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Optimizing Hybrid V2X Communication: An Intelligent Technology Selection Algorithm Using 5G, C-V2X PC5 and DSRC

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Abstract: Cooperative communications advancements in Vehicular-to-Everything (V2X) are bolstering the autonomous driving paradigm. V2X nodes are connected through communication technology, such as a short-range communication mode (Dedicated Short Range Communication (DSRC) and Cellular-V2X) or a long-range communication mode (Uu). Conventional vehicular networks employ static wireless vehicular communication technology without considering the traffic load on any individual V2X communication technology and the traffic dynamics in the vicinity of the V2X node, and are hence inefficient. In this study, we investigate hybrid V2X communication and propose an autonomous and intelligent technology selection algorithm using a decision tree. The algorithm uses the information from the received Cooperative Intelligent Transport Systems (C-ITS) Cooperative Awareness Messages (CAMs) to collect statistics such as inter vehicular distance, one-way end-to-end latency and CAM density. These statistics are then used as input for the decision tree for selecting the appropriate technology (DSRC, C-V2X PC5 or 5G) for the subsequent scheduled C-ITS message transmission. The assessment of the intelligent hybrid V2X algorithm's performance in our V2X test setup demonstrates enhancements in one-way end-to-end latency, reliability, and packet delivery rate when contrasted with the conventional utilization of static technology.

Keywords: hybrid; 5G; C-V2X PC5; DSRC; technology selection; communication; CAMINO; CAM; DENM; V2X

Citation: Khalid, I.; Maglogiannis, V.; Naudts, D.; Shahid, A.; Moerman, I. Optimizing Hybrid V2X Communication: An Intelligent Technology Selection Algorithm Using 5G, C-V2X PC5 and DSRC. *Future Internet* **2024**, *16*, 107. https://doi.org/10.3390/fi16040107

Academic Editor: Manabu Tsukada

Received: 19 February 2024
Revised: 8 March 2024
Accepted: 21 March 2024
Published: 23 March 2024

1. Introduction

According to reports, the estimated size of the worldwide connected car market was $33.73 billion in 2022, with a projected growth to approximately $136.11 billion by 2032. This expansion is anticipated to occur at a Compound Annual Growth Rate (CAGR) of 15.5% from 2023 to 2032 [1]. This sizeable market growth is driven by 5G connectivity. Based on the environment in which they operate, Vehicular-to-Everything (V2X) communication can take various forms, such as Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P) and Vehicle-to-Network (V2N) as depicted by the Cooperative Intelligent Transport Systems (C-ITS) landscape in Figure 1 [2]. Traffic dynamics in the V2X scenario change every moment due to the dynamically changing wireless and physical environment. A huge amount of data is generated and exchanged among various types of C-ITS nodes every second. Multiple short-range (C-V2X PC5, IEEE 802.11p-based Dedicated Short Range Communication (DSRC)/ITS-G5) and long-range (C-V2X Uu) technologies exist for communication between V2X nodes. With the advancements in Third Generation Partnership Project (3GPP)-based cellular communications in the last decade, V2X communication is becoming a reality. Connected, autonomous and teleoperated vehicles are changing the dynamics of the vehicular communications. Additionally, connected vehicles can improve traffic efficiency by better managing their flow on the roads and reducing fuel consumption.

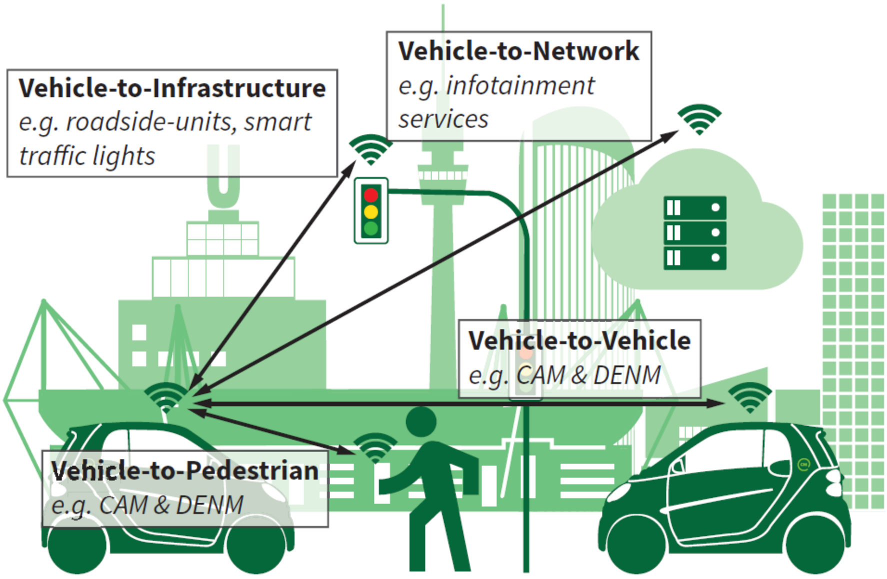

Figure 1. Vehicular-to-Everything (V2X) use cases: Vehicle-to-Vehicle (V2V), Vehicle-to-Pedestrian (V2P), Vehicle-to-Infrastructure (V2I) and Vehicle-to-Network (V2N) [2].

Currently, it is believed that approximately 95% of all road traffic accidents in the European Union are caused by human errors [3]. The use of Connected Autonomous Vehicles (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 enhance safety for all road users. For example, many vehicles nowadays 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. Various messages are used in C-ITS to communicate information using short-range and/or long-range V2X technologies. A Cooperative Awareness Message (CAM) serves as one of the messages transmitted among interconnected vehicles, containing vital details regarding a vehicle's state and behavior, encompassing its position, speed, heading, acceleration, and pertinent data. CAMs facilitate mutual awareness among vehicles, enabling them to comprehend each other's presence and movements. This, in turn, fosters collaborative actions aimed at enhancing both road safety and traffic efficiency. Another noteworthy message category is the Decentralized Environmental Notification Message (DENM), designed to disseminate information about the immediate traffic environment, potential disruptions, or hazards. The primary objective of DENM is to furnish real-time notifications pertaining to various events, such as road closures, accidents, adverse weather conditions, and other crucial information impacting traffic safety and efficiency. Through the dissemination of decentralized environmental notifications, vehicles can promptly receive updates concerning their surroundings, empowering them to adapt to dynamic conditions and undertake suitable actions.

The term "Hybrid vehicular communication" refers to the use of a combination of short-range and long-range V2X 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 DSRC/ITS-G5) and cellular networks (4G/5G) to provide reliable and efficient communication between V2X nodes. 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. Overall, hybrid vehicular communication is a promising sustainable solution that has the potential to revolutionize the transportation industry, along with the openness to integrate new V2X technologies.

In a hybrid V2X communication, based on the network statistics and positional information derived 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, optimizing the usage of wireless resources and enhancing the overall safety on the roads. However, until now, technologies are statically linked to specific use cases i.e., short-range direct communication technologies for safety related time-critical information and long-range infrastructure assisted cellular technologies for informative, non-safety and non-time-critical communication [4]. Hence, in this study, an intelligent algorithm for hybrid V2X communications is designed based on a set of selection criteria, 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 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 may also add extra load on the backhaul network. Considering the projected [1] surge in intelligent and autonomous vehicles on the roads, the current network may encounter elevated loads, particularly impacting latency-critical applications. Hence, we propose an intelligent real-time statistics-driven V2X technology selection algorithm running on every V2X node. This intelligent approach 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 laying the groundwork for next-generation connectivity, this study contributes to enhancing the safety and efficiency of future vehicular networks. The following are the main novelties/contributions of this paper:

- This is the first study within the hybrid V2X domain, wherein three technologies are taken into consideration for hybrid V2X communications. Specifically, two short-range technologies, namely C-V2X PC5 and DSRC, along with the long-range 5G Uu are included. This comprehensive approach offers increased flexibility in the selection of the most suitable V2X technology.
- A detailed intelligent hybrid V2X technology selection algorithm has been introduced to optimize the selection of V2X technology and adapting the C-ITS message generation rate. This algorithm takes into account various factors, including latencies associated with CAM receptions from different technologies, the speed of the V2X node, proximity to the neighboring V2X nodes, the type of C-ITS message, and the prevailing traffic density.
- The hybrid V2X technology selection algorithm under consideration also incorporates a scenario involving the concurrent transmission of CAM and DENM. Furthermore, the adjustments necessary for intelligent decision-making in this context are thoroughly examined and discussed.
- This study entails an experimentally driven investigation conducted in real-world conditions on a road, incorporating authentic environmental limitations and concurrent transmissions of CAM and DENM. The aim is to validate the real-time functionality of the proposed hybrid V2X technology selection algorithm.

The remainder of the paper is organized as follows. In Section 2, the related work in the domain of hybrid V2X is discussed, followed by the description of short-range and long-range V2X communication in Section 3. The system model and problem statement is presented in Section 4. An intelligent hybrid V2X technology selection algorithm is proposed in Section 5. Section 6 discusses the experimental V2X testbed setup consisting of DSRC, C-V2X PC5 and 5G capabilities, and the algorithm implementation. This is followed by the experimental results and their analysis in Section 7, while the conclusion and future work directions are drawn in Section 8.

2. Related Work

Dynamically changing wireless and physical environment in V2X communication demand efficient vehicular Radio Access Technology (RAT) selection. Because of this, numerous approaches have been proposed in recent years considering multi-technology enabled vehicular communication and RAT selection algorithms. A recent study in [5] considered the two short-range technologies i.e., ITS-G5 and C-V2X PC5, where ITS-G5 serves as a primary RAT, whereas C-V2X PC5 is used when ITS-G5 channel gets congested or if there is lack of transmission range. Reliability gains are seen with the constructive combination of ITS-G5 and C-V2X PC5. Two more recent studies in [6,7] have considered Deep Reinforcement Learning (DRL)-based selection strategy between DSRC and C-V2X PC5 mode 3. Specifically, the selection is based on the channel load, SNIR and latency. Using simulations, the DRL-based approach has shown improvements in packet reception ratio, reliability, throughput, Channel Busy Ratio (CBR) and message duplication percentage. Authors in another simulation-based study in [8] have proposed a joint LSTM multi-criteria technology selection approach for DSRC and C-V2X PC5 mode 3. Among the available technologies, the focus is on minimizing the load on stochastic queues and maximizing the throughput using the LSTM prediction technique. The implementation of mode 3 in [6–8] necessitates additional infrastructure and control signals, with mandatory base station coverage. An evolutionary game-based technology selection approach is considered in [9] for selection between DSRC and C-V2X mode 4 with a goal to maximize the transmission throughput. Using packet size and distance between the transmitter and receiver as the selection criteria, a total of 16 population profiles are considered each having a separate population share. The payoff function is the average transmission throughput for the concerned strategy and results have shown payoff gains for the simulated scenario.While [9] exclusively focuses on short-range technologies, the proposed solution necessitates the computation of payoff at the base station. Additionally, the broadcasting of both payoff and population profile to the V2X node incurs an extra communication link. Studies in [5–9] exclusively focus on short-range technologies, potentially resulting in coverage limitations. Furthermore, these studies lack consideration for various C-ITS messages and the adaptation of message rates. The saturation of short-range technologies in dense traffic scenarios can adversely affect the performance of V2X applications.

An adaptive RAT selection and vertical handover algorithm is presented in [10]. Only DSRC and Long Term Evolution (LTE) are considered in this simulation-based study where DSRC always serves as a primary RAT, whereas LTE acts as a secondary RAT. A simulation-based hybrid V2X study is performed in [11] consisting of C-V2X PC5 and DSRC where the emphasis is on the C-V2X mode 4 adaptive Semi-Persistent Scheduling (SPS) control. CAM delivery is ensured over C-V2X PC5 by adapting collision probability in each SPS period. The frequency of CAMs is controlled in an adaptive manner such that the C-V2X error probability limit for the CAM transmission is not exceeded. Simultaneous duplicated CAM are sent over DSRC if the proposed mechanism fails to satisfy the constraints of C-V2X collision probability. In order to facilitate applications related to V2X video streaming, a Quality of Service (QoS)-Aware video transmission approach over hybrid vehicular network is proposed in [12]. DSRC is considered as a primary RAT, whereas, the secondary RAT is LTE in this real-time experiments driven study. The secondary RAT is only used if the packet loss rate of primary RAT goes below a certain threshold. Scenarios with Line of Sight (LOS), non-LOS with buildings and non-LOS with vehicles are considered and Packet Delivery Rate (PDR) and Frame Delivery Rate (FDR) are monitored.

Authors in a simulation-based study in [13] have come up with a performance guaranteed optimized V2X handover decision algorithm between LTE and IEEE 802.11p. A central controller collects the real-time traffic information about the received signal strength, solves a joint optimization function and informs the vehicles about the appropriate access point (Road Side Unit (RSU) or base stations) to connect with. In the process, the algorithm considers load balancing among all access points, data rate maximization for the whole network, and the vehicle fairness in terms of satisfied vehicles. Another similar data traffic steering algorithm is presented in [14], where the hybrid V2X technology selection decision is based on the IEEE 802.11p channel congestion and the free LTE Physical Resource Blocks (PRBs) that can be scheduled. In turn, the transmission delay is optimized and more number of vehicles can achieve lower delays. Another related work in [15] considers WiFi and LTE as the possible technologies and their use is instructed by a simple decision tree. WiFi is used if the link quality is good with a possible fallback to LTE otherwise. An electrical autonomous vehicle is used to perform the experimentation in a limited off-road experiment scenario. None of the short-range V2X technologies such as C-V2X PC5 or DSRC/ITS-G5 are considered in this work.

