MŰEGYETEM 1782

Budapest University of Technology and Economics
Faculty of Electrical Engineering and Informatics
Department of Networked Systems and Services

Gergely Attila Kovács

MULTI-ACCESS EDGE COMPUTING WITH HYBRID 5G NR V2X TECHNOLOGIES FOR COLLECTIVE PERCEPTION-BASED SCENARIOS

SUPERVISOR

Dr. László Bokor

BUDAPEST, 2023

Contents

Abstract

Vehicle to Everything (V2X) communications are increasingly important in Advanced Driver Assistance Systems. Using V2X, many safety-related and traffic-optimizing applications can be implemented. Among other advantages, these services aim to reduce the severity and frequency of traffic accidents, balance fuel consumption, and reach optimal road usage [1]. With rapid developments in cellular technologies, a new LTE-based approach emerged in the form of C-V2X (Cellular V2X) [2] to compete with the original Wi-Fi-based access technology. C-V2X offers direct communication between devices (via PC5 interface) while also leveraging the cellular infrastructure (via Uu interface), which is a rather tempting feature. As the newest enhancements in radio technology and core functions become available with 5G NR, the strengths of C-V2X become more apparent. A new paradigm regarding cloud computing, namely Multi-Access Edge Computing (MEC), is a potentially great asset for cooperative V2X applications (e.g., cooperative lane change, Collective Perception, etc.) and other (partially) centralized services with heavy resource requirements. With the combination of 5G NR and MEC technologies, realizing advanced applications like remote driving becomes achievable [3]. This extreme example highlights the strictest requirements: high reliability and bandwidth, low packet loss rate, and latency. Satisfying these requirements becomes more complex in metropolitan areas where, e.g., user density and channel attenuation due to building structures impact the performance of V2X services. A possible solution might be the utilization of an expanded and optimized access technology via the hybrid use of PC5/Uu interfaces of 5G NR. With the addition of an adequate infrastructure (e.g., PC5-capable roadside units), vehicles can use multiple media to access MEC servers. However, to meet the strict requirements, the network must be able to dynamically switch between the interfaces and choose the appropriate routes, e.g., via network slicing, to maintain an optimal Quality of Service (QoS).

Real-world implementations of V2X services interacting with MEC platforms are either unavailable or very limited nowadays. Thus, the go-to option for model implementation and validation is the use of realistic simulation frameworks that create the bridge between V2X applications and novel 5G services [4]. Artery/OMNeT++ implements the entire V2X protocol stack and is extendable with the models of 5G

modems, core element, and MEC implementation of the Simu5G library. The integrated framework can simulate scenarios with various model and parameter settings. This way, the most essential QoS metrics, like Channel Busy Ratio (CBR), packet loss, or MEC load, can be collected and analyzed. With this study, I aim to further extend the available simulation framework with models capable of communicating via PC5 interface, including an adequate implementation of the control plane mechanisms so that some technical aspects of the aforementioned dynamic handling of hybrid interfaces can be simulated and studied. Using the extended model, another goal is to implement a Collective Perception-based application capable of forwarding Collective Perception Messages (CPM) towards a service hosted on an MEC server. The measurements focus on the effects of switching between PC5 and Uu interfaces while different CPM generation rules are applied. I plan to analyze some options for the switching mechanism of the interfaces by analyzing CBR and other QoS metrics like packet loss or latency.

1 Introduction

One of the key drivers behind cooperative intelligent transport systems (C-ITS) is the use of V2X (Vehicle-to-Everything) communication between vehicles and road infrastructure. Today, with Day 2 and beyond [5] services, the cooperative nature of the services relies heavily on shared sensory information to collectively build a shared view of the environment for greater safety and more optimized traffic. Collective Perception (CP) [6], [7] may be called the successor of the Day 1 application Cooperative Awareness (CA); its purpose beyond sending state information of the ego vehicle is to exchange data about the perceived environment. In Europe, ETSI published a report in 2019 [8] on the necessary background for a standardized CP service, i.e., use cases, the technical details about message dissipation, etc. Nevertheless, the concept and the potential use cases have occupied many researchers over the years [9]–[11]. The specification of the Collective Perception Service (CPS) containing the refined message format to be used (Collective Perception Message – CPM) and the thorough description of the service was finally released in June 2023 [12].

Not surprisingly, the sharing of real-time object data has rigorous requirements in terms of low latency for the data not to become obsolete or inaccurate and in terms of high throughput when it comes to, e.g., high-definition video feeds or very detailed 3D LiDAR point cloud. Therefore, such services' effectiveness depends on the underlying access technology, like the two most potent candidates, the IEEE 802.11p-based ITS-G5 (or DSRC in the U.S.) or the LTE-based C-V2X. Performance-wise, the two approaches – and their respective enhancements, 802.11bd and 5G NR V2X– seem similar in many situations [13]–[16]. The competition is complex between the Wi-Fi-based and the cellular approach. Instead of comparing the two, this study will focus on cellular-based solutions. Despite the competition, a plausible solution for massive deployment might be a hybrid-RAT approach, with each technology having a dedicated role. Cellular (especially 5G) is promising. It means the ultimate technology for V2X purposes to many because it offers connectivity to traditional Internet-based network environments while also providing direct, device-to-device access. On top of that, many other modern trends and enhancements of the 5GS can back up the ever-more-complex V2X services, like the architecture of the core network supporting edge cloud systems and the many (network) functions that can be implemented using technologies like network slicing or Network Function Virtualization (NFV) [11].

With the increasing amount of raw/preprocessed data shared through the vehicular or mobile network, additional resources might be needed to process and extract relevant information for safety applications like collision detection. Edge computing seems to be a great balance between additional latency and the additional processing power gained. Multi-access Edge Computing (MEC) is being standardized to also be a great asset in V2X scenarios besides IoT and other industries, potentially being an essential asset for realizing cooperative sensing and sensor fusion-based scenarios or implementing advanced logic for Misbehavior Detection. Under the supervision of ETSI with the cooperation of telecommunication and automotive organizations, it is to become an integral part of 5G networks and the V2X ecosystem [17]–[21]. However, the complexity and dynamic nature of the composition of the technologies under discussion make the evaluation and optimization challenging with traditional methods, not to mention that proper dedicated hardware and testbeds are often expensive. To address this incommodity, the essential tools in the R&D of V2X services and access technologies, and others like the 5G architecture or MEC, are simulation frameworks for many researchers.

Built upon the OMNeT++ engine, one of the most used V2X simulators is Artery, a powerful tool for testing V2X services and applications [22]. However, the support for 5G network elements and technologies, or the direct PC5 link of the cellular access technologies, are not yet available within Artery by default. In [23], we introduced how the existing Artery simulator can be extended with a standalone 5G simulation library based on the same OMNeT++ platform, Simu5G [24]. The resulting integrated framework is capable of simulating the mechanisms of the NR Uu interface, and powerful core functionalities, like 5G MEC (Multi-access Edge Computing), are also available. Moreover, this integrated model collection can be enhanced with instantiated applications in the edge cloud. This way, the factor of easing computation for vehicles or the effectiveness of edge services based on Collective Perception can be easily verified or rejected with highly configurable, complex, and precise simulations. As for implementations for the PC5 sidelink interface, two known open-source solutions exist. OpenCV2X implements the C-V2X sidelink Mode 4 as defined in 3GPP Release 14 [25] and Artery-C introduces an implementation for Mode 3 sidelink with the necessary control plane elements [26]. Both solutions are built upon the existing device-to-device (D2D) capabilities of the LTE simulation framework SimuLTE [27], [28] (the predecessor of Simu5G) and adapted the mechanisms to fit the C-V2X environment according to the 3GPP specifications. With this existing implementation for LTE, the new specifications, and many studies on the NR PC5, an identical extension to Simu5G seems possible to provide the necessary playground for the simulations of the whole range of opportunities that come with NR V2X, including the support for MEC-based services, as well as Uu and PC5-based hybrid communication.

The scope of this study is the implementation and evaluation of CPM message propagation over C-V2X / NR-V2X interfaces (Uu / PC5) towards an edge cloud simulated in a realistic, integrated simulation environment. The primary aim is to test whether a hybrid PC5/Uu multi-interface operation is feasible and beneficial for cooperative V2X use cases utilizing the edge infrastructure.

2 Background

2.1 Relevant Industry Groups and SDOs

The essence of industrial progress is innovation and the precise definition and description of the innovation in the form of standards to ensure proper implementation and interoperability between different implementations. The automotive industry – and as such, the subset of the industry with interests in V2X – is no exception; to ensure interoperability between various OEMs, third-party service providers, mobile network operators, and other stakeholders, the different V2X services, the message formats being used, the auxiliary technologies, etc. should all (or at least most of them) be standardized.

Many associations and cross-industry groups concerned with the future of connected automotive scenarios exist in this field. Some of them collect global members, like the 5G Automotive Association (5GAA) or the Automotive Edge Computing Consortium (AECC), and some of them are more regional, like the CAR 2 CAR Communication Consortium (C2C-CC) in Europe. These organizations are primarily responsible for the innovation, creating the vision of how different segments of this field (communication technology, services, infrastructural assistance) should work while aiming to be (financially) beneficial for most stakeholders and meeting the essential criteria for being "useful" for society at the same time, e.g., by significantly reducing the impact and number of traffic accidents. The work of such groups can be a direct input for standards-developing organizations, like SAE International, the 3rd Generation Partnership Project (3GPP), or the European Telecommunications Standards Institute (ETSI), some of the important SDOs – from the perspective of this study – in the automotive, cellular mobile network, and ICT fields, respectively.

The following subsections will briefly introduce technologies envisioned and developed by some of the organizations mentioned above, in some cases in unison, highlighting not only the essential idea and benefits or the purpose of the technology under discussion but also the state of the standardization process.

2.2 Collective Perception Service

The Collective Perception Service (CPS), an ETSI-standardized Day 2 solution, serves as a fundamental framework for advanced collaborative V2X applications, specifically in vehicles equipped with environmental sensing capabilities. Vehicles utilizing the CPS seamlessly exchange their sensory data wirelessly, facilitating both distributed and centralized processing of the acquired data. This collective data is invaluable for a broad spectrum of safety-related applications. The CPS represents a pivotal advancement towards realizing fully automated cooperative transportation systems and, in turn, holds the potential to reduce traffic accidents involving human drivers significantly.

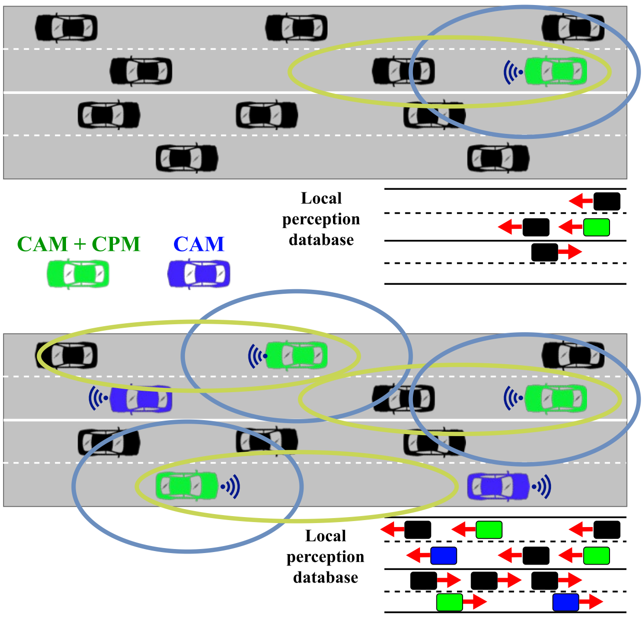


Figure 1. The effect of cooperative V2X services on the local perception database

To expand environmental awareness beyond the intrinsic sensor range of individual vehicles, the CPS employs the periodic transmission of messages, known as CPMs. These messages are structured to efficiently convey sensory data, encompassing crucial details such as the sender's static and dynamic attributes (which may vary based on the sender type, e.g., whether it is a Roadside Unit or a vehicle), sensor types and their corresponding parameters, as well as a catalog of detected objects with additional confidence values. The technical report preceding the standard [8] outlines the core concept of the CPS and its message format. It identifies two use cases where the service can be autonomously applied: detecting non-connected road users and identifying safety-critical objects. In both scenarios, the principal objective is to facilitate information sharing among vehicles regarding objects or other road participants that might remain obscured due to non-line-of-sight scenarios. Figure 1 illustrates the role of CPS in broadening the spectrum of perceived vehicles and its consequential impact on the local perception database of a given vehicle.

