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APPLIED RESEARCH

Sto-CAV: A Distributed Simulation Platform for Connected and Automated Vehicles Running With Heterogeneous Technologies and Devices in the Loop

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ABSTRACT The development and validation of vehicular applications require extensive testing, often constrained by high costs, logistical challenges, and safety concerns. To address these issues, we introduce Sto-CAV (SimulaTiOn platform for Connected and Automated Vehicles), a novel, flexible, and scalable simulation platform that enables remote access and modular testing for connected and automated vehicle applications. Sto-CAV integrates both virtual and physical components geographically distributed, allowing users to execute simulations without requiring local hardware or software. In addition, Sto-CAV supports heterogeneous vehicle-to-everything (V2X) radio access technologies, including ITS-G5 based on IEEE 802.11p, LTE-V2X and Visible Light Communication (VLC), facilitating the test of beyond 5G vehicular communication scenarios where traditional RF communications meet optical bands. Unlike existing solutions, Sto-CAV emphasizes ease of configuration, remote accessibility, and the integration of heterogeneous communication technologies, thus providing a comprehensive tool for testing vehicular systems, accessible to researchers and developers worldwide. This paper details the design, capabilities, and applications of Sto-CAV, highlighting its potential to advance the testing of innovative vehicle technologies, also when they are geographically distributed, allowing average latencies suitable for quasi-real time applications.

INDEX TERMS Distributed simulation, heterogeneous technologies, hardware in the loop, connected vehicles, remotely accessible simulator, vehicular communication, vehicle-to-everything (V2X), ITS-G5, LTE-V2X, visible light communication (VLC), 6G vehicular networks.

I. INTRODUCTION

Simulators play a fundamental role in the testing and validation of vehicle applications, providing a safe and controlled environment for experimentation, especially if they run with hardware in the loop (HIL) and software in the loop (SIL). The use of HIL and SIL frameworks accelerates the test and development cycle by reducing the time required for field testing by providing a controlled and repeatable environment before real-world deployment: simulations can run multiple tests in parallel, with faster-than-real-time execution, allowing one to identify and address system

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weaknesses early in the design phase. This iterative approach minimizes the number of costly and time-consuming real-world tests, while also offering the flexibility to rapidly adjust variables such as traffic patterns, network conditions, and vehicle behavior.

This is particularly true and useful when focusing on vehicular applications, since test of devices and applications can be expensive, time consuming and, sometimes, also dangerous for the people involved in the tests (e.g., when traveling with a connected and partially automated vehicle in regular roads populated by legacy vehicles) [1], [2], [3], [4].

Furthermore, the increasing complexity of vehicular systems implies more complex simulations, that can take hours or days to provide reliable results and expensive hardware requirements to run, such as fast processors and extensive amounts of memory that are not available to everyone. Such simulations also involve an increasing number of hardware and software components, such as different advanced driver assistance system (ADAS) sensors or heterogeneous devices for vehicle-to-anything (V2X) communications.

Thinking to future 6G vehicular communication, in fact, traditional V2X communications at 5.9 GHz (ITS-G5 based on IEEE 802.11p and LTE-V2X) will be supported by higher frequency bands, such as mmwaves and visible light communication (VLC) systems. Hence, it is of fundamental importance the availability of tools to test and integrate heterogeneous technologies.

If simulators integrating HiL and SIL based on traditional RF technologies are already available (see, e.g. [5], the availability of simulators with HiL integrating VLC transceiver is much lower. In [6], for example, a simulator of connected vehicles that uses light to communicate between vehicles and infrastructure with the aim to coordinate traffic interactions, is proposed, but no hardware has been integrated. An open source extension to the ns3 network simulator has been presented in [7] and validated using a test bed implemented with a software-defined radio system, photo detector, phosphor-converted and white LEDs. This module extends ns3 capability, but it has not been specifically designed or tested in vehicular scenarios. Another simulation is presented in [8] for hybrid VLC/RF networks but not in vehicular scenarios, whereas in an indoor hybrid environment composed of VLC and RF networks. Remote access to VLC system is proposed in [9], where a teleoperation system for a wheeled mobile robot is presented to not affect neither patients nor medical equipment.

The above mentioned reasons highlight a novel necessity: remote access to simulators integrating heterogeneous technologies and devices for both the industrial and academic communities to enable researchers conducting virtual tests and simulations from anywhere, eliminating the need for physical presence in specialized testing facilities. This not only reduces costs and logistical challenges, but also facilitates collaboration among geographically located teams and allows for scalability, enabling multiple users to conduct parallel experiments efficiently.

Recent works highlight the importance of simulation platforms with HIL and SIL in testing technologies for connected and automated vehicles [3], [10]. However, most of these works focus on applications based on automated vehicles, hence they typically enable to test ADAS sensors, artificial intelligence (AI) based algorithms and applications. Few works consider the integration of wireless V2X connectivity devices and optical VLC lamps and, at the best of the authors knowledge, none of these simulators is remotely accessible and easy to configure and use.

Hence, despite the growing interest in simulation platforms for CAVs, existing solutions typically suffer from important limitations. Most simulators focus on specific aspects of vehicle autonomy, such as perception, planning, or AI-based decision-making and are often restricted to SIL setups. Only a limited number of platforms support HIL configurations, and, among these, very few allow the integration of real communication devices based on RF technologies like ITS-G5 or LTE-V2X. Furthermore, support for VLC is almost entirely absent or restricted to emulated models with limited realism. Current platforms also tend to operate within a single physical location, requiring that all hardware components are co-located. This constrains scalability, accessibility, and collaborative development. In addition, remote access is rarely considered. These gaps highlight the need for a more flexible, modular, and remotely accessible simulation platform capable of integrating heterogeneous communication technologies and physical devices in realistic and distributed test scenarios.

Hence, differently from the current literature, in this paper we present a flexible, scalable, and modular simulation platform to test vehicular applications running with devices in the loop, remotely accessible and integrating both ITS-G5, LTE-V2X and VLC communication technologies. The simulator platform is named Sto-CAV that stands for SimulaTiOn platform for Connected and Automated Vehicles. Specifically:

- Sto-CAV is a distributed simulation platform integrating HIL and SIL; both virtual and physical components of Sto-CAV can be located in different places and can interoperate;
- Sto-CAV enables the integration of heterogeneous radio access technologies and, specifically, radio frequency (RF) components, such as on board units (OBUs) integrating ITS-G5 (based on IEEE 802.11p) standard, LTE-V2X and VLC components that can be alternatively or jointly used to enable V2X communication;
- Sto-CAV is remotely accessible; a user friendly control panel enables to set up, configure and run a simulation.

With the increasing need for testing next-generation vehicular applications with real devices and applications, Sto-CAV aims to bridge the gap between conventional simulators and real-world experimentation. It provides researchers with a unique tool to develop, test, and validate advanced vehicular systems by integrating real devices, supporting hybrid communication technologies, and enabling distributed, remote-access simulation scenarios that are otherwise difficult to realize.

The paper is organized as follows: in Section II, recent literature is presented and the main contribution of this work highlighted; in Section III the architecture of our Sto-CAV simulation platform is presented; in Section IV an application example is reported and in Section V our conclusions and discussions are reported.

II. RELATED WORKS

In the last years, the research on the design and development of simulation platform with HIL has improved in several field, including the automotive one. We here focus on articles related to simulation with HIL in vehicular scenarios.