The state of the art regarding multi-technology enabled vehicular communication and RAT selection algorithms is summarized in Table 1, however, these contributions only consider a subset of V2X technologies. This constrains the extent of flexibility attained and the RAT selection efficiency. To the best of our knowledge, this is the first study in hybrid V2X domain that considers three vehicular RATs including C-V2X PC5, 802.11p-based DSRC, and 5G long-range. Furthermore, mostly simulation-based studies are conducted in this domain in past. To address this gap, our study proposes and validates experimentally an intelligent decentralized hybrid V2X technology selection algorithm that can dynamically select a vehicular technology based on diverse parameters not limited to the received CAMs but also the current state of the sending V2X node. Moreover, this is the first study in this domain which considers V2X technology selection optimization for joint CAM and DENM transmission scenario.

Table 1. Summary of related work in multi-technology enabled vehicular communication and RAT selection algorithms.

Ref.	Technologies Considered			Experiment Driven	ITS Services Considered			Frequency Adaptation	KPIs	Selection Criteria
	PC5	DSRC/ ITS-G5	4G/5G		CAM	DENM	Joint			
[5]	mode 4	✓	×	✓	✓	×	×	×	Latency, range	ITS-G5 channel capacity
[6]	mode 3	✓	×	×	×	×	×	×	Reliability, PRR	SNIR, latency
[7]	mode 3	✓	×	×	✓	×	×	×	CBR, PRR, throughput	SNIR, channel load, latency
[8]	mode 3	✓	×	×	×	×	×	×	Throughput, PDR, network satisfaction	Queuing delay, capacity, connectivity time, cost.
[9]	mode 4	✓	×	×	✓	✓	×	×	Throughput	packet size, distance
[10]	×	✓	✓(4G)	×	✓	✓	×	✓	Data rate, latency, PDR, handovers	LTE LLI, DSRC Channel Occupancy
[11]	mode 4	✓	×	×	✓	×	×	✓	PDR	SPS period control
[12]	×	✓	✓(4G)	✓	×	×	×	×	PDR, FDR	DSRC PLR
[13]	×	✓	✓(4G)	×	×	×	×	×	Load balancing, data rate, vehicle fairness	RSS (of RSUs and BSs)
[14]	×	✓	✓(4G)	×	✓	×	×	×	Delay	LTE LLI, 802.11p load
[15]	×	×	✓(4G)	✓	×	×	×	×	RTT	WiFi signal strength
This work	mode 4	✓	✓(5G)	✓	✓	✓	✓	✓	Latency, PDR, Reliability, CAM/DENM frequency	distance, latency, CAM traffic density, C-ITS message type, speed

3. Overview of 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 [16] is shown in Figure 2. Both short-range direct and long-range V2X communication both have their own characteristics, benefits, and challenges. Both are important for enabling Advanced Driver Assistance Systems (ADAS), C-ITS, autonomous driving, and hybrid V2X communication. In this section, the characteristics, benefits, and challenges of each type of communication are explored.

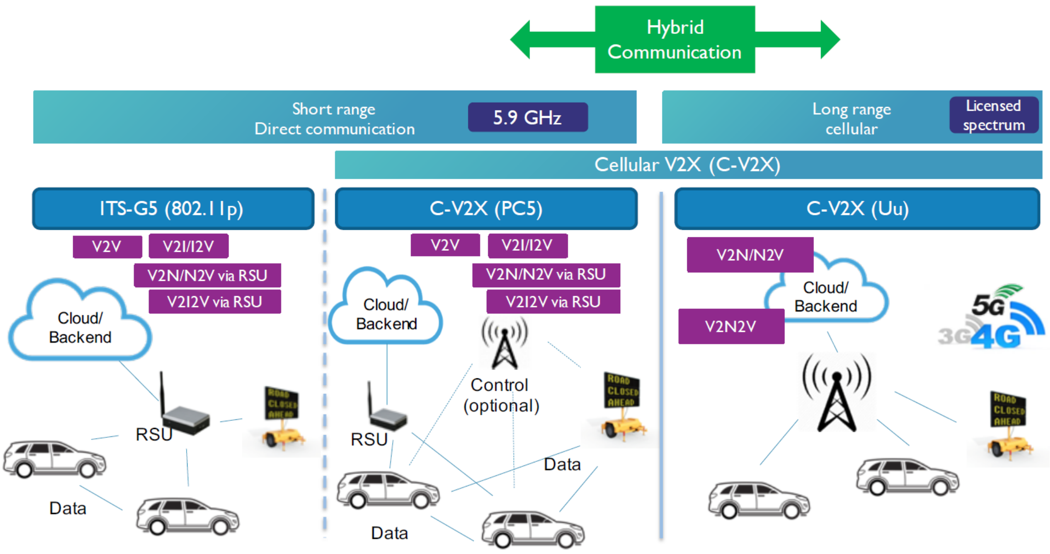

Figure 2. V2X technology classification [16].

3.1. Short-Range Direct V2X Communication

In order to facilitate direct exchange of information between V2X nodes within the allotted spectrum, mainly two technologies exist. The initial protocol, based on IEEE 802.11p, comprises separate ITS protocol stacks in Europe (ITS-G5) and the U.S. (DSRC). The second technology is C-V2X PC5, commonly referred 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 function within the allocated frequency bands specifically designated for ITS at 5.9 GHz and provide low-latency communication that is well-suited for safety-critical applications. ITS-G5 and DSRC are constructed upon the 802.11p standard, employing Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for wireless medium access.

Conversely, C-V2X PC5, introduced in 3GPP Release 14 as a more recent technology, provides two operational modes: Mode 3 and Mode 4 [17]. In mode 3, also known as LTE sidelink mode 3, a network entity named Sidelink Communication Manager (SCM) is responsible for managing sidelink resources and establishing sidelink connections between devices. In mode 4, autonomous scheduling is performed by V2X nodes with the help of sensing-based SPS. In SPS, each V2X node orchestrates its allocated resources, spreading them out in time for mitigating collisions with concurrent transmissions on identical subcarriers [18]. However, in dense environments, scalability issues can impact latency and collisions are imminent if more than one V2X node chooses identical resource blocks, leading to transmission collisions. 3GPP Release 16 introduced 5G New Radio (NR) sidelink, which allows direct communication between vehicles using 5G technology. 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. However, Release 16 Sidelink equipment is not yet available on the market.

3.2. 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 V2X, which is designed mainly for safety-critical applications, long-range V2X is mainly intended to provide a broader range of services, such as high throughput data transfer and streaming, infotainment, navigation, and remote vehicle management. Long-range V2X communication can provide real-time traffic information, such as congestion and road closures, over much wider areas than short-range 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 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. Additionally, traffic from other users, may have a negative impact on the network performance and QoS provision may not be guaranteed. This issue could be resolved by exploiting 5G network slicing. Network slicing in 5G allows 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. Tailor-made slicing provision and configuration for different V2X use-cases needs to be supported by the Mobile Network Operators (MNOs). This may be a challenging task that has several techno-economic aspects, especially in cross-border scenarios, where a V2X service (e.g., remote driving) using a dedicated slice from a certain MNO must be handed over seamlessly to another similar slice from another MNO as the vehicle crosses the border. Moreover, advanced 5G NR capabilities, the use of Frequency Division Duplex (FDD) and mini-slot level scheduling make 5G NR worthy enough to provide low latency communication in V2X scenarios.

3.3. NR-V2X Use Cases

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. While LTE-V2X is focused on basic safety services, NR-V2X can be used for advanced safety services and cooperative and connected autonomous driving. Table 2 shows the use case requirements including reliability, latency and range for various use cases as in 3GPP Technical Specification 22.186 [19].

Table 2. V2X use case requirements.

Use Case	Reliability	Max. Latency	Max. Range
Vehicle Platooning	99.99%	10 ms	350 m
Advanced Driving	99.999%	3 ms	700 m
Extended Sensors	99.999%	3 ms	1000 m
Remote Driving	99.999%	5 ms	-

4. System Model and Problem Statement

The system model for V2X technology selection is described in this section. Consider two V2X nodes, referred as On-Board Units (OBUs), and named as OBU1 and OBU2, as in Figure 3. There is a direct V2V communication link between OBU1 and OBU2. Also, both OBUs have a V2I link with a 5G gNB. Following assumptions are considered in this regard:

- Each V2X node is equipped with DSRC, C-V2X PC5, and 5G Uu capabilities.
- Each V2X node sends periodic CAMs.

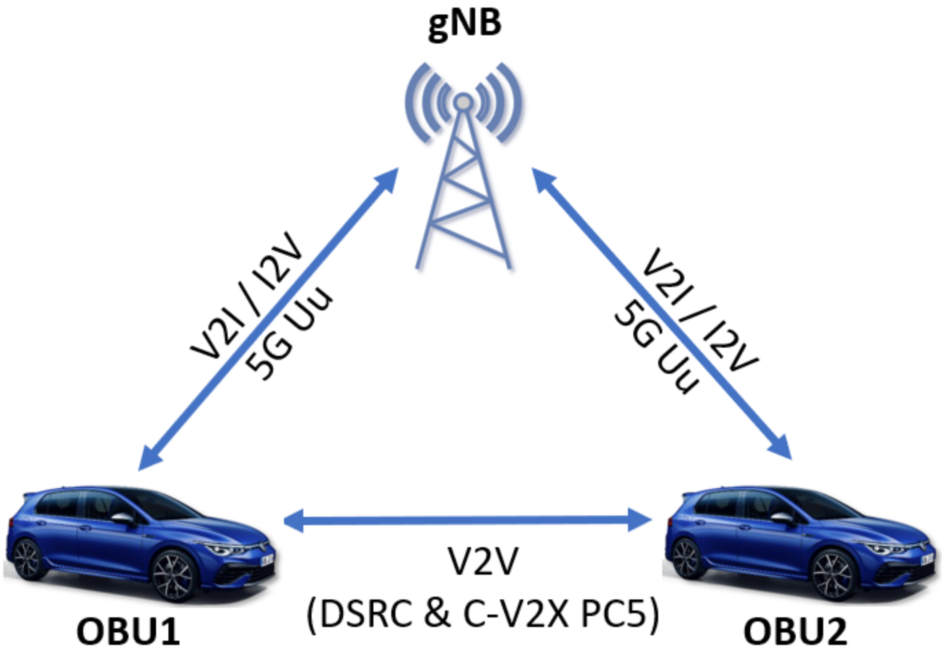

Figure 3. System model for technology selection with two multi-technology enabled V2X nodes.

With two short-range and one long-range V2X technology at hand, the problem lies in the real-time selection of the most suitable single/multiple technology(ies) for sending the C-ITS messages. This technology selection should be such that the Key Performance Indicators (KPIs) are maximized. Let $t_{generation}$ be the timestamp added to the CAM by the sending V2X node. Similarly, $t_{reception}$ is the current timestamp of the V2X node where CAM is received. The one-way end-to-end CAM latency (L_X) is given as:

$$L_X = t_{reception} - t_{generation}. \tag{1}$$

where X represents any one of the three technologies or the hybrid approach. Let N_{DSRC}, N_{PC5}, N_{5G} and N_{Hybrid} be the total number of CAMs received via DSRC, C-V2X PC5, 5G or hybrid technology, respectively, during a decision window on a V2X node. The decision window is a time sliding window during which CAMs are received and their statistics are observed. Similarly, T_{DSRC}, T_{PC5}, T_{5G} and T_{Hybrid} represent the total number of CAMs sent via respective technologies. Packet Delivery Rate (PDR) via a particular technology or the hybrid approach, represented as (PDR_X), is defined as:

$$PDR_X = \frac{N_X}{T_X} * 100. \tag{2}$$

Similarly, CAMs are considered reliable if they are received within the latency threshold of a V2X application. CAM transmission reliability for a particular technology or the hybrid approach, represented as (REL_X), is defined as:

$$REL_X = \frac{N_X \text{ within } L_{thr}}{N_X} * 100, \tag{3}$$

where L_{thr} is the latency performance threshold of the V2X application. This threshold can vary depending on the QoS constraints of the V2X use cases.

Rather than statically using short-range for safety related and long-range for non-safety related V2X communication, this work aims to formulate an intelligent hybrid V2X technology selection algorithm that optimizes latency, PDR and reliability.

5. Proposed Hybrid V2X Technology Selection Algorithm

In this paper, we propose an intelligent rule-based algorithm for hybrid V2X wireless communication technology selection. In the following subsections, the considered selection criteria and the KPIs are defined, followed by the simplified version of the intelligent hybrid V2X technology selection decision tree.

5.1. Selection Criteria

The following selection criteria are considered in the proposed intelligent hybrid V2X technology selection decision making algorithm.

1. One-way end-to-end CAM latency: Elapsed time from the instant a data packet is generated at the source application to the instant it is received by the destination application, calculated using the timestamps i.e., CAM creation time and CAM reception time. This in further divided into three parameters, one for each of the three considered technologies i.e., DSRC, PC5 and 5G Uu, and denoted as L_D, L_P and L_{Uu}, respectively. Each of them represents an average value based on all CAM receptions from a specific technology during the time sliding window.
2. Inter-vehicular distance: Distance between V2X nodes, calculated using the longitude and latitude information from the received CAM and the current longitude and latitude of the V2X node where intelligent decision is to be made. This is further divided into three parameters, one for each of the three considered technologies and denoted as D_D, D_P and D_{Uu} for DSRC, C-V2X PC5 and 5G Uu, respectively. Each of them represents an average value based on all CAM receptions from a specific technology during the time sliding window.
3. CAM density: Number of CAMs received via DSRC, C-V2X PC5 and 5G Uu during the time sliding window, denoted as $Dense_D$, $Dense_P$ and $Dense_{Uu}$, respectively.
4. C-ITS message type: CAM only or CAM with DENM. This is a crucial parameter as efficient resource allocation and technology selection is needed to avoid compromising the DENM transmission performance.
5. Speed: Speed (S) in km/h of the V2X node where the intelligent decision is to be made. Speed is compared with a speed threshold, S_{thr}, to decide if the V2X node is moving fast, with an aim to preempt possibly rapidly changing traffic dynamics.

