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Vehicular Communication Management Framework: A Flexible Hybrid Connectivity Platform for CCAM Services

Dries Naudts [1,*,†], Vasilis Maglogiannis [1,*,†], Seilendria Hadiwardoyo [2], Daniel van den Akker [2], Simon Vanneste [3], Siegfried Mercelis [3], Peter Hellinckx [3], Bart Lannoo [2], Johann Marquez-Barja [2] and Ingrid Moerman [1]

[1] IDLab, Department of Information Technology, imec—Ghent University, Technologiepark Zwijnaarde 126, B-9052 Ghent, Belgium; ingrid.moerman@ugent.be
[2] IDLab, Department of Electronics—ICT, imec—University of Antwerp, Sint-Pietersvliet 7, B-2000 Antwerp, Belgium; seilendria.hadiwardoyo@uantwerpen.be (S.H.); daniel.vandenakker@uantwerpen.be (D.v.d.A.); bart.lannoo@uantwerpen.be (B.L.); johann.marquez-barja@uantwerpen.be (J.M.-B.)
[3] IDLab, Faculty of Applied Engineering, imec—University of Antwerp, Sint-Pietersvliet 7, B-2000 Antwerp, Belgium; simon.vanneste@uantwerpen.be (S.V.); siegfried.mercelis@uantwerpen.be (S.M.); peter.hellinckx@uantwerpen.be (P.H.)
* Correspondence: dries.naudts@ugent.be (D.N.); vasilis.maglogiannis@ugent.be (V.M.)
† These authors contributed equally to this work.

Abstract: In the upcoming decade and beyond, the Cooperative, Connected and Automated Mobility (CCAM) initiative will play a huge role in increasing road safety, traffic efficiency and comfort of driving in Europe. While several individual vehicular wireless communication technologies exist, there is still a lack of real flexible and modular platforms that can support the need for hybrid communication. In this paper, we propose a novel vehicular communication management framework (CAMINO), which incorporates flexible support for both short-range direct and long-range cellular technologies and offers built-in Cooperative Intelligent Transport Systems' (C-ITS) services for experimental validation in real-life settings. Moreover, integration with vehicle and infrastructure sensors/actuators and external services is enabled using a Distributed Uniform Streaming (DUST) framework. The framework is implemented and evaluated in the Smart Highway test site for two targeted use cases, proofing the functional operation in realistic environments. The flexibility and the modular architecture of the hybrid CAMINO framework offers valuable research potential in the field of vehicular communications and CCAM services and can enable cross-technology vehicular connectivity.

Keywords: V2X; hybrid; communication; CCAM; C-ITS; C-V2X; ITS-G5; vehicular; framework; testbed

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1. Introduction

In recent years, vehicles with autonomous driving functionalities have become more and more a reality on our roads. To drastically increase road safety and to further push this revolution, huge research and innovation efforts are being made to add connectivity features to these vehicles in order to allow information exchange between them and their surroundings, also known as Vehicle-to-Everything (V2X) communications. Depending on the nature of these surroundings these communications can be Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), Vehicle-to-Network (V2N), etc. To further support EU countries and the European automotive industry in their transition to connected and automated driving, the European Commission started the Cooperative, Connected and Automated Mobility (CCAM) initiative [1].

The last decade, two wireless communication technologies have been developed to provide direct data exchange in dedicated spectrum. The first one is 802.11p-based and consists of different Intelligent Transport Systems (ITS) protocol stacks in Europe and the

U.S., namely ITS-G5 and Dedicated Short Range Communication (DSRC) respectively. The second is the cellular based C-V2X PC5 technology. Furthermore, 4G and especially 5G are seen as the technologies to further drive this CCAM paradigm and provide longer range communication to infrastructure and cloud services [2]. A classification of the different V2X technologies is shown in Figure 1.

In spring 2019, the European Commission attempted to provide clarity around the technology to be used by automotive Original Equipment Manufacturers (OEMs) by publishing a Delegated Act on Cooperative ITS (C-ITS), based on ITS Directive 2010/40/EU [3]. The Delegated Act aimed to define requirements for C-ITS stations and services, endorsing the ITS-G5 standard as the baseline technology for direct communication between vehicles and infrastructure. However, according to the European spectrum regulations, the 5855–5925 MHz ITS band must be technology neutral. This implies that any radio technology, which can demonstrate conformance with the essential requirements of the Radio Equipment Directive (e.g., through compliance with EN 302 571 [4]) can operate in the ITS band. For this reason, the Delegated Act was rejected by the EU Member States, as being in favor of one technology does not ensure the technology neutrality of the 5.9 GHz ITS band. As a result, each automotive OEM can independently select its favorable short-range communication technology. Today, most car and truck manufacturers hesitate to select and integrate a specific technology, but they keep monitoring the progress happening in both domains so that they can chose the one that potentially dominates in the future. However, some OEMs have already started integrating a specific short-range V2X technology. For example, Volkswagen, one of the best selling OEMs in Europe, has announced that the new Golf 8 will use ITS-G5 for its Car2X technology [5]. On the contrary, other OEMs such as BMW, Audi and Ford focus more on C-V2X PC5 [6].

Today, long- and short-range technologies are typically targeting different use cases where each technology has its own characteristics, advantages and drawbacks that make it more or less capable in addressing the diverse requirements of connected and autonomous driving applications, such as end-to-end latency, throughput, reliability, etc. For instance, short-range technologies (C-V2X PC5 and ITS-G5) are more suitable for serving low latency use cases such as truck platooning, while long-range technologies (4G/5G C-V2X Uu) can provide the necessary throughput for passenger infotainment applications.

