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Automated Passive Interoperability Testing for Cellular V2X

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***Abstract*—Cellular Vehicle-to-Everything (C-V2X), a critical component of Intelligent Transportation Systems (ITS), is a wireless technology that enables vehicles to communicate with their surroundings (e.g., other vehicles, roadway infrastructure like traffic lights, and pedestrians) to improve road safety and efficiency of safety-critical applications (e.g., emergency brake warning, intersection collision warning). However, a significant challenge for the mass deployment of C-V2X technology is the mutual interoperability and seamless communication between diverse On-Board Units (OBUs) and Road-Side Units (RSUs). Therefore, interoperability testing, measurement, and assessment methodologies are crucial to overcome this challenge. This paper presents an open-source, automated, passive interoperability testing tool designed to orchestrate synchronized data acquisition across heterogeneous C-V2X hardware platforms. By utilizing a passive or non-intrusive approach on the C-V2X device, the tool automates the lifecycle of packet capture on the PC5 sidelink interface without altering the radio environment or requiring proprietary software access. Our tool provides a vendor-agnostic, scalable, and extensible framework for collecting high-fidelity traces necessary for cross-vendor protocol validation and standardized interoperability analysis.**

Keywords*—Cellular V2X, Interoperability, OBU, Passive Interoperability Testing, RSU, Sidelink, V2I, V2V.

I. Introduction

The rapid advancement of Cooperative Intelligent Transportation Systems (C-ITS) has moved beyond theoretical methodologies into large-scale, real-world deployments [1, 2, 3]. At the core of this revolution is Cellular Vehicle-to-Everything (C-V2X) technology, specifically the PC5 sidelink interface. Unlike traditional cellular communication that relies on base stations (Uu interface), PC5 allows vehicles to communicate directly with each other and with road-side infrastructure with minimal latency. This capability is the fundamental enabler for safety-critical applications, such as Emergency Electronic Brake Lights (EEBL), Intersection Movement Assist (IMA), and Vulnerable Road User (VRU) alerts [4]. For these life-saving applications to function, a vehicle manufactured by one company must be able to seamlessly receive and interpret data sent by an RSU from a different vendor or a vehicle from another manufacturer. Without assured interoperability, the cooperative element of C-ITS collapses, creating islands of communication that compromise the safety of the entire network.

This seamless exchange of information is governed by a complex hierarchy of standards. The physical and MAC layers are defined by 3GPP (LTE-V2X and NR-V2X) [5, 6], while the network, transport, and security layers are defined by the IEEE 1609 family, also known as Wireless Access in Vehicular Environments (WAVE), in particular IEEE 1609.2 [7] for security/certificates and IEEE 1609.3 [8] for networking services. The message and application layers are defined by SAE J2735 [9], which specifies the data dictionary for messages like the Basic Safety Message (BSM), Signal Phase and Timing (SPaT), Map Data (MAP), and Traveler Information Message (TIM). Despite the existence of these standards, interoperability issues often arise from subtle misinterpretations and corresponding erroneous implementations of standards or proprietary extensions in vendor firmware. Thus, small differences in how a vendor implements the Abstract Syntax Notation One (ASN.1) encoding or how they populate optional fields can lead to silent failures. In such cases, a packet is physically received but discarded by the application layer because the payload is deemed malformed or non-compliant with the expected schema.

Traditional testing methods are often insufficient for the scale of modern deployments. Manual packet inspection using general-purpose tools like Wireshark is labor-intensive, error-prone, and difficult to reproduce across thousands of message exchanges. Furthermore, active testing—where a tester sends specific stimuli to a device—can sometimes mask bugs that only appear during the device's autonomous, high-frequency broadcasting state. To address these challenges, we introduce a fully automated software tool for passive C-V2X interoperability testing. By acting as a silent listener, this tool orchestrates the simultaneous capture of live, over-the-air traffic across heterogeneous OBU and RSU devices without interfering with the radio environment. The primary contributions of this paper are:

- The design and implementation of an extensible, vendor-agnostic software framework that automates the lifecycle of V2X packet-level data acquisition for interoperability testing.
- A methodology for synchronized passive monitoring on the PC5 interface to capture real-world device behavior.

- A scalable pathway for protocol-level validation that ensures devices are "speaking the same language" at the semantic layer.

By enabling the automated validation of the IEEE 1609 and SAE J2735 protocol stacks, this software provides a robust foundation for verifying that C-V2X hardware is ready for integration into public safety infrastructure.