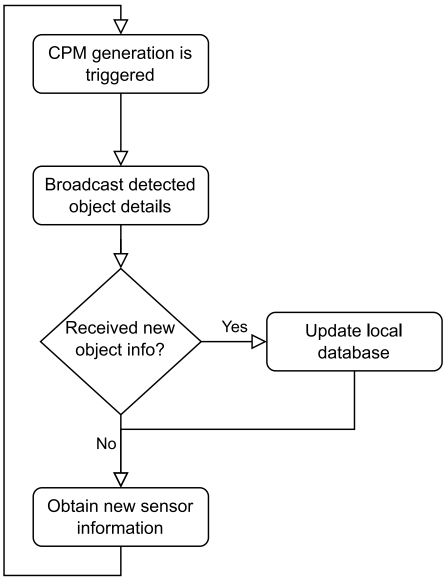


Figure 2. CPM generation flow

Within the domain of automated vehicles, the knowledge gathered through collective environmental perception becomes the bedrock for enhanced algorithms, such as those governing the computation of both standard and emergency trajectories. The report also contemplates the assimilation of information received via Cooperative Awareness Messages (CAM), the messages used by the Day 1 Cooperative Awareness (CA) service, thus elevating the quality of the services delivered by the infrastructure. One conceivable scenario involves a central entity aggregating data from multiple CAM and CPM sources near an intersection and subsequently relaying pertinent information to approaching vehicles from divergent directions, thereby enhancing their environmental awareness. It is essential to underscore that both CAM and CPM messages are broadcast periodically within the proximity of the sender vehicle, obviating the necessity for response messages from recipients. However, channel congestion can still cause service discontinuity with the increase in vehicle density. Therefore, the support for Multi-channel Operation (MCO) is valuable. Figure 2 offers a simplified schematic, presenting the key states involved in the periodic message generation process for a vehicle housing an operational CP service instance in the Facilities layer of its V2X stack.

2.3 Multi-access Edge Computing

Mission-critical safety applications require ultra-low latency. However, as we have seen, with Day 2+ applications, the amount of shared data increases rapidly, which then must be processed naturally to make sense. However, these calculations (e.g., object fusion or collision detection based on accurate trajectory calculation) often require computational capacity that is not available to the OBUs installed in the vehicles. Unfortunately, traditional cloud-based solutions might not meet the rigorous latency requirements of safety use cases due to the additional time it takes for both the raw and processed data to travel through the network (round-trip time) and the accumulated network load of the massive number of users. This problem outweighs the fact that cloud systems offer practically unlimited hardware resources for computationally heavy calculations and algorithms from the perspective of vehicle OBUs. Balancing this tradeoff, for the moment, one of the critical features of 5G mobile networks, namely Multi-access Edge Computing (MEC), seems to be a feasible solution to this problem in the automotive domain for quite a while now [18], [29].

MEC aims to reduce network load and, thus, the overall latency by placing server capacity to the network edge, offering cloud-like services locally, closer to the users. Not only safety applications could benefit from these advantages, but also infotainment services, especially as 5G mobile connectivity offering sufficiently high bandwidth becomes more widespread. For example, MEC might also play a role in video stream content distribution. But, the paradigm generally can satisfy a few other domains besides automotive, like Massive IoT or concepts like Tactile Internet [30], where, similarly to V2X use cases, many end-devices are running (often) delay-sensitive applications and constantly sharing extensive amounts of data to be processed. The name ‘multi-access’ comes exactly from the wide range of fields providing the potential devices using the edge services. MEC’s optimized network and high-performance computing abilities might also appeal to other domains, like industrial applications for smart manufacturing or even the maintenance and control of power grids [31], [32].

Cellular is a popular and, in many cases, a straightforward access technology for the above domains since, e.g., mobility is inherently a part of automotive, or in the case of IoT, many devices are installed in remote locations where no other convenient (or possible) means exist to connect to the Internet. MEC is being developed parallel to 5G mobile networks to integrate it tightly into the cellular ecosystem. Therefore, accessing the services provided by MEC should be effortless as 5G networks with MEC servers deployed become increasingly available. Another key enabler for MEC in automotive use cases is the fact that 5G seemingly has the potential to serve as an all-around access technology. NR V2X implements many fifth-generation enhancements, offering lower latency, higher bandwidth on the traditional Uu interface, and much more versatile functionality on the PC5 direct interface than the previous generation C-V2X. Since MEC and 5G are tightly coupled, opting for NR V2X means easy access to MEC or vice versa: the need for MEC makes cellular access technology more favorable.

2.4 Standards Enabling MEC

To create a standardized, multi-vendor platform where applications can be integrated and run seamlessly, ETSI took the initiative and created the Mobile-Edge Computing Industry Specification Group in late 2014. Since then, the group has published many technical reports and specifications focusing on all the aspects of MEC: the architecture, the APIs through which applications can connect to the system, interoperability considerations, and so on. The group, as the technology itself, has been renamed since then: the term ‘mobile’ was replaced with ‘multi-access’ to represent the different domains more accurately. Although ETSI is developing MEC itself, integrating into cellular networks and the elaboration of V2N solutions would not be possible without 3GPP and its support for edge solutions. Unsurprisingly, the two SDOs work closely on this topic [33]. Therefore, besides introducing the essential ETSI MEC specifications, this section will describe the key specifications that enable edge computing to be integrated into the classical 3GPP mobile networks.

2.4.1 ETSI MEC

The following subsections will introduce the ETSI MEC infrastructure and some of its essential features and mechanisms for advanced scenarios like V2X. Although the platform itself can support many more domains, to stay within the scope of the study, the emphasis is still on the MEC enablers for V2X services.

2.4.1.1 Framework and Architecture

Among the handful of specifications, the heart and soul of the whole platform is defined in GS MEC 003, laying down the framework and reference architecture with a high-level description of the functional elements and logical reference points [21]. In

Figure 3, the generic entities of the system are visible. The framework itself enables the quick and easy implementation of software-only MEC applications running in a virtualized environment, which is located near the network edge, as discussed above. The entity running the applications is the *MEC host*, which also contains a *MEC platform* collecting essential functionality for running applications and offering MEC services (e.g., Location Service), and the *Virtualization infrastructure,* which provides physical and network resources for running the application instances. The MEC apps are configured and instantiated based on external requests validated by the MEC management entities and realized as virtualized applications (e.g., virtual machines or containers).

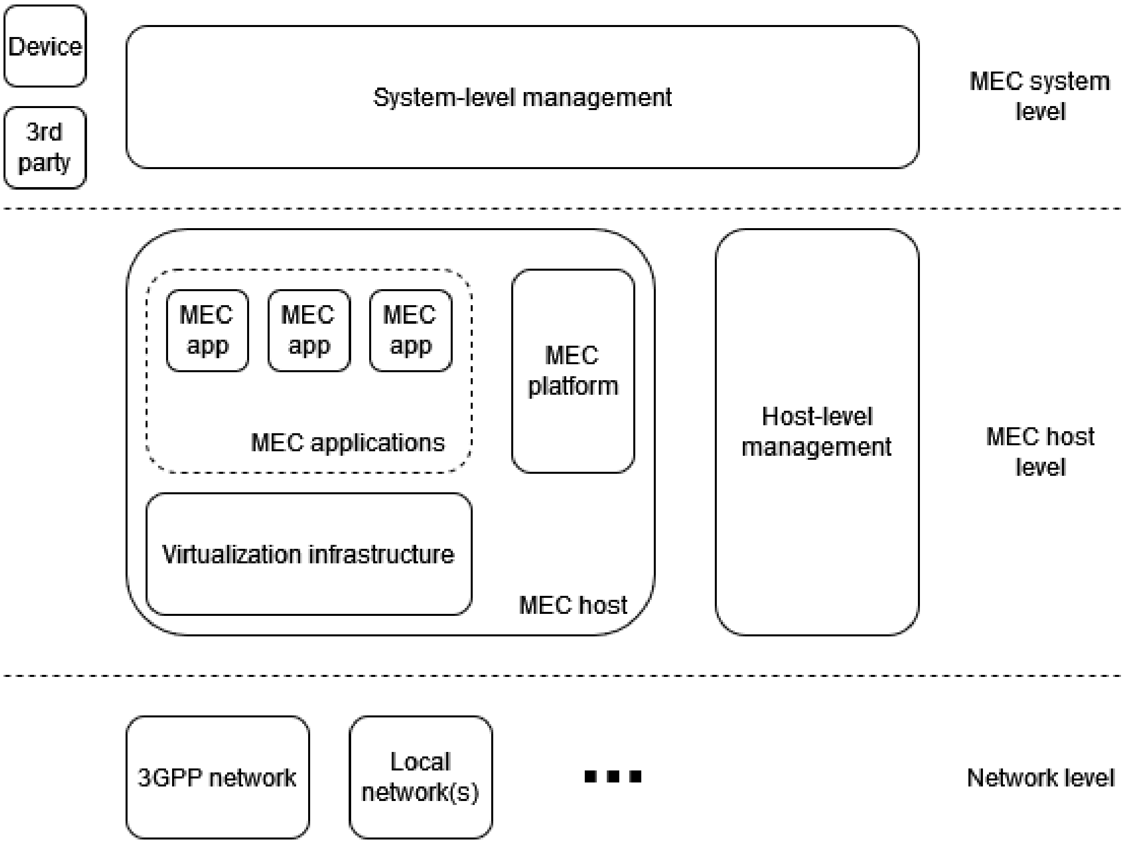


Figure 3. MEC framework

The management level can be further divided into system-level management and host-level management. The host-level management handles the management tasks of a particular MEC host and the application instances hosted on it. One of its two components is the *MEC platform manager*, which is responsible for the applications' lifecycle management and the general rules and requirements of the app instances (e.g., DNS resolution, traffic rules, etc.). The other is the *Virtualization infrastructure manager*, which handles resource management for the Virtualization infrastructure, the proper execution of the software images, and application relocation from/to external clouds if supported (e.g., another MEC system operated by a different party). On the other hand, the system-level management manages issues that are not specific to a MEC host. Its core component is the MEC orchestrator, which maintains an overview of the whole system (incl. topology and state of deployed MEC hosts), selects the appropriate host for an application instance, and triggers the instantiation, termination, and relocation processes. The *operator's Operations Support System (OSS) receives application instantiation/termination requests* via the CFS portal or the device applications (applications with the ability to interact with the MEC system) and either rejects them or sends them to the orchestrator after accepting them. In many cases, it is a better practice if the device applications cannot directly interact with the OSS or the orchestrator. Therefore, a *user application lifecycle management proxy (UALCMP)* entity can be maintained to handle incoming requests first before forwarding them for further processing to the aforementioned management entities.

Besides the description of the generic architecture, the standard also delivers an architecture variant for deploying MEC in an NFV environment since the two are essentially interdependent concepts. Many of the above entities can be realized using VNFs, allowing for deploying MEC applications and some of the NFV-based orchestration and management elements on the same Virtualization infrastructure. Another interesting architecture variant describes MEC federation, i.e., the cooperation between different MEC implementations of different stakeholders. A federated MEC environment enables the offering of MEC service capabilities for consumption and application development between separate MEC systems.

2.4.1.2 V2X Information Service API (GS MEC 030)

Automotive is no exception from those domains where the end devices are manufactured by various vendors and are connected to networks with different operators. Universal services such as CPS can only be provided in multi-vendor, multi-operator, and even multi-access scenarios if seamless interoperability exists. Therefore, there must be a unified platform with well-defined interfaces to connect to, and different end-device or end-user software implementations must conform to these definitions. To better accommodate these automotive scenarios, ETSI has standardized the V2X Information Service (VIS) for the MEC with the adherent data types, information flows, and the common API for interacting with the service [34]. The document collects and presents the reference scenarios combining single/multi-operator use cases from the perspective of OEMs and Mobile Network Operators (MNO) providing certain V2X services (e.g., a vehicle OEM provides the service to its vehicles that are connected to multiple MNOs respectively).

