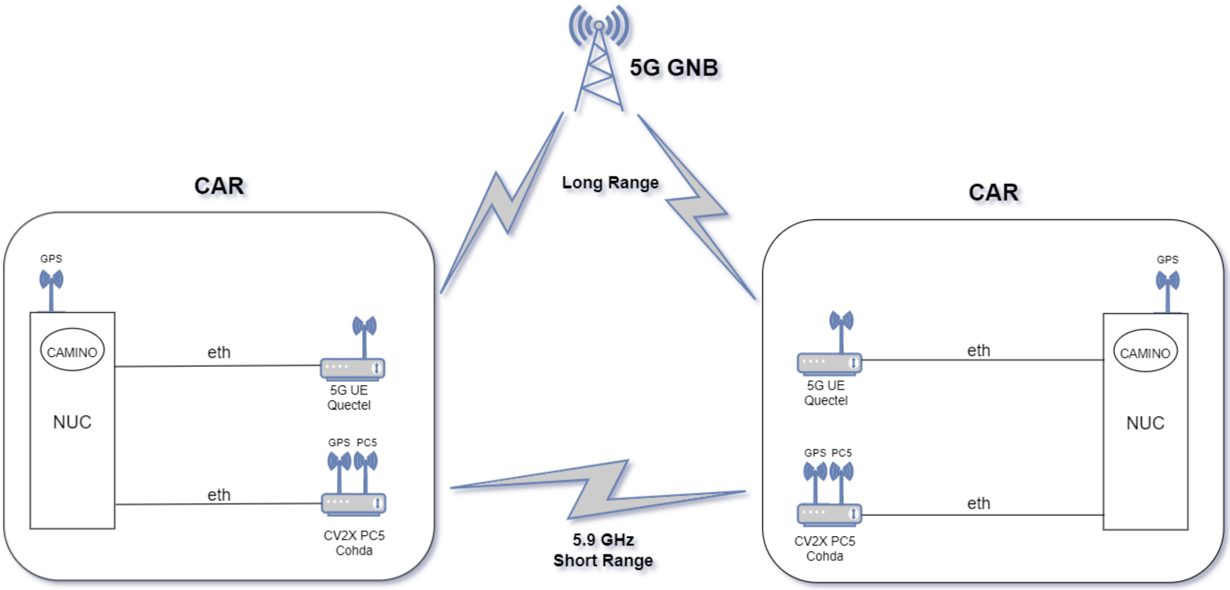


Figure 20: IDLab's V2X test setup.

This setup, as shown in Figure 21, consists of two V2X nodes, both having Intel NUCs as the main processing using. The CAMINO framework is setup on top of them for managing the different V2X communication technologies and the services running on top of them. The NUCs are connected via ethernet cable with the Cohda's MK6C C-V2X PC5 modules. The Cohda MK6c modules and NUCs both have GPS receivers for precise positioning information. Two 5G Quectel UEs are connected to the NUCs via USB cables, and both of them connect using the Uu link with the 5G portable unit as shown in Figure 22. A MQTT server located in IMEC Ghent premises is used for the long-range C-ITS message exchange between V2X nodes.

Figure 21: The two nodes of IDLab's V2X test setup.

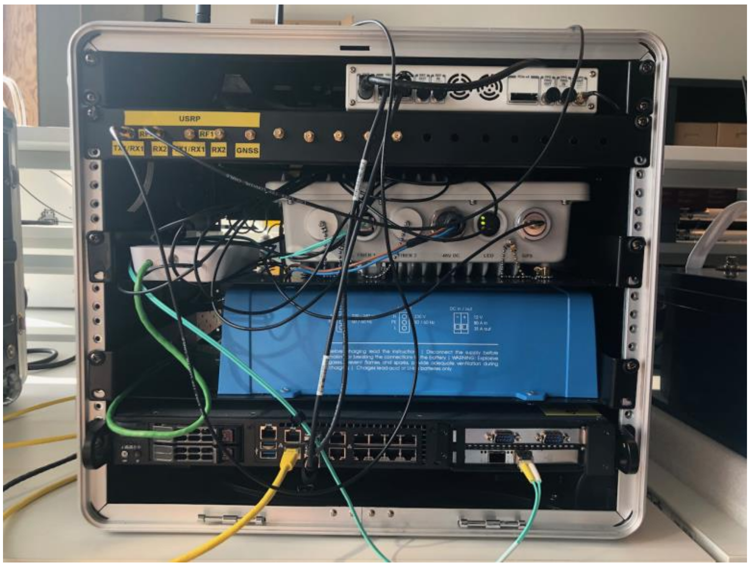


Figure 22: 5G portable unit.

9 HYBRID C-V2X PROOF-OF-CONCEPT AND RESULTS

The proposed intelligent hybrid C-V2X algorithm has been evaluated on top of the lab V2X test setup. The lab V2X setup offers 5G Standalone (SA) NR capabilities compared to the Smart Highway testbed, which currently only supports LTE. The code of CAMINO has been modified, so that decision making parameters of the proposed algorithm are calculated, such as one-way end-to-end latency and distance between V2X nodes, exploiting information contained inside the received CAMs. For every C-ITS message transmission, a decision is made to use PC5, Uu or both for sending the next C-ITS message. The one-way end-to-end latency of CAM receptions via both PC5 and Uu are calculated and averaged over a moving window of 10 seconds. Also, the distance between V2X nodes is calculated and averaged for CAM receptions via Uu. These values are communicated before every CAM message transmission from the logging service to the CA service, the two services inside the Service layer of CAMINO-Core, as in Figure 19, where PC5, Uu or both technologies are selected for sending the next CAM message. Similarly, for sending DENM or IVIM, the statistics are communicated to the DEN service or IVI service, respectively. These values are fed into the decision tree which intelligently selects a particular or both technologies.