Criteria 1–3 are based on the received CAMs, whereas, criteria 4 and 5 are relevant to the V2X node on which the intelligent V2X technology selection decision is to be made.

5.2. KPIs

To evaluate the performance of the proposed hybrid V2X technology selection algorithm, the following KPIs are considered:

1. One-way end-to-end hybrid CAM latency: This is the one-way end-to-end latency of the hybrid CAMs i.e., intelligently sent CAMs. This parameter gives an overview of the performance improvement with the use of intelligent hybrid V2X technology selection algorithm.
2. Packet Delivery Rate (PDR): It is measured as the ratio of the number of CAMs delivered to the total number of CAMs sent from source node to the destination node in the network.
3. Reliability: Among the received CAMs, reliability refers to the proportion of CAMs that exhibit a one-way end-to-end latency below the specified latency threshold, represented as L_{thr}.

5.3. Intelligent Hybrid V2X Technology Selection Algorithm

In this subsection, an intelligent hybrid V2X wireless communication technology selection algorithm is presented for transmission of C-ITS messages. For this, a decision tree has been generated to facilitate the intelligent technology selection based on a set of selection criteria. The proposed algorithm assumes that all V2X nodes support C-ITS services and transmit periodic CAMs. 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. Contrarily, the high throughput connections like infotainment and remote driving using video streaming use long-range Uu link, as described in Section 6.2.2. Considering the size of the proposed intelligent hybrid V2X technology selection decision tree, only a simplified version is shown in Figure 4. The detailed decision tree can be found in the Appendix A of the paper.

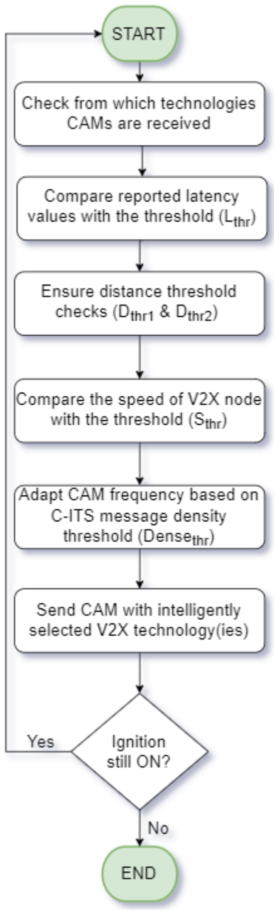

Figure 4. Simplified hybrid V2X technology selection decision tree.

In a V2V scenario, the execution of the algorithm starts as soon as the vehicle ignition is turned on. In the first phase, also known as the warm-up phase, the environment is scanned and different statistics (referred as selection criteria) are evaluated. During this phase, also denoted as the time sliding window, every vehicle unintelligibly transmits CAMs via all three technologies and the received CAMs from the nearly nodes, if any, are logged. In the second phase, based on the observed traffic situation in the vicinity, CAMs and/or DENMs are sent intelligently using hybrid V2X. It is checked if CAM(s) from other vehicles are being received or not. If CAMs are not received, statistics-driven decision cannot be made. In this scenario, CAMs are sent via DSRC, PC5 and 5G links in an attempt to maximize the chances of CAM reception in the vicinity of the V2X node by one of the technologies. If CAMs are received, it is checked if receptions are from DSRC and/or PC5 and/or 5G. Depending on the receptions, a specific branch is followed in the detailed decision tree (as shown in the Figures in Appendix A), whereas, for simplicity purposes, in Figure 4, the reported average one-way end-to-end CAM reception latency values are compared with the latency threshold. For this to be accurate, synchronized clocks are needed between all the V2X nodes e.g., using GPS synchronization. After this, the 95th percentile of the distance for CAMs received via respective technologies is also calculated by using the GPS coordinates included in the CAMs. For latency, a threshold, L_{thr}, is defined for all three technologies in our study, whereas, the 95th percentile distance threshold values for DSRC and PC5 are denoted as D_{thr1} and D_{thr2}, respectively.

After taking latency and distance into consideration, the speed of the V2X node is checked in order to adapt the V2X technology selection. If the speed is below the S_{thr}, and the 95th percentile of the speed of other V2X nodes in the vicinity is also below S_{thr}, it means that the traffic dynamics do not change a lot, meaning that it is not necessary to enforce CAM transmission via multiple technologies during the next technology selection decision. If speed is higher than S_{thr}, implying relatively frequent variation in traffic dynamics, CAM is sent via multiple technologies to enhance the V2X communication reliability. Afterwards, a check has been placed on the network traffic density (received CAMs $\geq Dense_{thr}$ in the time sensing window) so that the CAM transmission frequency can be optimized. $Dense_{thr}$ is also a flexible parameter and can be adapted according to the QoS requirements. The frequency of technology selection decisions is contingent upon the dynamics of traffic. In instances of nearly stationary conditions, such as a traffic jam, the decision frequency can be reduced and multiple CAMs can be sent via the previously chosen technology(ies), as traffic dynamics are anticipated to exhibit prolonged stability. Conversely, in scenarios where the average vehicle speed surpasses a specified threshold, indicating rapidly changing traffic dynamics, the decision frequency for technology selection can be increased. If the network traffic is dense via a specific technology, the frequency of CAM transmissions via that technology is reduced (while satisfying the minimum and maximum frequency bounds based on ETSI standard i.e., 1 Hz to 10 Hz) and vice versa. From the decision tree in the Appendix A, based on the specific decision tree branch, a single or a set of technologies is selected to be used for the next CAM transmission along with a higher/lower CAM frequency. After this intelligent decision making, the process is continued for transmitting subsequent CAMs. For space constraints and to avoid redundancy, the decision tree for joint CAM and DENM transmission scenario is not shown separately. When DENMs are also enabled in any V2X node, both CAMs and DENMs are sent via the chosen technology, as in the detailed decision tree in Appendix A. However, the transmission frequencies of CAMs and DENMs can be adapted to avoid network overload in case of joint CAM and DENM transmission.

A small part of the decision tree is shown in Figure 5 as an example to showcase the selection between the three technologies. DSRC, C-V2X PC5 and 5G are referred to as D, P and Uu, respectively. Based on the received CAMs, the reported latency values via all three technologies satisfy the latency threshold, L_{thr}. After this, the 95th percentile of the distance is monitored. If both D_P and D_{Uu} are less than D_{thr1} (following blue dashed box) and the speed is below the threshold, S_{thr}, only DSRC is selected for the next CAM transmission. If the speed is higher than S_{thr}, implying highly varying traffic, both DSRC and C-V2X PC5 are selected to maximize CAM reachability even in cases where D_{thr1} is not satisfied. An extra check on traffic density ensures that the frequency of CAM transmission can be set to a minimum if traffic is dense, in turn adapting the technology selection in a better way without overloading a particular technology. The red dashed box is followed if both D_P and/or D_{Uu} are not less than D_{thr1}. In this scenario, firstly, if D_P is greater than D_{thr1} and/or D_{Uu} is between $D_{thr1}$and D_{thr2}, it implies that both C-V2X PC5 and 5G Uu are the contender technologies. A similar logic (as for the blue dashed box) is followed after this point to check the speed and traffic density and selecting either C-V2X PC5 or both C-V2X PC5 and 5G Uu with respective CAM frequency setting. Within the red dashed box, if the distance checks are not met, only 5G Uu can potentially cater all the nodes in the vicinity so a straightforward decision is made to use 5G Uu link.

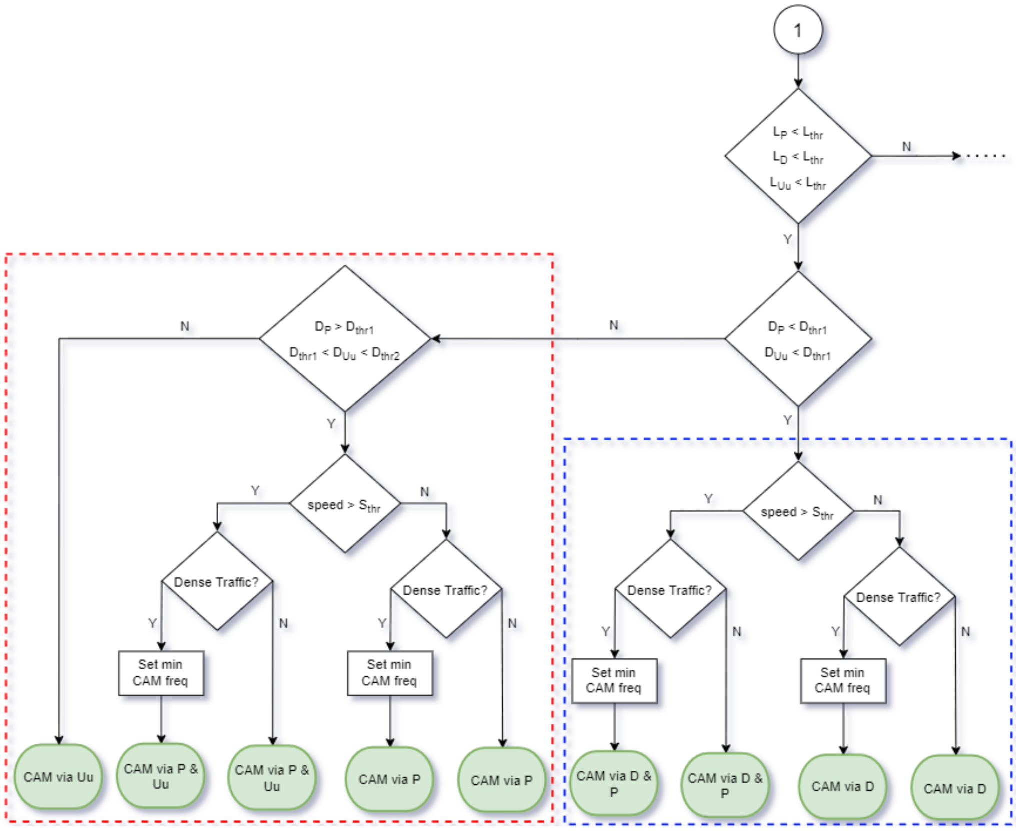

Figure 5. A small part of the detailed decision tree showing selection between the three technologies.

6. V2X Testbed Setup and Algorithm Implementation

6.1. Hardware Setup and Network Diagram

In this section, we elaborate on how we implement the proposed V2X technology selection algorithm in our V2X testbed. For this, we created a small-scale V2X testbed setup, as shown in Figure 6. We have integrated the following technologies such as DSRC, C-V2X PC5 and 5G NR Uu in the testbed.

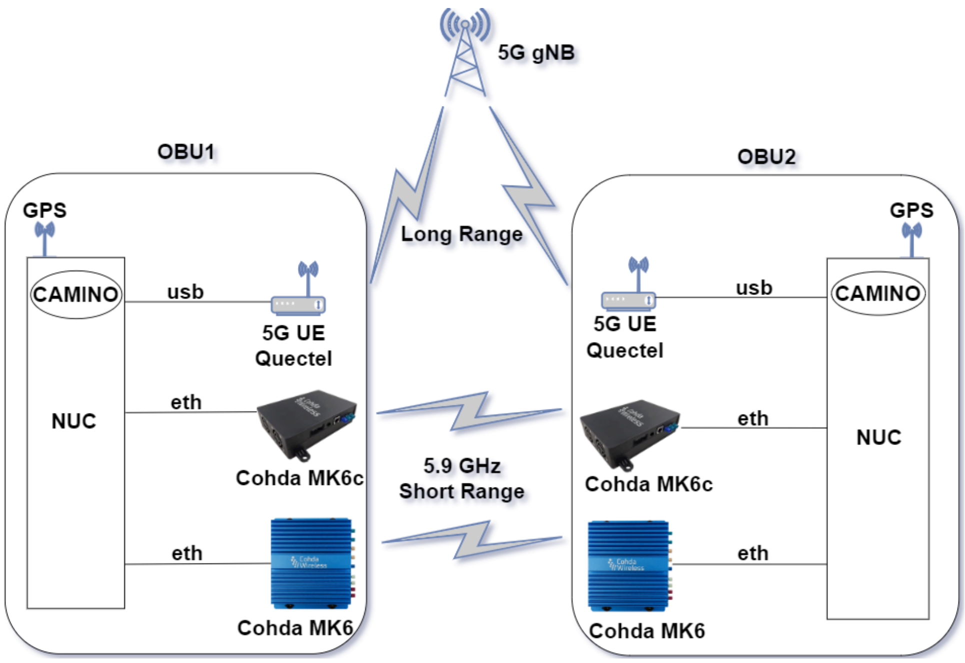

Figure 6. Network diagram of the experimental V2X setup.

The hardware setup, as shown in Figures 7–10, consists of two V2X nodes, both having Intel NUCs as the main processing units. An in-house developed vehiCulAr coMmunIcation maNagement framewOrk (CAMINO) framework [16] 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 [20] and MK6 [21] modules. MK6c module provides C-V2X PC5 functionality whereas MK6 is used in DSRC mode. For precise positioning information, each device (Cohda MK6c, MK6 and NUCs) has its own GPS receiver. A portable Open RAN-based 5G standalone (SA) setup (Figure 7) is used for long-range V2X communication. It consists of a general high-end processing unit, a power unit, a Benetel 5G outdoor Radio Unit RAN650 [22], a 4G modem (for remote access and management), and a USRP. The Open RAN-based SA 5G solution is hosted on the processing unit along with the Open5GS Core, an open source 5G network core compatible with 3GPP Release 16. Two 5G Quectel UEs are connected to the NUCs via USB cables, and both of them connect using the Uu link with the Benetel 5G radio unit (Figure 7). A total of two V2X nodes, referred to as OBUs have been set up and named as OBU1 and OBU2. A Message Queuing Telemetry Transport (MQTT) server deployed on the 5G in-a-box setup is used for the long-range C-ITS message exchange between OBUs. For experimentation with mobility, OBU2 is placed inside a vehicle, whereas OBU1 is kept stationary. The stationary unit (OBU1) and the mobile unit (OBU2) are shown in Figure 8 and Figure 9, respectively. Figure 10 shows the Tx/Rx and GPS antennas on the roof of the vehicle.