A historical overview of simulation with HIL is reported in [10], where different challenges in the field of automotive, power electronics systems, and different industrial drives have been considered. However, a part for generally introducing the reader to the simulation with HIL, the paper does not provide insight on specific fields, neither in vehicular communications.

One of the most common characteristic of papers related to simulation with HIL in vehicular scenarios is that they are typically related to autonomous driving without considering V2X communication issues. For example, in [3] the authors identify critical issues in open-source simulators, such as the fidelity of sensory data, representation of traffic scenarios, and insufficient support for HIL. The paper provides a current and complete overview, but it is focused on vehicular automation and not on vehicular communication.

Similar considerations can be done for the work in [11], where a co-simulation framework between vehicle dynamics and traffic flow simulation is presented; it is implemented on a highly dynamic vehicle-in-the-loop test bed that replicates non-linear vehicle dynamics and high tire slip values. ADAS verification is the focus of [12] which presents a meta-model-based visual editor to facilitate the design of co- simulation testing scenarios. In [13], V2XSim is presented: it is a HIL-simulator for validating connected and automated vehicles moving in a scenario with simulated static and dynamic objects; it relies on robot operating system (ROS) for the modeling of the vehicles and on a virtual road side unit (RSU) to collect and redistribute messages that are compliant with the specifications of short-range communications. Although it addresses V2X and related standard messages, it does not include V2X communication OBUs in the loop and cannot be used to test the hardware part of connectivity. Another interesting platform is described in [14], where a digital twin based on a multi-source game model is proposed to measure autonomous vehicle dynamics, perform decision strategy and plan routes. The proposed digital twin aims to integrate HIL to control the accuracy of dynamic safety decisions for connected vehicles, however, in [14] results based on virtual environments only are proposed. The concept of digital twin is also exploited in [15] where a methodology for creating and validating a digital twin-based framework for software defined vehicles is described: by decoupling hardware and software, the digital twin structure enhances flexibility and customization.

The development of a distributed simulation platform comprising heterogeneous simulators based on High Level Architecture (HLA) is presented in [16], with results from five different scenarios integrating five different simulation tools: Ptolemy II, SystemC, Omnet++, Veins, Stage and physical robots. These experiments demonstrate the successful application of power estimation in circuit design, robotic simulation, and co-simulation with real robots. This system has been considered also to simulate vehicular applications; however, at the best of our understanding, this work does not include communication devices as HIL, but simulates the message transmissions. An interesting simulation platform is described in [17] for conventional, connected and automated driving: three open-source simulators SUMO, Omnet++, and Webots are integrated and the whole simulation platform has been deployed in a Client/Server model. This simulation platform is useful to model vehicles behavior and driving strategies, but it does not integrate HIL.

Only a few HIL platforms focus on connectivity beside considering ADAS systems. One example can be found in [19], where a smartphone used in a car is interfaced with the SUMO simulator, which receives the car's position in real time from the smartphone. This work proposes an interesting implementation, but it is neither related to wireless access technologies for V2X such as ITS-G5 or LTE-V2X, nor to future advanced technologies for 6G-V2X such as VLC. Specifically, VLC for ITS (VLC-ITS) has already proved itself as a promising technology for future vehicular communication because it offers enhanced road safety, high speed, and low latency communication links. Despite VLC can be used as a cooperative technology coexisting with other communication platforms in V2X [23], no tests of VLC-ITS in HIL implementations have been reported to date.

A simulation platform mainly focused on communication among vehicles is ms-van3t, presented in [5]; it enables the simulation of ETSI-compliant V2X applications using SUMO and ns-3 with the possibility of easily switching stack and communication technology. It could also enable the simulation with HIL for specific components. However, the main objective of ms-van3t is the evaluation of network performance on large scale scenario and not to focus on specific use cases and applications. Another example of simulation platform to test both ADAS and V2X connectivity is introduced in [20], in which the authors use the CarMaker vehicle simulator [18] and the ROS to analyze the performance of ADAS. They introduce accurate modeling of IEEE 802.11p and side-link LTE-V2X for the connectivity aspect. Although the framework allows testing V2X applications when considering real traffic data and vehicle dynamics, it does not include HIL, hence it does not involve the testing of real devices. TRUDI is another simulation platform

TABLE 1. Summary of the main related papers. The symbol ✓ indicates a property that is clearly present in the document. Brackets are used if a given property is only partly within the focus of the paper.

Reference	ITS-G5/ 802.11p	LTE-V2X	VLC	HiL	Distributed	Remote access	Main focus
Mihalifç, 2022 [10]				✓			Overview of HiL simulations through different engineering challenges, including automotive
Li, 2024 [3]				✓			Review of simulators with HiL focused on automation not including communication issues.
Li, 2021 [11]				✓			Co-simulation framework between vehicle dynamics and traffic flow simulation
Basciani, 2023 [12]				✓			A meta-model- based visual editor to facilitate the design of co- simulation testing scenarios
Automotive, 2021 [18]				✓			CarMaker simulator, designed for the development and seamless testing of cars and light-duty vehicles in all development stages. Not dedicate to communication.
Shoukat, 2021 [14]	(✓)	(✓)		(✓)			A digital twin model to measure autonomous vehicle dynamics, perform decision strategy and plan routes
Purohit, 2023 [15]				(✓)			A methodology for creating and validating a digital twin-based framework for software defined vehicles
Zhang, 2020 [13]	(✓)	(✓)					V2XSim: a HIL-simulator for validating connected and automated vehicles
Brito, 2015 [16]	(✓)	(✓)			✓		A distributed simulation platform for complex embedded systems design
Jia, 2021 [17]	(✓)	(✓)					Integration of three open-source simulators SUMO, Omnet++, and Webots in a Client/Server model to model vehicles behaviour and driving strategies
Griggs, 2015 [19]				(✓)			Interface between a smartphone in a car with Simulation of Urban MObility (SUMO).
Malinverno, 2020 [5]	✓	✓		✓		✓	A simulation platform, ms-van3t, that enables the simulation of ETSI-compliant V2X applications using SUMO and ns-3. The main objective is the evaluation of network performance on large scale scenario and not to focus on specific use cases and applications
Schiegg, 2019 [20]	✓	✓		✓			Simulation platform to test both ADAS and V2X connectivity based on CarMaker to analyze the performance of ADAS with modeling of IEEE 802.11p and LTE-V2X for the connectivity aspects.
Menarini, 2019 [1]	✓			✓	✓		TRUDI simualtion platform to test safety applications based on real OBUs
Mafakheri, 2021 [21]	✓	✓		✓			CarLink, a simulation platform with HiL testing both long- and short-range wireless communication and integrating also ADAS in the loop
Cantas, 2019 [22]	✓			✓			A simulator that includes RSU and OBU as HiL to test V2I communication.
Galvão, 2023 [6]			✓				Simulation of VLC between vehicles the infrastructure to manage intersections
Aldalbahi, 2017 [7]			✓				A ns3-based VLC module that can be used to study VLC-RF heterogeneous networks via simulation
Alvarez, 2024 [8]			✓				A simulator for hybrid VLC/RF indoor networks
Tsunoda, 2021 [9]			✓	✓			A teleoperation system for a wheeled mobile robot using VLC to not impact neither patients nor medical equipment
Sto-CAV (this work)	✓	✓	✓	✓	✓	✓	*Distributed simulation platform integrating both RF and VLC HiL accessible from remote*

running with HIL [1]; it was developed to test safety applications based on real OBUs integrated in the simulation loop. However, TRUDI works only locally and just with one wireless access technology, which is ITS-G5/IEEE 802.11p. A similar platform is CarLink, a simulation platform with HIL, designed to simulate a generic traffic scenario and let each vehicle in it communicate with a vehicle under test equipped with long- and short-range wireless communications [21]. An improvement of this platform has been presented in [24] where the simulation of non- ideal