The nodes in our lab V2X setup are installed at fixed locations during the experimentation, however, to realize a real-life scenario and to test the proposed intelligent hybrid C-V2X solution, gpsfake [24], a test harness for gpsd and its clients is used. An online tool [25] is used to generate NMEA file containing GPS points on the map. Among the two nodes in our lab V2X setup, one of them uses gpsfake, whilethe other one relies on the actual GPS information. The latitude and longitude values for the gpsfake tool are chosen in the vicinity of IMEC building, located at the Technology park at the city of Ghent, as shown in Figure 23.

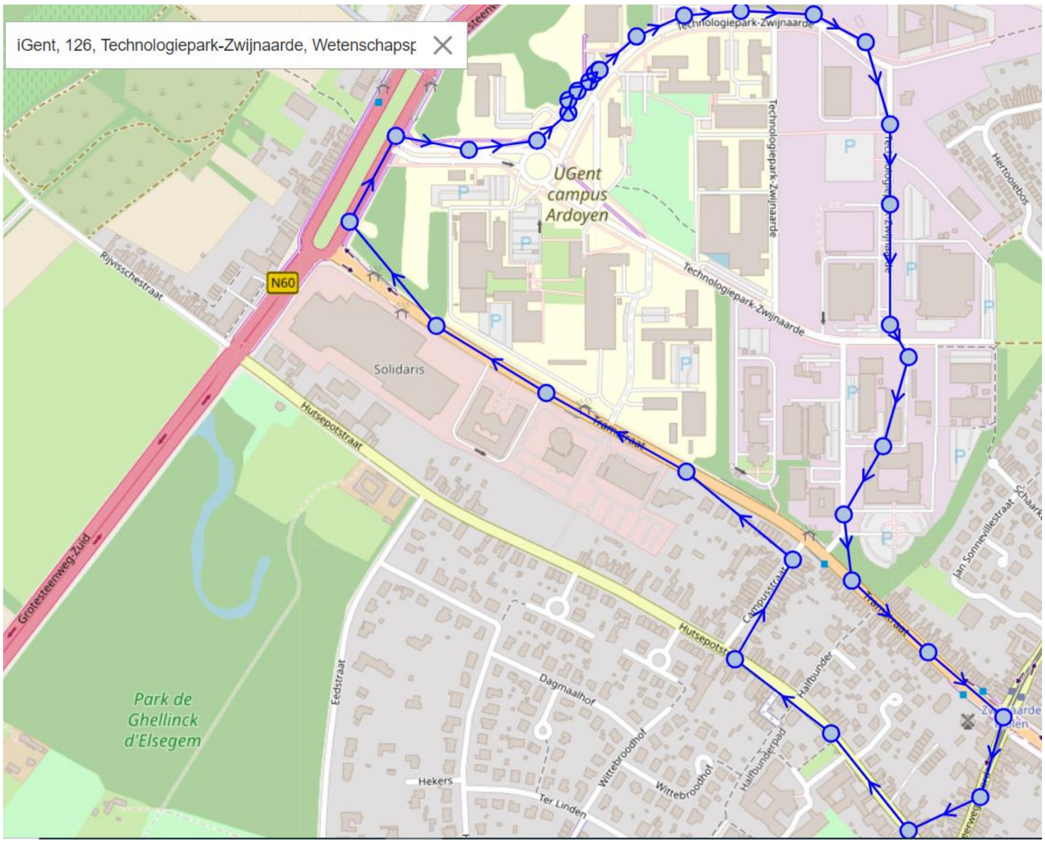


Figure 23: gpsfake points and trajectory using the nmeagen tool [25].

In Figure 24, the one-way end-to-end latency values are plotted for the CAMs received via PC5 and Uu links with red and blue colours, respectively. CAMs are received from both technologies every second. It can be observed that a particular technology does not perform better than the other all the time, hence proving experimentally that a static technology for V2X communication is inefficient. Also, within the chosen decision threshold of 20 ms, as motivated in Section 7, the long-range Uu link outperforms the short-range PC5 link for approximately 10 percent of the time. The selected C-V2X technology for sending the next C-ITS message based on the decision tree output is also plotted at the bottom of Figure 24. It can be observed C-V2X technology selection decision is relatively simpler if CAM receptions via both, PC5 and Uu, report latencies above 20 ms. In this case, C-ITS messages are sent via both technologies. However, if one or both technologies report latency values less than the chosen threshold of 20 ms, PC5 and Uu latency values are compared, and the technology selection decision is made. For this experiment, the distance between the two V2X nodes is always less than 300 meters.