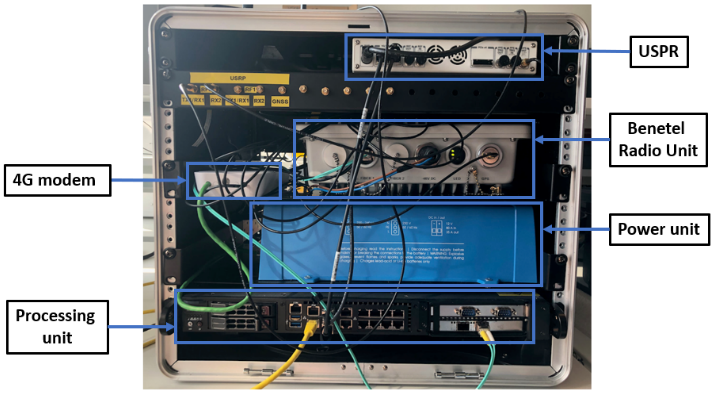

Figure 7. A portable Open Radio Access Network (RAN)-based 5G standalone (SA) setup.

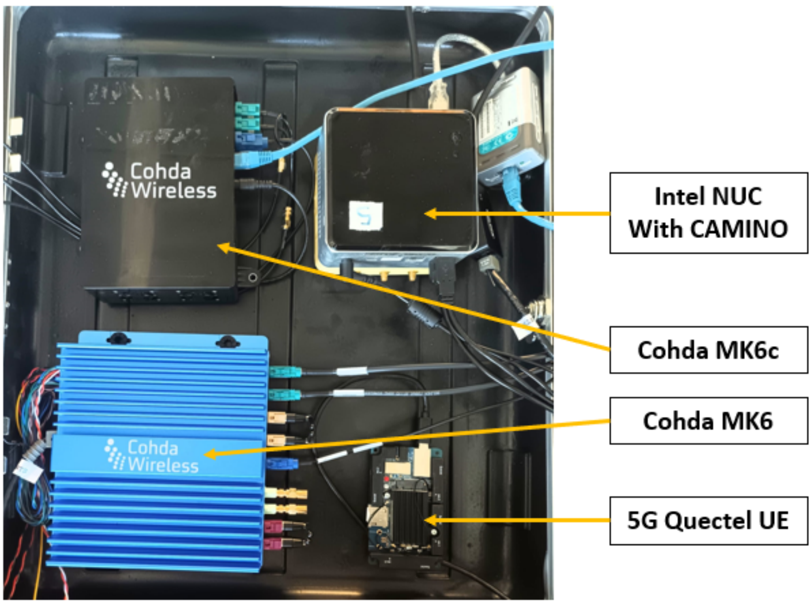

Figure 8. Stationary unit, referred as On-Board Unit 1 (OBU1).

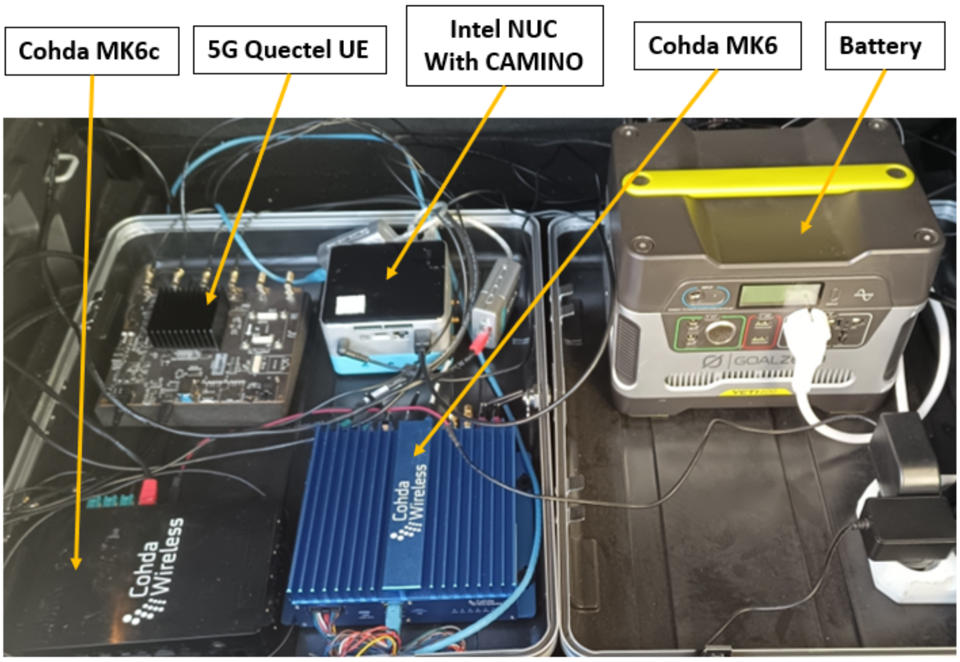

Figure 9. Mobile unit inside vehicle, referred as On-Board Unit 2 (OBU2).

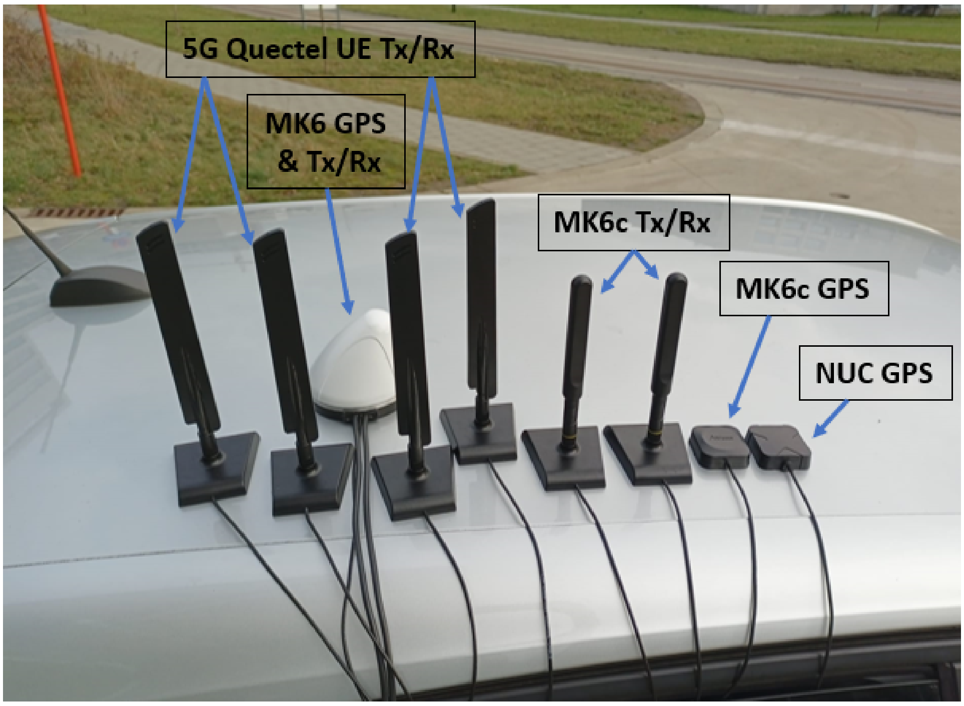

Figure 10. Tx/Rx and Global Positioning System (GPS) antennas on the roof of OBU2.

6.2. Algorithm Implementation

To ensure a fair comparison of short-range communication performance between DSRC and C-V2X PC5, both technologies were set up to transmit concurrently on distinct channels within the 5.9 GHz ITS band. This approach facilitates the evaluation of their performance under identical conditions, encompassing factors such as the distance between V2X nodes, traffic situation, and obstructions. The investigated ITS channels, 180 (for DSRC) and 184 (for C-V2X PC5), are strategically chosen to be non-adjacent, with the bandwidth between them serving as a guard frequency. We assume that all V2X nodes use these exact channel numbers for DSRC and C-V2X PC5. For 5G long-range transmissions, a licensed

40 MHz bandwidth with a center frequency of 3820 MHz is used. A MQTT server deployed on the 5G in-a-box setup is used for the long-range C-ITS message exchange between OBUs. Furthermore, each individual test underwent multiple repetitions with consistent settings to assess and validate the reproducibility of results. Both OBUs are provisioned with a Global Navigation Satellite System (GNSS) device for synchronization with respect to time, accomplished by deploying the Network Time Protocol (NTP) [23]. According to the standardization, these GNSS devices provide a time precision of 1 ms. Experiments were conducted in Technology park, Ghent, Belgium as shown in Figure 11. Each test starts from a LOS scenario (co-located OBU1 and OBU2) and then OBU2 moves away (dotted blue points) and then again gets back towards OBU1. At the testing site, LOS is available for every test up to the distance of 150–170 m approximately. All communication after this point is non-LOS.

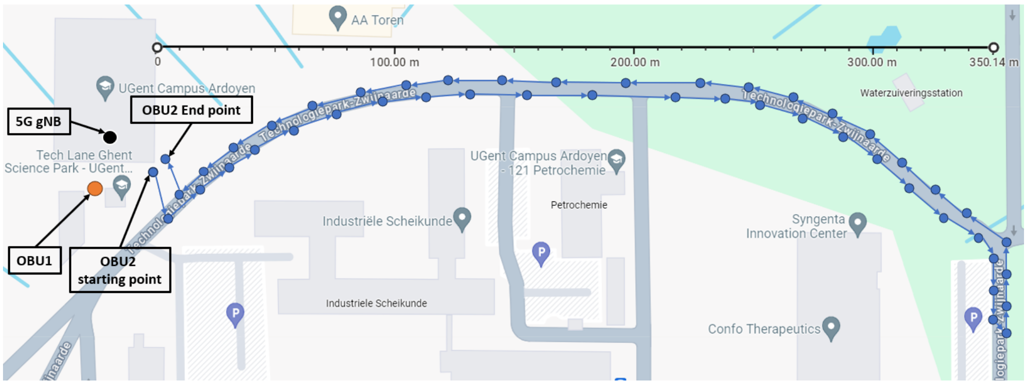

Figure 11. Location of OBU1 and driving trajectory of OBU2 for experiments conducted in Technology park, Ghent, Belgium.

The initial step involves the transmission and/or reception of CAMs and/or DENMs by OBUs, utilizing chosen V2X communication technology(ies), based on the defined selection criteria in alignment with the designated experimental scenario. Logging of messages (transmitted and received) is done at both OBUs, ensuring data integrity. Data could also be logged at a remote repository but this approach can suffer in case of disruptions in connectivity. The orchestration of diverse V2X technologies, the execution of associated services, and the data logging are managed by the internally devised CAMINO framework [16]. Following the experimentation, the post-processing is performed on the acquired data sets for the analysis of predefined KPIs. Throughout each test, both OBUs independently log transmitted and received data locally to mitigate potential data loss from connectivity disruptions. There are separate log files for CAMs and DENMs on each OBU unit. Table 3 provides a snapshot of CAMs logged in a local log file during the test campaign conducted on 20 December 2023. This snapshot shows CAMs being sent from one of the OBU unit via the long-range 5G link (denoted as CELLULAR), as well as the two short-range technologies i.e., DSRC and C-V2X PC5 (denoted as LTE-V2X).The details about CAMINO framework and geocasting for C-ITS long-range message exchange are as follows:

Table 3. Snapshot of a log file showing Cooperative Awareness Message (CAM) transmission and reception via Dedicated Short Range Communication (DSRC), LTE-V2X (PC5) and CELLULAR (5G).

Timestamp	Log Station Id	App Id	Action	Generated Station Id	V2X Technology	Message Type	TAI Time	UTC Time	asn1data
1703071463323	101	1	SENT	101	DSRC	ETSI.CAM	..53218	..16218	0102...
1703071463323	101	1	SENT	101	LTE-V2X	ETSI.CAM	..53218	..16218	0102...
1703071463323	101	1	SENT	101	CELLULAR	ETSI.CAM	..53218	..16218	0102...
1703071464288	101	1	RECEIVED	102	DSRC	ETSI.CAM	..54180	..17180	0102...
1703071464298	101	1	RECEIVED	102	LTE-V2X	ETSI.CAM	..54180	..17180	0102...
1703071464304	101	1	RECEIVED	102	CELLULAR	ETSI.CAM	..54180	..17180	0102...

6.2.1. The CAMINO Framework

The CAMINO framework [16] running inside NUCs serves as the central system for managing V2X communication technologies and services. It can seamlessly incorporate with present and forthcoming V2X technologies, new sensing elements, Human Machine Interface (HMIs), and external service providers. It can integrate with both current and future short and long-range V2X technologies such as DSRC, C-V2X PC5, and C-V2X Uu (5G/4G), as well as vehicle or roadside infrastructure sensors, actuators, Human Machine Interface (HMIs), and third-party service providers. Currently, the CAMINO-Core supports multiple ITS applications and provides basic implementation of Cooperative Awareness (CA), Decentralized Environmental Notification (DEN) and In-Vehicle Information (IVI). This allows sending and receiving CAM, DENM and In-Vehicle Information Message (IVIM). Prior to this study, V2X technology selection in CAMINO platform is based on the configuration settings without intelligence support. The code of CAMINO is modified in order to support intelligent hybrid V2X technology selection, which is described in detail in Section 5.