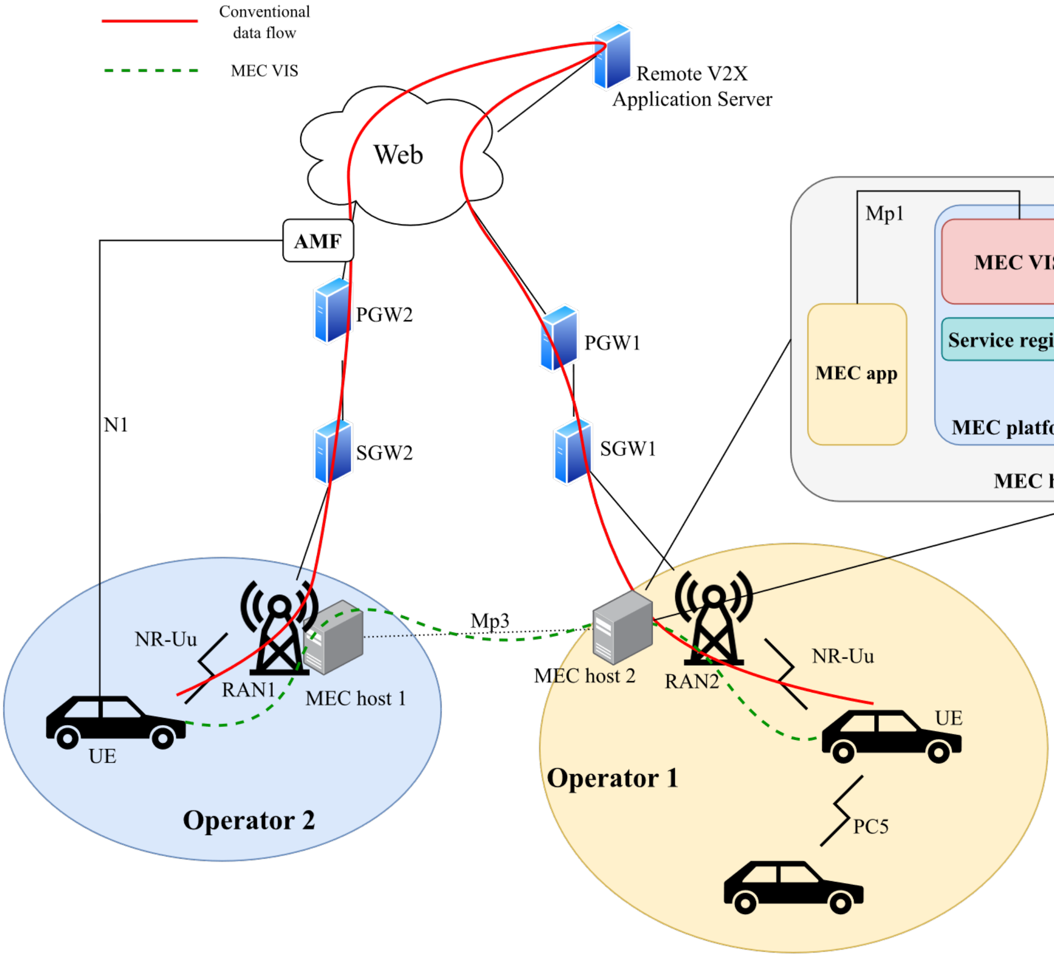


Figure 4: Data flows with and without V2X Information Service [35]

The question of interoperability for multi-operator, MEC-assisted automotive scenarios was and still is a key topic within 5GAA, for example [36]. The “horizontal communication” between MEC services deployed in different MNO domains is shown in Figure 4. This connection enabled by VIS and its API results in lower end-to-end latency and keeps the locality principle of the edge cloud paradigm. However, to ensure service continuity for users and the accessibility to MEC services in automotive scenarios for most car manufacturers, on-board unit OEMs, MEC platform/service providers, MNOs, etc., mobile network-level cooperation is needed, and all the involved stakeholders must adapt the defined APIs and mechanisms.

MEC VIS includes the following functionalities:

- Gathering of PC5 V2X-related information from the 3GPP network (authorized Ues, subscription info, configuration parameters);
- Exposure of this information to MEC apps;
- Enablement of secure communication between MEC apps and the logical functions in the core network;
- Enablement of secure communication between MEC apps in different MEC systems;
- Possibly gather and process information available in other MEC APIs to predict RAN congestion and notify Ues.

Fitting into the framework, all the deployed apps and services communicate via the Mp1 interface to exchange relevant information; therefore, the Mp1 reference point is of most relevance for VIS. The Mp3 reference point is also possible if inter-system communication is needed, e.g., between an application and its peer applications in other systems or if a certain MEC service is exposed to external MEC systems. Application peer discovery can be assisted by exposing endpoint information via the VIS API, and traffic rule configuration may also utilize mechanisms through VIS. Similarly, service exposure and discovery via VIS can ensure that a UE application can see certain services appear in the local MEC host's registry and access it, even if it is hosted in another system. In some cases, there might be a need to collect user information, e.g., obtaining user subscription data for the proper functioning of the service. Since the V2X Application Server (as in the 3GPP terminology [2]) can be deployed as a MEC application, the VIS could obtain such user information from the V2X Control Function without significant overhead by using the V2X AS as a proxy.

High mobility and dynamic changes in topology are an inherent part of V2X scenarios. Therefore, UE location information and the characteristics of the radio network connection are constantly changing. These changes might influence the available functionality of certain V2X services or content delivery processes. However, in some situations, this state information's accuracy or validity might be hindered. Consider the case when most of the users simultaneously want to provide measurements about the radio connection to the eNodeB/gNodeB collocated by a MEC host in a dense cell, for example. In such a situation, a MEC application serving a vehicle following a given trajectory might need to be informed beforehand about radio conditions. With the help of VIS, a journey-specific QoS prediction framework could be established to effectively collect, process, and distribute information about correlations between space-time and radio quality for authorized Ues, V2X applications, service providers, or other third parties. The collected data could be distributed using QoS notifications, and the predictions could help to optimize the MEC Points-of-Presence (i.e., optimal application relocation between MEC hosts or VM upscaling according to the load) or be used as an input for work offload decisions from a vehicle to a MEC host. VIS might also enable such predictive QoS notifications in multi-domain scenarios, where data collected from Prediction Functions residing in external domains are used to predict end-to-end QoS in V2N2V situations where multiple MNOs and/or Data Networks are involved.

2.5 Cellular V2X

Vehicular networks were imagined to be ad-hoc networks with peers directly interacting with each other within a relevant range (typically the broadcast range) according to the original idea of a VANET [37], [38]. The reason was that for many safety applications, most of the information available was relevant to vehicles within a certain proximity. That is why the 802.11-based DSRC was created as the go-to access technology for V2X. In the mid-2010s, however, as cellular technologies became more focused on content delivery, became even faster, and 4G LTE technology became more and more widespread, a new idea of a cellular-based access technology emerged. With IoT getting growing attention and the increase in Internet-based services, opting for cellular was truly an appealing solution. It was a more direct medium to introduce the by-then traditional Internet-like world to the automotive domain and offer services like fleet management and diagnostics collection for OEMs.

As a result, 3GPP has standardized C-V2X to introduce an LTE-based access technology supporting vehicular communications in Release 14 [39]. The exciting thing about the approach was that not only the traditional cellular technologies were extended with V2X support, but also the device-to-device communication capabilities of LTE (i.e., Proximity-based Services [40]) were modified to fit more into the automotive scenarios. This meant the birth of a competent rival for DSRC in providing direct communication through the LTE PC5 interface. The fact that C-V2X offered (and still offers) V2N capabilities via the traditional Uu interface and V2V/V2I via PC5 made many parties believe that the solution would, ultimately and with immediate effect, make DSRC-based access technologies obsolete.

That was not at all the case, at least not C-V2X based on 4G LTE connectivity. Many studies have compared the performance of 802.11p and the LTE approach in different scenarios [13], [14], [41]–[43]. The results, however, were mixed all together. Some studies found C-V2X to perform better, e.g., because of the greater range, while others found that DSRC works better, e.g., working with aperiodic messages. Handling channel congestion was an issue for both approaches, and performance would drop in both cases as the number of vehicles increased. Ultimately, a sane conclusion was that both technologies offer sophisticated solutions that can serve as a good basis, but the results need to be the input for further enhancements to reach the functionality that satisfies all the latency and reliability requirements of cooperative V2X safety applications.

With 5G on the horizon for C-V2X, the New Radio access technology enhancements promised the desired performance that LTE lacked. Newer 3GPP releases gradually introduced the radio and the architectural enhancements to support the advanced V2X use cases, creating NR V2X as a complementary system to C-V2X. Because of the rapid development and frequent releases, and because with 5G technology, many problems of the previous generation seem to vanish (achieving lower latency, better channel utilization, etc.), in the U.S. it seems that the tide has turned and C-V2X will be the officially approved method for V2X communications after the FCC modified the spectrum range used for V2X and reallocated a big chunk previously used by DSRC to be used for C-V2X solutions [44].

2.5.1 Differences between LTE PC5 & NR PC5

Enhancements of the fifth generation of cellular connectivity affect all aspects of the cellular ecosystem, ranging from the radio access network through the architecture of the core network, as far as to the application & service layer. Although there is no doubt that all these combined mean the true strength of 5G, from the perspective of V2X, the enhancements to the PC5 sidelink interface may be the most interesting and the greatest leap so far in the evolution of V2V communication. To support advanced V2X scenarios [3], the sidelink procedures and properties had to be redesigned in such a manner that criteria were met for both the newly considered V2X applications and the ones already established in the previous generation. It seems that NR V2X is not meant to replace current C-V2X technology (at least for not a while) but rather to support the new advanced features while providing interoperability to older implementations. In general, the structure and purpose of sidelink modes, the use of physical channels, and other mechanisms like scheduling are all developed to coexist with the LTE-based predecessor [45]. Table 1 summarizes the key differences between the two generations of cellular-based V2X access technology (both interfaces, PC5 and Uu).

NR V2X inherits a lot from C-V2X, like the use of two sidelink modes, one for scenarios where cell coverage is available and one for scenarios without cell coverage. The purpose and the high-level functionality of the two sidelink modes are also common. The terminology has changed, as the modes are now called *mode 1* and *mode 2*, respectively, instead of sidelink mode 3 and mode 4. Another change is that mode 2 in NR V2X supports multiple resource selection methods when a base station is not there to orchestrate it. An interesting feature previously existing in LTE D2D but not in C-V2X is the appearance of two new transmission modes. Previously, DSRC-based or LTE PC5-based communications were imagined as broadcast transmissions where each vehicle would listen to all messages within range. With NR V2X, more options are available. In addition to broadcast messages, unicast messages can also be sent, just like groupcast messages, which are meant for a specific subset of nearby recipients. A UE can have simultaneous connections of different types as well. The approach is also backed by the fact that the distinction between transmission modes is now handled in the physical layer rather than the medium access control layer, as was true for LTE D2D.

Some other key enhancements of NR are/will be introduced to NR V2X by taking the general NR as a baseline and adding the modifications for advanced V2X support [45]. One of the vital features that enable the high bandwidth and lower latency promised by 5G is the support for flexible numerologies. This appears in supporting sub-carrier spacings of different sizes that are multiples of the spacing of LTE (see Table 1 for numerical values) also to ensure backward compatibility. This way, symbol and slot times decrease as the sub-carrier spacing increases, reducing latency. With shorter slot times, the DMRS symbols must be inserted less frequently. Therefore, DMRS insertion is flexible and depends on the sub-carrier spacing in use.

Table 1: Properties of C-V2X and NR V2X

Parameters	(LTE) C-V2X		5G NR V2X	
	Short range (PC5 sidelink)	Long range (Uu)	Short range (PC5 sidelink)	Long range (Uu)
Modulation and coding scheme	Rel. 14: QPSK/16-QAM with turbo codes		up to 256-QAM with LDPC codes	
	Rel. 15: 64-QAM			
Doppler shift resistance methods	DMRS, 4/subframe		flexible DMRS	
Carrier frequency [GHz]	5.9	0.7, 0.8	5.9, 60 (mmWave)	available 5G bands
Sub-carrier spacing [kHz]	15		sub-6 GHz: 15, 30, 60	
			mmWave: 60, 120	x
Feedback channel	x		PSFCH	
Control & data multiplexing	FDM		FDM + TDM	
PHY layer (waveform)	SC-FDMA		OFDM/DFTsOFDM	
Bandwidth [MHz]	flexible: 1.4/5/10/20		sub-6 GHz: max. 100	
			mmWave: max. 400	x
Re-transmission	blind		HARQ (blind for PC5 broadcast)	
Communication types	broadcast	unicast	broadcast, groupcast, unicast	unicast
Scheduling interval	one sub-frame		slot / mini-slot / multi-slot	
Sidelink modes	mode 3 & mode 4		mode 1 & mode 2	

To better optimize resource allocation, i.e., slot scheduling for downlink and uplink transmission for different Ues, NR V2X supports mini-slot and multi-slot scheduling in addition to the default slot scheduling. Mini-slot scheduling means that a UE can send data with any of the 14 OFDM symbols of a slot; therefore, a whole slot does not have to be granted to a UE if the message does not fill out all the 14 OFDM symbols of the slot. Additionally, latency-critical applications might not need to wait for the beginning of the next slot whenever the data packet becomes ready to transmit but might have permission to transmit at any time within the slot. Multi-slot scheduling, on the other hand, means an option to aggregate slots if more data is needed to be transmitted.