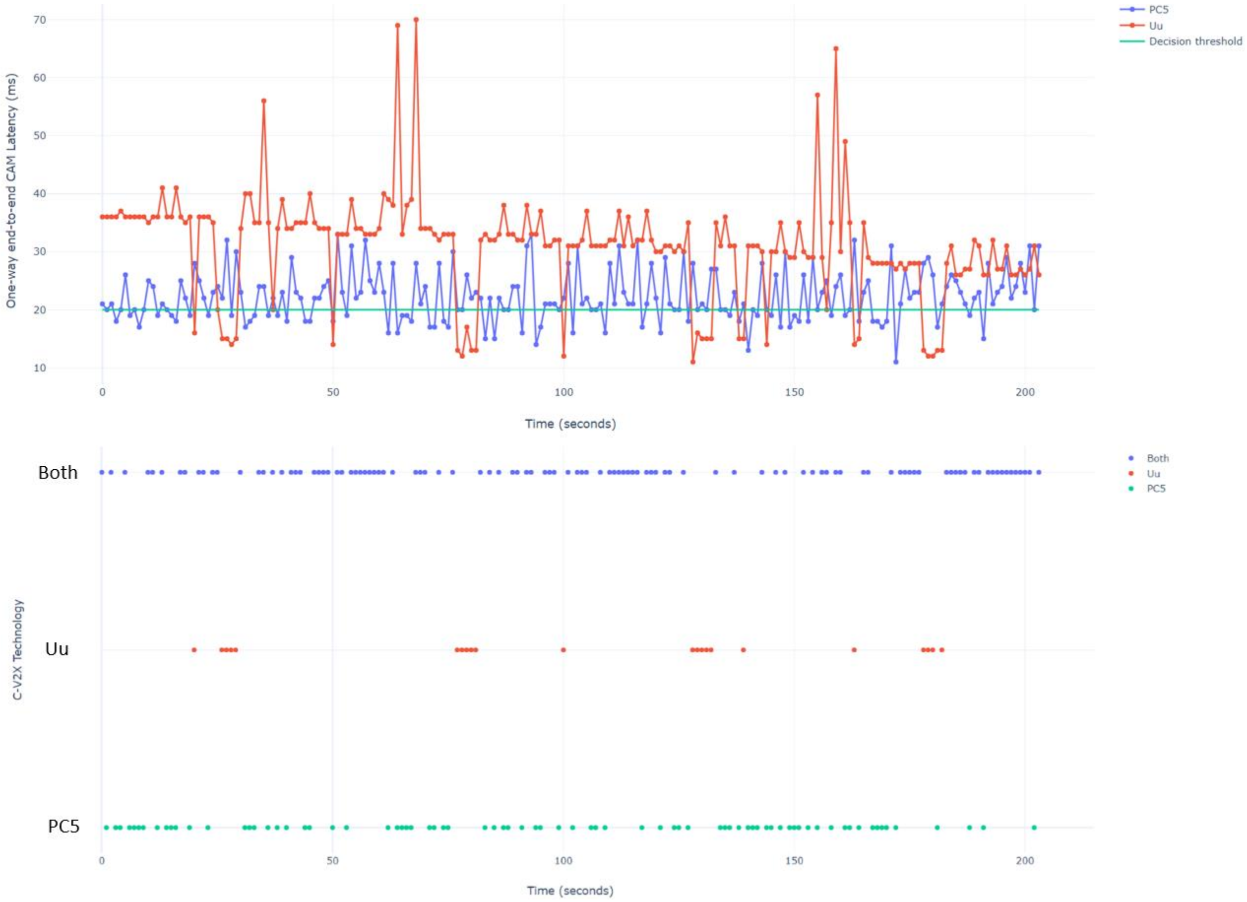


Figure 24: One-way end-to-end CAM latencies and the respective hybrid C-V2X technology selection.

The distance between the two V2X nodes for the duration of the experiment is plotted at the top part of Figure 25. Moreover, the selected C-V2X technology for sending the next CAM message is shown at the bottom part of the figure. When the distance between V2X nodes increases beyond the threshold of 300 meters, as motivated in Section 7, short-range PC5 technology is not selected, and Uu link is chosen irrespective of the reported latency values. However, as soon as the distance falls below the threshold of 300 meters, the reported latency values are again considered in the decision making, as highlighted in Figure 25. Hybrid C-V2X latency is compared with static PC5 and Uu scenarios in Figure 26. Hybrid C-V2X performs better than the two static scenarios. For hybrid C-V2X, about 10 percent reduction in one-way end-to-end CAM latency is observed as compared to the static PC5 scenario. These experiments present a small-scale proof of concept of the proposed hybrid C-V2X communications solution. A scalable implementation on a simulation environment is foreseen as a next step in this direction.