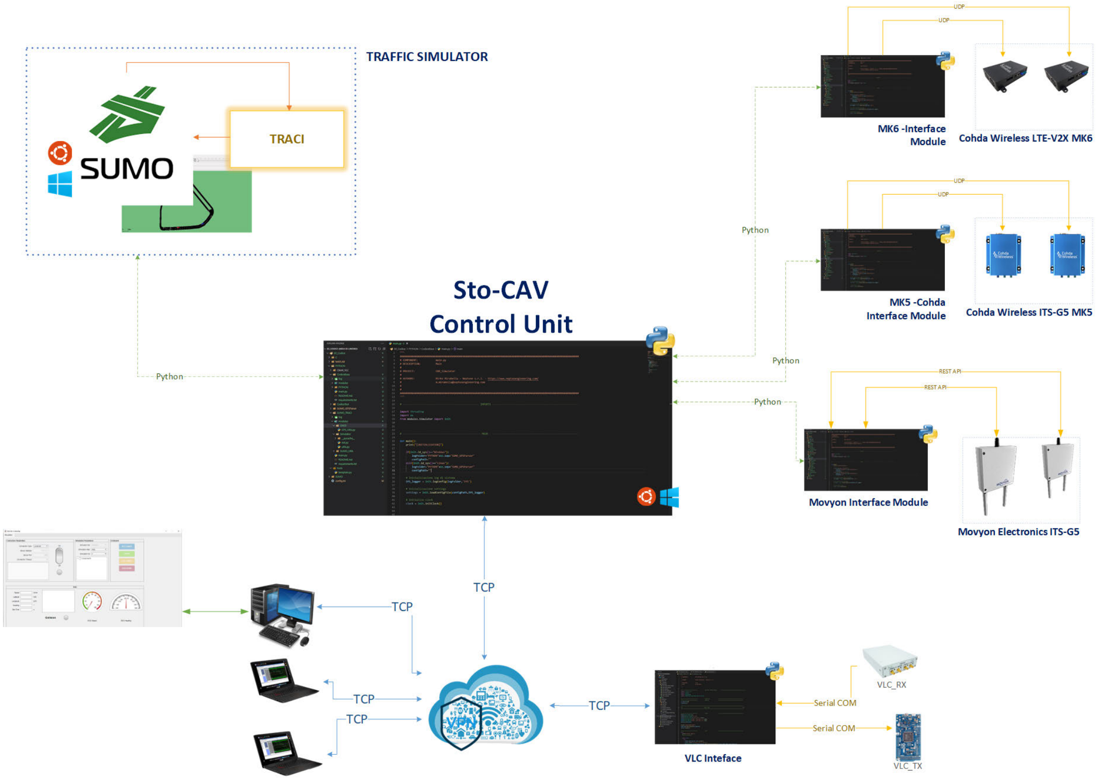

FIGURE 1. Sto-CAV architecture with main components highlighted.

positioning and channel propagation have been taken into account, also considering optimization solutions that allowed us to trade-off minor loss in accuracy with a reduction of the computational time.

To accelerate V2I application development, a HIL simulator with IEEE 802.11p RSU and OBU is presented in [22] and tested on the green-wave application. This simulator allows the integration of HIL not including VLC. In addition, at the best of the authors understanding, it is neither remotely accessible, nor distributed.

The availability of simulation platforms integrating VLC transceivers in HIL configurations remains significantly more limited compared to those focused on RF technologies. The work in [6] presents a simulator for connected vehicles that uses light-based communication to coordinate traffic interactions between vehicles and infrastructure; however, it does not include any hardware integration. An open-source extension for the ns-3 network simulator was introduced in [7] and validated using a testbed composed of a software-defined radio system, photodetector, and phosphor-converted white LEDs. While this module enhances ns-3's capabilities, it was neither designed for nor validated in vehicular scenarios. Similarly, the simulation framework proposed in [8] focuses on hybrid VLC/RF networks but is limited to indoor environments rather than vehicular applications. A notable example of remote access to VLC systems is presented in [9], where a teleoperation system is developed for a wheeled mobile robot, designed to operate safely in medical environments without interfering with patients or equipment.

Remotely accessible simulators with HIL are mainly available for teaching purposes, such as [25], where the authors made available a racing car simulator to help the students during CODIV pandemic.

Differently, Sto-CAV is a simulation platform to test vehicular application running with heterogeneous devices in the loop; currently, both ITS-G5, LTE-VX and VLC communication devices are included. In addition, the platform is remotely accessible.[1]

III. ARCHITECTURE OF THE DISTRIBUTED STO-CAV SIMULATION PLATFORM

Sto-CAV integrates HIL and SIL components to ensure seamless data exchange between the virtual and physical domains and to enable accurate testing of communication protocols, control strategies, and real-time decision-making algorithms.

The design principles underlying Sto-CAV architecture have been chosen to satisfy the following requirements:

- to enable the test, in a controlled laboratory environment, of hardware components related to connectivity

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[1] Currently, Sto-CAV is available upon request. In the next future, it will be open and still easier to access.

systems (extendable to ADAS components) and the test of software applications (such as forward collision warning, safe overtaking, etc.) before going on expensive field trials operations;
- to jointly make interoperate software and hardware components located in geographically distributed laboratories to facilitate the sharing of devices and knowledge;
- to be remotely accessible and easy to use also for a not expert;
- to test specific traffic scenarios and applications (e.g., small urban scenarios, an intersection crossing, roundabouts, an overtake, etc.).

Specifically, SIL simulations are executed using SUMO for traffic modeling and Phyton components for network communication and management. The vehicle dynamics, perception models, and decision-making algorithms are tested in a purely virtual environment before being integrated with physical hardware. The SIL environment supports co-simulation with MATLAB/Simulink, allowing control algorithms to be validated before deployment on real hardware. The HIL framework consists of physical automotive hardware, including OBUs and VLC modules. These components interact with the virtual simulation environment in real-time, allowing for testing of real-world hardware within simulated scenarios. The hardware devices are connected via a dedicated network interface, enabling real-time bidirectional data exchange.

Sto-CAV is already prepared to integrate ADAS components such as radar, cameras and lidars. Specifically, Sto-CAV already integrates two main families of V2X communication devices: i) different (i.e. provided by different vendors) OBUs and RSUs based on ITS-G5/IEEE 802.11p at 5.9 GHz, ii) LTE-V2X-based OBUs and iii) VLC lamps. OBUs and RSUs are physically located at CNR-IEIIT laboratory in Bologna, whereas, VLC lamps together with their modulators and demodulators are located in CNR-INO laboratory in Sesto Fiorentino (Florence, Italy). Sto-CAV overall architecture is shown in Fig. 1 and the main components are described hereafter.

Sto-CAV ensures real-time synchronization between SIL and HIL components through a well-defined data exchange mechanism: data are exchanged using TCP/IP sockets within a secure VPN, ensuring low-latency and high-reliability communication. The system can also support Message Queue Telemetry Transport (MQTT) for lightweight messaging and User Datagram Protocol (UDP) for time-sensitive data transmissions.