Another important difference is the multiplexing of control and data channels for the sidelink. In LTE-based C-V2X, PSCCH and PSSCH were multiplexed in the frequency domain, whereas in NR V2X, they are multiplexed both in the time and the frequency domain [46]. A further enhancement is the addition of a feedback channel (PSFCH) for HARQ feedback in case of unicast and groupcast transmission that can be optionally inserted at the end of a slot (i.e., also multiplexed in time). This addition enables feedback-based re-transmissions and channel state information acquisition. Lastly, the various resource acquisition methods of sidelink mode 2 are also worth mentioning. The sensing-based method reused from C-V2X Mode 4 filters those slots that are used by other Ues according to the measurements, and then, based on the collected information, slots are selected from the available ones. However, if, for some reason, the sensing procedure would be considered costly, this section can be omitted, and a random selection of slots used for transmission can be performed. The complexity of long-term sensing and the extra power consumption during the procedure might be the reason for choosing random selection in some cases to save the extra costs [47].

2.5.2 Multi-Interface Operation

Channel congestion in direct V2X communication is one of the significant issues that can hinder the quality of V2X services in scenarios with high vehicle density, regardless of the access medium that is used. This is because the available radio frequency is a very limited resource. To mitigate the issue, various parties study and form a resource management mechanism called Multi-Channel Operation (MCO) that enables the better and more efficient utilization of the available ITS-G5 frequency bands. It is a complex service that functions across various layers of the C-ITS architecture. The C2C-CC has released a series of white papers investigating the most important aspects of MCO [48]–[50], some of which were a direct input to a comprehensive technical report by ETSI [51]. These reports include functional requirements for MCO (regulatory issues, backward compatibility, requirements for C-ITS applications), technical details and limitations backed up by performance evaluations, as well as the detailed description and the communication architecture (the latter already standardized [52]) of the MCO concept.

Similar problems must be faced when using direct communication via the PC5 interface (be it LTE or NR-based), so techniques against channel congestion are also implemented in C-V2X. The performance of PC5-based V2X communication, however, shows varying results. Even though it may seem a better alternative to “traditional” V2X, it is not flawless in all situations [13], [14], [16], [53]. Of course, there is always room for improving resource allocation and management algorithms, but C-V2X has a unique advantage compared to ITS-G5, which is not yet being utilized for enhancing V2X use cases: the two separate radio interfaces, specifically the parallel utilization of the PC5 and Uu interfaces.

Lianghai et al. evaluated various multi-RAT schemes for increasing reliability using both PC5 and Uu interfaces [54]. This valuable contribution is one of the few literature addressing this topic. However, similarly to the MCO concept for C-ITS, there is also potential in the coordinated usage of both air interfaces for achieving optimal channel access in dense areas by extending the available radio resources. The resulting Multi-Interface Operation could ensure that the proper access medium is selected for individual traffic flows to maintain the necessary QoS for the services. This operation would mean that there would be a need to be able to change dynamically between the interfaces as the circumstances and available resources change dynamically. This complex problem heavily depends on the advanced V2X-supporting architecture enhancements and analytics exposure functionalities of the 5GS [55], [56].

For example, in a dense urban scenario, Uu coverage is handled using small cells, so ideally, all C-V2X-capable vehicles are connected to the 3GPP network. Therefore, the PC5 sidelink can be reserved for the most safety-critical applications, and any other V2V communication (e.g., informative applications) can be handled just like infotainment and any other traffic: using the Uu interface and the routing capabilities of the V2X Application Servers residing in the 3GPP network. The decision on how and under which conditions to use either interface could be a matter of V2X profiles, and depending on the conditions, vehicles would be obligated to switch between pre-defined profiles. Another approach could be deploying PC5-capable road infrastructure and creating a similar access stratum to the existing one. In this case, the network could predict the expected load and channel availability in advance, decide on the optimal medium, and use that on a per-vehicle basis. For, if it was impossible to serve a client in a given region using PC5 or Uu wanting to use a particular service, the network could serve that client using the other access medium and connect the user to other peers, even those using the other medium. Naturally, this idea puts an enormous responsibility on the network, and implementing a mechanism described above that can also satisfy the safety-critical requirements is questionable without further research.

3 MEC-assisted V2X

Beyond being a more general asset, MEC is envisioned to play an essential role in the realization of many 5G-based V2X use cases [3], [36], [57]. The locally available computational capacity and the supposed minimal additional network latency make MEC an appealing platform for hosting cooperative V2X services and applications. This approach is not only interesting for people with academic backgrounds but also multiple industrial stakeholders and organizations. This chapter is about the short introduction of some possibilities for supporting V2X use cases with the utilization of MEC, focusing on the V2X support enablers in the ETSI standard and initial efforts within 5GAA to select and test some use cases that can be enhanced using MEC.

3.1 MEC support for V2X according to ETSI (GR MEC 022)

MEC and all the potential benefits it can provide, from the perspective of this study, are most important in the automotive domain, especially since V2X might be one of the greatest markets for applying MEC. To support MEC-assisted V2X, ETSI has studied the potential use cases and evaluated the existing and the new requirements for using MEC in V2X scenarios in 2018 [58]. The four use case groups recognized by 5GAA are "safety", "convenience", "advanced driving assistance" and "vulnerable road user" (VRU) [17]. Among safety applications, the report mentions two V2X scenarios relevant to MEC; the first is a classic, namely Intersection Movement Assist (IMA) [59], and the second is Queue Warning (QW). Both use cases aim to reduce the risk and effect of crashes; IMA warns drivers closing in on an intersection about traffic coming from the lateral direction, and QW warns drivers or vehicles about dangerous queues (e.g., a large turning queue) so that preventive actions can be made to avoid crashes. Note that these two use cases are labeled as V2V and V2I scenarios, whereas a MEC-assisted scenario might be considered more like a V2N scenario.

The convenience use cases do not face MEC systems with a need for novel solutions, as over-the-air software updates and telematic software are already widespread among many manufacturers. The report mentions the support to work in a multi-operator environment as the only requirement to ensure service continuity for users of all vendors and operators regardless of the geographical location and roaming/non-roaming scenarios. Advanced driving assistance use cases are a bit more challenging as these use cases often work with large amounts of data and must provide high reliability with very strict latency. Real-Time Situational Awareness & HD Maps are use cases both sharing data of the changing road and traffic conditions; the first doing it in real-time, making it essential for autonomous vehicles, the latter at a bit slower pace, making it practical for the distribution of aggregated data coming from various sources (vehicles, RSUs, smart infrastructure, etc.). Another interesting use case is See-through, where the live video feed from the sensors of a vehicle is made accessible to other users behind them. Lastly, the VRU use case involves highly sensitive traffic participants, such as bicycle riders, scooters, and pedestrians.

The study also mentions key issues and potential solutions (mobility & QoE support & QoS prediction, low latency for multi-operator scenarios, and communication traffic coordination).

3.2 5GAA MEC4AUTO work item

In 2020, 5GAA created a technical report on the use cases and test specifications of a new work item called MEC4AUTO [60] (made publicly available in 2021). The work item specifies, evaluates, and supports the development of use cases where the automotive can benefit from MEC; hence the name MEC for Automotive. The document refers to use cases identified by other organizations as a baseline, like those in the previous section according to ETSI, and others, namely by AECC and IMT-2020. In the document, the group thoroughly analyzes the relevance of MEC for each specific use case, i.e., how and why MEC is beneficial for the use case. Since 5GAA has several kinds of stakeholders, they do so with great care for interoperability in this multi-stakeholder environment. This includes scenarios where different OEMs are interworking with different MNOs, as well as the interactions between two or more MNOs possibly having MEC systems of different kinds.

With a focus on 5G-enabled V2X, 5GAA chose five use cases that can utilize a MEC system for further study (including demo trials with board members) as part of the work item. Among these use cases, three of the five fall under the safety category. According to the work item, MEC could play an important role in the See-through use case in providing interoperability between vehicles of different OEMs through the exposed standardized MEC APIs and services. The 'RESTful' approach of the MEC API could enable effective message exchange even if the edge service was running on different servers and with clients accessing through different network operators. Managing video streams is not the only benefit of using MEC. Other services/applications could be hosted that provide fused information based on several inputs in addition to the video stream using standardized messages for object data sharing. Interoperability and the scalability of the control and information fusion applications also validate the MEC-based approach for implementing IMA. However, the safety use case that concerns 5GAA the most seems to be VRU protection, as many of the organized field tests and demo events feature this use case [61]. The VRU use case is generally split into two sub-categories. There is an infrastructure-based approach, where most of the incoming information is provided by a wide variety of sensors, e.g., surveillance cameras or wireless detection, that monitor VRU movements. On the other hand, the in-vehicle sensor-based approach mainly relies on a vehicle's front-facing camera. In both cases, the video feed or other data are processed by machine-learning-based or other AI-based applications hosted on a local MEC. The system must provide a scalable platform for these resource-hungry applications to calculate trajectories and predict any collisions or other dangerous situations so that a warning can be sent to the vehicles or VRUs with active devices in time.

From the convenience of the infotainment category, the work item considers the In-vehicle entertainment (IVE) use case. This essentially means content delivery scenarios (e.g., video-on-demand services, gaming) for the passengers of a moving or stationary vehicle, applicable for both automated and non-automated vehicles. MEC applications could be critical in ensuring the necessary QoS performance needed for the consumption of certain content and, again, in providing interoperability during data exchange between different OEMs. The fifth use case, Vehicle platooning, is important not only from a safety perspective but also for traffic flow efficiency and fewer emissions. In platooning, the leading vehicle of the group receives information (e.g., road status and weather conditions) from external sources as well as the member vehicles of the group. It makes decisions accordingly, to which the members then respond by appropriately adapting their behavior. The exchange of time-sensitive control information, aiding the identification of leading and member vehicles, and collecting and propagating status information could all be handled by MEC applications. This is especially true for high-density use cases, like urban scenarios or cooperative lane changing (CLC) scenarios on dense highways, where the identification of different platoons must be rapid and where the QoS requirements might be constantly changing along the path of a platoon.

The relevance of the topics that this work item studied is beyond doubt, as two subsequent work items, called gMEC4AUTO (short for global MEC4AUTO) [61] and the currently work-in-progress 5gMEC4AUTO have been managed by 5GAA since the original initiative. These work items are the result of the close collaboration of various important stakeholders in the automotive industry, like vehicle OEMs, hardware/software OEMs, mobile network operators, and more.

4 Modeling and Simulation

This chapter provides an in-depth overview of the modeling and simulation endeavors. The foundation for the scenarios and model components derives from the environment outlined in our most recent journal publication [4].

4.1 Simulation Frameworks

The most readily available resources in the V2X domain are simulation tools. These tools serve to quickly test concepts and implement proof-of-concept scenarios. It is essential that these tools accurately model and calculate virtually all aspects of real-world behavior. However, achieving precise results for all elements, such as network traffic and physical participants, can be practically impossible. Consequently, researchers typically adopt the practice of relying on multiple libraries and standalone frameworks, each specializing in a specific aspect of the target environment, such as network stacks or traffic simulation. This approach is favored over using a single, all-encompassing simulator. The following sections outline the structure of the integrated framework in use, and a brief introduction to the libraries utilized is provided.

4.1.1 Artery

Artery stands as a comprehensive framework tailored for simulating V2X applications [22]. It is constructed upon OMNeT++, a well-recognized discrete event simulator. Originally conceived as an extension for Veins [62], a similar framework, Artery has since evolved into an independent environment. This transition was driven by the desire to adhere to European standards instead of those defined by American organizations and to enhance simulation capabilities by permitting the execution of multiple applications per vehicle, a feature not supported by Veins.

Artery's distinguishing feature, which grants it power in this domain, is its Middleware functionality. This serves as an additional layer of software that sits between the application instances and the lower layers, such as the network or physical layers provided by tools like Vanetza. The Middleware offers valuable interfaces in both directions while managing application lifecycles and actively participating in message transmission. Moreover, Artery's Middleware instantiates the entire stack within each simulated vehicle to faithfully replicate real-world behavior.

In addition to libraries that offer the C-ITS stack, like Vanetza, Artery relies on others responsible for the access and physical layers. There are two alternatives: Veins, which already implements these layers, and INET [63], a standalone library for simulating mobile, wireless, or wired networks. While INET provides basic mobility support, the precise simulation of vehicle movement is achieved through SUMO (Simulation of Urban Mobility), an extensive traffic simulator. Like Artery, SUMO is a microscopic simulator, crafting individual models and trajectories for all nodes.

Although Artery comes pre-equipped with Day 1 V2X applications, such as Collective Awareness Basic Service and Decentralized Environment Notification Basic Service, our research pertains to Collective Perception. Consequently, our own CP model had to be seamlessly integrated, updated, and put into use [10].