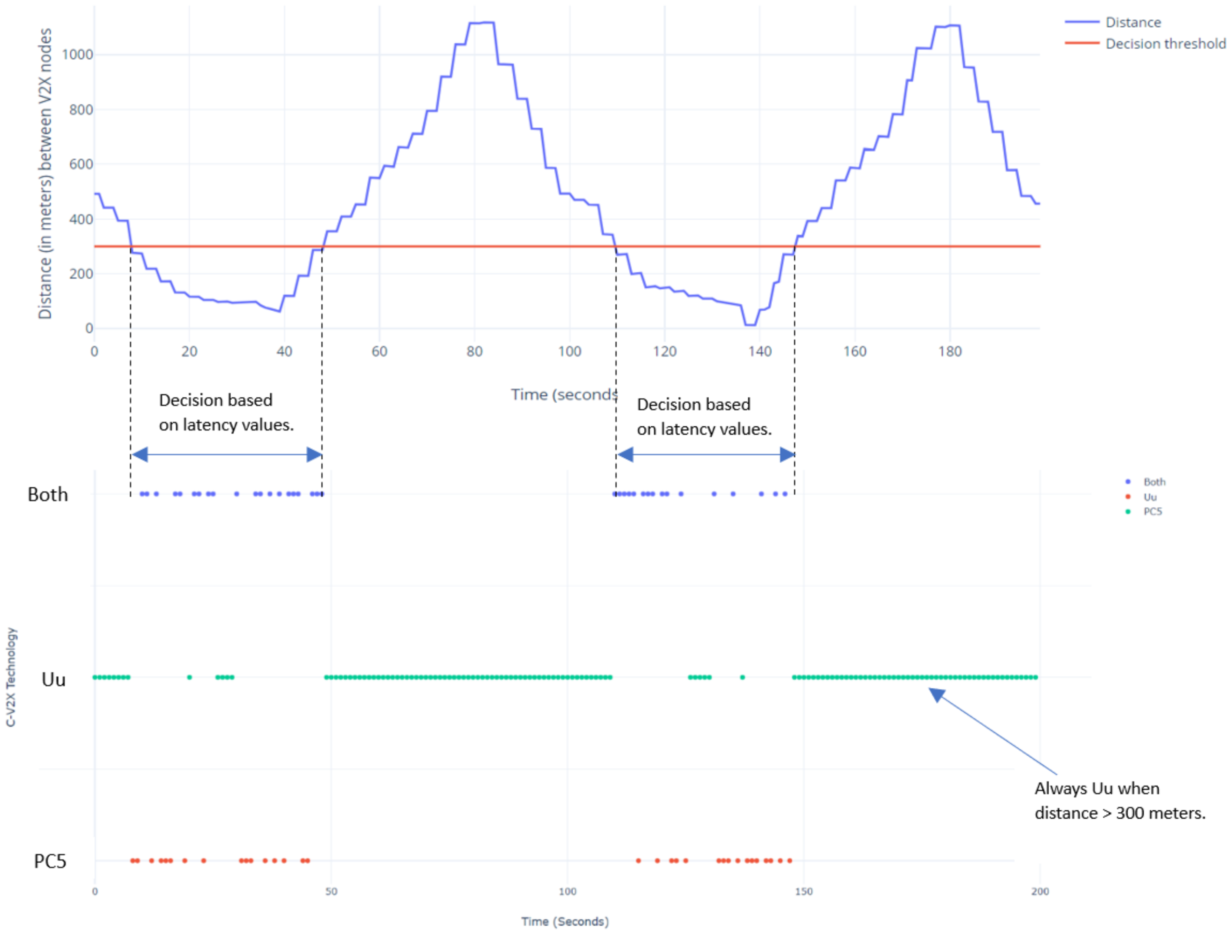


Figure 25: Effect of distance between V2X nodes on hybrid C-V2X technology selection.

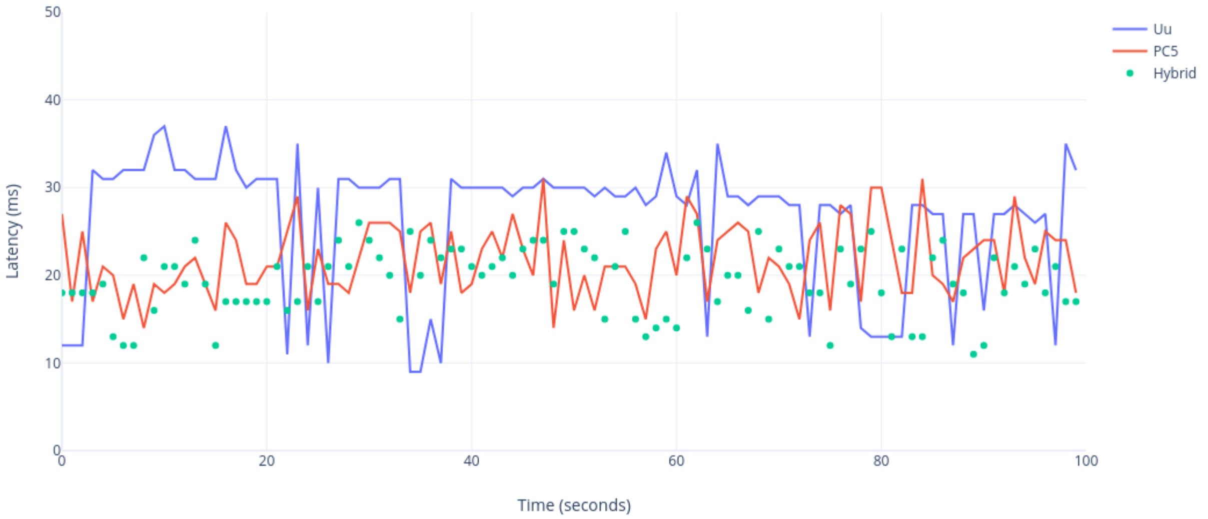


Figure 26: Latency comparison between static technology and hybrid C-V2X.

10 RECOMMENDATIONS FOR MNO'S AND V2X SERVICE PROVIDERS

Hybrid vehicular communication, which combines short-range communication (such as IEEE 802.11p, C-V2X PC5) with cellular communication (such as LTE or 5G NR), has emerged as a promising solution to provide reliable and efficient communication for vehicular applications. As more and more intelligent vehicles are becoming a reality, V2X stakeholders can put efforts individually and collectively to optimize the V2X communication. Based on the study under this deliverable, this section provides several recommendations for strengthening the hybrid C-V2X communications. Afterwards, the recommendations are mapped to different V2X stakeholders.