6.2.2. C-ITS Long-Range Message Exchange via Uu Using Geocasting

Contrary to the direct short-range message exchange between V2X nodes that focuses on broadcasting messages via C-V2X PC5 and DSRC/ITS-G5, long-range message exchange requires additional mechanisms and configurations due to its unicast nature. In [24], a broker-centric architecture is introduced for C-V2X communication, characterized by its openness and scalability. The messaging transport protocol employed is MQTT, which follows a Client-Server model utilizing a publish/subscribe pattern. This approach enables V2X nodes to exclusively receive messages relevant to their interests. The MQTT protocol operates over Transmission Control Protocol/Internet Protocol (TCP/IP) or other reliable network protocols, ensuring ordered, lossless, and bidirectional connections. In summary, MQTT's adaptable features render it a dependable and efficient choice for various communication requirements, particularly in resource-constrained environments where efficiency is crucial. The content of MQTT messages adheres to SAE standards [25], which delineate various message types, encompassing CAM, DENM, and IVIM, contingent upon the specific service provided. Similarly, an Advanced Message Queuing Protocol (AMQP)-based alternative broker-centric architecture called the Interchange has been developed in the NordicWay project [26], and later on adopted in the C-Roads specifications on hybrid C-ITS [27], and in the 5G Automotive Association (5GAA) V2X Application Layer Reference Architecture [28]. In this work, an open source MQTT broker, named 'Mosquitto' is set up in the portable O-RAN-based 5G standalone (SA) setup (Figure 7) that is used for long-range V2X communication. The architecture of the geocasting solution is intricately tied to the topic structure within the central broker. Intrinsic geocasting occurs when data is disseminated through short-range wireless communication, usually within a reception range spanning 300 to 1000 m, contingent upon local conditions. Conversely, when employing internet-based communication through cellular networks, a dedicated geocasting solution becomes imperative to uphold scalability. Multiple geocasting solutions exist, with one such approach being the tiling concept presented in [29]. The objective of geocasting is to guarantee that only messages pertinent to the recipient's location are transmitted.

7. Results and Analysis

In this section, results and analysis are presented based on the real measurements using our V2X testbed setup. Considering the spacial limitations of the used 5G licenses, as well as the non-LOS experimental scenario, the 5G range is limited to approximately 350 m. Similarly, using the maximum transmit power in our experimental scenario, the range for DSRC and C-V2X PC5 is approximately 220 m and 400 m, respectively. In order to evaluate the performance of the proposed hybrid V2X technology selection algorithm in a realistic manner, the transmit power values for DSRC and C-V2X PC5 have been reduced in order to have distinct coverage range for the three technologies. More specifically, with

10 dBm and 12 dBm transmit power for DSRC and C-V2X PC5, the effective transmission range reduces to approximately 125 m (denoted as D_{thr1}) for DSRC and 250 m (denoted as D_{thr2}) for C-V2X PC5. The reliability of the proposed hybrid V2X technology selection algorithm can vary a lot depending of the chosen L_{thr}. L_{thr} of 20 ms is used during the experimentation. These threshold values are derived considering the spacial limitations of the used 5G licenses, as well as on the basis of studies [5,30,31] of typical ranges and latencies. The speed threshold, S_{thr}, is set to 100 Km/h for the tests, however, it can be adapted depending on the traffic dynamics. Similarly, the CAM density threshold, $Dense_{thr}$, is set to 100 CAMs per second for experimentation as only two V2X nodes are considered. This depends on the available bandwidth and the number of V2X nodes in the vicinity. The time sliding window of five seconds is used, which means that the statistics are observed for the last five seconds before hybrid V2X technology selection decision is made for every CAM/DENM transmission. The lower value of the time sliding window can lead to less accurate analysis of the environment, which can lead to inefficient V2X technology selection decision making. However, using a higher value also comes with a cost. It can lead to a higher computational load and potentially may not represent the accurate and up-to-date traffic dynamics. In the next subsections, the KPIs have been plotted for the individual considered technologies without intelligence and the proposed intelligent hybrid V2X technology selection algorithm. A time accuracy of 1 ms is ensured in accordance with the specifications of the GNSS devices used for time synchronization. The performance of the proposed hybrid V2X technology selection algorithm is analyzed for CAM only as well as joint CAM and DENM transmission scenarios. Experimental statistics are shown in Table 4.

Table 4. Experimental statistics.

Parameter	Value
Testing rounds	10
Total testing days	5
Total CAMs sent	22,000
Total DENMs sent	52,000

7.1. One-Way End-to-End Latency

Figure 12 shows the Cumulative Distribution Function (CDF) of the observed one-way end-to-end CAM reception latency on OBU2 (the vehicle). The distance between OBU1 and OBU2 is varied from 1 to 350 m for this experiment and multiple trials were conducted to ensure statistical significance. Being built on top of 802.11p, DSRC uses CSMA/CA for accessing the wireless medium. Considering a small scale experimental setup, DSRC channel is always available and the CDF of DSRC is concentrated between 3–5 ms. This makes DSRC as a top contender for latency critical applications in low dense scenarios. However, as explained later, the drawback for DSRC lies in its limited coverage compared to the 5G long-range. Also, CSMA/CA can have an impact on latency in more dense scenarios. For C-V2X PC5 operating in mode 4, sensing-based SPS is used for radio resource selection. It can be observed that the one-way end-to-end CAM transmission latency for C-V2X PC5 and 5G long-range is higher than the one for DSRC but both of them provide better coverage than DSRC in our setup. For the hybrid scenario where technology selection decision is based on a number of selection criteria as described in Section 5, DSRC is preferred mode of communication for distances less than D_{thr1}. The intelligent algorithm senses the variation in distance and as soon as the distance between V2X nodes is higher than D_{thr1}, C-V2X PC5 is selected. Similarly, when the distance between V2X nodes is higher than D_{thr2}, 5G is selected. The curve for hybrid communication is a mixture of DSRC, C-V2X PC5 and 5G owing to the intelligent real-time statistics-driven V2X technology selection.

Figure 13 shows the distance variation between $OBU1$ and $OBU2$, the observed one-way end-to-end CAM transmission latency and the intelligently selected V2X technology. The distance and latency thresholds used for the tests are also plotted in Figure 13a and Figure 13b, respectively. $OBU1$ maintains a stationary position, while $OBU2$ (the vehicle) drives both away from and towards the $OBU1$. It should be noted that D_{thr1} and D_{thr2} are tuneable parameters and could be adapted based on the transmission ranges for DSRC and C-V2X PC5. Similarly, L_{thr} is another tuneable parameter and depends on the QoS requirements of the considered use case. Again, it can be observed from Figure 13 that DSRC is the only technology being used in hybrid scenario when the distance is less than D_{thr1}. However, when the distance is between D_{thr1} and D_{thr2}, both C-V2X PC5 and 5G have been selected intelligently as in Figure 13c. The reason for this is the L_{thr} of 20 ms. If the average C-V2X PC5 latency during the previous sensing window goes beyond the L_{thr}, CAMs are also sent via 5G as well in an attempt to reduce the transmission latency of CAM(s).

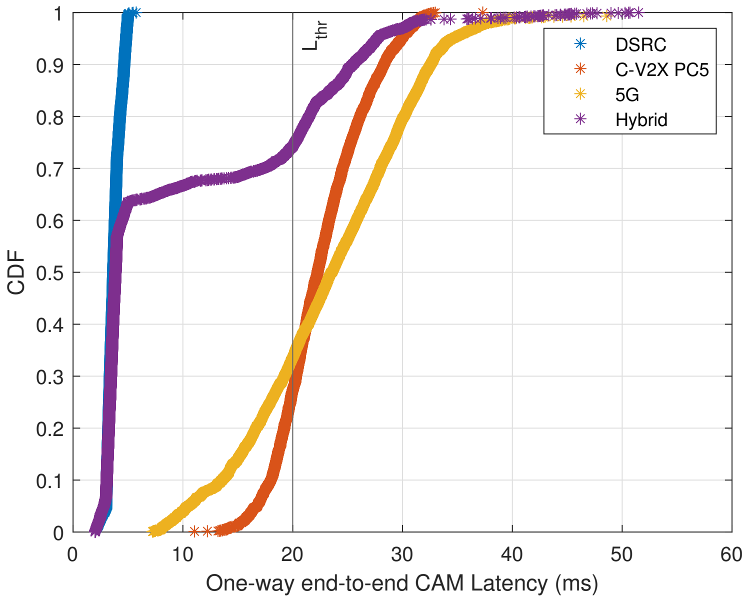

Figure 12. CDF of one-way end-to-end CAM latency showcasing improvement with hybrid V2X technology selection.

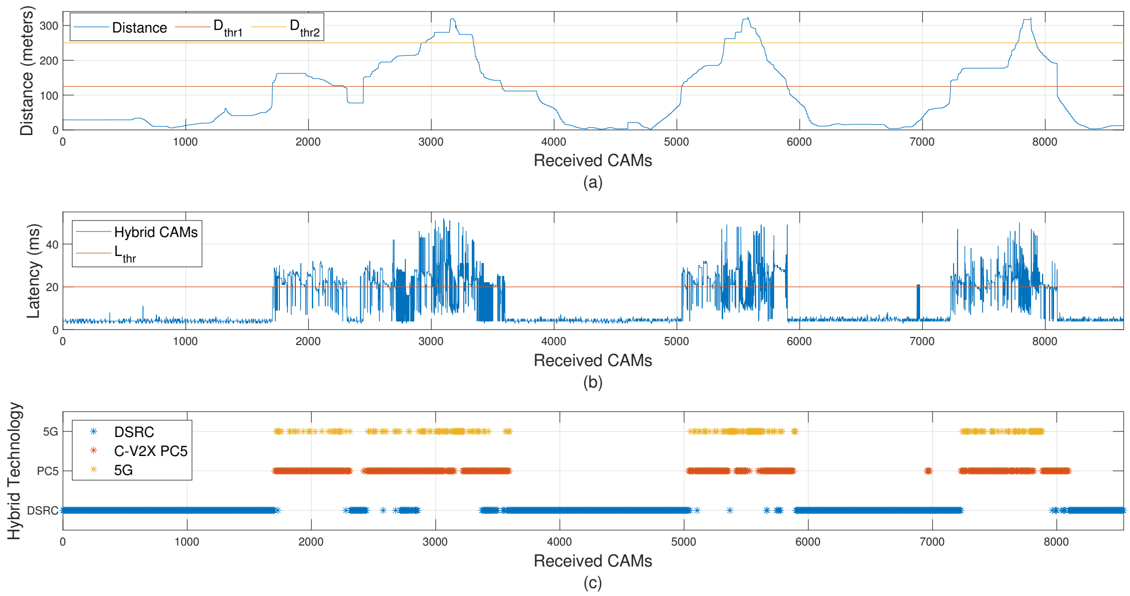

Figure 13. CAM transmission using hybrid V2X, (**a**) distance between OBU1 and OBU2, (**b**) observed one-way end-to-end CAM latency on OBU2, and (**c**) intelligently selected V2X technology on OBU1.

7.2. Packet Delivery Rate

Figure 14 shows the PDR of CAMs received on *OBU*2 (the vehicle). PDR is approximately 100% for both 5G and hybrid, irrespective of the distance. For DSRC and C-V2X PC5, due to the transmission power selection for Cohda MK6 (DSRC) and MK6c (C-V2X PC5) modules, PDR stays approximately 100% till D_{thr1} and D_{thr2}, respectively. Whereas, PDR is badly affected for both DSRC and C-V2X PC5 if the CAM transmissions continue beyond these distance thresholds. Even though the PDR for 5G is similar to that of hybrid scenario, Figure 12 suggests that the performance in terms of CAM transmission latency is far better for the hybrid as compared to the 5G only scenario. Moreover, the hybrid algorithm tries to maximize the transmissions in the 5.9 GHz ITS band, rather than utilizing the 5G band.

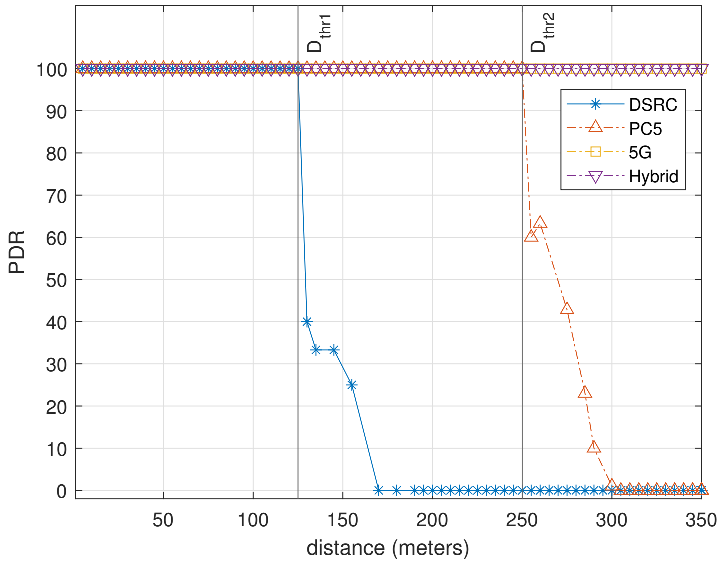

Figure 14. Packet Delivery Rate (PDR) maximization with hybrid approach along with the latency improvement shown in Figure 12.

7.3. Reliability

Figure 15 shows the CAM reliability for various sample latency thresholds. Here, the reliability is only plotted for the three individual technologies without incorporating the hybrid V2X. Reliability for DSRC is always 100% if the distance is less than D_{thr1}. For L_{thr} of 20 ms, the CAM reliability percentage is 37.4% and 38.5% for C-V2X PC5 and 5G, respectively. However, for higher thresholds of 25 ms and 30 ms, C-V2X PC5 is 18.43% and 13.83%, respectively, more reliable than 5G long-range. This is also evident from Figure 12 as the CDF plots of one-way end-to-end CAM latency for C-V2X PC5 and 5G long-range are more distant at 25 ms and 30 ms mark, as compared to the 20 ms mark. L_{thr} can be selected appropriately for any V2X application depending on the QoS constraints.