The interaction between SUMO and the physical devices (OBUs, VLC) occurs through a TCP/IP-based communication over an ad-hoc VPN network: each device is connected to the VPN through a dedicated network interface that ensures secure and controlled access, protecting the communication from external interference.

The SUMO simulator initiates communication via TCP/IP sockets. Then,at each simulation step, SUMO packages and transmits a structured data message to the physical device (e.g., VLC module or Movyon unit). The system waits for a response from the hardware before proceeding with the next simulation step. The V2X OBUs receive data from the simulator, process it, and respond, ensuring a continuous exchange of information between the virtual and physical environments.

Sto-CAV brain is constituted by the Control Unit (CU) that allows to manage the overall platform, addressing the other software and hardware components. The CU is developed in Phyton and runs on a Server at the CNR-IEIIT laboratory located in Bologna; it handles both the simulation and application algorithms through TraCI, but more importantly is in charge of handling both the remote commands and all the sub-modules and their communication via TCP sockets. Server and Clients are connected by means of a virtual private network (VPN). The server platform can be controlled both locally (directly from the Server console) and remotely, through a user-friendly interface. All possible commands and configuration parameters can be set client-side and sent in JavaScript object notation (JSON) encoding before running the desired simulation; moreover, external components, such as hardware devices, can be selected or not to be included in the simulation, based on the specific test the user aims to perform. Those components, as mentioned, all have their dedicated custom library, both server-side and client-side, with the former enabling full modularity of the main platform, and the latter providing an interface between the platform and the desired hardware. More importantly, with this approach, the platform is able to integrate new hardware by developing a new sub-module for the specific integration.

At the current state, sub-modules for both OBUs and VLC communications have been developed and tested, with the former being physically set in the same facility of the simulator at CNR-IEIIT in Bologna, and the latter at CNR-INO in Florence.

Concerning the OBUs for V2X communications, two units from Cohda Wireless (MK5) and two units from Movyon Electronics have been used for ITS-G5 communication, whereas two units from Cohda Wireless (MK6) have been integrated for LTE-V2X communication, along with some specific tweaks. In both cases, currently the OBUs transmit and receive cooperative awareness messages (CAMs) following ETSI EN 302 637-2 V1.4.1 [26].

At the best of the authors' knowledge, devices based on IEEE 802.11bd or 5G NR-V2X are not available on the market, yet. However, Sto-CAV has been designed and developed in a scalable way such that new devices can be integrated as soon as they become available on the market.

One main function of the CU is the virtualization of the vehicle movements, which are shared through the CAMs. In fact, in order to emulate vehicles movement, the CU injects in the CAMs generated by the OBUs, the GPS coordinates, in particular, latitude, longitude together with speed and heading. Hence, message generation has been substituted with the data structure simulated by a traffic simulator

All devices connected to the Sto-CAV simulator require consistent data regarding the vehicle dynamics within the scenario. The formatting of the CAM data necessary for proper communication between V2X devices is handled and integrated into the system in a specific section dedicated to each vehicle. Specifically, GPS coordinates (latitude, longitude), speed, and heading are extracted from the simulation data and injected into the CAM packets at each simulation step, then transmitted to the subsystem managing the operation of the devices. Conversely, the received packets follow the reverse process: they are extracted from the CAM message structure, stored in specific structures dedicated to each vehicle, and used by the simulator.

Thanks to the remotization infrastructure, Sto-CAV enables the interoperability between simulators located in different places and, specifically, between the simulation of the communication at RF 5.9 GHz following ETSI ITS-G5 or LTE-V2X standards located at CNR-IEIIT in Bologna and the simulation of VLC located at CNR-INO in Florence.

A. TRAFFIC SIMULATION

We adopted SUMO as traffic simulator [27] to represent the scenario, hence to build the map and the vehicles running with different characteristics. SUMO is an open source, microscopic, multi-modal traffic simulation that allows to simulate the movement of single vehicles through a given road map. The simulation is microscopic, hence each vehicle is singularly modelled, has an own route, and moves individually in the map.

To access traffic simulation and control the behavior of multiple simulation objects during a live simulation, we used Traffic Control Interface (TraCI) module. It allows for external scripts to interact with the simulation and its vehicles, pedestrians, and infrastructure. TraCI uses a TCP based client/server architecture to provide access to SUMO. SUMO acts as server, then, after starting SUMO, clients connect to SUMO by setting up a TCP connection to the appointed SUMO port.

For the choice of the map to give in input and on which to build the simulation and the vehicle dynamics, the information was taken from OpenStreetMap [28]. This was a necessary choice in order to obtain GPS coordinates for the entire selected map. SUMO, when creating a custom map, does not provide this information by default. However, by importing external maps, it is possible to access this essential information for the proper functioning of the system.

The simulation can be realized through command line or through the SUMO-GUI in order to have a graphic feedback. Through the control panel described in Section IV we enabled both choices.

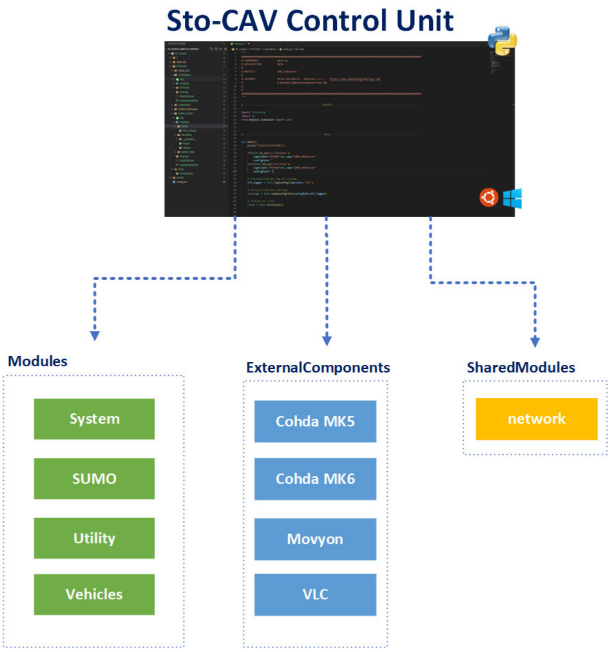

FIGURE 2. Sto-CAV modules interfaced by the Control Unit (CU).At each simuloation step, the CU manages the interfaces of each of the listed components.

B. STO-CAV CONTROL UNIT (CU)

Sto-CAV Control Unit represents the core of the simulation platform. It is a modularly structured system implemented in Python. Each module provides functionality through a series of methods and classes that contribute to the configuration, execution, and management of user-customized scenario simulations. Fig. 2 shows the various module interconnecting with the CU. It also ensures easy portability across different devices and operating systems. The primary objective of Sto-CAV is to facilitate the interfacing between hardware devices and the SUMO traffic simulator, leveraging network communication protocols based on TCP sockets. Furthermore, it modifies the behavior of vehicles within the SUMO simulation based on data received from the hardware devices. This continuous exchange of information allows for the easy implementation of control algorithms and warning generation methods based on the information received from the devices. This approach enables the scalability of the implemented functionalities to verification and validation activities in real-world road contexts.