1. **New concurrent technology solutions:** Efforts can be made for developing connectivity solutions that incorporate multiple technologies (PC5, ITS-G5, Cellular). This not only nurtures the fulfilment of modern day V2X use cases in connected and intelligent transport systems but can also attract automotive manufacturers in deploying state of the art solutions in their upcoming smart vehicles.

2. **Optimize network coverage and capacity:** Mobile networks need to provide reliable coverage and sufficient capacity to support vehicular applications. This can include deployment of small cells in the areas where network coverage is poor and using network slicing and other techniques to allocate sufficient network resources to vehicular applications.

3. **Develop hybrid communication protocols:** Hybrid V2X communication protocols should be developed aiming to enable seamless switching between short-range and long-range vehicular wireless communication technologies. These protocols should be designed to ensure that intelligent vehicles can always communicate using the most appropriate technology. A few considerations that could be useful for developing efficient hybrid V2X communication algorithms include:

    - The end-to-end latency of C-ITS messages should be minimized with the hybrid technology selection.
    - Redundant communication links can be used to enhance reliability depending on the use case, such as mission critical communications. This can be achieved by using multiple communication technologies simultaneously, which can improve communication reliability and reduce the impact of communication failures.
    - In dense traffic scenarios, hybrid V2X communication algorithms should be able to prioritize certain C-ITS nodes such as emergency and mission critical vehicles.
    - Hybrid V2X algorithm should be able to deal with high density scenarios where many V2X nodes want to transmit simultaneously.

4. **Coordinate with other stakeholders:** All V2X stakeholders, such as automotive manufacturers, network operators, infrastructure providers, service providers, traffic management authorities, government authorities, and standardization bodies, should work closely to ensure that the hybrid vehicular communication solutions are interoperable with other systems and technologies. This can help to ensure that the benefits of hybrid vehicular communication are realized across the entire transportation ecosystem.

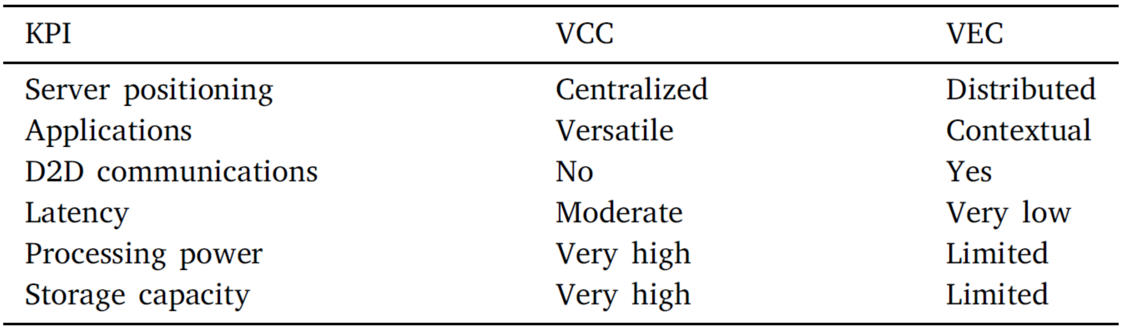
5. **Flexibility in communication technology:** As hybrid V2X communication involves both short-range and long-range communication, service providers should ensure that their services are flexible enough to support multiple communication technologies. This will allow them to provide reliable communication across different types of environments, such as urban and rural areas.

6. **Ensure security and privacy:** V2X communication involves the exchange of sensitive information, such as vehicle position and speed. Therefore, efforts for securing the communications by implementing encryption and authentication mechanisms could be fruitful. This includes the use of encryption, PKI and other security measures to protect against cyber-attacks, and the implementation of privacy-preserving measures to ensure that sensitive data is not compromised. By ensuring the security and privacy of vehicular communication, concerned V2X stakeholders can help to build trust in the safety and reliability of connected and autonomous vehicles.

7. **Integration with other services:** V2X communication can be integrated with other services such as intelligent transportation systems, traffic management systems, and emergency services. Therefore, V2X stakeholders could ensure that their services are compatible with other systems and can integrate with them seamlessly.

8. **Standards compliance:** Hybrid V2X communication involves several standards, such as IEEE 802.11p, 3GPP LTE-V2X, 3GPP NR-V2X and certain enhancements of 3GPP standards for V2X support. V2X stakeholders should ensure that their services comply with these standards to ensure interoperability with other devices and systems.

9. **Edge computing:** Implement VEC (Vehicular Edge Computing) technology to reduce latency in C-V2X communication, which is essential for safety-critical applications. VEC brings compute facilities closer to the edge to fulfil network KPI requirements in latency constrained networks. Previously, VCC (Vehicular Cloud Computing), a cloud-based computing solution was considered as a promising option, however, considering the latency critical applications that modern day V2X systems must support, it is of extreme importance that vehicular edge computing architectures are explored along with the hybrid V2X communication protocols. Figure 27 [26] presents a comparison between VCC and VEC as far as certain KPIs are concerned. Although, the processing power and storage capacity is limited in VEC scenario, considering its distributed nature, VEC still stands out as a better candidature for vehicular computing.