Contrary to Figure 15, in Figure 16, CAM reliability has been plotted versus the distance for a fixed L_{thr} of 20 ms, as used in the hybrid V2X technology selection algorithm. It can be observed that the CAM transmission via DSRC is 100% reliable for distance up to 160 m. This is also evident from the CAM latency CDF in Figure 12. After 160 m, CAMs are no more reachable implying infinite transmission time, as replicated by 0% reliability values for DSRC. However, it is important to clarify that CAM PDR is badly affected if the distance increases beyond D_{thr1}. Hence, it will be inefficient if CAM transmissions are continued via DSRC after D_{thr1}. A sudden drop in CAM reliability is observed once the distance is higher than D_{thr1} for hybrid scenario, implying usage of C-V2X PC5 or 5G. It is justified because the CAM PDR is still 100% for these two technologies past D_{thr1}. As also observed from Figure 13, when the distance is between D_{thr1} and D_{thr2}, the hybrid V2X technology selection algorithm mostly chooses C-V2X PC5. However, depending on the latency constraints of a particular V2X application, occasional use of 5G long-range is also observed. Due to this flexibility, CAM reliability is sometimes slightly better between the range of D_{thr1} and D_{thr2}. When the distance goes beyond the D_{thr2} threshold, and as the PDR of C-V2X PC5 is also adversely affected, it is crucial to rely on long-range 5G communication link for which the PDR stays very high over the longer distances. Over the whole distance sweep till D_{thr2}, C-V2X PC5 and 5G have almost similar CAM reliability. It is important to clarify that the behaviour could be different if the latency threshold changes to any other value. For example, for latency threshold of 30 ms, in can be observed from Figure 12 that the 95% of the CAMs received via C-V2X PC5 have latency less than 30 ms, while for 5G, only 80% of them have latency less than 30 ms. These values are based on actual measurements in our testbed. Nonetheless, it is important to mention that depending on the number of V2X nodes in a broader setup and the load on any particular technology, these numbers can change. These variations have been catered via different branches of the proposed hybrid V2X technology selection decision tree, as shown in the Appendix A. The CAM reliability curve for the hybrid scenario showcases the usefulness of hybrid V2X technology selection as it strives to constantly maximize the CAM transmission reliability irrespective of the distance.

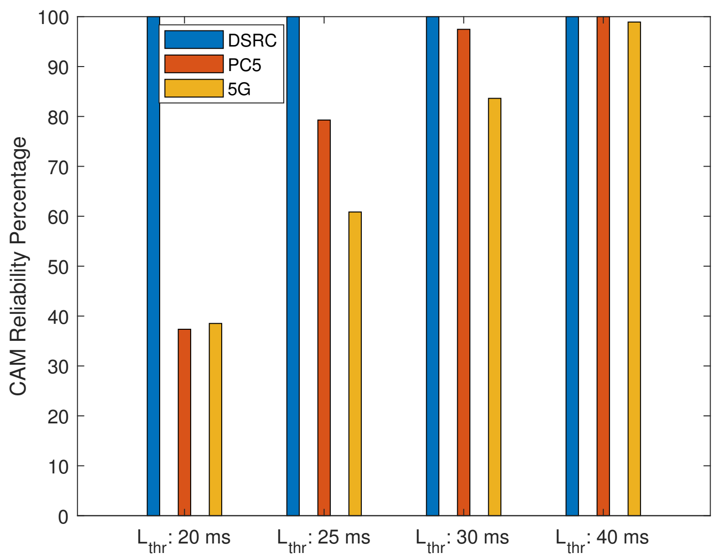

Figure 15. CAM reliability percentage for different latency thresholds at any distance $\leq D_{\text{thr1}}$.

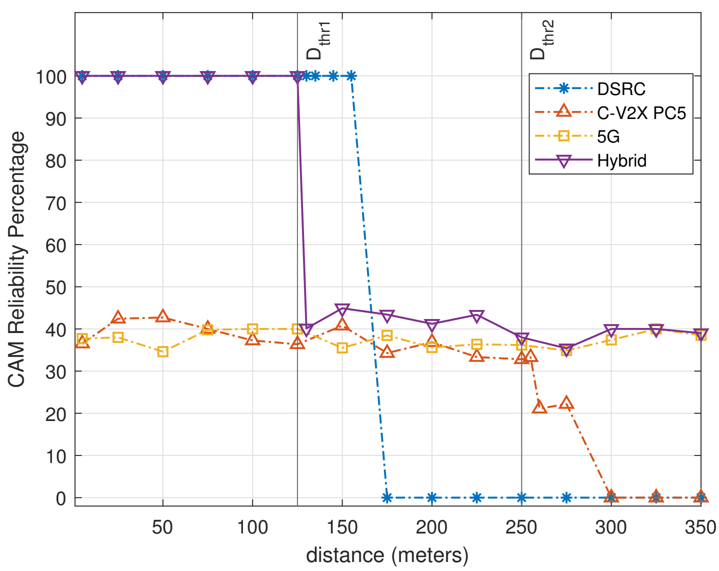

Figure 16. CAM reliability maximization with hybrid approach for L_{thr} = 20 ms.

7.4. Simultaneous CAM and DENM Transmission

In conjunction with the periodically transmitted CAMs, there may be a necessity to transmit dynamically triggered DENMs for various reasons. DENMs can be sent for notifications such as Slow or Stationary Vehicle (SSV), Road Works Warning (RRW), Accident Notification (AN), and Emergency Vehicle Alert (EVA), among others. The proposed hybrid V2X technology selection algorithm also accommodates DENMs and tries to create a balance between CAMs and DENMs. In this regard, multiple approaches can be considered, such as: (a) to pause CAMs for a certain duration, (b) to use different technologies for CAMs and DENMs, and (c) to adapt CAM and DENM frequency in order to minimize the load on the network, meaning, the traffic densities for CAMs and DENMs. In this study, option (c) has been considered. For highly dense traffic scenarios, combination of option (b) and (c) could also be considered along with the underlying pros and cons. This is outside the scope of this paper and will be considered in our future work. Table 5 summarizes CAM/DENM transmission frequencies being used by the proposed hybrid V2X technology selection algorithm for (1) CAM only, and (2) CAM with DENM scenarios. For CAM only scenario, the decision about CAM transmission frequency is based on the CAM density in the last sensing window and its comparison with the density threshold for a particular technology. The vehicle speed is also considered for the selection of CAM transmission frequency. Contrary to it, for joint CAM and DENM transmission scenario, the proposed algorithm considers the minimum possible frequency for CAMs i.e., 1 Hz, whereas, for a better dissemination of crucial time-limited DENMs, the average frequency value has been used i.e., 5 Hz. The reason behind this DENM frequency selection is to create a balance between putting too much load on the network, in turn optimizing resource utilization, and also avoiding the usage of minimum DENM frequency value, in turn, optimizing the reachability of DENMs.

Table 5. CAM and DENM rate adaptation for joint transmission scenarios.

	CAM Only	**CAM & DENM**
CAM density $< Dense_{thr}$	$f_{CAM} = 10$	$f_{CAM} = 1$, $f_{DENM} = 5$
CAM density $\geq Dense_{thr}$	$f_{CAM} = 1$	$f_{CAM} = 1$, $f_{DENM} = 5$

Figure 17 shows the results for the test where both CAMs and DENMs are sent intelligently. The distance between $OBU1$ and $OBU2$ is shown in Figure 17a. The observed one-way end-to-end latency for hybrid CAMs and hybrid DENMs is plotted in Figure 17b as the $OBU2$ (the vehicle) moves towards and away from the $OBU1$. The same latency and distance thresholds have been used for this experiment as well. As the distance is varied, the hybrid V2X technology selection algorithm selects different technologies, as in Figure 17c for sending the next scheduled CAM/DENM. The highest latency values were observed when the distance was greater than D_{thr2}, implying long-range 5G as the only possible technology for maximizing CAM/DENM PDR. It can also be compared with the CDF of the received CAM latency from Figure 12, where the curve for 5G accounts for the portion of values greater than 40 ms. For distance greater than D_{thr2}, irrespective of the fact that both CAMs and DENMs also experience high latency values as in Figure 17b, C-V2X PC5 and/or DSRC are not considered due to their limited transmission ranges. For distances between D_{thr1} and D_{thr2}, it is observed that mostly both CAMs and DENMs are sent via C-V2X PC5. However, to maximize the reliability of CAMs and DENMs between D_{thr1} and D_{thr2}, CAMs and DENMs are occasionally sent via 5G if the average one-way end-to-end CAM reception latency via C-V2X PC5 falls below the L_{thr}. As emphasized in Table 5, the proposed hybrid V2X technology selection algorithm adapts the CAM transmission frequency in order to better accommodate the DENMs without burdening the network in the presence of DENMs.

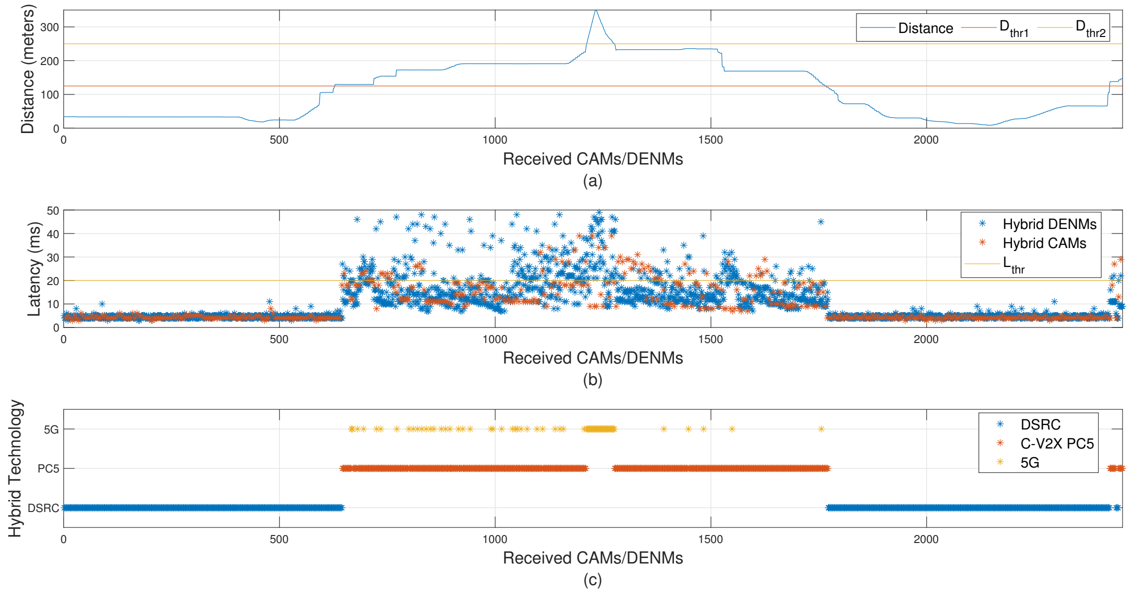

Figure 17. Joint CAM and Decentralized Environmental Notification Message (DENM) transmission scenario using hybrid V2X, (**a**) distance between OBU1 and OBU2, (**b**) observed one-way end-to-end latency for CAMs and DENMs on OBU2, and (**c**) intelligently selected V2X technology on OBU1.

8. Conclusions & Future Directions

This article has proposed an intelligent hybrid V2X technology selection algorithm by combining the strengths of both short-range and long-range vehicular communication technologies. DSRC, CV2X PC5, and 5G Uu capabilities have been integrated in V2X nodes and the selected KPIs, including one-way end-to-end latency, PDR, and Reliability have been evaluated. A fair experimental analysis of hybrid V2X communications has been conducted in a real-life road environment with two V2X nodes. Through the utilization of our in-house developed CAMINO V2X communication management framework along with the hybrid V2X extensions, we conducted a rigorous assessment of the technologies under uniform conditions. This encompassed various transmission-related parameters such as transmission intervals, packets sizes and simultaneous transmissions from different V2X technologies. Each test iteration was repeated multiple times to guarantee the reproducibility of the results.

According to the experimentation results, hybrid V2X technology selection optimizes CAM transmission latency, PDR, and reliability. Although DSRC offers lower latency than C-V2X PC5 and 5G, it has the smallest range in our setup. Contrary to it, C-V2X PC5 has a better range in our experimental setup but it suffers in terms of latency. Intelligently adapting the CAM and DENM transmission frequency in a joint CAM and DENM transmission scenario is shown to proactively minimize the network congestion and degradation of KPIs, especially in dense scenarios. Conducting scalability tests becomes imperative to derive broader conclusions regarding the impact of a high user density environment on the one-way end-to-end latency performance of individual technologies, as well as to assess the influence of DENM messages on technology performance. Nevertheless, executing these tests with real-hardware presents considerable challenges due to the demanding prerequisites, necessitating a substantial number of V2X nodes.

Some of the future research directions in this domain include a more scalable implementation, variable number of V2X nodes, and inclusion of further C-ITS message types and their respective use cases. Novel machine learning-based solutions and clustering of V2X nodes could also be explored for hybrid V2X communications. Moreover, LiFi, an interesting technology that can use headlamps of vehicles and/or street lights for communication, could be explored in the context of hybrid V2X communications. The potential use of

NR sidelink considering its unicast capabilities alongside the usual multicast features could be explored. This could be useful for applications such as critical/crisis communication.