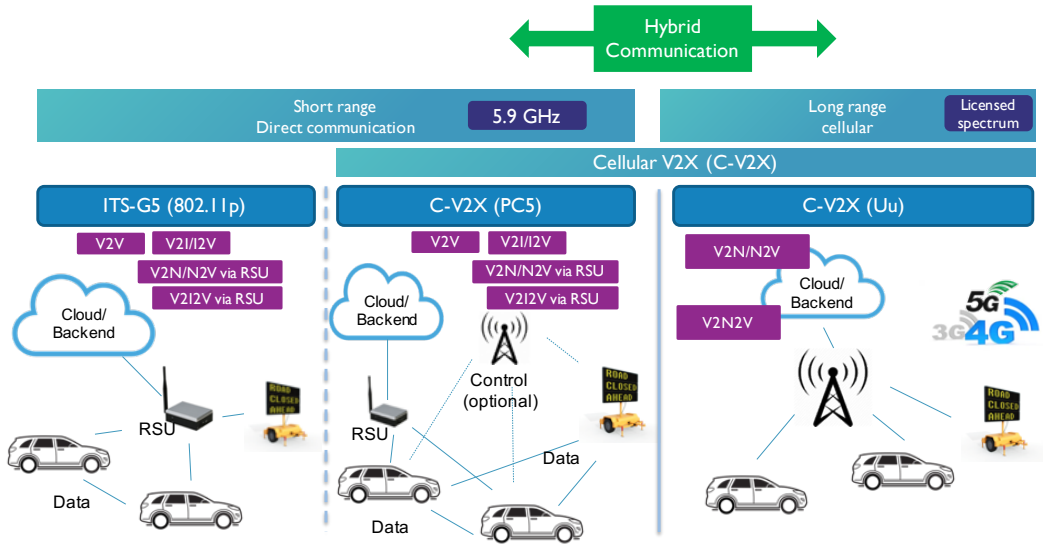

Figure 1. Vehicle-to-Everything (V2X) technology classification.

Currently, more and more attention is paid towards the concept of hybrid communication solutions where envisioned use cases can leverage on a combination of multiple technologies, including long-range cellular communications, providing connectivity in a intelligent, reliable and optimal manner. In this paper, we propose the vehicular com-

munication management framework (CAMINO), which empowers the use of hybrid V2X wireless technologies to support a multitude of CCAM services. CAMINO enables dynamic and flexible management of the different available V2X technologies and the services running on top of them. In addition, it allows integration with different vehicle/infrastructure sensors, actuators, Human-Machine Interfaces (HMIs) and external third-party service providers. CAMINO is an ITS device agnostic framework, meaning that it can be used on top of any network entity of the vehicular communication world such as vehicles, infrastructure, smartphones, Mobile Edge Computing (MEC) servers, service providers, etc. Furthermore, CAMINO allows monitoring and logging of valuable information like transmitted and received messages, Global Navigation Satellite System (GNSS) data, triggering of events, etc. This information can be used for real-time or offline analysis of various Key Performance Indicators (KPIs).

The adoption of different technologies from different OEMs carries the risk of ending up with different groups of vehicles each using different communication technologies and as a result, only vehicles that belong to a certain group can communicate with each other. This could have a negative impact on the vision of the CCAM initiative for enabling enhanced safety and advanced services between connected and autonomous vehicles. OEMs could integrate multiple technologies in their vehicles, which requires the use of flexible hybrid communication solutions such as CAMINO. These solutions can provide the ability to use the same platform for supporting multiple communication technologies and using them in a dynamic way, acting as a low-complexity convergence layer for V2X interoperability and at the same time increasing reliability.

The remainder of the article is organized as follows. Section 2 gives an overview of the current literature on V2X hybrid communication systems. In Section 3, we describe in detail the overall CAMINO architecture, the building blocks and how they interconnect with each other. Section 4 presents the different services that have been implemented within the CAMINO framework and how they can be used in a flexible manner on top of the different V2X technologies. Next, Section 5 describes how CAMINO can be integrated with different sensors, actuators and third-party service providers. In Section 6, we discuss the logging capabilities and the logging format of the framework for real-time or offline processing of KPIs. Section 7 shows how CAMINO can be used in practice for real-time CCAM experimentation. Finally, Section 8 concludes the article and discusses how CAMINO will be used in our future work.

2. Related Work

During the past few years, several solutions for connected vehicles, infrastructure and pedestrians have penetrated the market. These products offer better cooperative perception and are built on top of V2X communication technologies that have been standardized in the last decade. These communication modules typically are closed source, have limited flexibility and only offer support for a single wireless communication technology. They lack an open, modular design to support hybrid communication based solutions. In research, several papers have addressed the topic of hybrid communication for V2X applications.

The authors in [7] give an overview of hybrid V2X communications, describe their potentials, identify challenges and discuss main design aspects. As they explain, none of the today's V2X technologies is capable of serving the diverse Quality of Service (QoS) requirements of connected/autonomous driving applications. Hybrid V2X communications may enable Multi-Radio Access Technology (RAT) coordination to efficiently adapt to the conditions of the vehicular environment and serve the QoS requirements by selecting the best suited technologies. The authors introduce different communication profiles consisting of the RAT, its operation mode (e.g., long-range or direct) and other specific configurations. Multiple profiles could either be aggregated for increased throughput or be used concurrently for increased transmission reliability. In addition, the authors state that the dynamic selection of the appropriate communication profiles will be crucial for

the overall system's performance and suggest a number of strategies for providing this dynamic selection.

The current literature includes several hybrid V2X concepts [8–10] indicating the importance of combining different V2X technologies in an intelligent way according to the different use case/application requirements. However, to the best of our knowledge these concepts are only implemented and evaluated in simulations and lack the capability to offer a flexible, extendable, technology/service/vendor agnostic hybrid V2X system for real-life operation.

In [8], a framework for hybrid V2X communication was developed, which aims to enhance the safety of vulnerable users at 'un-signalized' intersections. Hence, a lightweight communication node has been developed capable to communicate with connected vehicles via LoRa and DSRC technologies, and with pedestrians or unconnected vehicles through Bluetooth. The authors developed a crash prediction algorithm to identify unsafe conditions and warn the users. The VISSIM simulator was used to evaluate the proposed methodology under several traffic and landscape conditions.

The authors in [9] propose a V2X simulation framework which allows vehicles to share their profiles and sensor data through V2X communication technologies. This way, researchers can test their V2X solutions for intelligent and autonomous driving at low cost. This framework allows vehicles to exploit received information from neighboring vehicles (e.g., camera feed or LIDAR data) and combine it with their own sensor data through data fusion algorithms. Hence, the vehicles can enhance their environment awareness and select a more optimal driving strategy.