4.1.2 Simu5G

Simu5G [24] plays a crucial role in incorporating 5G network components into the simulations. This framework, also built upon OMNeT++, is responsible for implementing various aspects of the 5G network, including its core functionality, NR access technology through the Uu interface, and other network elements like the gNodeB and functionalities of the MEC (Multi-Access Edge Computing) infrastructure. Simu5G also relies on INET, allowing nodes that utilize 5G, 4G, 3G, or other access technologies to seamlessly collaborate within the simulation environment.

4.1.3 Integration

Undoubtedly, the real achievement resides in the flawless integration of the discussed frameworks. While the developers of Artery initially recommended using Cmake to manage the build system when adding extra libraries [64], to simplify the integration process, we encountered challenges when it came to linking code from these various libraries. Furthermore, we had to make minor adjustments to specific API endpoints to resolve version conflicts and ensure the smooth operation of the OMNeT++ simulator’s dynamic lifecycle management.

As a result of this integration, our simulation model’s capabilities have significantly expanded. We’ve effectively integrated all components of 5G radio and core systems, in addition to incorporating an ETSI-compliant MEC implementation provided by Simu5G. This necessitated the replacement of the existing LTE radio equipment and

EPC core functionality in both the car model and the world model. Moreover, we have introduced a MEC node module into the simulated network setup to serve as a host for applications used by the vehicles.

4.2 Model extensions

Understanding Simu5G's implementation of the MEC platform and implementing both client- and edge-side applications was quite straightforward, thanks to the abundance of example use cases. Drawing inspiration from these examples, our goal was to create a MEC application that is as simple as possible, tailored for vehicular scenarios, and designed with modularity in mind to facilitate future modifications. In the initial stages of our implementation, the key task was to transmit the CPMs to the MEC host, simulating the processing activities of a higher-level application that relies on the received data. The framework permits the on-the-fly instantiation of supported MEC applications. Consequently, we expanded the available application pool by introducing a CP service application capable of receiving data from a single sender vehicle. Each vehicle can initiate an application as needed.

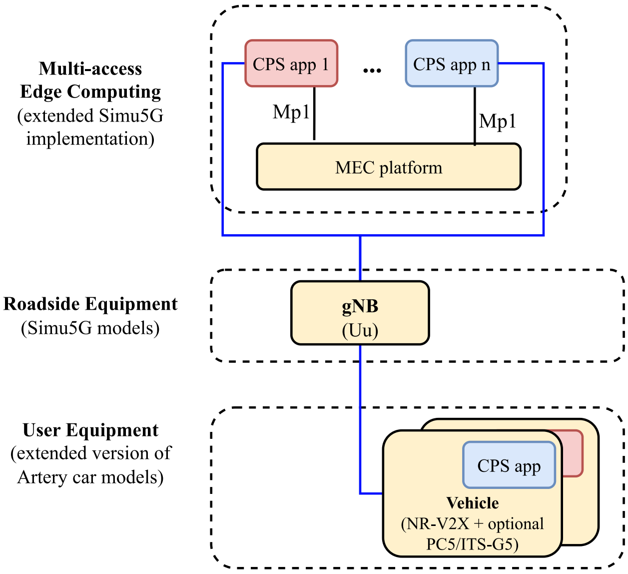


Figure 5. System architecture

The architectural configuration is visually depicted in Figure 5, while a simplified representation of the implemented modules is presented in Figure 6, with our specific implementation highlighted by shading the corresponding boxes. Notably, each application instance operating on the MEC host has access exclusively to the message stream of an individual vehicle. Consequently, any form of data aggregation, such as object fusion or other safety-centric applications, necessitates either establishing connections between these application instances or introducing an additional entity within the MEC host. The first approach, connecting the application instances, would rapidly proliferate connections between these submodules. Furthermore, it would compromise the modularity and the principle of single responsibility for these application instance modules, as their primary role is to receive messages and relay them for subsequent processing. Therefore, the second approach appears to be a more promising alternative, particularly considering that the ETSI MEC framework supports hosting services, such as Location Services, which are readily available for each application instance running on the host.

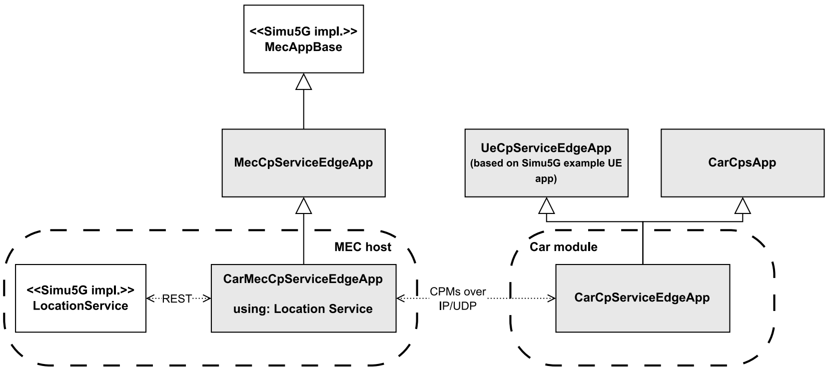


Figure 6. Implemented modules in a simple representation

Incorporating bidirectional traffic between MEC application instances and vehicles was a vital aspect of our experimentation to gather measurement data. Typically, the envisaged service could transmit vital information to the vehicles, such as the results of data fusion. To emulate this in a simplified model, we leveraged the pre-existing connections that each application instance on the MEC host had with its corresponding instance on each vehicle. As part of this simulation, we emulated the processing time required for a higher-level service and dispatched metadata about the specific CPM that triggered processes on the edge platform. This transmission of metadata allowed the server application to confirm the successful reception and digestion of the message.

It is also crucial to investigate how edge application instances handle CPMs and obtain additional metadata. As previously mentioned, we repurposed and enhanced an existing Collective Perception model [10], including the ASN.1 representation of the CPM. Creating and managing ASN.1 message formats was streamlined using wrapper classes and other utility techniques provided by Vanetza. These methods for serializing and deserializing messages enabled seamless message transfer between the Vanetza and INET frameworks.

To clarify, Vanetza is tasked with implementing V2X messages like CPM, while our model's cellular and other network components rely on INET's implementation. Therefore, the conversion of data between these two frameworks is imperative. This means that the edge application instances can process the very same CPM generated by the CP service running within the V2X stack of the vehicle. This encompasses all the mandatory and optional components of the standard message format, with particular emphasis on the Perceived Object Container, which plays a pivotal role in scenarios where dynamic processing time calculations are involved.

Given that the CP service does not necessitate the identification of specific messages, we introduced an additional field before each CPM for sequence numbering, a parameter managed by the client vehicles. This sequence number serves as the sole item of metadata transmitted back to the client following message processing to minimize the added network load. Equipped with this metadata, the client can independently calculate the precise response time for the messages. Moreover, this message identification facilitates the computation of other statistical metrics, such as packet loss, with greater ease.

The current foundation of the model primarily involves vehicles disseminating CPMs over IP/UDP to application instances hosted on the local MEC (Multi-Access Edge Computing) server. These application instances are responsible for dissecting and processing the received messages. This setup represents a minimal operational network configuration. Our plan includes substantial future expansions, incorporating the implementation of higher-level applications, such as an object fusion service, within the MEC host's service registry [35]. These services are accessible to the application instances via a REST API. In this future phase, the simplified processes will be replaced with more advanced and extended functionalities.

Additionally, our forthcoming extensions will focus on the access medium and the logic governing mode switching between these different mediums.

4.3 Simulation: scenario and parameter settings

The underlying concept of this entire scenario was to validate the integrated framework through straightforward yet successful simulation runs. These runs aimed to establish a proof-of-concept, demonstrating how the usage of MEC could positively impact Collective Perception-based use cases in the long term. The test simulations were conducted within a grid-based urban environment.

To focus on evaluating the performance of the MEC infrastructure under heavy loads rather than replicating realistic traffic conditions, we utilized a base scenario with a simple map where vehicles traverse a four-by-four grid consisting of 100-meter-long road segments. At the center of this grid, several devices are deployed, including a gNodeB equipped with a MEC server.

4.3.1 Modeling CPM propagation over Uu interface

As the simulation commences, the vehicles initiate the transmission of CPMs to the MEC server via the NR Uu link, utilizing a 2.1 GHz carrier frequency. Within the MEC server, the receiving application instances function as the designated endpoints for a complex service hosted on the server, actively managing the designated region. V2X-capable nodes within the simulation environment are equipped with a CPS application module to facilitate this operation. This module is responsible for relaying CPMs originating from the Artery Middleware. The integrated framework effectively simulates the network traffic transmitted over the NR Uu interfaces, thanks to the incorporation of Artery-based Car model extensions. The instantiation of MEC applications proceeds without encountering issues, and the MEC modules efficiently process the reception of CP information from the vehicles' Middleware CP service.

As the simulation progresses, the total number of vehicles steadily increases. This deliberate escalation of vehicular presence is designed to place a progressively mounting load on the edge cloud infrastructure, as visually represented in Figure 7. Each graph in the figure represents different traffic densities where a new car is inserted on average according to the labels of the graphs. With the underlying network architecture in place and the traffic generation settings established, we examine the MEC server's behavior by adjusting to specific simulation parameters.

These experiments encompass various scenarios related to the availability of physical resources on the server and the resource requirements of the application instances. In our model, we gauge CPU computational power in MIPS (Million Instructions Per Second), with both the server's capacity and the application's requirements specified in MIPS. Additionally, we configure the available and required memory (RAM) and disk capacity for each application instance. It's worth noting that these pre-configured values are shared across all instances.

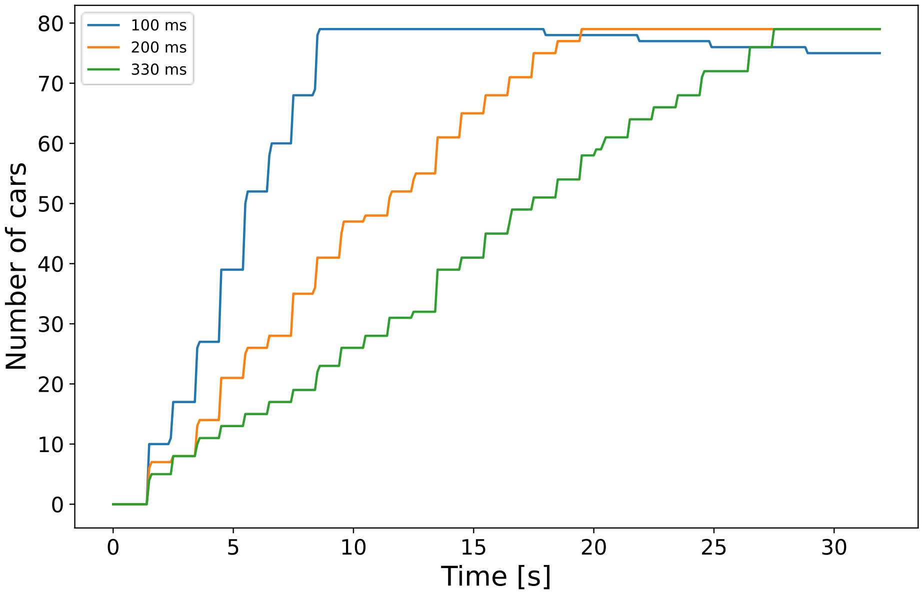


Figure 7. Total number of cars in the simulation for different traffic densities

The main emphasis is on the computational demands, particularly the processing time for incoming CPMs. We model the response time of the envisioned edge-side CP service using the built-in "calculateProcessingTime" method. This modeling assumes a fair resource-sharing model among applications, in which resources are allocated and distributed equitably. The "total response time," as defined below in Equation (1), serves as a key metric for our analysis. It encapsulates the Uplink (UL) delay for transmitting the CPM to the MEC host, the processing time of the CPM, and the Downlink (DL) delay associated with the transmission of response messages. This complex metric provides an adequate view of the system's performance. The simulations can be further categorized into two groups: one group with fixed CPU requirement parameters and another where the simulated processing time is determined based on information extracted from the CPMs.

$$resp = d_{UL} + t_{process} + d_{DL} \quad (1)$$

The rationale behind selecting the capacity and CPU requirement parameters is straightforward. Primarily, the objective is not to discern the characteristics of a real implementation of a complex V2X service. Instead, the aim is to offer a glimpse into the potential and constraints of the system, essentially providing a proof of concept to demonstrate the operability of the integrated simulator.