Author Contributions: Conceptualization, I.K., V.M. and D.N.; methodology, I.K., V.M. and D.N.; software, I.K., V.M. and D.N.; validation, I.K.; formal analysis, I.K.; investigation, I.K.; resources, I.K.; data curation, I.K.; writing—original draft preparation, I.K.; writing—review and editing, I.K., V.M., D.N., A.S. and I.M.; visualization, I.K.; supervision, I.M.; project administration, V.M., D.N., A.S. and I.M.; funding acquisition, D.N., A.S. and I.M. All authors have read and agreed to the published version of the manuscript.

Funding: This article has received funding from the European H2020 Program under grant agreement 952189 (5G-BLUEPRINT project) and by the Horizon Europe program under the MCSA Staff Exchanges 2021 grant agreement 101086218 (EVOLVE project).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

3GPP	Third Generation Partnership Project
5GAA	5G Automotive Association
ADAS	Advanced Driver Assistance Systems
AMQP	Advanced Message Queuing Protocol
AN	Accident Notification
BSM	Basic Safety Message
CA	Cooperative Awareness
CAGR	Compound Annual Growth Rate
CAM	Cooperative Awareness Message
CAMINO	vehiCulAr coMmunIcation maNagement framewOrk
CAV	Connected Autonomous Vehicles
CDF	Cumulative Distribution Function
C-ITS	Cooperative Intelligent Transport Systems
CSMA/CA	Carrier-Sense Multiple Access with Collision Avoidance
DEN	Decentralized Environmental Notification
DENM	Decentralized Environmental Notification Message
DSRC	Direct Short Range Communication
EVA	Emergency Vehicle Alert
FDD	Frequency Division Duplex
FDR	Frame Delivery Rate
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMI	Human Machine Interface
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IVI	Infrastructure to Vehicle Information
IVIM	Infrastructure to Vehicle Information Message
KPI	Key Performance Indicators
LOS	Line of Sight
LTE	Long Term Evolution
MNO	Mobile Network Operator
MQTT	Message Queuing Telemetry Transport
NR	New Radio

NTP	Network Time Protocol
OBU	On-Board Unit
PDR	Packet Delivery Rate
PRB	Physical Resource Block
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RRW	Road Works Warning
RSU	Road Side Unit
RTT	Round Trip Time
SAE	Society of Automotive Engineers
SCM	Sidelink Communication Manager
SPS	Semi Persistent Scheduling
SSV	Slow or Stationary Vehicle
TCP	Transmission Control Protocol
UE	User Equipment
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

Appendix A

The complete and detailed decision tree for CAM transmission is shown below with numbered tags representing further branches. Here DSRC, PC5, 5G Uu are referred as D, P and Uu, respectively.

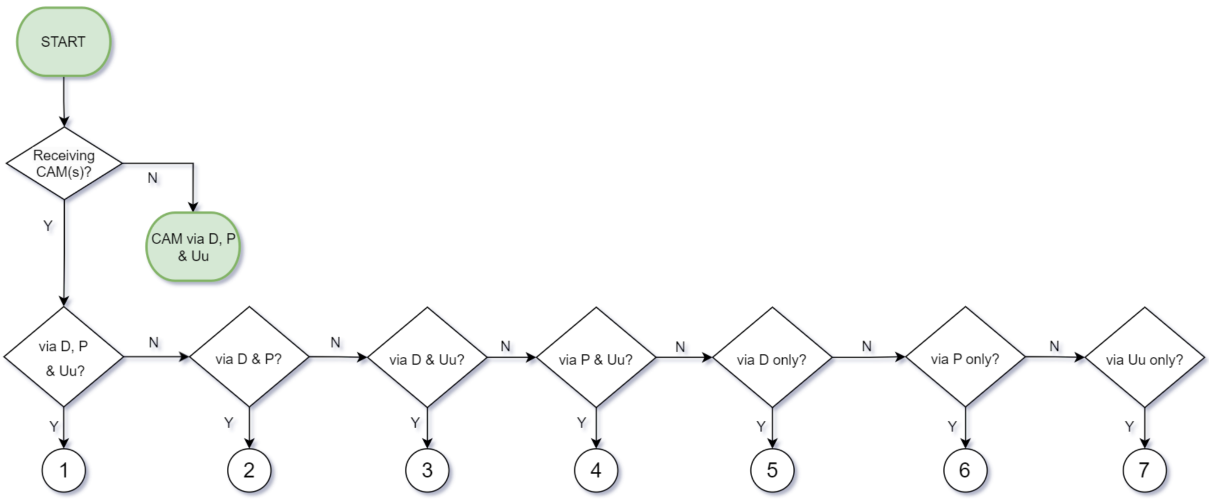

Figure A1. Start of the intelligent hybrid V2X technology selection algorithm.

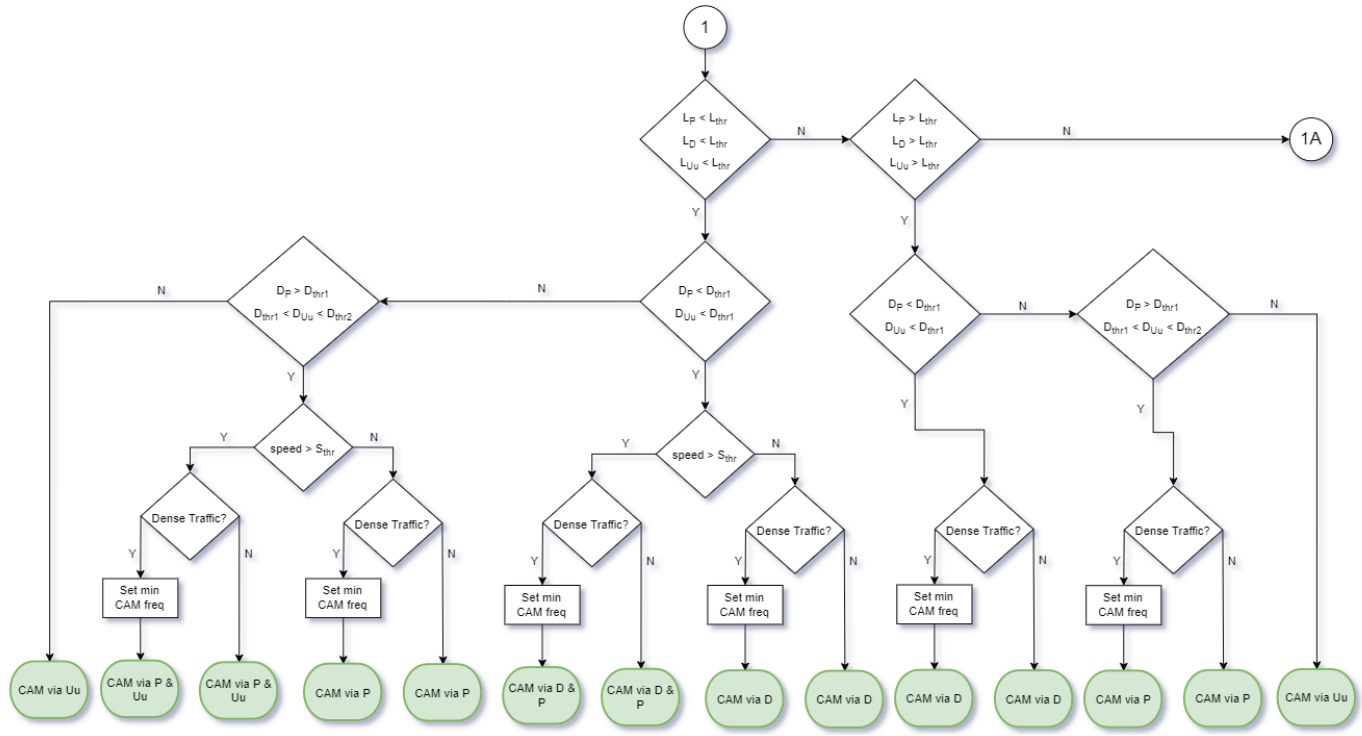

Figure A2. Receptions via all three technologies (numbered tag 1).

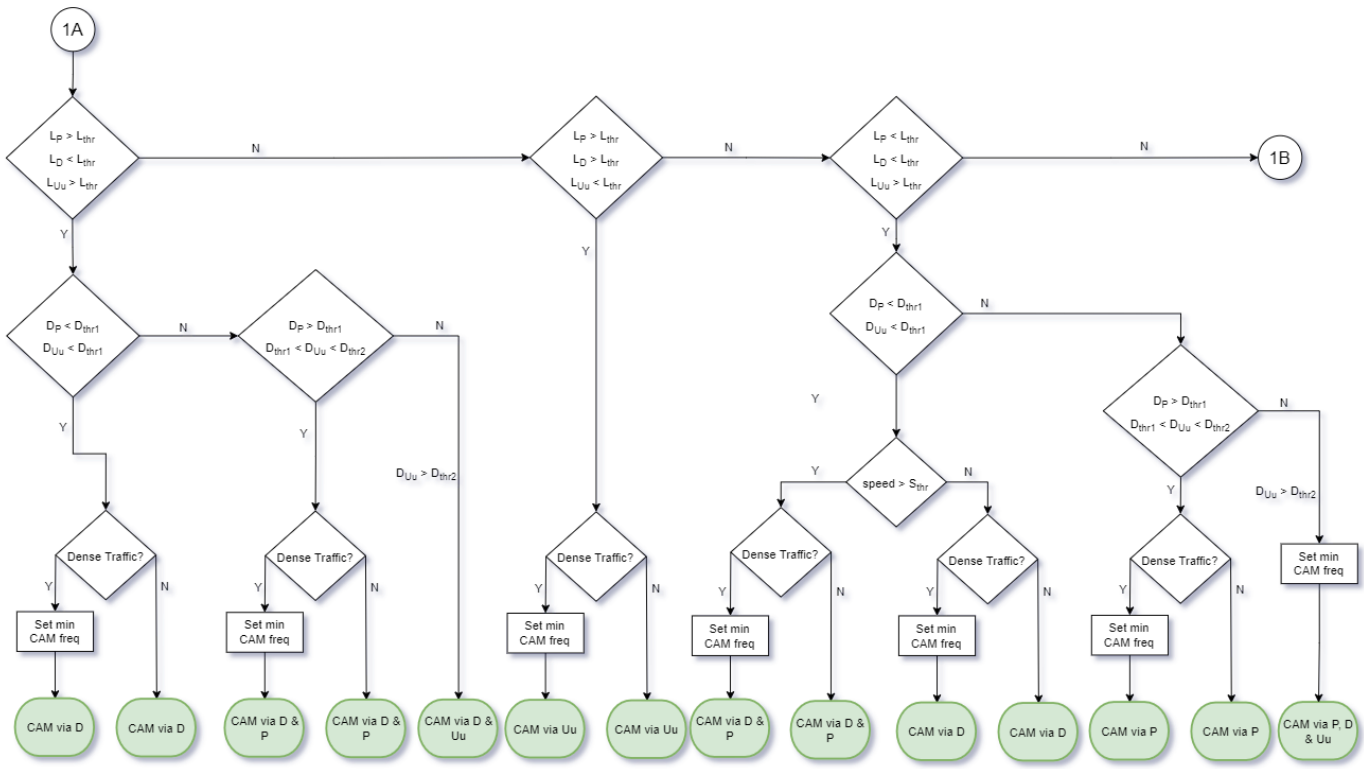

Figure A3. Receptions via all three technologies (numbered tag 1A).

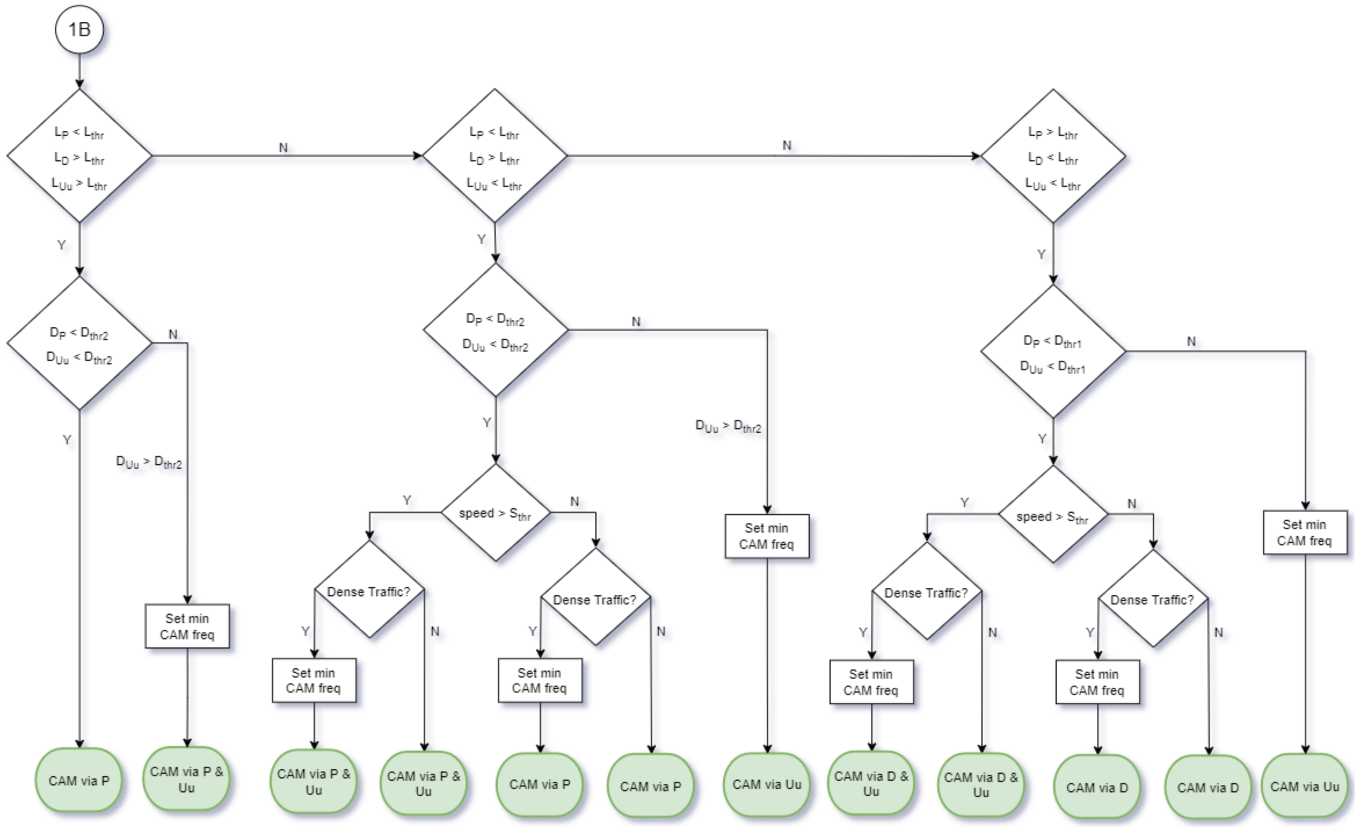

Figure A4. Receptions via all three technologies (numbered tag 1B).