According to [10], there is a clear need for virtual test drives for design and testing of automated driving technologies to reduce the overall testing expenditure. Therefore the authors have developed a simulation framework based on the existing vehicle simulator "CarMaker", in combination with the middleware platform "Robot Operating System". The simulator was fed with real traffic data. To this end, a novel performance evaluation framework for Advanced Driver-Assistance Systems (ADAS) is presented. Furthermore, it allows to analyze the performance of V2X-communication for all kinds of scenarios and input parameters. Regarding the V2X communication, the authors have implemented IEEE 802.11p and C-V2X Mode 4 (without control of the network).

In addition to the research focusing on simulation environments, there are currently a few proposals of hybrid V2X systems that are based on real implementations. In [11], the authors propose an alternative system for V2X communication that does not rely on WAVE/DSRC and instead propose a hybrid system that embodies a mix of cellular network and Wi-Fi Direct. Their system provides seamless connectivity and vehicle monitoring through long-range cellular technology combined with local data transmission via Wi-Fi Direct, and incorporates a solution for reducing the long connection time of Wi-Fi Direct. In their paper, the authors only focus on optimizing the Wi-Fi Direct technology to reduce discovery times and the hybrid concept is limited to using a management system in the cloud to control local Wi-Fi Direct networks via long range technology. The performance of the proposed system is evaluated in a real environment for three different scenarios, but they only use smartphones in their evaluation.

Finally, the technology company Continental announced that it is developing a hybrid V2X platform that allows mobile network communication (4G/5G) to be combined with direct V2X communication technologies such as DSRC and C-V2X PC5 [12]. This allows the vehicle manufacturers to integrate in their vehicles a system that would allow V2X communication on a global scale. According to Continental, combining short- and long-range communications results in a system applicable for any type of networking. For instance, short-range communications could be used to enhance the driving safety. On the other hand, long-range communications could enable infotainment access to the drivers and passengers, and could disseminate the safety related messages over longer distances, enhancing the awareness of drivers and automated vehicles. However, this platform is a closed commercial "black box" system supporting a set of existing standardized services.

In contrast to existing solutions, the CAMINO framework is an open system that offers flexible support for standardized, future and custom C-ITS services. Additionally, CAMINO can be integrated with any existing and future V2X wireless technology in a vendor agnostic way. This means that commercial V2X technology modules from different vendors can be used within the framework. Furthermore, the CAMINO framework provides rich logging capabilities, allowing to evaluate the performance of the V2X technologies and services running on top of them. In Table 1, the CAMINO framework is compared with the solutions described in this section in terms of several key features.

Table 1. Comparison of the vehicular communication management framework (CAMINO) with other state-of-the-art solutions on several key features.

	[8]	[9]	[10]	[11]	[12]	**CAMINO**
Type of solution	Lightweight communication node device	V2X simulation framework	Simulation framework for advanced driver assistant systems	Hybrid V2X system for safety critical applications	Commercial 5G hybrid V2X platform	V2X communication management framework for real hardware
Type of evaluation	Simulation-based (VISSIM)	Simulation-based (CARLA)	Simulation-based (CarMaker)	Real experimental environment	Real-life environment	Real-life highway environment
Considered V2X technologies	LoRa, DSRC, Bluetooth	Not specified	IEEE 802.11p, C-V2X Mode	Wi-Fi Direct, Long-range cellular	Commercial modules for C-V2X PC5, DSRC, 4G, 5G	Commercial modules for C-V2X PC5, ITS-G5, 4G, 5G
Type of communication supported	V2V, V2P	V2V	V2V	V2V, V2I, V2N	V2V, V2I, V2N	V2V, V2I, V2N
Services supported	Crash prediction at unsignalized intersection	Augmented reality driving assistive application	Vehicle merging into a freeway	Accident detector	Standardized C-ITS	Standardized C-ITS and custom services
Extendability	N/A	Simulator-based modular approach	Possible through the Robot Operating System platform	N/A	N/A	High due to the modular design
Logging features	Within the simulator	Dataset generation module for image and sensor logging	Within the simulator	N/A	N/A	Transmitted/received messages based on Intercor format, triggered events, positioning information
Time synchronization	Within the simulator	Within the simulator	Within the simulator	N/A	N/A	NTP-based using GNSS

3. Camino Architecture for V2X Communication

The architecture of the CAMINO framework is shown in Figure 2. CAMINO provides flexible, modular support for C-ITS services and embraces hybrid communication by interfacing with a variety of different communication modules.

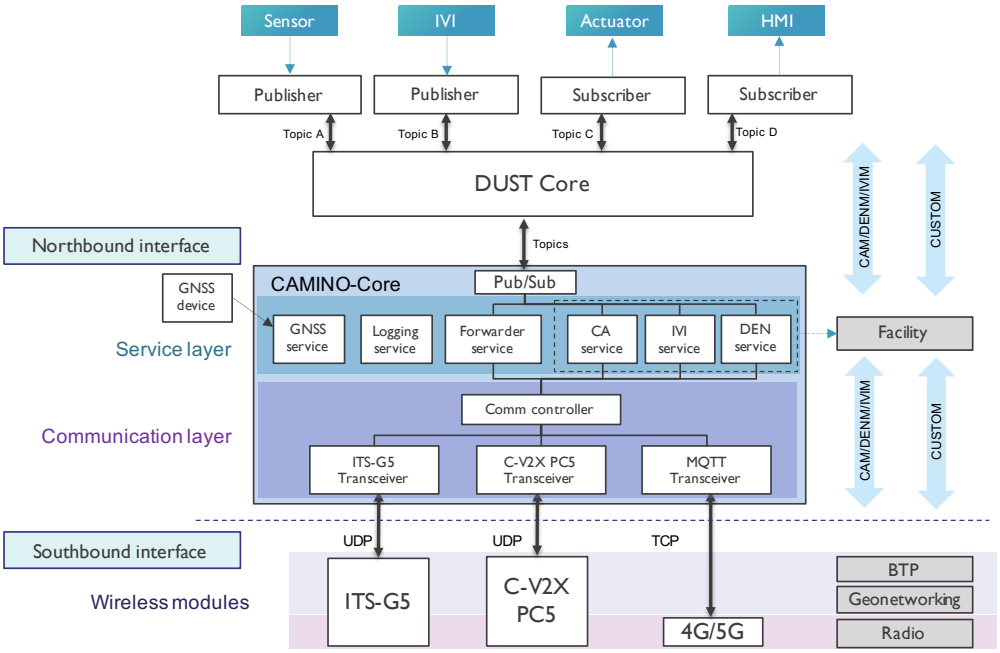

Figure 2. Overall CAMINO framework architecture.