4.3.1.1 Scenarios with fixed CPU requirements

The MEC host maintains a consistent CPU capacity across all simulation runs in the first subset of simulation scenarios. However, the client applications exhibit varying CPU requirement values in each run, simulating an increasing workload. All application instances maintain the same constant value for each function call within each run. Our primary focus during these simulations was the collection of response times for each transmitted CPM in every vehicle. Additionally, we recorded the end-to-end network latency, encompassing the duration from the vehicles to the MEC application instances, as this network latency contributes significantly to the overall response time [65]. The results about the average end-to-end latency per vehicle reveal that the network latency experienced by most nodes in this specific scenario falls within the range of 12 to 15 milliseconds. Even the most exceptional outlier remains below 50 milliseconds. We assumed that the end-to-end network latency in the DL direction was similar in magnitude to the experienced UL latency. Interestingly, the obtained latency values did not appear to exhibit a correlation with the increasing density of vehicles over time. However, substantial variations become evident in the response times as defined in Equation (1). Figure 8 illustrates the observable upward trend in the average response time calculated for each entire simulation run, which involves computing the average of each node’s response time. The boxplot diagrams depict the distribution of response times experienced by nodes in simulation runs with varying CPU requirement values.

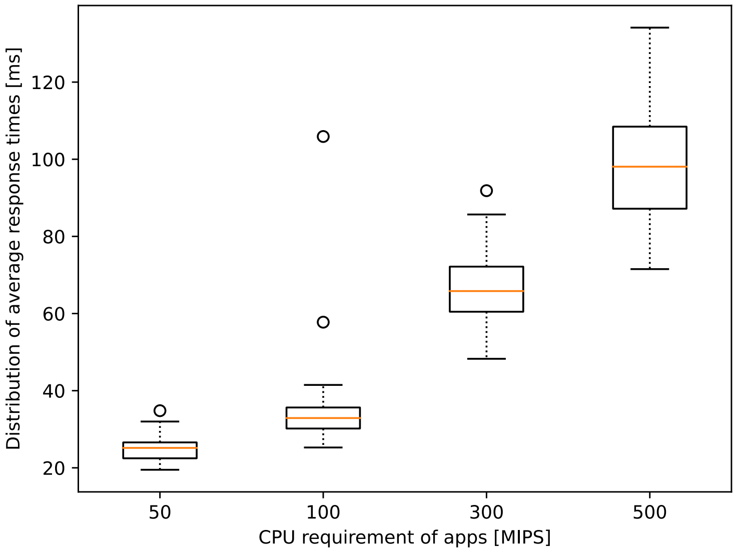


Figure 8. Distribution of per-car response time averages for different CPU requirements

Notably, the median values are not the only metrics exhibiting an increase. The interquartile range, as well as the overall range of the entire dataset, is also expanding. This suggests that the deteriorating quality of service may not only result in anticipated increases in response time but also introduce a growing level of stochasticity. This is indicated by the broader distribution of response time values. Another possibility is that the model simulating the computational load may be overly simplistic and serve as a limiting factor. Nevertheless, these results affirm that the initial model is functioning as intended and stands ready for further enhancements, guided by the valuable insights drawn from these findings.

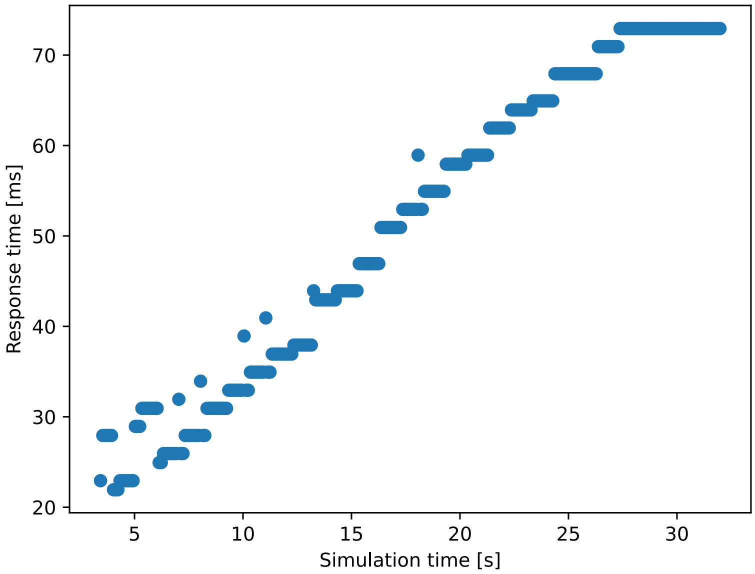


Figure 9. The measured response times of a selected vehicle during a simulation

When examining a specific node that entered the simulation relatively early (precisely at 2 seconds), a noticeable correlation becomes evident between the graph depicting the measured response times in Figure 9 and the escalating vehicle density illustrated in Figure 8. This correlation is expected but remains a pertinent observation. Note that the correlation was not this evident for all the vehicles. Still, the findings demonstrate that the framework can handle scenarios where actual services and algorithms are implemented on the MEC host, leading to results that resemble real-world conditions. This highlights the potential of the framework when utilizing appropriately selected parameter sets in future research endeavors within the domain.

4.3.1.2 Scenario with dynamic CPU requirements

In the subsequent set of scenarios, we delve into the implementation of a more realistic behavior, which entails a more sophisticated model of the abstract CP edge service performing, e.g., object fusion. To achieve this, we introduce dynamic changes in the processing time for each CPM. This processing time dynamically adapts based on the number of perceived objects whose information is encapsulated within the relevant container of the message body. This approach can influence the performance of the MEC system in two key ways. Firstly, as the number of vehicles in the simulation continues to rise, the MEC host must cater to an increasing number of clients, similar to the previous scenarios. However, a novel dimension is introduced. Since all clients have diverse experiences within their respective environments, their specific computational requirements are anticipated to fluctuate throughout the simulation. This, in turn, may lead to more noticeable variations in the recorded response times.

To assess the actual impact on the edge server, three distinct parameters were identified for experimentation:

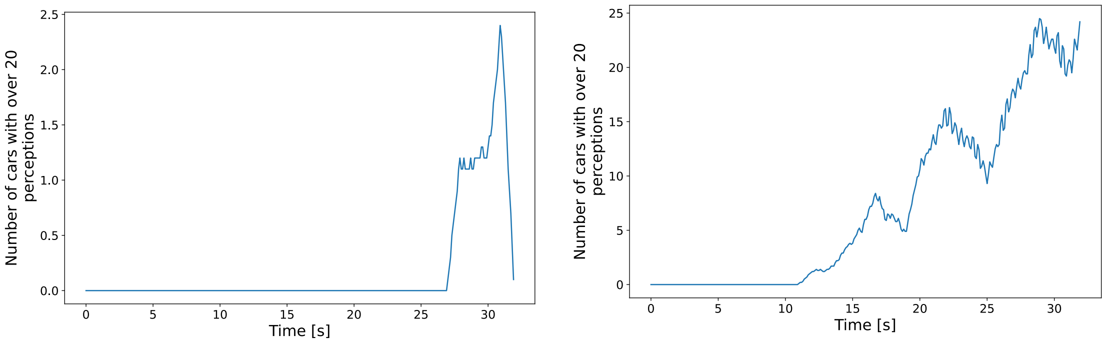
1. **Vehicle density:** Within the simulation, we manipulated the density of vehicles, creating even denser traffic flows on the same grid map. The total number of vehicles simulated simultaneously remained capped at approximately 80 vehicles. However, as the traffic density increased, this number was reached more rapidly.
2. **Sensor Parameters:** We explored adjustments to the parameters of the sensors responsible for detecting these vehicles. In the simulation, the cars were equipped with front radars featuring optimized range and Field of

View (FOV) settings to maximize the capture of nearby vehicles. These sensor settings were fine-tuned to accommodate the increased traffic density effectively.

3. **Number of Perceived Objects:** In response to the challenges posed by the number of detected objects as a result of changes to the first two parameters, a temporary solution was implemented. The packet size could potentially exceed the maximum data unit size of a GeoNetworking packet when there were too many detected objects. This issue disrupted the simulation in many cases. To mitigate this, we had to impose a temporary limit on the number of objects embedded within CPMs to ensure the simulations ran smoothly. Under typical circumstances, this limitation wouldn't be a concern because the rules for CPM dissemination and data inclusion allow for discrepancies between the total number of perceived objects (a mandatory field in the Perceived Object Container) and the number of additional perception data elements. However, our current model lacks object tracking, resulting in the V2X stack packing object data into the CPMs without prioritization. This practice ultimately caused the data unit size limit to be exceeded. To address this, implementing data inclusion rules outlined by the standard or a proprietary solution would be the ideal solution. Nevertheless, for the sake of simplicity, the maximum number of objects was set at 25 for these simulations.

The dynamic model for CPU requirements was constructed without hidden limitations. To maintain consistency with the previous set of scenarios and address the previously mentioned constraints related to the number of detections in a CPM, we fine-tuned the parameters of a polynomial equation (see more detail in [4]). The objective was to ensure that the required CPU MIPS would reach the range of 500 to 600 when dealing with approximately 20 perceived objects. This adjustment aligns with the highest possible MIPS values within the fixed parameter scenarios. In doing so, the response times are anticipated to remain within an acceptable range of 100 milliseconds, which represents a technically stringent limit. This limit is imposed because CPMs are generated every 100 milliseconds at the highest frequency. Exceeding this limit would render the CPMs outdated.

The applications on the MEC node allocate the necessary CPU capacity according to the polynomial for each CPM, and this result is directly mirrored in the processing required times. Before delving into a detailed analysis of the results, it's imperative to consider a fundamental expectation. Denser traffic is anticipated to yield a higher average number of total detections accumulated within the MEC host. Since the model lacks object tracking or fusion capabilities at this stage, the simplest method to visualize the incoming data for the edge application instances, specifically the count of perceived objects, is to sum them. It is worth noting that this aggregated number may encompass several vehicles that were counted multiple times.



(a) **(b)**

Figure 10. Number of cars (moving window average) with more than 20 perceptions in scenarios with different traffic densities

With this substantial volume of overall detections, the assumption was that denser traffic would likely lead to a decline in the MEC host's performance and an increase in response times experienced by the vehicles, just as it did when increasing the MIPS requirements in scenarios with fixed parameters. To gain insights into how many vehicles possessed the most demanding requirements, we averaged and analyzed the number of vehicles with more than 20 detections throughout the simulations. Figure 10 offers valuable insights, with subplots (a) and (b) referring to scenarios where a new car was inserted every 330 ms and 100 ms on average, respectively. A reasonable expectation is that the growing number of vehicles with a significant number of detections would contribute to higher response times and increased variance in the results for denser traffic scenarios. The evident upward trend of the "many" detections in the case of the densest traffic serves as one indicator. Furthermore, the difference between the maximum number of such vehicles (i.e. with "many" detections) in the simulation runs, measured in scenarios with the lightest and densest traffic, is substantial. In scenarios with the lightest traffic, the maximum number of vehicles in this category is 8, representing one-tenth of the total number of cars. However, in scenarios with the densest traffic, this number rises to 35, accounting for almost half of the simulated vehicles.

Turning our attention to Figure 11, a notable observation is that while there is a slight increase in the median of the average response times, the variance remains largely unchanged, and the presence of outliers tends to be smaller. Surprisingly, despite our initial expectations and the patterns seen in Figure 8, the simulation runs with denser traffic appears to be more stable in terms of performance. This deviation from the earlier scenario might be attributed to the fact that, although there were instances during the simulations when nearly half of the vehicles had high demands, the number of such vehicles exhibited constant fluctuations. Consequently, at no single point in time did all vehicles necessitate such extensive resources, unlike the initial scenarios. As a result, the MEC host effectively managed to fulfill requests without a significant performance drop.

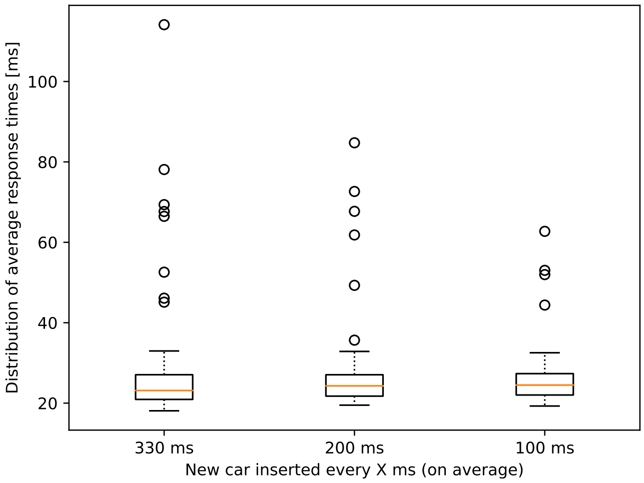


Figure 11. Distribution of per-car average response times for different traffic density scenarios (with dynamic CPU requirement)

Regarding the reduction in the variance of observed response times, it's inferred that the outlier values absorbed most of the extra latency at the network level. These anomalies may be linked to irregularities in the OMNeT++ framework's event system. A more comprehensive examination of both the resource allocation methods within the MEC implementation and the event management within OMNeT++ could provide deeper insights into the precise reasons behind these findings. In any case, the successful utilization of the integrated simulation framework for assessing both MEC performance and advanced Collective Perception-based V2X services in diverse scenarios is a noteworthy achievement.