KPI	VCC	VEC
Server positioning	Centralized	Distributed
Applications	Versatile	Contextual
D2D communications	No	Yes
Latency	Moderate	Very low
Processing power	Very high	Limited
Storage capacity	Very high	Limited

Figure 27: Summary of vehicular cloud and edge computing KPIs.

10. **Advanced antennas:** Advanced antenna technologies, such as beamforming could be used to improve the accuracy, reliability, and range of C-V2X communication. This could be crucial for fulfilling the dream of modern-day hybrid C-V2X communications.

Some of these recommendations are relevant for multiple stakeholders. Specifically for MNOs, we believe that recommendation # 2 and 4 can be useful. For system integrators, recommendation # 1, 3, 4, 9 and 10 could be of interest. For V2X service providers, recommendation # 4 to 8 are relevant. We hope that the respective V2X stakeholders can find these recommendations useful in their efforts to strengthen hybrid V2X communications. It is pertinent to mention that the associated standards (ETSI, 3GPP) need to be taken into consideration. Likewise, newer protocols could lead to newer standardization as well. These recommendations can help different V2X stakeholders to stay competitive and meet the growing demands for V2X communications.

11 CONCLUSIONS

Hybrid C-V2X communication is a promising solution for achieving reliable and efficient V2X communication in a variety of scenarios, including teleoperation and platooning. Combining the strengths of both short-range and long-range wireless vehicular communication technologies can provide a high level of connectivity, flexibility, and scalability. In addition, it can support a wide range of applications and services, including safety, traffic efficiency, environmental monitoring, and infotainment. In this study, an intelligent wireless vehicular communication technology selection algorithm has been presented, implemented, and evaluated in the lab V2X test setup. Although it is a small-scale evaluation setup, it shows the benefits in terms of extremely crucial aspects including latency and reliability.

However, at the commercial level, the deployment and operation of hybrid C-V2X communication systems require careful planning and coordination among different stakeholders, including MNOs, V2X service providers, and automotive OEMs (Original Equipment Manufacturers). To ensure interoperability and compatibility, they need to follow common standards and protocols, such as 3GPP and ETSI, and conduct rigorous testing and certification processes. Moreover, they need to address various technical and non-technical challenges, such as spectrum allocation, cybersecurity, privacy, and regulatory compliance.

Overall, hybrid C-V2X communication has the potential to revolutionize the way we move and interact with our vehicles and the surrounding environment. It can enable a new era of connected and autonomous mobility that is safer, more efficient, and more sustainable. Therefore, it is essential for all stakeholders to work together and collaborate closely to realize this vision and create value for society as a whole.

APPENDIX A

With reference to the Section 7 about the intelligent hybrid C-V2X algorithm, the decision trees for numbered tag 2 (joint CAM and DENM transmission) and numbered tag 3 (IVIM transmission) are shared in this appendix. With continuation from Figure 11, the numbered tag 2 which relates to intelligent hybrid C-V2X in case of both CAM and DENM transmission is shown in Figure 28 to Figure 30. On the similar lines, the numbered tag 3 which relates to intelligent hybrid C-V2X in case of IVIM transmission is shown from Figure 31 to Figure 33.

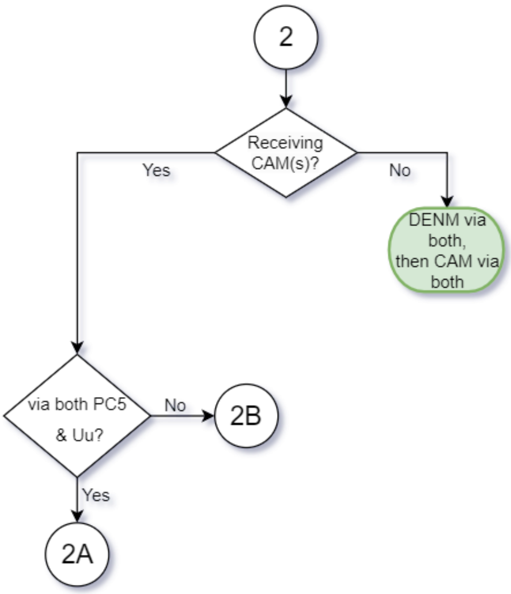


Figure 28: Decision tree for CAM & DENM transmission (part 1).