The CAMINO-Core component implements the main functionality that is needed to control the incoming and outcoming data flows between the northbound and southbound interfaces. At the southbound interface, CAMINO-Core interconnects with the different V2X wireless technologies using the different transceiver classes. For example, it can communicate with commercial C-V2X PC5 and ITS-G5 modules via UDP sockets, for which a proprietary header is added to the messages, and with an MQTT broker through TCP over wired or cellular networks. The transceiver classes can interact with the CAMINO-Core services via the Communication (Comm) Controller.

The Comm Controller is a component in the CAMINO-Core architecture that is responsible for managing the C-ITS messages that are transceived by the services via the supported communication paths. Messages that are coming from the services will be mapped onto the transceivers based on the configuration settings. The Comm Controller passes the service identifier so that it can be used as part of the Basis Transport Protocol (BTP) header in the ITSG5 and C-V2X PC5 transceiver and wireless modules, or in the topic for the MQTT transceiver. Messages that are received by the transceivers via the southbound interface, will be forwarded and processed by the Comm Controller. Based on the service identifier, derived from the BTP header or MQTT topic, the Comm Controller will pass the message to the correct service.

At the northbound interface, CAMINO-Core is integrated with the Distributed Uniform Streaming (DUST) open-source framework [13,14] that provides interconnection to sensors, actuators, third-party services and HMI by using a publisher/subscriber architecture. More information about the northbound interface is provided in Section 5.

The facility layer of the ITS stack, as specified in ETSI, can be managed by the CAMINO-Core. Several C-ITS services are supported, such as Cooperative Awareness (CA), Decentralized Environment Notification (DEN) and Infrastructure to Vehicle Information (IVI). The different services can run in the CAMINO-Core, independently or simultaneously, transmitting standardized messages such as Cooperative Awareness Message (CAM), Decentralized Environmental Notification Message (DENM) and Infrastructure to Vehicle Information Message (IVIM). Additionally, CAMINO allows for the transmission of custom messages and it provides the forwarder service. This service can forward the messages coming to CAMINO-Core via any V2X technology at the southbound interface to the northbound actuators, or can forward incoming message from sensors on the northbound interface to the V2X communication modules on the southbound interface.

The CAMINO-Core is designed in a way that different V2X communication technology modules can be connected via dedicated interfaces. The interface can differ between the modules that are linked to the unit that runs the CAMINO-Core. The C-ITS services can exchange the same messages over different communication paths in an intelligent and flexible way. As an example, the In-Vehicle Signage service running in the CAMINO-Core can send IVI messages via ITS-G5, C-V2X PC5 and/or 4G depending on the required operation mode. Even more, the same generated message can be easily transmitted over multiple technologies in parallel. At the receiver side, the CAMINO-Core can process messages that are received via multiple communication technologies. Providing support for multiple communication modes, allows flexible testing of C-ITS services over multiple V2X radio technologies. Furthermore, it can offer communication redundancy by allowing to transfer messages over multiple technologies in an intelligent way, based on the current environmental characteristics (e.g., link quality, congestion, interference, ...). Currently, the selection of the communication path is based on configuration settings. Adding an intelligent selection algorithm could further improve the performance of the communication and can be part of future studies.

Moreover, the CAMINO-Core provides the logging service that enables several logging capabilities. It stores information either locally or in a remote database and can log among others transmitted or received messages, triggered events, positioning information, etc. For positioning and timing information, the CAMINO-Core is linked to a GNSS device via the GNSS service. Section 6 provides more information about the logging service.

3.1. Direct Short-Range Communication

Two wireless standards are currently being used for direct short-range communication in the dedicated 5.9 GHz ITS frequency bands: the ETSI ITS-5G standard and the cellular based C-V2X PC5 technology (Figure 1). The CAMINO framework assumes that, for each technology, the actual transmission and reception is handled by a dedicated commercial module. The lower layers of the ETSI ITS stack, such as the Basic Transport Protocol (BTP), Geonetworking and radio layers, are managed by the V2X wireless modules, while the facility layer is managed by CAMINO-Core. The radio parameters (e.g., channel, transmission power, transmission diversity, etc.) are configured in the commercial modules.

3.2. Cellular Long-Range Communication

In addition to the short-range technologies, CAMINO supports cellular long-range communication using 4G or even 5G modems, also addressed as C-V2X Uu, where Uu refers to the interface used for the communication between the UE and the base station. The cellular interface provides a routable internet uplink. Within CAMINO-Core, an MQTT client enables message transfer towards an MQTT broker that can run on the edge or the core. This way, the same facility layer messages that are generated in the CAMINO-Core services (see Section 4), can also be exchanged via the MQTT broker on specific topics. The MQTT client can subscribe to several topics and direct incoming messages to the proper service. GeoCasting services could be used for distributing the messages to the vehicles using a geo-tiling mechanism, where users automatically receive the data relevant for their tile [15]. Furthermore, the forwarder service in CAMINO-Core allows transparent exchange of external messages via the cellular long-range interface using MQTT.

4. C-ITS Services within CAMINO

As part of the ETSI C-ITS specifications, several facility services have been standardized to be used by ITS applications, such as CA, DEN, IVI, Traffic Light Maneuvering (TLM), Traffic Light Control (TLC) and more [16]. CAMINO-Core currently provides a basic implementation of CA, DEN and IVI, that allows transmission and reception of CAM, DENM and IVIM respectively. The services are built based on the Vanetza library [17] that is an an open-source implementation of the ETSI C-ITS protocol suite.