5 Conclusions

The utilization of simulation frameworks, such as Artery, greatly facilitates the deployment and testing of V2X applications and novel algorithms. This approach offers researchers a means to expedite their work, reduce costs, and simplify testing. Artery, in particular, stands out as a practical tool that plays a pivotal role in this regard. With Simu5G successfully integrated, the extended will significantly facilitate the exploration of applications falling within the use case groups identified by 3GPP [3] and many more.

The simulation results I have gathered prove that the integrated framework is capable of modeling advanced V2X services relying on 5G technology. The proposed CPS application is an excellent example of testing edge cloud assistance in cooperative V2X use cases. I have implemented the client and edge side versions of the 5G MEC-ready V2X application to relay CPMs to the edge network, thus connecting the CP service running in the C-ITS stack to the 5G MEC system. I also designed a new simulation scenario to test the integrated model's capabilities. I have shown that Simu5G's out-of-the-box MEC implementation, together with my extensions, is adequate for testing the performance of such V2X services. The QoS and the MEC load were measured in parallel by collecting the average and median response times of the CPMs sent to the MEC host. The results indicate that the response times are within the acceptable threshold for fixed and dynamic CPU requirement scenarios alike.

Future developments in the implementation hold the potential for significant advancements. These may include implementing NR V2X PC5 (i.e., replacing the simple D2D model of Simu5G to Mode 1 or Mode 2 sidelink communication), integrating CP MEC service for object fusion, and exploring different scenarios such as directly comparing NR Uu interface-based operations with ITS-G5 or NR PC5 access types. Additionally, we can delve into the analysis of collective perception performance using various sensor fusion approaches and different MEC optimization possibilities. With a complete NR V2X implementation, the simulator could serve as a platform to investigate diverse resource acquisition methods, potentially shedding light on the role of MEC in this process. It's also worth exploring alternative V2X messaging options over the Uu interface, such as assessing the performance of AMQP/MQTT or other message queuing solutions for this purpose. The question of whether standalone 5G (Uu+PC5) can fulfill all the requirements or if hybrid-RAT-based systems involving ITS-G5 and cellular schemes are necessary remains intriguing.

The proposed Multi-Interface Operation in MEC-based situations is also a challenging task worth investigating. Based on personal experience with stakeholders in the automotive industry, the most acceptable solution for most stakeholders would be to utilize the PC5-capable road infrastructure to enhance connectivity to the edge/cloud services. Therefore, future work must be based on extending the existing RSU model to incorporate a D2D-capable NR radio interface. Vehicles could dynamically switch between the interfaces to connect to the edge/cloud services via Uu or PC5 with the RSU involved as a relay. However, to truly model standard behavior, the model and the simulation environment must be prepared to use IPv6, as there is no support for IPv4 over PC5 in the 3GPP standards.

Furthermore, refining the model and equations to determine dynamic processing time requirements based on real-world data or more advanced statistical techniques presents an exciting challenge for our future work. We sincerely hope that our contribution will prove valuable to the research community focused on MEC-based vehicular applications. Whether by offering a ready-to-use testing environment for CP-based V2X applications leveraging MEC or by providing a stable platform for even more intricate scenarios hosting advanced V2X services, we aspire to aid researchers in their endeavors.

Abbreviations

AMQP	Advanced Message Queuing Protocol
CAM	Cooperative Awareness Message
CBR	Channel Busy Ratio
CFS	Customer Facing Service
C-ITS	Cooperative Intelligent Transport Systems
CPM	Collective Perception Message
CPS	Collective Perception Service
D2D	Device-to-device communications
DSRC	Dedicated Short-Range Communications
FOV	Field of view
IMA	Intersection Movement Assist
MCO	Multi-Channel Operation
MEC	Multi-access Edge Computing
MNO	Mobile Network Operator
MQTT	Message Queuing Telemetry Transport
NFV	Network Function Virtualization
OEM	Original Equipment Manufacturer
PSCCH	Physical sidelink control channel
PSCCH	Physical sidelink shared channel
PSFCH	physical sidelink feedback channel
RAT	Radio Access-Technology
VANET	Vehicular Ad-hoc Network
VIS	V2X Information Service

References

[1] Petkovics Ármin, Szabó Csaba Attila, Wippelhauser András, Varga Norbert, and Bokor László, “A V2X járműkommunikáció alapjai,” *Útügyi Lapok*, vol. 8, no. 14, 2020, doi: 10.36246/UL.2020.2.01.

[2] 3GPP, “Architecture enhancements for V2X services,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 23.285. [Online]. Available: http://www.3gpp.org/DynaReport/23285.htm

[3] A. Alalewi, I. Dayoub, and S. Cherkaoui, “On 5G-V2X Use Cases and Enabling Technologies: A Comprehensive Survey,” *IEEE Access*, vol. 9, pp. 107710–107737, 2021, doi: 10.1109/ACCESS.2021.3100472.

[4] G. A. Kovács and L. Bokor, “Implementation of MEC-Assisted Collective Perception in an Integrated Artery/Simu5G Simulation Framework,” *Sensors*, vol. 23, no. 18, 2023, doi: 10.3390/s23187968.

[5] C2C-CC, “Guidance for day 2 and beyond roadmap.” Jul. 09, 2021. [Online]. Available: https://www.car-2-car.org/fileadmin/documents/General_Documents/C2CCC_WP_2072_RoadmapDay2AndBeyond_V1.2.pdf

[6] G. Thandavarayan, M. Sepulcre, and J. Gozalvez, “Cooperative Perception for Connected and Automated Vehicles: Evaluation and Impact of Congestion Control,” *IEEE Access*, vol. 8, pp. 197665–197683, 2020, doi: 10.1109/ACCESS.2020.3035119.

[7] F. A. Schiegg, I. Llatser, D. Bischoff, and G. Volk, “Collective Perception: A Safety Perspective,” *Sensors*, vol. 21, no. 1, 2021, doi: 10.3390/s21010159.

[8] ETSI, “ETSI TR 103 562 V2.1.1 (2019-12) – Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Analysis or the Collective Perception Service (CPS); Release 2.” Dec. 2019. [Online]. Available: https://www.etsi.org/deliver/etsi_tr/103500_103599/103562/02.01.01_60/tr_103562v020101p.pdf

[9] H.-J. Günther, R. Riebl, L. Wolf, and C. Facchi, “Collective perception and decentralized congestion control in vehicular ad-hoc networks,” in *2016 IEEE Vehicular Networking Conference (VNC)*, 2016, pp. 1–8. doi: 10.1109/VNC.2016.7835931.

[10] M. Herbert, A. Váradi, and L. Bokor, “Modelling and Examination of Collective Perception Service for V2X Supported Autonomous Driving,” in *Proceedings of the 11th International Conference on Applied Informatics (ICAI 2020)*, Eger, Hungary, Jan. 2020, pp. 138–149. [Online]. Available: http://ceur-ws.org/Vol-2650/paper15.pdf

[11] M. Correia, J. Almeida, P. C. Bartolomeu, J. A. Fonseca, and J. Ferreira, “Performance Assessment of Collective Perception Service Supported by the Roadside Infrastructure,” *Electronics*, vol. 11, no. 3, 2022, doi: 10.3390/electronics11030347.

[12] ETSI, “ETSI TS 103 324 V2.1.1 (2023-06) – Intelligent Transport System (ITS); Vehicular Communications; Basic Set of Applications; Collective Perception Service; Release 2.” Jun. 2023. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/103300_103399/103324/02.01.01_60/ts_103324v020101p.pdf

[13] A. Bazzi, B. M. Masini, A. Zanella, and I. Thibault, “On the Performance of IEEE 802.11p and LTE-V2V for the Cooperative Awareness of Connected Vehicles,” *IEEE Transactions on Vehicular Technology*, vol. 66, no. 11, pp. 10419–10432, 2017, doi: 10.1109/TVT.2017.2750803.

[14] R. Sattiraju, D. Wang, A. Weinand, and H. D. Schotten, “Link Level Performance Comparison of C-V2X and ITS-G5 for Vehicular Channel Models,” in *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, 2020, pp. 1–7. doi: 10.1109/VTC2020-Spring48590.2020.9129366.

[15] R. Jacob, W. Anwar, N. Schwarzenberg, N. Franchi, and G. Fettweis, “System-level Performance Comparison of IEEE 802.11p and 802.11bd Draft in Highway Scenarios,” in *2020 27th International Conference on Telecommunications (ICT)*, 2020, pp. 1–6. doi: 10.1109/ICT49546.2020.9239538.

[16] V. V. Moshkov, A. D. Badin, and O. A. Guminskiy, “Research of Characteristics of Radio Technologies of V2V/V2P Systems,” in *2022 Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus)*, 2022, pp. 64–68. doi: 10.1109/ElConRus54750.2022.9755670.

[17] 5GAA, “Toward fully connected vehicles: Edge computing for advanced automotive communications,” White Paper 170219, Dec. 2017. [Online]. Available: https://5gaa.org/wp-content/uploads/2017/12/5GAA_T-170219-whitepaper-EdgeComputing_5GAA.pdf

[18] F. Giust *et al.*, “Multi-Access Edge Computing: The Driver Behind the Wheel of 5G-Connected Cars,” *IEEE Communications Standards Magazine*, vol. 2, no. 3, pp. 66–73, 2018, doi: 10.1109/MCOMSTD.2018.1800013.

[19] Z. W. Lamb and D. P. Agrawal, “Analysis of Mobile Edge Computing for Vehicular Networks,” *Sensors*, vol. 19, no. 6, 2019, doi: 10.3390/s19061303.

[20] AECC, “Connected Cars: On The Edge Of A Breakthrough (White Paper) – Version 1.0.0.” May 27, 2021. [Online]. Available: https://aecc.org/resources/publications/

[21] ETSI, “ETSI GS MEC 003 V3.1.1 (2022-03) – Multi-access Edge Computing (MEC); Framework and Reference Architecture.” Mar. 2022. [Online]. Available: https://www.etsi.org/deliver/etsi_gs/MEC/001_099/003/03.01.01_60/gs_MEC003v030101p.pdf

[22] R. Riebl, C. Obermaier, and H.-J. Günther, “Artery: Large Scale Simulation Environment for ITS Applications,” in *Recent Advances in Network Simulation: The OMNeT++ Environment and its Ecosystem*, A. Virdis and M. Kirsche, Eds., Cham: Springer International Publishing, 2019, pp. 365–406. doi: 10.1007/978-3-030-12842-5_12.

[23] Gergely Attila Kovács and László Bokor, “Integrating Artery and Simu5G: A Mobile Edge Computing use case for Collective Perception-based V2X safety applications,” in *2022 45th International Conference on Telecommunications and Signal Processing (TSP)*, 2022, pp. 360–366. doi: 10.1109/TSP55681.2022.9851276.

[24] G. Nardini, D. Sabella, G. Stea, P. Thakkar, and A. Virdis, “Simu5G–An OMNeT++ Library for End-to-End Performance Evaluation of 5G Networks,” *IEEE Access*, vol. 8, pp. 181176–181191, 2020, doi: 10.1109/ACCESS.2020.3028550.

[25] B. McCarthy, A. Burbano-Abril, V. R. Licea, and A. O’Driscoll, “OpenCV2X: Modelling of the V2X Cellular Sidelink and Performance Evaluation for Aperiodic Traffic.” arXiv, 2021. doi: 10.48550/ARXIV.2103.13212.

[26] A. Hegde and A. Festag, “Artery-C: An OMNeT++ Based Discrete Event Simulation Framework for Cellular V2X,” in *Proceedings of the 23rd International ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile*

Systems, in MSWiM ’20. New York, NY, USA: Association for Computing Machinery, 2020, pp. 47–51. doi: 10.1145/3416010.3423240.

[27] A. Virdis, G. Stea, and G. Nardini, “SimuLTE - A modular system-level simulator for LTE/LTE-A networks based on OMNeT++,” in *2014 4th International Conference On Simulation And Modeling Methodologies, Technologies And Applications (SIMULTECH)*, 2014, pp. 59–70. doi: 10.5220/0005040000590070.

[28] G. Nardini, A. Virdis, and G. Stea, “Modeling Network-Controlled Device-to-Device Communications in SimuLTE,” *Sensors*, vol. 18, no. 10, 2018, doi: 10.3390/s18103551.

[29] R. Soua, I. Turcanu, F. Adamsky, D. Führer, and T. Engel, “Multi-Access Edge Computing for Vehicular Networks: A Position Paper,” in *2018 IEEE Globecom Workshops (GC Wkshps)*, 2018, pp. 1–6. doi: 10.1109/GLOCOMW.2018.8644392.