The Sto-CAV CU performs three important functions through a multitasking approach that allows the cooperation of its various subsystems: i) it manages the evolution of the SUMO simulation through UDP interfacing with TRACI, ii) it handles the data and functionalities of hardware connected to the system, and iii) it manages devices connected to the VPN. Information exchange takes place through UDP and TCP/IP network protocols, which are appropriately managed by the network module responsible for instantiating the various sockets to be used. The configuration parameters are read from a *.conf* file included with the project. The modification of this file allows the system to be reconfigured to meet network requirements for a new personal installation. The start and configuration of a simulation are managed through a control panel that can be installed on any PC within the VPN. The panel communicates the user's selections to the active Sto-CAV server by sending data in JSON format.

The CU can operate by activating either a remote server connected to the VPN or a local server accessible via localhost. Once the configuration is completed and the simulation is started, the CU activates all the necessary subsystems to manage the devices in the loop and handle the simulation. At each step of the SUMO simulation, essential data such as GPS positions, speed, and direction of each vehicle are stored in appropriate data structures. However, only a few vehicles in the simulation are connected and have access to VLC and V2X technologies, specifically the vehicle named EGO and the first vehicle in front of it, indicated as VH_1. The modularity of Sto-CAV's approach can, in the future, enable to extend the number of vehicles equipped with V2X or VLC hardware.

In addition to sending data to geographically distributed devices, Sto-CAV CU also waits for the reception of exchanged data to update control algorithms and trigger the request for a new simulation step. The number of simulations managed can also be easily increased by adding new maps and new TRACI management dynamics within the module named SUMO. Functions managing data exchange between different hardware components can, therefore, be easily integrated into new simulations or control algorithms.

C. V2X COMMUNICATION MODULES AT 5.9 GHZ: ITS-G5 AND LTE-V2X

ITS-G5 standard is a wireless communication technology based on IEEE 802.11p specifically designed for V2X applications. It enables direct communication between vehicles (V2V) and with infrastructure (V2I), thus offering low latency and high reliability. As one of the most widely adopted V2X technologies, ITS-G5 is recognized for its maturity and proven functionality. It has been integrated into commercial vehicles, with manufacturers like Volkswagen leading the way by equipping their models with this technology [29].

Beside ITS-G5, also LTE-V2X is gaining an increasing interest, especially because it benefits from cellular network support for long-range scenarios and enhanced data throughput [30], but its broader adoption faces challenges due to dependency on mobile infrastructure [31], [32], [33]. It is probably together that these technologies will provide complementary approaches to advancing safer and more efficient connected transportation systems [34]. For these reasons, also LTE-V2X OBUs have been integrated in the platform; hence, Sto-CAV also allows to investigate a recent important topic: the coexistence between ITS-G5 and LTE-V2X, so carefully addressed in the last few years [34], [35].

Having in mind to also verify interoperability among different devices, two different vendors were chosen for ITS-G5 OBUs: Cohda Wireless MK5 OBUs, and Movyon Electronics RSUs. As far as LTE-V2X devices are instead concerned, two Cohda Wireless MK6 OBUs have been integrated in the loop. For all cases, a GPS coordinate injection mechanism has been created to allow their functionalities inside Sto-CAV simulator. In this way, the real positioning information provided by the installed antennas is no longer used in the transmitted packet, but instead, the synthetic positions provided by the simulator are used. For the two kinds of devices provided by different vendors, it was necessary to implement different injection methods, as specified in the following sections.

1) COHDA WIRELESS OBUS

Mk5 and Mk6 are the Cohda Wireless OBUs that have been integrated inside Sto-CAV. Both the devices do not allow direct injection of vehicle positioning information into the data packet. However, to achieve the desired objective, an alternative approach is used by leveraging a pre-installed Linux daemon for managing GPS data, called GPSD. This software allows the device to be "tricked" by configuring it to receive GPS data via a socket communication. The GPS data must then be provided in a fully pre-formatted NMEA format.

Sto-CAV performs this task by establishing a UDP network connection through a socket to the specific device's identifier address and initiating a transmission of pre-formatted packets. Additionally, for the system to correctly recognize the transmitted information, consistency in the time field is required. To ensure this, another service in the MK5 Linux environment was configured to acquire the reference time from the NTP server. After completing these complex procedures, which are not immediately straightforward, the preloaded source code on the devices can be executed, which starts transmission via the ITS-G5 protocol.

For these devices, there is no direct access to either transmitted or received messages, but for the operation of the application, communication was utilized between the devices and an additional HMI device natively through UDP socket. This data traffic is no longer routed to the HMI's address but instead to a specific Sto-CAV communication port, which extracts the warning information contained in the message.

This approach, although complex, does not represent an optimal solution for developing and testing new algorithms and functionalities integrated within the Sto-CAV simulator. However, it does allow for effective testing of the devices based on their implementation and pre-installed services.

2) MOVYON ELECTRONICS RSU

Movyon Electronics RSUs are based on ITS-G5 standard and implement an HTTP/HTTPs server that provides a set of different API and a WebSocket connection for data reception. The Content-type present in the body of the requests and the response of GET/POST requests is application/json.

The management of devices by Sto-CAV is carried out using a Python module which contains the *MovyonDevice* class, designed to facilitate communication with these devices. The structure of the code and its functionalities focus on the generation, sending, and receiving of CAMs between devices, supporting simulation and analysis scenarios.

One of the fundamental features is the ability to generate and format CAM messages in XML allowing the construction of a XML document containing key information such as vehicle position, speed, driving direction, vehicle length and width, longitudinal acceleration, and other crucial parameters for cooperative vehicular communication. This formatting phase is essential to ensure that the data are transmitted in the correct format, compatible with industry-standard communication protocols.

To send the generated messages, the *MovyonDevice* class includes methods that allow to send a POST request with the CAM message using a specifically formatted URL.

A distinctive element of the code is the implementation of an asynchronous communication mechanism based on WebSocket, which enables the class to receive and process data in real-time from the devices. The WebSocket management is handled in a separate thread to keep the connection open and continuously receive updates. The received data is interpreted and used to update the latest information about the vehicle.

D. VLC MODULES

VLC is attracting growing attention in the field of vehicular communications due to its potential to offer higher data throughput and lower latency compared to conventional 5.9 GHz RF-based technologies [36]. Nonetheless, the deployment of VLC in real-world vehicular scenarios presents several challenges that significantly affect its communication reliability and performance. One of the primary limitations stems from the inherently directional nature of light, which requires a stable line-of-sight (LoS) between the transmitter and receiver, a demanding condition in highly dynamic vehicular environments. To mitigate this constraint, advanced techniques such as beam steering and adaptive optics are being explored to dynamically align optical beams in response to vehicle movement and orientation changes [37]. Additionally, the use of indirect paths through environmental reflections has been investigated as a means to enhance link robustness under partial or intermittent LoS conditions [38]. Secondly, ambient light interferes posing significant challenges [39], [40]. Therefore, VLC cannot be considered a standalone solution for V2X communications but rather serves as a valuable complementary access technology in specific scenarios. It is particularly well-suited for short-range communication use cases, such as vehicle platooning or cooperative maneuvers, where vehicles travel in close proximity and low-latency communication is critical for coordination and safety.

The integration architecture of the VLC modules within the Sto-CAV simulation platform is illustrated in Fig. 3. In this setup, a Virtual Private Network (VPN) has been established to enable interoperability between the Central Unit (CU), located in Bologna, and the VLC-related components and software deployed remotely in Sesto Fiorentino. Communication between these distributed elements is managed through TCP/IP packet exchange, ensuring secure and synchronized operation across geographically separated sites.