Depending on the configuration, one or more of these services will automatically run at startup of the CAMINO-Core. Each running service will initiate message transmission with a pre-configured sending interval. The CAM, DENM and IVIM messages are ASN.1 encoded as per the ETSI and ISO standards. An overview of the supported specifications are given in Table 2. When a message is sent towards the southbound interface via the Comm Controller and Transceiver modules, a header containing a so-called "service identifier" is added if the message is to be transmitted using one of the short range communication modules. When such messages are received from the southbound interface, they are directed towards the correct service based on this service identifier. For long-range communication CAMINO does not add any headers to the messages and instead uses separate MQTT topics to differentiate between different services.

Table 2. Supported Cooperative Intelligent Transport Systems (C-ITS) application specifications.

C-ITS Application	Version
CAM	ETSI EN 302 637-2 V1.4.1 and ETSI EN 302 637-2 V1.3.2
DENM	ETSI EN 302 637-3 V1.3.1 and ETSI EN 302 637-3 V1.2.2
IVIM	ETSI TS 103 301, version 1, 2016, ISO/TS 19321:2015

The content of the messages can be constructed based on static configuration parameters and dynamic GNSS information, but can also be fed in real-time by the external northbound applications (sensor input, external services) via the DUST-Core. Inversely, the CAMINO-Core services can push information to the northbound services and actuators through the DUST-Core. This allows for a flexible and modular programming environment to create tailored C-ITS services based on standardized ETSI specifications that can be easily updated and extended.

In addition to the C-ITS and logging services, CAMINO-Core also contains a GNSS service, which retrieves positioning data with a configurable interval from an external GNSS device via the GPS daemon (GPSd). These positioning data can then be used in the C-ITS services and added to the messages that are being transmitted. Moreover, the GNSS device is used for timing synchronization through the use of the Network Time Protocol (NTP) [18].

5. Sensors, Actuators and External Services Integration

At the northbound interface, CAMINO-Core is integrated with the DUST framework [13] using publisher/subscriber architecture. DUST optimizes the distribution of resources in a modern IoT environment. The core of the DUST framework, called DUST-Core, allows different application components to stream events between each other by using DUST messages. As the components should be able to migrate between devices, the underlying middleware configuration must be interchangeable. As such, the DUST-Core makes an abstraction of this towards the application components. Currently, MQTT, ZeroMQ and Data Distribution Service messaging protocols are supported by DUST. To integrate the DUST framework in the CAMINO framework, we have developed a series of publishers that can be used to trigger specific services at CAMINO-Core based on information that may derive from the CAN BUS or the sensors of the vehicle/Road-Side Unit (RSU) and a series of subscribers that bring the information from the different ITS services in the vehicle/RSU. This information may be used to trigger an actuator (e.g., towards autonomous driving) or to be visualized using an HMI. The DUST enabled applications can run on the same computing unit as the CAMINO-Core but can also be distributed to other processing units.

The capabilities of the CAMINO framework to dynamically trigger services, communicate with the environment (e.g., sensors) and bring information in the vehicle (actuators, HMIs) can enable several C-ITS use cases such as Road Hazard Warning (RHW), In-Vehicle Signage (IVS), Electronic Emergency Brake Light (EEBL) and many more. In order to trig-

ger DENM and IVIM messages that can enable such use cases, the CAMINO framework provides implementations of related DUST publisher and subscribers.

For instance, regarding the RHW or the EEBL, the developed DUST publishers can trigger the transmission of DENM messages for a series of virtual or real hazardous situations that are identified by the sensors of the vehicle, such as a slow or stationary vehicle, roadworks, brake event, etc. On the other hand, when the CAMINO-Core instance of a vehicle receives a DENM message through a V2X wireless technology, it decodes it and publishes the relevant information to the developed DUST DENM subscriber. The DUST subscriber of the DENM messages, receives this information, and according to the considered scenario, it either depicts a warning to the driver of the vehicle or triggers a relevant actuator (e.g., slowing down the vehicle). As an example, an EEBL demo was implemented, where a brake event at the vehicle was detected by reading out CAN BUS data from the brake pedal. When the pressure on the brake pedal exceeded a certain threshold, an event message was generated and sent to the CAMINO via the DUST-Core. The CAMINO-Core was then able to transmit this event message using a DENM over the different V2X technologies [19].

For the IVS use case, we have developed a DUST publisher that gives vehicles real-time access to the information on the electronic traffic signs located on top of the gantries along the Belgian highways. To this end, we have developed an application that periodically fetches the traffic sign values from the public datasets provided by the Belgian Government and thus acts as an external third party service provider. Based on the desired configuration parameters, the DUST publisher filters out the data and creates a JSON message that includes all the relevant information, such as the traffic sign per lane, the coordinates of the gantry, the timestamp when each sign was updated, etc. This message is then transmitted to the CAMINO-Core instance running on each RSU. When the CAMINO-Core receives such a message, it updates the IVI service with the newly received information and broadcasts the updated IVIM to the vehicles. At the vehicle side, when CAMINO-Core receives an IVIM through a V2X wireless technology, it decodes it and publishes the relevant information to the developed DUST IVI subscriber. The DUST IVI subscriber receives this information and when the vehicle is in the relevance zone of the IVIM, it depicts the signage of each lane to the driver in a related HMI, as shown in Figure 3.