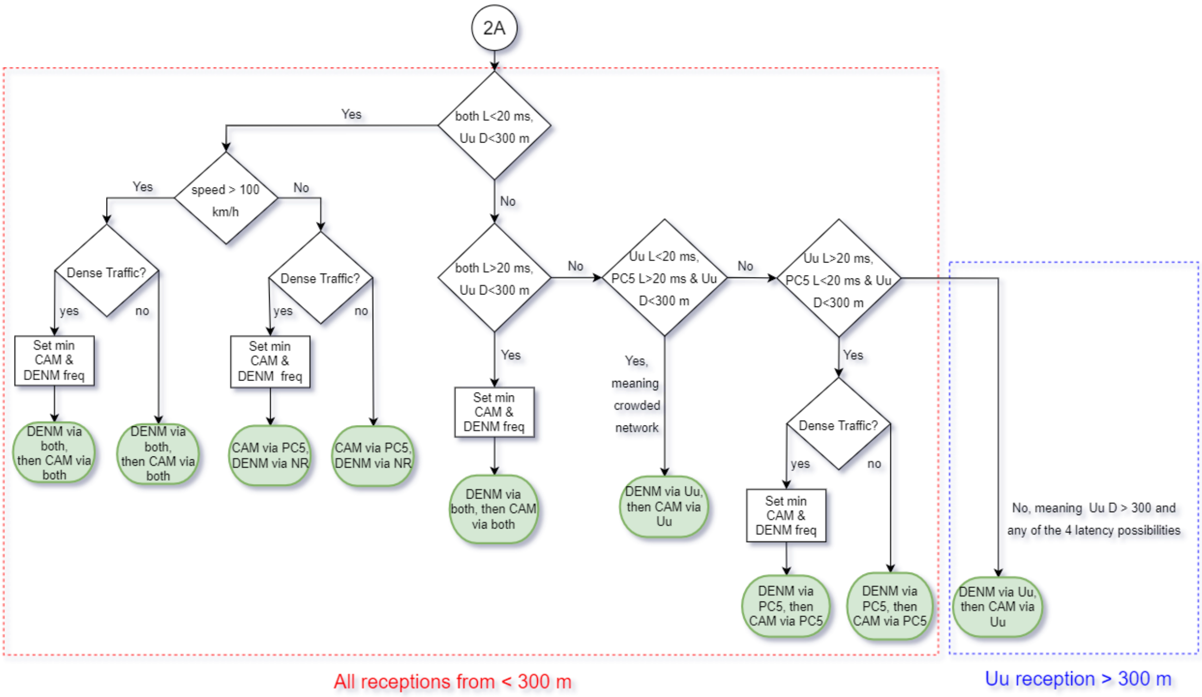


Figure 29: Decision tree for CAM & DENM transmission (part 2).

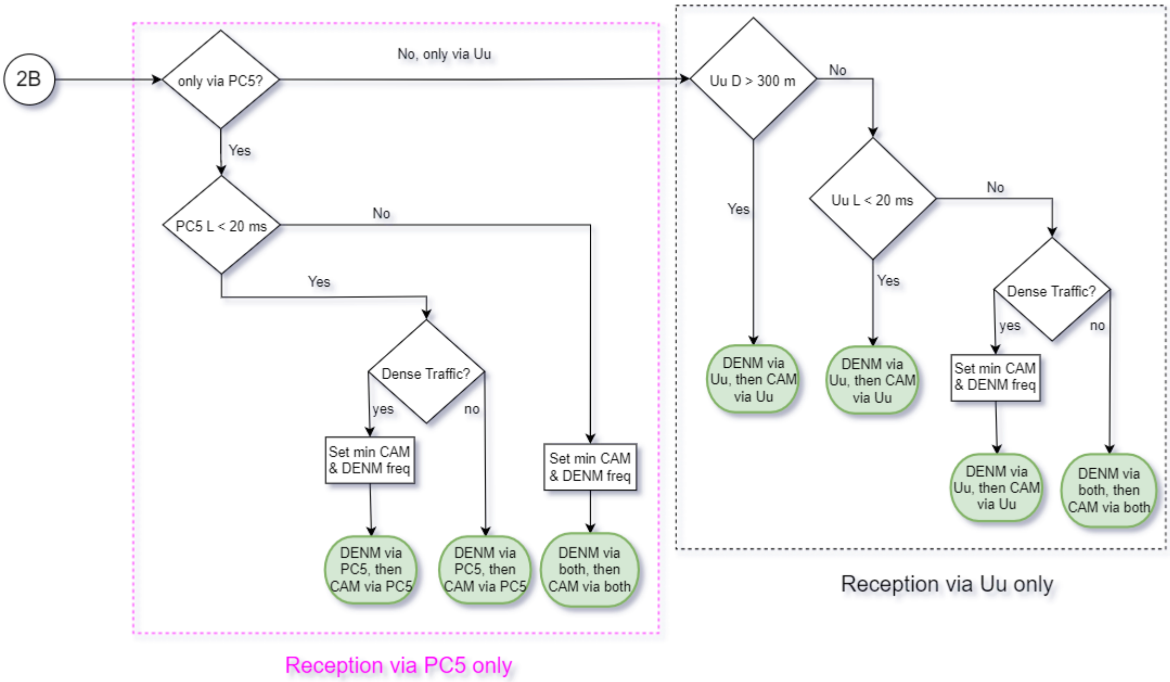


Figure 30: Decision tree for CAM & DENM transmission (part 3).

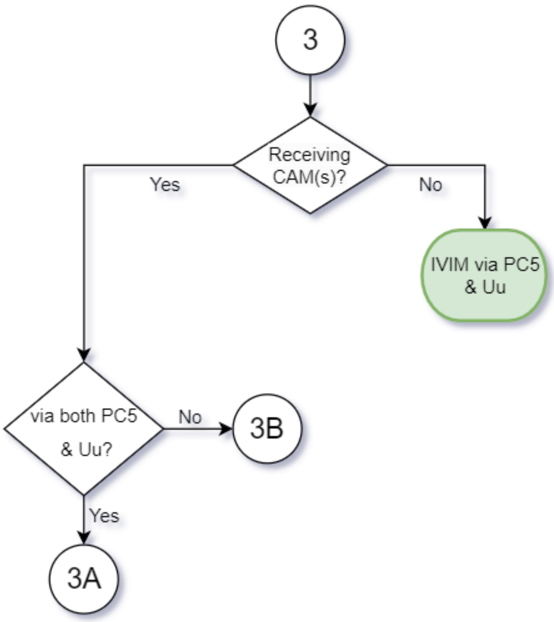


Figure 31: Decision tree for IVIM transmission (part 1).