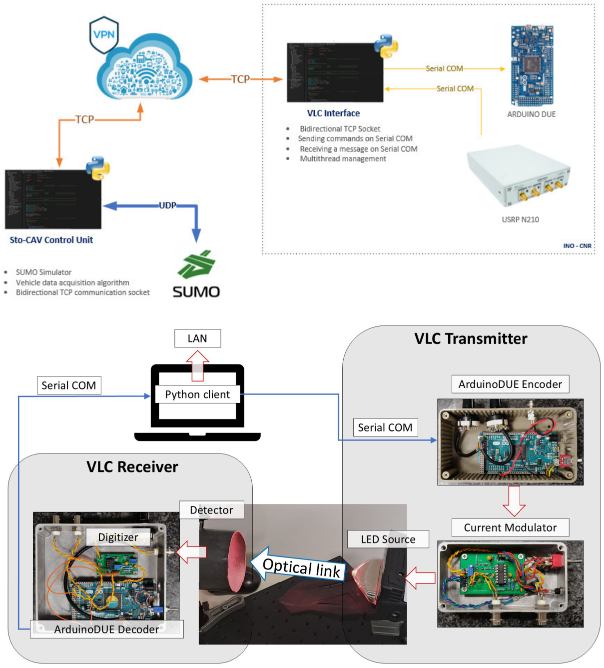

FIGURE 3. **Simulation running exploiting devices located both in Bologna and Sesto Fiorentino: on the top the scheme of the connection and interoperability; on the bottom, the VLC components and devices operated from Bologna.**

The VLC subsystem is composed of a transmitter and a receiver stage for the signal transmission through commercial LED automotive 12 V lamps. The transmitter consists of a low-cost digital, open-source microcontroller board (Arduino DUE), which generates digital data packets that are injected into a custom analog current modulator stage. This stage provides both the nominal DC supply current to the LED lamp and the current modulation which encodes the digital data into a LED intensity modulation. The amplitude modulation is performed using 0-200% of the nominal intensity of the lamp (12V, 160mA), which ensures a correct average nominal luminosity (100%) without affecting the LED lifetime and without flickering effect for the human eye.[2] The VLC data are sent at 115.2 kbps non-return-to-zero (NRZ) on-off keying (OOK) modulation with Manchester encoding. Following the recommendation of IEEE 802.15.7 PHY I standard for outdoor communication, no forward error correction (FEC) has been adopted. Data are transmitted organized in packets. The packet frame is composed by 2 pre-equalization bytes, used to stabilize the optical signal transient, 1 synchronization byte used to synchronize the transmitter and the receiver on each packet, and a data payload message. The payload contains the following information: vehicle ID, speed in Km/h, latitude, longitude, direction, breaking and simulation step

The VLC receiver is based on a modified version of a commercial large-area photodetector (Thorlabs PDA100A2),

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[2] We used an inter packets delays that always respect this condition.

featuring an active surface area of 75 mm^2. It is optically coupled with a 2-inch uncoated aspherical lens (Thorlabs ACL50832U) with a focal length of 32 mm, resulting in a Field of View (FoV) of approximately 17°. To mitigate the effects of ambient direct current (DC) light—particularly from solar radiation—a physical DC-blocking stage is implemented upstream of the transimpedance amplifier (TIA). This design choice enables reliable reception of the VLC signal under outdoor lighting conditions by preventing saturation of the TIA due to high-intensity DC components. Consequently, it is possible to configure the TIA with substantial gain levels (up to 30 dB at the specified baud rate) without compromising signal integrity. The analog signal output from the TIA is then digitized using a Schmitt-trigger comparator with adjustable threshold levels, followed by decoding through a microcontroller-based digital decoder.

Remote access to the VLC chain takes place through a VPN network. The VLC interface operates with multi-threading capabilities to manage interfacing between the CU, located in Bologna, and the Arduino microcontrollers integrated in the physical VLC section in Sesto Fiorentino. Data between the two systems is exchanged via TCP/IP. If the VLC interface is included in the simulation by the user, the CU initiates the data exchange with the VLC devices. The VLC interface is always active and listening on a specific communication port for the arrival of pre-formatted information containing GPS position data. The VLC interface transfers the data to the USB serial port where the transmitter based on an Arduino DUE is physically connected. The packets are processed by the microcontroller to compose the VLC message with OOK Manchester modulation and transmitted via VLC channel to the receiver stage. The optical signal is processed by the optoelectronic front-end, amplified by the TIA stage, digitized by the comparator, and acquired by the serial port of the receiver, based on another Arduino DUE. The received packets are decoded by the microcontroller and sent via USB serial communication to the VLC interface. The data received by the interface are then forwarded via TCP/IP on a different port to the CU. The received data are processed within the simulation before proceeding with a new simulation step, where the process is repeated. It is important to remark that, thanks to the modular design of the VLC blocks and to the flexibility of the Sto-CAV simulator architecture (particularly the independence of the remote control of the VLC chain from the specific network configuration, either LAN, Wi-Fi, or 4G/5G) real-world VLC settings can be encompassed by future developments of the simulator, extending the proof-of-concept demonstration reported in this work. We will leverage recent advancements reported in I2V and V2V (bidirectional) experiments, such as [40], [41], to realize upgraded versions of the simulator where realistic outdoor VLC links will be studied into Sto-CAV, using SNR values corresponding to various relative positions between vehicles. This will enable a detailed analysis of the impact of VLC technology on realistic driving simulations through the Sto-CAV environment, through the evaluation of key metrics such as latency and position-dependent SNR values.