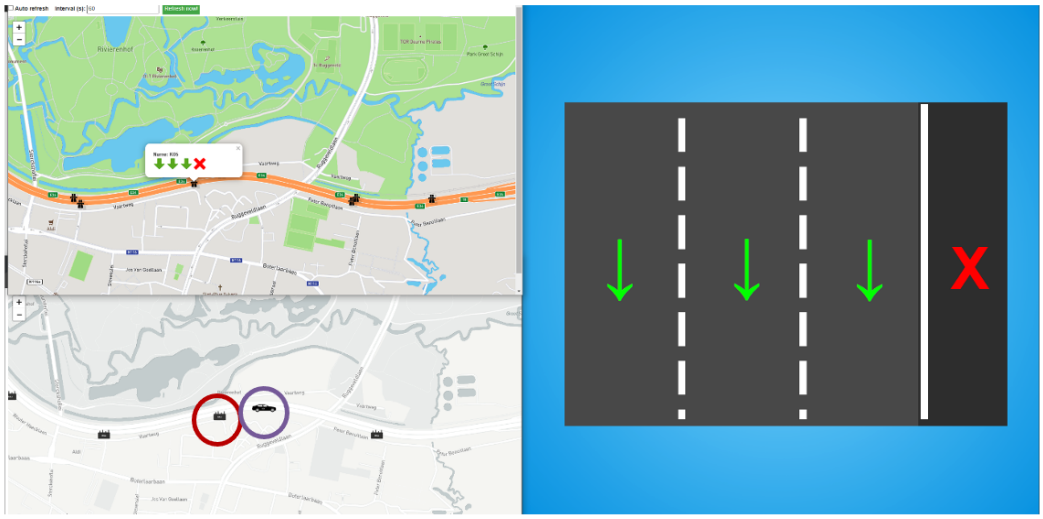

Figure 3. Information presented on the Human-Machine Interface (HMI) when the vehicle is in the Infrastructure to Vehicle Information (IVI) relevance zone.

6. CAMINO-Core Logging Features

The CAMINO-Core implementation supports data logging of all the messages being transmitted and received via the southbound Interface from the different wireless communication modules (ITS-G5, C-V2X PC5 and Cellular modem). The data are logged locally on

the device where the CAMINO-Core is running, in logfiles. Each time the CAMINO-Core application is started, a new log directory is created using the current timestamp as the directory name, <*yyyyMMDDTHHMMss*>, to avoid overwriting any of the locally stored logfiles. The logdata can also be pushed in real-time to a remote database for demo purposes but this is not recommended for evaluation, as logdata can be lost when the remote connection fails.

The following data can be logged by CAMINO-Core:

- Transmitted/received messages via the southbound Interface (ITS-G5, C-V2X PC5, 4G/5G) for CA, IVI, DEN services and forwarded messages
- Incoming/outgoing messages via the northbound Interface
- Positioning/speed data retrieved from the GNSS

All the data that are logged by CAMINO-Core on the southbound, as well as recorded positioning/speed data, follow the InterCor logging format [20]. As an example, in Table 3, a summary is given of the logging format that is used by CAMINO for the transmitted and received C-ITS messages, listing all the data fields that are recorded in local logfiles.

To analyze the local logfiles, central post-processing evaluation tools are implemented. The data in the logfiles is parsed and centrally recorded in a database. Several scripts are provided to analyze this data in order to calculate well-defined KPIs (e.g., latency, packet delivery rate, range, etc.) and present them in graphs.

Table 3. Logging format.

Name	Type	Range	Unit	Description
log_timestamp	long	0 to $2^{42}-1$	msec	Timestamp at which the log_stationid logs the data row, elapsed time since midnight January 1st 1970 UTC
log_stationid	long	0 to $2^{32}-1$	n/a	Unique id of the host that logs this log data row
log_applicationid	0 to $2^{32}-1$	long	n/a	Unique id of the application, instance or thread, on the log_stationid host that logs this log data row
log_action	enum	['SENT', 'RECEIVED']	n/a	Action that triggered the logging event
stationid	long	0 to $2^{32}-1$	n/a	Unique id of the station that has sent this log data row
log_communicationprofile	enum	['ITS_G5', 'LTE_V2X', 'CELLULAR']	n/a	Communication profile, medium or path used to send or receive the message
log_messagetype	enum	['ETSI.CAM', 'ETSI.DENM', 'ISO.IVI']	n/a	Type of standardised message, used for automated processing in case multiple message types are combined in a single log file
generationtimestamptai	long	0 to $2^{42}-1$	msec	International Atomic Time when message was generated
generationtimestamputc	long	0 to $2^{42}-1$	msec	Coordinated Universal Time when message was generated
asn1data	string		n/a	HEX string of UPER encoded ASN.1 message such as a CAM, DENM, IVI

7. Using CAMINO for Real-Life CCAM Experimentation

This section describes how the CAMINO framework can be used in practice for real-life CCAM experimentation in the context of two use cases. The first use case refers to the evaluation of different V2X technologies based on a series of performance related KPIs. The second use case refers to interoperability testing of CCAM services using commercial V2X communication equipment deployed in Belgium and in the Netherlands.

7.1. Use Case 1: V2X Technology Evaluation

For the evaluation of different V2X technologies in the context of this use case, the Smart Highway testbed [21] was used. Smart Highway is a cutting-edge ITS testbed deployed by IDLab at main highway locations in Flanders (E313 highway near Antwerp) and was extended to the (urban) road network. The Smart Highway testbed consists of several RSUs with Multi-Access Edge Computing capabilities and On-Board Units (OBUs) that can be integrated in vehicles. The testbed is a unique platform that allows in-depth experimental analysis in view of novel ITS use-cases, by exploiting Commercial Off-the-Shelf (COTS) and Software-Defined Radio (SDR) equipment for both legacy and future technologies. The Smart Highway testbed enables hybrid V2X experimentation providing both short-range (5.9 GHz) and long-range wireless technologies, including C-V2X PC5, ITS-G5, 4G and 5G. The Smart Highway testbed offers an ideal environment for research and experimentation with V2X technologies, as a researcher or an experimenter can exploit real hardware at dynamic conditions, like variable vehicle speeds, weather conditions and traffic densities. Figure 4 shows the roadside infrastructure and vehicle that were used for the evaluation of V2X technologies, while Figure 5 shows the location of the seven deployed RSUs on a map.

In the context of this use case, the CAMINO framework could be used to evaluate the wireless communication technologies included in the testbed based on selected KPIs such as packet-loss and latency. Hence, the CAMINO-Core was installed on every RSU and OBU in order to manage the services running on top of the wireless technologies and enable the logging of the transmitted and received messages. These logged data were used during the post processing analysis to evaluate the desired KPIs.