[30] Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief, “A Survey on Mobile Edge Computing: The Communication Perspective,” *IEEE Communications Surveys Tutorials*, vol. 19, no. 4, pp. 2322–2358, 2017, doi: 10.1109/COMST.2017.2745201.

[31] N. Mu, S. Gong, W. Sun, and Q. Gan, “The 5G MEC Applications in Smart Manufacturing,” in *2020 IEEE International Conference on Edge Computing (EDGE)*, 2020, pp. 45–48. doi: 10.1109/EDGE50951.2020.00014.

[32] B. Li *et al.*, “Research on The Requirements and Deployment of 5G MEC in Power Grid Applications,” in *2021 IEEE 2nd International Conference on Information Technology, Big Data and Artificial Intelligence (ICIBA)*, 2021, pp. 351–355. doi: 10.1109/ICIBA52610.2021.9687891.

[33] ETSI, “Harmonizing standards for edge computing - A synergized architecture leveraging ETSI ISG MEC and 3GPP specifications,” White Paper 36, Jul. 2020. [Online]. Available: https://www.etsi.org/images/files/ETSIWhitePapers/ETSI_wp36_Harmonizing-standards-for-edge-computing.pdf

[34] ETSI, “ETSI GS MEC 030 V3.1.1 (2023-03) – Multi-access Edge Computing (MEC); V2X Information Service API.” Mar. 2023. [Online]. Available: https://www.etsi.org/deliver/etsi_gs/MEC/001_099/030/03.01.01_60/gs_MEC030v030101p.pdf

[35] Gergely Kovács and László Bokor, “Towards realistic simulation of MEC-based Collective Perception: an initial edge service design for the Artery/Simu5G framework,” in *1st Workshop on Intelligent Infocommunication Networks, Systems and Services*, BME-VIK, Budapest, Hungary, Feb. 2023. [Online]. Available: https://repozitorium.omikk.bme.hu/bitstream/handle/10890/40711/WINS2023-010.pdf?sequence=1&isAllowed=y

[36] 5GAA, “MEC for Automotive in Multi-Operator Scenarios,” Technical Report, Mar. 2021. [Online]. Available: https://5gaa.org/content/uploads/2021/03/5GAA_A-200150_MEC4AUTO_Task2_TR_MEC-for-Automotive-in-Multi-Operator-Scenarios.pdf

[37] K. Zheng, Q. Zheng, P. Chatzimisios, W. Xiang, and Y. Zhou, “Heterogeneous Vehicular Networking: A Survey on Architecture, Challenges, and Solutions,” *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 2377–2396, 2015, doi: 10.1109/COMST.2015.2440103.

[38] Z. MacHardy, A. Khan, K. Obana, and S. Iwashina, “V2X Access Technologies: Regulation, Research, and Remaining Challenges,” *IEEE Communications Surveys*

Tutorials, vol. 20, no. 3, pp. 1858–1877, 2018, doi: 10.1109/COMST.2018.2808444.

[39] 3GPP, "Release 14 Description; Summary of Rel-14 Work Items," 3rd Generation Partnership Project (3GPP), Technical Report (TR) 21.914. [Online]. Available: http://www.3gpp.org/DynaReport/21914.htm

[40] 3GPP, "Proximity-based Services (ProSe); Stage 2," Technical Specification (TS) TS 23.303. [Online]. Available: https://www.3gpp.org/DynaReport/23303.htm

[41] R. Molina-Masegosa, J. Gozalvez, and M. Sepulcre, "Comparison of IEEE 802.11p and LTE-V2X: An Evaluation With Periodic and Aperiodic Messages of Constant and Variable Size," *IEEE Access*, vol. 8, pp. 121526–121548, 2020, doi: 10.1109/ACCESS.2020.3007115.

[42] Á. Knapp, A. Wippelhauser, D. Magyar, and G. Gódor, "An Overview of Current and Future Vehicular Communication Technologies," *Periodica Polytechnica Transportation Engineering*, vol. 48, no. 4, pp. 341–348, 2020, doi: 10.3311/PPtr.15922.

[43] Y. Jin, X. Liu, and Q. Zhu, "DSRC & C-V2X Comparison for Connected and Automated Vehicles in Different Traffic Scenarios." 2022.

[44] Jonathan M. Gitlin, "Court rules FCC is allowed to reassign 5.9 GHz bandwidth, killing V2X." [Online]. Available: https://arstechnica.com/cars/2022/08/v2x-is-finally-dead-as-court-refuses-to-stop-fccs-5-9-ghz-reallocation/

[45] G. Naik, B. Choudhury, and J.-M. Park, "IEEE 802.11bd & 5G NR V2X: Evolution of Radio Access Technologies for V2X Communications," *IEEE Access*, vol. 7, pp. 70169–70184, 2019, doi: 10.1109/ACCESS.2019.2919489.

[46] 3GPP, "Release 16 Description; Summary of Rel-16 Work Items," 3rd Generation Partnership Project (3GPP), Technical Report (TR) 21.916. [Online]. Available: http://www.3gpp.org/DynaReport/21916.htm

[47] Z. Ali, S. Lagén, L. Giupponi, and R. Rouil, "3GPP NR V2X Mode 2: Overview, Models and System-Level Evaluation," *IEEE Access*, vol. 9, pp. 89554–89579, 2021, doi: 10.1109/ACCESS.2021.3090855.

[48] C2C-CC, "Multi-Channel Operation (MCO); Part 1; Functional requirements." Oct. 2020. [Online]. Available: https://www.car-2-car.org/fileadmin/documents/General_Documents/C2CCC_WP_2082_MCO-Requirements_V1.1.pdf

[49] C2C-CC, "Multi-Channel Operation (MCO); Part 2; Technical capabilities and limits." Oct. 2020. [Online]. Available: https://www.car-2-car.org/fileadmin/documents/General_Documents/C2CCC_WP_2084_MCO-TechnicalCapabilies_V1.0.pdf

[50] C2C-CC, "Multi-Channel Operation (MCO); Part 3; MCO Concept." Oct. 2022. [Online]. Available: https://www.car-2-car.org/fileadmin/documents/General_Documents/C2CCC_WP_2085_MCO-Concept_V1.0.pdf

[51] ETSI, "ETSI TS 103 439 V2.1.1 (2021-10) – Intelligent Transport Systems (ITS); Multi-Channel Operation study; Release 2." Oct. 2021. [Online]. Available: https://www.etsi.org/deliver/etsi_tr/103400_103499/103439/02.01.01_60/tr_103439v020101p.pdf

[52] ETSI, "ETSI TS 103 696 V2.1.1 (2021-11) – Intelligent Transport Systems (ITS); Communication Architecture for Multi-Channel Operation (MCO); Release 2." Nov. 2021. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/103600_103699/103696/02.01.01_60/ts_103696v020101p.pdf

[53] R. Molina-Masegosa and J. Gozalvez, “LTE-V for Sidelink 5G V2X Vehicular Communications: A New 5G Technology for Short-Range Vehicle-to-Everything Communications,” *IEEE Vehicular Technology Magazine*, vol. 12, no. 4, pp. 30–39, 2017, doi: 10.1109/MVT.2017.2752798.

[54] J. Lianghai, A. Weinand, B. Han, and H. D. Schotten, “Applying Multiradio Access Technologies for Reliability Enhancement in Vehicle-to-Everything Communication,” *IEEE Access*, vol. 6, pp. 23079–23094, 2018, doi: 10.1109/ACCESS.2018.2829606.

[55] 3GPP, “Architecture enhancements for 5G System (5GS) to support Vehicle-to-Everything (V2X) services,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 23.287. [Online]. Available: http://www.3gpp.org/DynaReport/23287.htm

[56] 3GPP, “System architecture for the 5G System (5GS),” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 23.501. [Online]. Available: http://www.3gpp.org/DynaReport/23501.htm

[57] S. A. A. Shah, E. Ahmed, M. Imran, and S. Zeadally, “5G for Vehicular Communications,” *IEEE Communications Magazine*, vol. 56, no. 1, pp. 111–117, 2018, doi: 10.1109/MCOM.2018.1700467.

[58] ETSI, “ETSI GR MEC 022 V2.1.1 (2018-09) – Multi-access Edge Computing (MEC); Study on MEC Support for V2X Use Cases.” Sep. 2018. [Online]. Available: https://www.etsi.org/deliver/etsi_gr/mec/001_099/022/02.01.01_60/gr_mec022v020101p.pdf

[59] R. Miucic, A. Sheikh, Z. Medenica, and R. Kunde, “V2X Applications Using Collaborative Perception,” in *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*, 2018, pp. 1–6. doi: 10.1109/VTCFall.2018.8690818.

[60] 5GAA, “Working Item MEC4AUTO,” Technical Report, Jul. 2021. [Online]. Available: https://5gaa.org/content/uploads/2021/07/5GAA_MEC4AUTO.pdf

[61] 5GAA, “Moving towards federated MEC demos/trials (global MEC),” Technical Report. [Online]. Available: https://5gaa.org/content/uploads/2023/04/5gaa-moving-toward-federated-mec-demos-trials.pdf

[62] R. Riebl, H.-J. Günther, C. Facchi, and L. Wolf, “Artery: Extending Veins for VANET applications,” in *2015 International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS)*, 2015, pp. 450–456. doi: 10.1109/MTITS.2015.7223293.

[63] “INET Framework - last visited in 2023 February.” [Online]. Available: https://inet.omnetpp.org/Introduction.html

[64] Raphael Reibl and Christian Facchi, “Regain Control of Growing Dependencies in OMNeT++ Simulations,” in *Proceedings of the “OMNeT++ Community Summit 2015,”* [Online]. Available: https://arxiv.org/ftp/arxiv/papers/1509/1509.03561.pdf

[65] A. Noferi, G. Nardini, G. Stea, and A. Virdis, “Rapid prototyping and performance evaluation of ETSI MEC-based applications,” *Simulation Modelling Practice and Theory*, vol. 123, p. 102700, 2023, doi: https://doi.org/10.1016/j.simpat.2022.102700.

Annex

Notes on modeling simplified Multi-Interface Operation

For simulating Multi-Interface Operation, the idea was to utilize PC5-capable roadside infrastructure and to alter the existing code for the CPS application sending CPMs via the Uu interface to be able to switch to PC5. The first step was to enhance the available RSU model and integrate a cellular radio interface capable of receiving messages via PC5. The NR radio implementation that is shipped with Simu5G was a perfect choice for initial testing. Note that this implementation is not the same as either of the standardized D2D modes in LTE or 5G NR, hence the simplification for Multi-Interface Operation. There is room for improvement in this regard, which can be implemented in future work. Unfortunately, the procedure was not plug-and-play because dynamic submodule handling is a bit tricky in the newest versions of OMNeT++. (The source of the conflict is that Artery, by nature, handles vehicle models dynamically, which was handled differently in older versions of OMNeT++. Simu5G, on the other hand, does not rely on dynamic insertions but requires newer OMNeT++.) The issue was specific to the automatic network configuration procedures upon building the scenario environment. The IP subnets and address pools had to be cleverly redesigned for the nodes using cellular radio (i.e., the vehicles and the newly inserted RSU) because, otherwise, one of the simulated network elements broke the simulation by routing the messages meant for the vehicles to the RSU.

The setup was first tested using a simple UDP stream application to check whether D2D communication worked in the system. However, in this case, the switching between Uu or PC5 is determined by the serving gNodeB if and only if the vehicle and the RSU are both served by the same cell. This solution stands somewhere between Mode 1 and Mode 2 of NR V2X, but clearly, the desirable solution was to use either of the two standard methodologies. Without implementing the PC5 mechanisms of NR V2X, putting the switching logic within the application layer of the vehicles seemed a reasonable solution.

The idea was to utilize the Location Service subscription of the client edge application and set it up to notify the vehicle when it is close to the RSU. An edge application had to be implemented to run on the RSU and relay any CPMs received on its

PC5 interface to the corresponding edge-side application instance running on the MEC. This way, the application logic in the vehicles can simply switch between two pre-configured destination addresses: one for the corresponding MEC app instance and the other for the application running on the RSU. This way, outside the “PC5 relevant zone”, everything works the same way as in the Uu-based scenarios, and while near the RSU, the CPMs are directly sent to the RSU using PC5, and then the RSU relays the messages to the MEC via fiber.

Though implementing the switching logic in the applications and proper configuration meant little hardships, the network could not handle the packets sent to the RSU upon switching the destination addresses. The error occurred in the MAC layer of the serving gNodeB during the operation of the HARQ mechanism after receiving the first packet addressed to the RSU. I assume that the serving gNodeB is not prepared to handle the request for a D2D flow in this manner, and the decision to put the switching logic in the application layer is simply an abuse of Simu5G’s D2D implementation. The exact cause of the problem and the possible solutions are still under investigation.