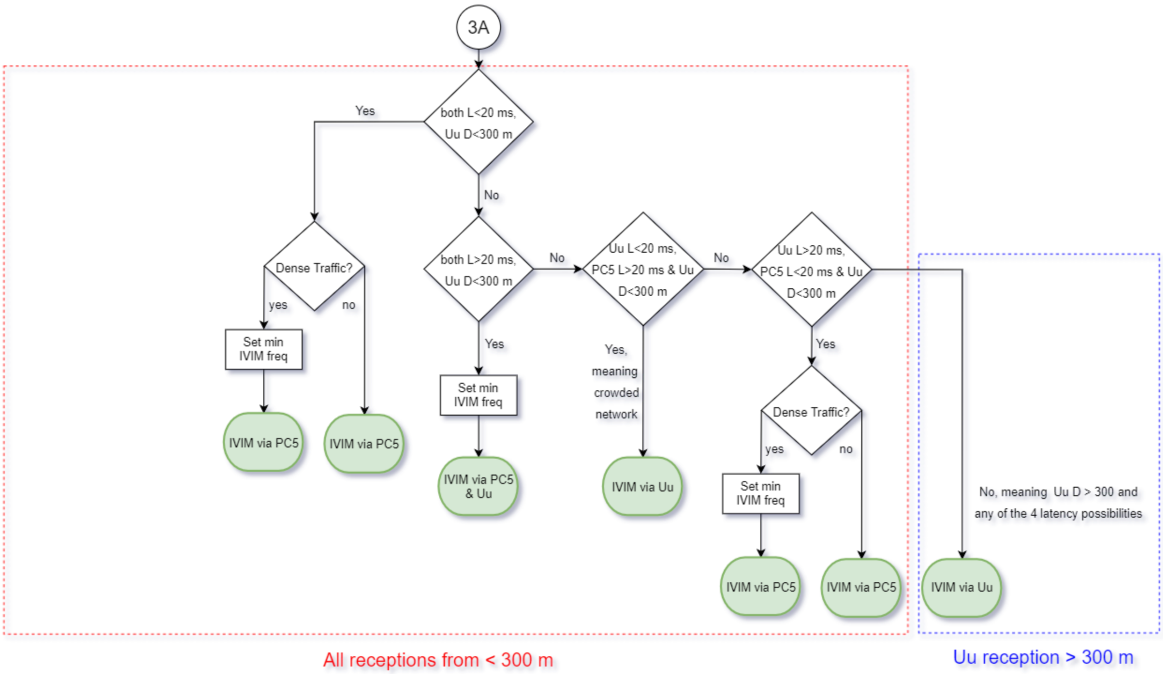


Figure 32: Decision tree for IVIM transmission (part 2).

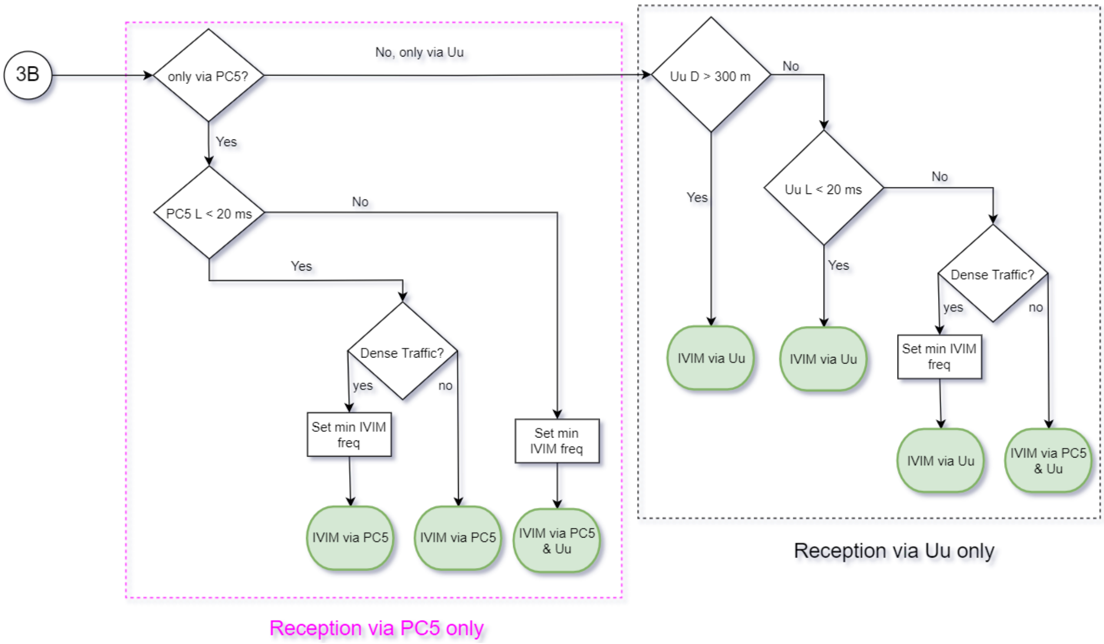


Figure 33: Decision tree for IVIM transmission (part 3).

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