Figure 4. Vehicle and roadside infrastructure at the highway.

Figure 5. The positions of the Road-Side Units (RSUs) deployed along the E313 highway.

Figure 6 shows an indicative example of such an evaluation, indicating the Packet Delivery Rate (PDR) (Figure 6a) for packets transmitted from the "RSU8" to the OBU and the Cumulative Distribution Function (CDF) plot of the end-to-end one way latency (Figure 6b) for packets transmitted from the "RSU1" to the OBU. In these figures, the performance of both short-range technologies, namely ITS-G5 and C-V2X PC5 was shown. During these experiments CAM messages were transmitted from the RSUs to the vehicle, while the latter was driving on the highway using both technologies simultaneously. The two technologies were configured to operate in different channels in the 5.9 GHz band to avoid mutual interference and both transmitters used the same transmission power. This way, both technologies could be evaluated under exactly the same circumstances such as distance between the transmitter and the receiver, surrounding conditions (e.g., trees, trucks), weather conditions, etc., in the very complex and dynamically changing environment of the highway. In order to take into account the impact of the channel in the performance of the technologies (e.g., signal propagation loss), we switched the channels and we repeated the experiments. In the end, the results from all the rounds have been summarized to produce the final graphs.

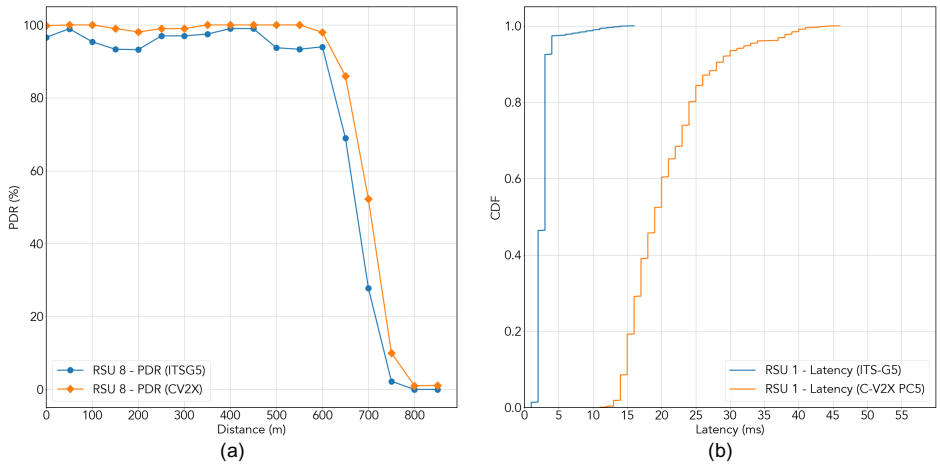

Figure 6. (**a**) Packet Delivery Rate (PDR) and (**b**) one way latency for ITS-G5 and C-V2X PC5 from RSU to vehicle on the highway at the Belgian pilot site.

In Figure 6a, it can be seen that both technologies offered quite similar PDR performance for the specific RSU, however C-V2X PC5 offered slightly more stable PDR for distances up to 600 meters as well as longer transmission range compared to ITS-G5. Figure 6b shows that the latency offered by ITS-G5 was lower than the latency of C-V2X PC5. More specifically, 95% of the packets transmitted by ITS-G5 had a latency up to 4 ms, while 95% of the C-V2X PC5 packets had one way latency up to 33 ms. The achieved latency was a result of the mechanisms that each technology used to access to wireless

medium. ITS-G5 is based on 802.11p, which uses Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA). According to CSMA/CA, each station evaluated the availability of the medium before a transmission. If the medium was idle, it transmitted, otherwise it performed a random backoff before it estimated the availability of the medium again. On the other hand, C-V2X PC5 used a Semi-Persistent Scheduler (SPS), according to which, each station scheduled its own resource blocks for transmissions. In order to minimize potential collisions with other transmissions during the same moment and at the same sub-carriers, each ITS station scheduleds resource blocked more spread in time. Thus, the latency of C-V2X PC5 was typically higher than ITS-G5. However, at more crowded wireless environments when multiple ITS-G5 stations compete to access the medium, the ITS-G5 latency might increase. Detailed analysis of the different V2X technologies is not the scope of this article and will be presented in future work.

7.2. Use Case 2: Interoperability Testing

This use case aimed to evaluate the interoperability of V2X communications and services between the Belgian and the Dutch pilot sites, using commercial V2X communication equipment. Among others, the interoperability tests included compatibility of data transmissions at the radio level of short-range technologies (ITS-G5 and C-V2X PC5), compatibility of facility layer messages (CAM, DENM, IVIM) at the service level over short- and long-range communication paths, security compatibility, etc. In that direction, firstly, vehicles from the Dutch pilot performed tests at the Belgian Smart Highway testbed (E313 highway) in order to evaluate their interoperability with the Belgian RSUs and vehicles. In a second phase, a Belgian vehicle performed tests at the Metropool Regio Amsterdam (A16 highway) to evaluate its interoperability with RSUs and vehicles form the Dutch pilot.

The CAMINO framework was used by the OBU of the Belgian vehicle and the RSUs at the E313 highway to manage the V2X wireless technologies and services running on top of them, as well as to provide the necessary logging of the transmitted and received data. As it has been described in Section 6, the CAMINO-Core supports logging according to the InterCor logging format, which is also used by the Dutch pilot. Hence, the consistency of the logged data was very valuable for the post-processing analysis, based on the selected KPIs.

Figure 7 shows the packet loss observed by the vehicle of the Belgian pilot for CAM messages transmitted by a specific RSU of the Amsterdam Pilot site, using ITS-G5. The packet loss was calculated for both driving directions of the highway for CAM messages transmitted at a frequency of 1 Hz. As shown in this figure, the packet loss was zero when the vehicle was close to the RSU and it increased as the vehicle drove away. In the direction towards the North, the measured transmission range was around 600 m, towards the South it was around 500 m. This was potentially a result of the placement of the RSU on the gantry and the curvature of the highway. When the vehicle entered the tunnel that was part of the highway, the GNSS signal was lost and the transmissions of ITS-G5 were interrupted, as a GPS signal was required by the ITS-G5 modules in order to transmit. Further discussion on the interoperability testing is not in the scope of this article and it will be addressed in our future work.