E. REMOTE ACCESS

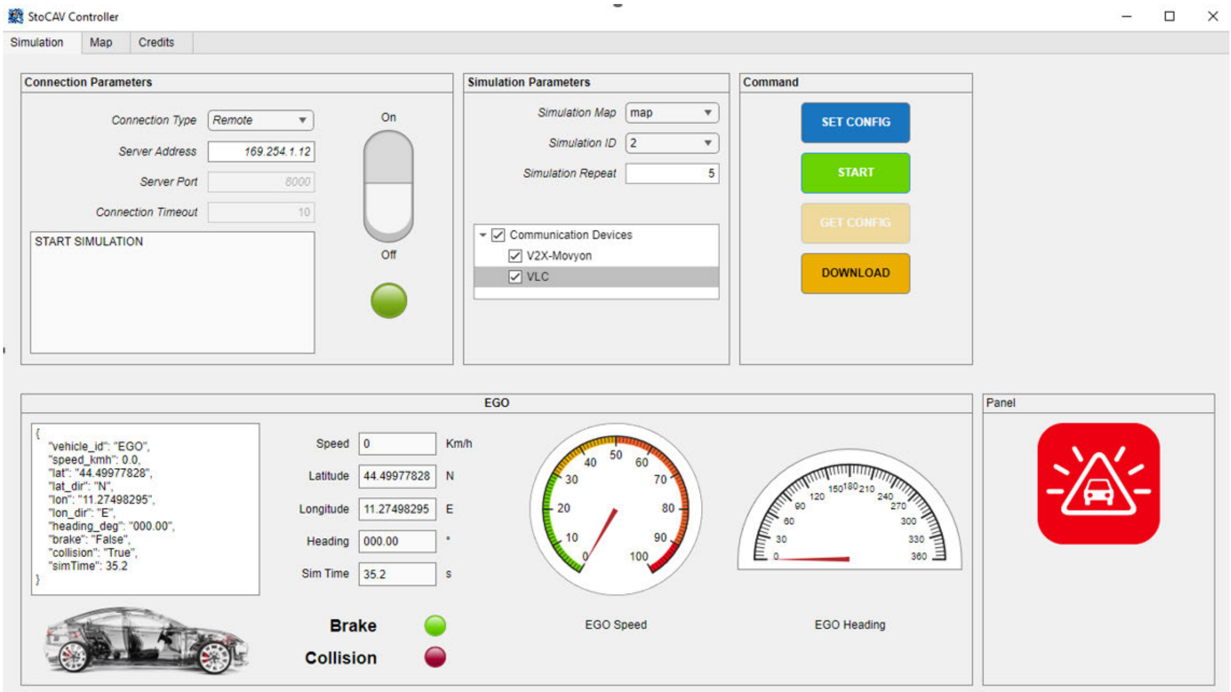
Remote access in the Sto-CAV system is implemented through a VPN, ensuring a secure and encrypted connection between distributed hardware components and the central simulation platform. This setup allows geographically separated devices and software modules to interoperate seamlessly, as if they were part of a single private network, despite relying on public infrastructure like the Internet. The VPN establishes an encrypted communication tunnel between the central CU and remote hardware modules (e.g., OBUs, VLC transceivers). Only authorized devices with valid cryptographic certificates can access the Sto-CAV network, ensuring strict access control. Data between the CU and remote components is exchanged using TCP/IP sockets, ensuring reliable and ordered packet transmission. Each device connected to the VPN operates as a network node, allowing bidirectional data transfer between simulated vehicles and real hardware in the loop. Real-time control data, including vehicle dynamics (position, speed, heading) and simulation parameters, is encapsulated in JSON-based messages and transmitted over TCP/IP. Hence, the CU acts as a message broker, ensuring synchronization between simulated environments (SUMO-based) and physical devices. To maintain low latency and consistency, heartbeat signals are periodically exchanged between the CU and remote hardware to detect connectivity status and prevent desynchronization.

As far as security to prevent unauthorized access and ensure data integrity are concerned, the following measures have been adopted.

- Only pre-approved devices and users with valid credentials can connect: Aa certificate-based authentication mechanism prevents unauthorized devices from joining the simulation network.
- All traffic within the VPN is encrypted using AES-256, ensuring confidentiality and protection against packet sniffing. The use of encrypted TLS connections for remote command execution further enhances security.
- Cryptographic hash functions (SHA-256) are used to verify data integrity. Messages exchanged over the network include integrity checks to detect potential data corruption or malicious interference.
- The Sto-CAV VPN is not exposed to the public Internet, but all connections must originate from the authorized network.

IV. STO-CAV APPLICATION EXAMPLE: FORWARD COLLISION WARNING (FCW)

Sto-CAV simulation platform has been designed to simulate a generic V2X application in scenarios that can be also uploaded by the users. An an example application, we here present forward collision warning (FCW) application in a Bologna area. The choice of FCW has been done since it



Connection Type: Remote
Server Address: 169.254.1.12
Server Port: 8000
Connection Timeout: 10

START SIMULATION

Simulation Map: map
Simulation ID: 2
Simulation Repeat: 5

☑ Communication Devices
  ☑ V2X-Movyon
  ☑ VLC

```
{
  "vehicle_id": "EGO",
  "speed_kmh": 0.0,
  "lat": "44.49977828",
  "lat_dir": "N",
  "lon": "11.27498295",
  "lon_dir": "E",
  "heading_deg": "000.00",
  "brake": "False",
  "collision": "True",
  "simTime": 35.2
}
```

Speed: 0 Km/h
Latitude: 44.49977828 N
Longitude: 11.27498295 E
Heading: 000.00 °
Sim Time: 35.2 s

FIGURE 4. Sto-CAV control panel enabling both local use and remote access to configure, run and download results.

represents one of the first safety applications that will be on our road following the ETSI roadmap [26], [42]. In fact, accidents due to rear-end collisions represent between the 20% and 30% of crashes in the United States and nearly a third of fatal crashes when vehicles move at speeds over 72 km/h [43]. In this context, FCW, can provide significant improvements in terms of collisions reduction.

Specifically, the FCW application provides an alert to the EGO vehicle when the inter-vehicular distance with the forthcoming vehicle is below a target parametric threshold or when it is moving at a speed higher than a parametric threshold. It is worth noting that, objective of this work is not to demonstrate the validity of the FCW applications which is already well known in the literature [43], [44], [45], but to exploit this application to demonstrate the overall platform operation before going on field trials.

Existing studies (e.g., simulations using SUMO or ns-3) often analyze forward collision warning (FCW) under specific conditions but may lack real-time adaptability or comprehensive V2X communication devices integration. Some works focus on theoretical models without validation in physical environments, others are based on large-scale simulations. Sto-CAV, instead, improves FCW accuracy by incorporating real devices validation and, hence, real V2V communications between those devices.

Since the two OBUs are located one near the other on the measurement bench, to emulate the realistic behavior of the wireless channel, we consider a packet error rate as a funciton of the distance following the 3GPP channel model presented in [34].

As shown in Fig. 4, a control panel has been developed to manage the overall simulation:

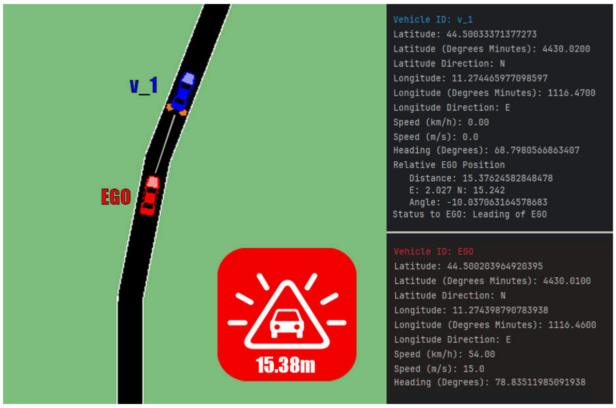
- On the upper left part of the control panel, connection parameters can be configured: the user can select if the simulation runs locally or remotely; typically, the local simulation is used by the authors to test new functionalities, whereas remote operation is the method adopted for normal use. Once the server address has been inserted, the simulation button can be pushed to "on".
- Simulation parameters such as the operating system and the map can be selected from the central top part of the control panel, so as the number of simulations.
- Once all the configurations have been set up, the blue *set config* button can be activated on the upper right part of the commands and then, the simulation start using the green button.
- Parameters of the EGO vehicle are visible on the bottom: speed, latitude, longitude, heading and simulation time are numerically reported; speed and heading are also graphically represented as in a real car interface.
- The colors red and green represent the high and low risk of collision, respectively. If a collision is going to occur, a red warning appears on the right of the control panel.
- Once the simulation ends, the user can get the configuration clicking on the *get config* button and also download the results in terms of latency that are provided both in terms of .csv files and also through .png figures.

An overall view of the components in both sites running with the FCW application is reported in Fig. 5: the main components located in Bologna are highlighted in the top figure whereas, the VLC components appear in the bottom.

FIGURE 5. **Simulation running exploiting devices located both in Bologna and Sesto Fiorentino: on the top the Bologna laboratory highlighting various modules; on the bottom the VLC components operated from Bologna.**

Fig. 6, instead, shows the user interface when a warning message is received by the EGO vehicle: together with a stylized map, the interface shows the presence of the preceding vehicle, specifying its speed and distance from the EGO vehicle. Detailed parameters of the two vehicles involved (latitude, longitude, speed, direction, relative distance) are reported to the left.