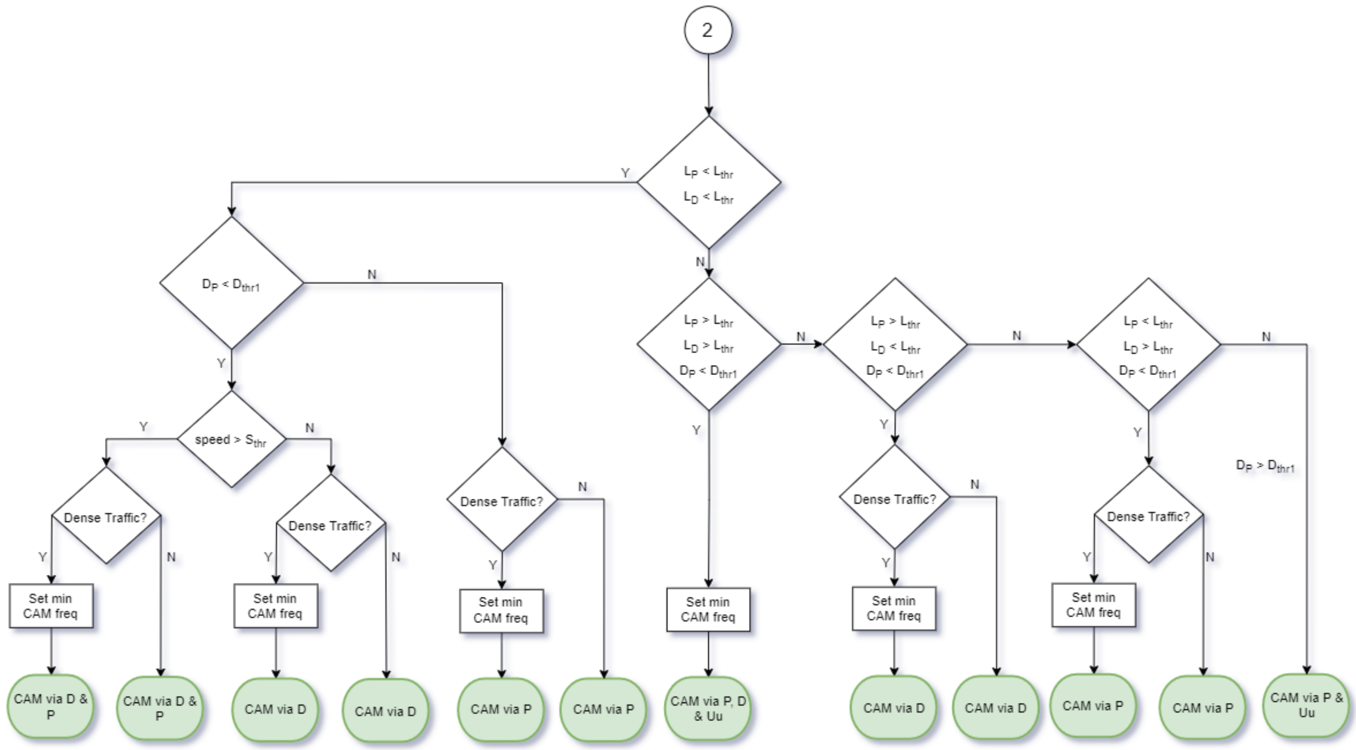

Figure A5. Receptions via DSRC and PC5 only (numbered tag 2).

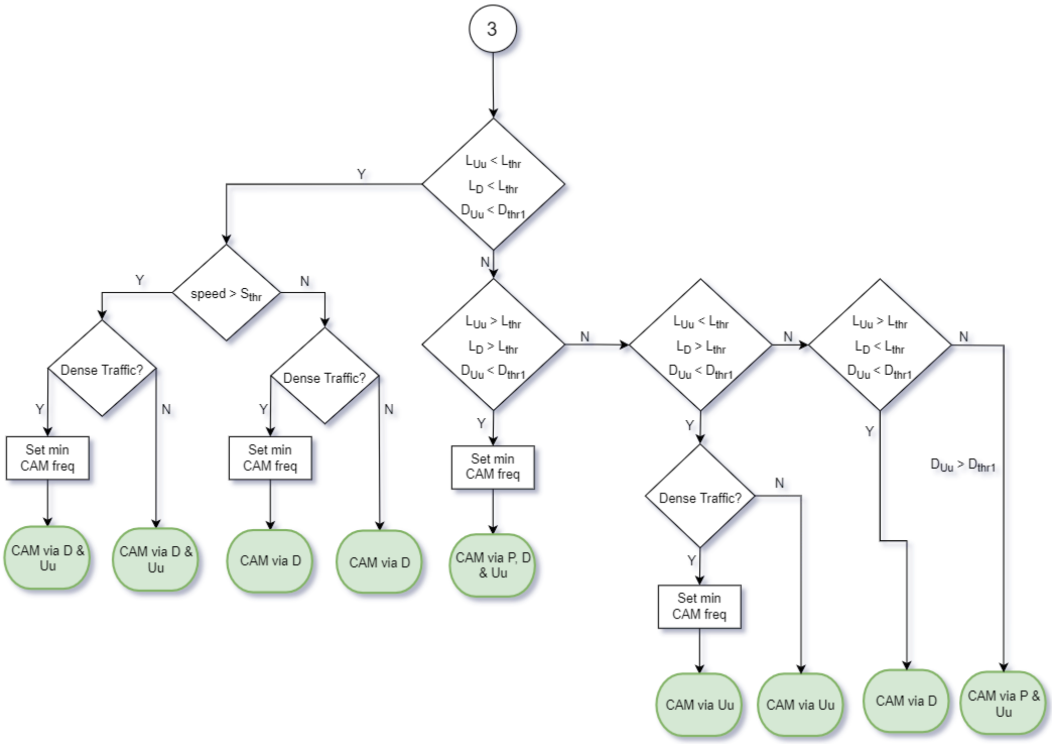

Figure A6. Receptions via DSRC and 5G only (numbered tag 3).

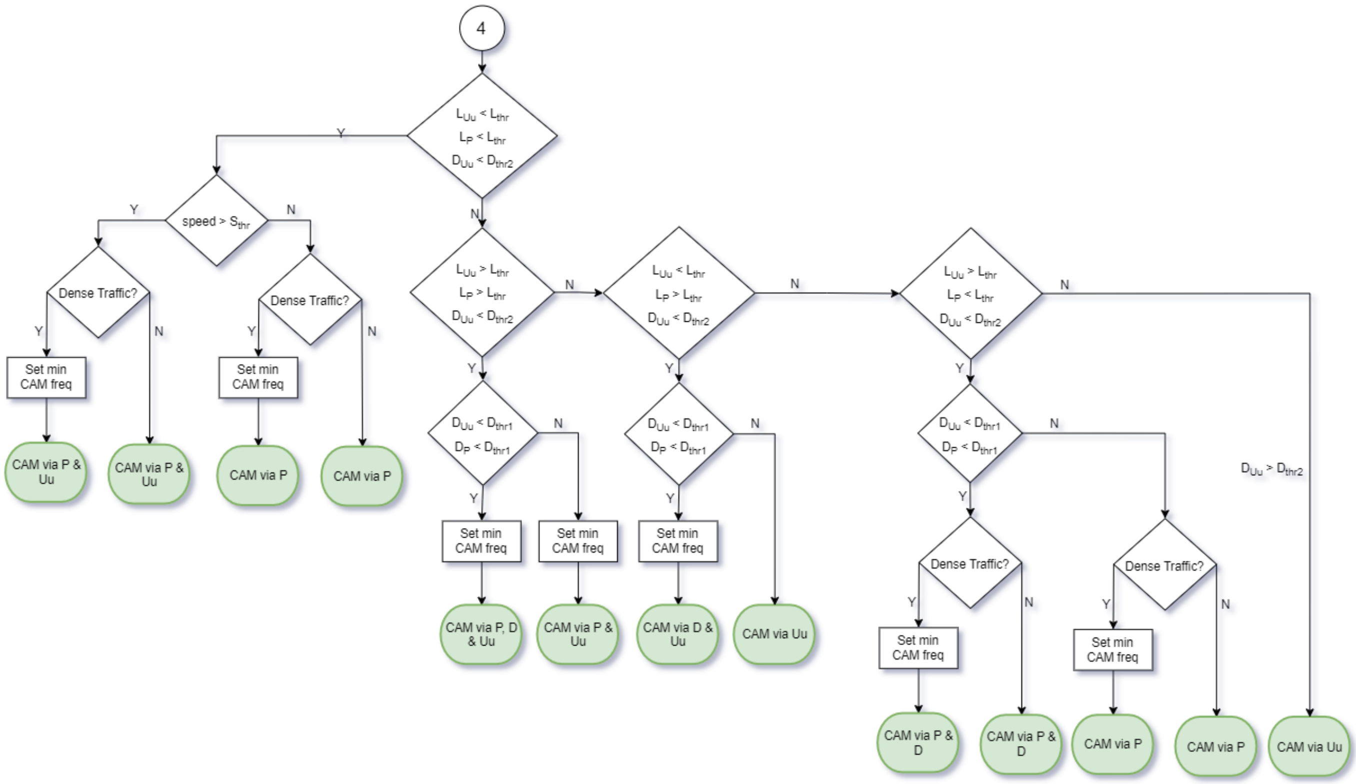

Figure A7. Receptions via PC5 and 5G only (numbered tag 4).

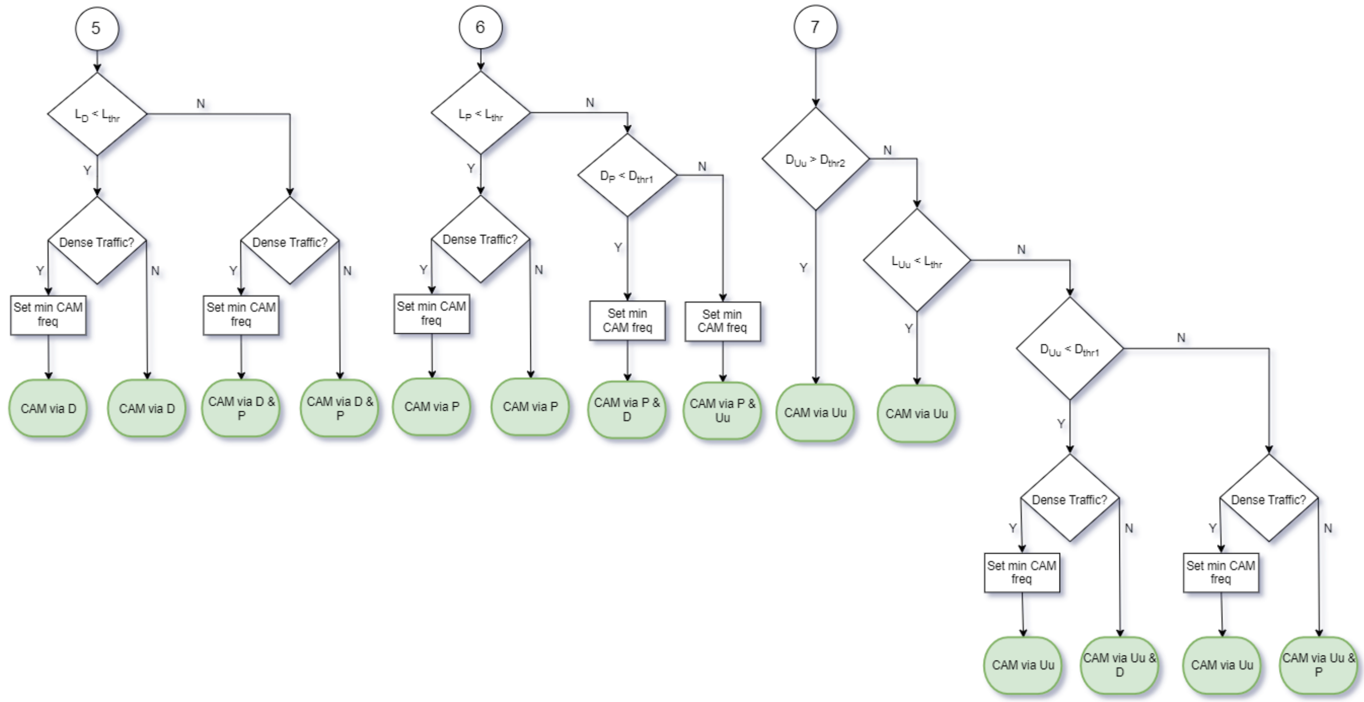

Figure A8. Receptions via DSRC or PC5 or 5G (numbered tag 5, 6 and 7).

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