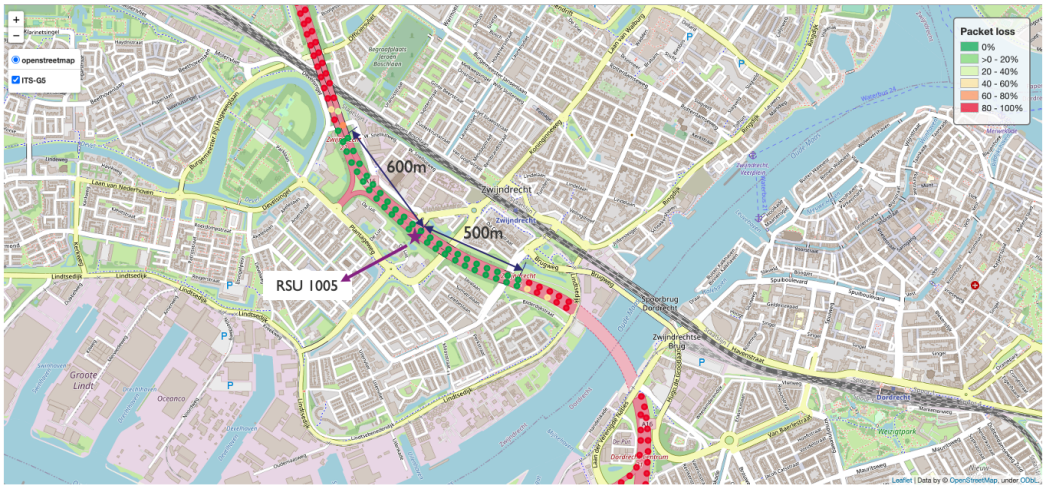

Figure 7. Packet loss over ITS-G5 between the Belgian vehicle and a Dutch RSU at the Amsterdam pilot site.

8. Conclusions and Future Work

In this article, we have proposed the CAMINO framework, a flexible hybrid V2X connectivity platform for CCAM services. CAMINO is designed to be dynamic, aiming to be the core framework for managing multiple vehicular communication technologies and the services running on top of them. The framework provides integration with existing and future short- and long-range V2X technologies such as ITS-G5, C-V2X PC5 and C-V2X Uu (5G/4G). In addition, it allows integration with vehicle or infrastructure sensors, vehicle actuators, HMIs and third-party service providers. CAMINO can support several standardized, future or custom C-ITS services (e.g., CA, DEN, IVI) that can be triggered dynamically. The corresponding generated messages can be transmitted in a flexible way by one or multiple V2X technologies increasing the transmission capacity or enhancing the transmission reliability. Furthermore, the CAMINO framework is ITS device agnostic, meaning that it can run on top of any type of station such as OBU, RSU, UE, servers, etc. Rich logging capabilities allow the collection of valuable information that enable the performance evaluation of the V2X technologies and the services running on top of them.

The flexibility and the modular architecture of the CAMINO framework offer endless research possibilities in the field of vehicular communications and CCAM services. In the near future, we are planning to exploit CAMINO for evaluating the performance of the different V2X technologies available in the Smart Highway testbed. This will allow us to draw valuable conclusions about the real-life performance of the different wireless technologies and identify protocol limitations under various non-deterministic conditions of public streets, where multiple vehicles create dynamic typologies, moving at different speeds and directions during different environmental conditions.

The CAMINO framework will also be used to investigate the coexistence of different technologies operating in the 5.9 GHz band based on performance related KPIs such as spectrum occupancy of each technology, packet-loss, latency, etc. This study will give insights into the technology behaviour under mutual interference conditions and will allow to analyse interference solutions in real-life scenarios.

Furthermore, Artificial Intelligence (AI) and Machine Learning (ML) techniques will be investigated for autonomous selection of the optimal wireless technology or combination of multiple technologies for transmission and reception of messages from different C-ITS application and services. This selection may take into account several parameters such as the QoS requirements of the application/service (bounded latency, throughput, etc.), RAN parameters (radio link quality, radio resource utilization parameters), environment conditions (number of neighboring vehicles, distance between them, speed, weather conditions, etc.), nature of the application (safety/non-safety critical), and more.

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Abbreviations

The following abbreviations are used in this manuscript:

ADAS	Advanced Driver-Assistance Systems
AI	Artificial Intelligence
BTP	Basic Transport Protocol
CA	Cooperative Awareness
CAM	Cooperative Awareness Message
CAMINO	vehiCulAr coMmunicatIon maNagement framewOrk
CCAM	Cooperative, Connected and Automated Mobility
CDF	Cumulative Distribution Function
C-ITS	Cooperative Intelligent Transport Systems
COTS	Commercial Off-the-Shelf
CSMA-CA	Carrier-Sense Multiple Access with Collision Avoidance
DEN	Decentralized Environment Notification
DENM	Decentralized Environment Notification Message
DSRC	Dedicated Short Range Communication
DUST	Distributed Uniform Streaming
EEBL	Electronic Emergency Brake Light
GNSS	Global Navigation Satellite System
GPSd	GPS deamon
HMI	Human-Machine Interface
ITS	Intelligent Transport Systems
IVI	Infrastructure to Vehicle Information
IVIM	Infrastructure to Vehicle Information Message
IVS	In-Vehicle Signage
KPI	Key Performance Indicator
MEC	Mobile Edge Computing
ML	Machine Learning
NTP	Network Time Protocol
OBU	On Board Unit
OEM	Original Equipment Manufacturer
PDR	Packet Delivery Rate
QoS	Quality of Service
RAT	Radio Access Technology
RHW	Road Hazard Warning
RSU	Road Side Unit

SDR	Software-Defined Radio
SPS	Semi-Persistent Scheduler
TLC	Traffic Light Control
TLM	Traffic Light Maneuvering
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

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