A demo video is available at [46] to demonstrate how a remote user can access the overall platform and select the hardware to insert in the loop before activating the application of FCW.[3]



```
Vehicle ID: v_1
Latitude: 44.50033371377273
Latitude (Degrees Minutes): 4430.0200
Latitude Direction: N
Longitude: 11.274465977098597
Longitude (Degrees Minutes): 1116.4700
Longitude Direction: E
Speed (km/h): 0.00
Speed (m/s): 0.0
Heading (Degrees): 68.7980566863407
Relative EGO Position
   Distance: 15.37624582848478
   E: 2.027 N: 15.242
   Angle: -10.037063164578683
Status to EGO: Leading of EGO
```

```
Vehicle ID: EGO
Latitude: 44.500203964920395
Latitude (Degrees Minutes): 4430.0100
Latitude Direction: N
Longitude: 11.274398790783938
Longitude (Degrees Minutes): 1116.4600
Longitude Direction: E
Speed (km/h): 54.00
Speed (m/s): 15.0
Heading (Degrees): 78.83511985091938
```

FIGURE 6. **Example of tested application: forward collision warning (FCW).**

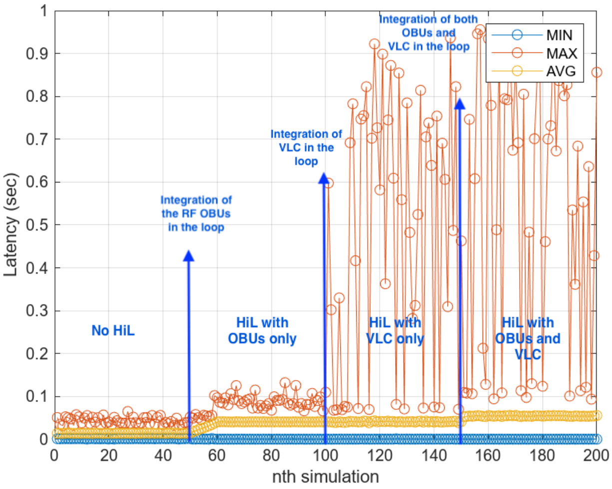


FIGURE 7. **Minimum, maximum and average latency as a function of time expressed as number of simulation using Sto-CAV in i) simulation mode for 50 simulations, ii) with ITS-G5 OBUs integrated in the loop and iii) with both OBUs and VLC transcievers in the loop. The graphical user interface (GUI) is always active.**

Fig. 7 shows a comparison among the minimum, average and maximum latency for different Sto-CAV configurations when the graphical user interface (GUI) is always active, hence when the user can appreciate also SUMO running in real time with cars accelerating and breaking following the FCW application. As it can be observed, the maximum latency is always below 50 ms in the case of no hardware in the loop, then it presents some peaks above 100 ms inserting the OBUs in the loop. The maximum latency increases when inserting VLC in the loop, independently on the presence of the OBUs. In fact, since the VLC transceivers are distributed in Florence whereas the Sto-CAV CU runs in Bologna, results show the impact of the geographical distribution and network random impairments. It is important to observe that these latency values are mostly introduced by the remotization infrastructure of the overall platform and are not due to the introduction of the VLC channel itself, which, instead, most

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[3] The video was prepared using ITS-G5 and VLC OBUs.

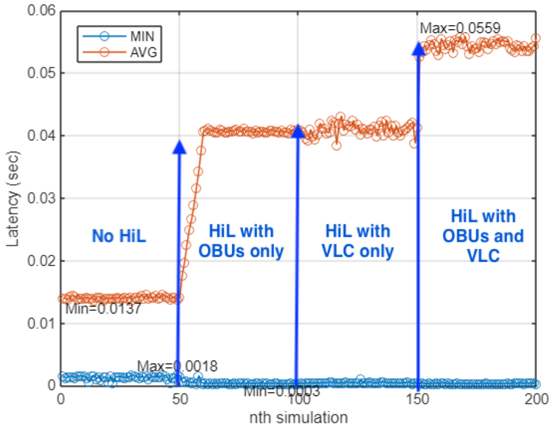

FIGURE 8. Minimum and average latency as a function of time expressed as number of simulation using Sto-CAV in i) simulation mode for 50 simulations, ii) with ITS-G5 OBUs integrated in the loop and iii) with both OBUs and VLC transcievers in the loop. The graphical user interface (GUI) is always active.

likely yields transmission latencies which can be lower than 1 ms in low-error-rate regime, as demonstrated in [47].

Since the GUI is always active, the case when both the OBUs and VLC are integrated in the loop represents the worst possible case and, as it can be appreciated, the average latency is always below 100 ms, hence the system allows nearly real time evaluation even if the network and the hardware could still be optimized.

As it can better observed from Fig. 8, the minimum latency is always below 2 ms, and the average latency does not go beyond 56 ms also when both the OBUs and the VLC transceivers are in the loop. This implies that, in average, the system can manage quasi-real time simulations.

We expect that future extensions can impact the overall latency especially if the number of geographically distributed devices increases. Instead, the use of more devices physically co-located with the CU could have a negligible impact on the overall functioning.

As far as the throughput of the overall simulation is concerned, it must be considered that, currently, we exchange an amount of several hundreds bytes every 100 ms. Hence, the amount of data is totally manageable in quasi-real time also considering the distributed nature of the platform.

V. CONCLUSION AND FUTURE DIRECTIONS

Sto-CAV has been designed and developed to test hardware and software in the loop for vehicular safety applications with devices distributed in different labs and applications made available based on heterogeneous communication technologies.

During the development of a new application and prior to conducting field trials with real vehicles, Sto-Cav enables software debugging and optimization through laboratory tests that use actual devices and simulated positions. Unlike other HIL simulation platforms, Sto-Cav is not tailored to a specific application and provides a solution ready for field testing. As an example use case, we demonstrated FCW application.

Future implementations foresee the following.

- Integration of NR V2X and IEEE 802.11bd/ac: as vehicular communication technologies evolve, incorporating next-generation standards will enhance the realism and applicability of Sto-CAV simulations.
- Enhanced AI-driven traffic and communication models: the adoption of machine learning techniques for traffic prediction, network optimization, and vehicle coordination can provide more realistic and adaptable simulations.
- Extended support for cooperative driving scenarios: future work will focus on implementing and testing more complex cooperative driving applications such as intersection management, dynamic platooning, and coordinated lane merging.
- Integration of additional HIL components: Beyond current OBUs and VLC modules, Sto-CAV will explore the inclusion of radar, LiDAR, and cameras to enable more comprehensive testing of ADAS applications.
- The use of other kind of messages to enable cooperative driving and maneuvers based on the exchange of collective perception message (CPM) and maneuver coordination message (MCM). Hence, future scenarios will consider safety applications in intersection, overtaking and platooning.
- Scalability improvements: further optimizations in the distributed computing architecture will allow larger-scale simulations with thousands of vehicles and multiple communication nodes across different geographic locations.
- Standardization and interoperability testing: Sto-CAV can serve as a platform for evaluating interoperability among different V2X technologies and validating compliance with emerging standards.
- Real-world testbed integration: A long-term goal is to connect Sto-CAV simulations with physical testbeds, allowing seamless transitions between virtual and real-world testing environments.

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