II. Motivation and Related Work

Standardized testing for V2X is typically governed by organizations like the OmniAir Consortium [10] and ETSI [11]. While these organizations provide rigorous certification programs, they often involve expensive, proprietary test equipment and active testing where the test system interacts directly with the Device Under Test (DUT). These organizations also plan and coordinate periodic industry-wide "plugfest" events. These events provide a vital forum for vendors to test their V2X implementations against peers in a real-world, multi-vendor environment. However, while essential for baseline compatibility and interactive troubleshooting, plugfests are not always sufficient for the development cycles and controlled testing required for modern V2X stacks. In the United States, the first Department of Transportation V2X interoperability test took place in October 2024 in Wyoming [12]. The purpose of this interoperability test was to verify whether one participant's TIM broadcast by the RSUs could be received and correctly displayed by the other participants' OBUs under six predefined scenarios. However, since these events occur infrequently and require significant physical logistics and travel, they cannot support the iterative regression testing needed to catch compatibility issues introduced during frequent firmware updates. Furthermore, the manual nature of data collection and orchestration at these events often leads to fragmented traces and delayed analysis, making it difficult to pinpoint the root cause of transient interoperability failures in real-time. This points to a clear need for a locally deployable, automated testing framework that can easily be utilized in a multi-vendor environment.

Active testing involves a dedicated tester that initiates communication to elicit a response from the DUT. For instance, Song and Lee [13] developed active interoperability test systems for IEEE 1451.5-based wireless sensors. In these frameworks, the system actively sends commands and evaluates the resulting response messages against the IEEE 1451 standards. While this method provides a direct way to verify protocol compliance and command-response cycles, it requires the testing tool to participate as an active node in the network, which may alter the network traffic profile in high-density V2X environments.

To avoid the "observer effect" and test devices in their natural operating state, passive testing methodologies have been proposed. Unlike active methods, passive testing focuses on sniffing existing traffic without injecting new packets. This approach has been successfully applied across various critical infrastructure standards. For instance, Song et al. demonstrated passive testing for IEEE 1451.5-802.11 wireless sensors by monitoring command and response message formats [14]. This methodology was further extended to high-precision power system components such as the IEC 61850-9-2 standard-based merging units [15]. In these contexts, passive monitoring allows for the verification of data integrity and timing without interrupting the continuous flow of telemetry data. Our work adopts this passive philosophy, applying it to the PC5 sidelink interface of C-V2X to monitor safety message exchanges between vehicles and infrastructure.

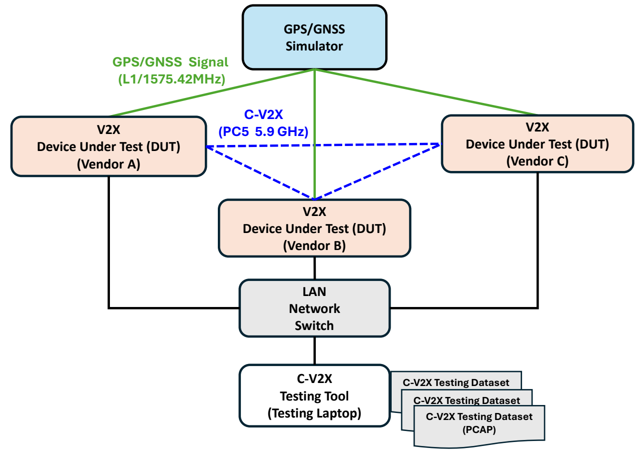

Fig. 1. C-V2X interoperability testing system design.

Both active and passive test methods are used for device-to-device interoperability testing that mainly focus on testing how to exchange information, not use the information exchanged. Song and Lee [16] recently proposed an Hardware-in-the-Loop (HIL) simulation-based interoperability testing method for smart sensors in smart grids. By integrating physical hardware into a simulated environment, this method allows for testing interoperability under complex, dynamic conditions that are difficult to replicate in a static lab setting. This method not only tests how to exchange information between an MU-based smart sensor and the simulated protective relay (PR) but also tests how the PR can use the information from the smart sensor for MPC applications. For C-V2X, HIL-based methods are particularly relevant for simulating a variety of traffic scenarios and edge cases in a controlled environment before deploying passive monitoring tools in the field.

While the aforementioned works provide a robust foundation for interoperability testing in industrial and smart grid domains, applying these techniques to C-V2X presents unique challenges. Unlike the request-response patterns of smart sensors [13, 14, 17], C-V2X relies on high-frequency, ad-hoc broadcast messages (e.g., BSMs, TIMs). There is a need for a tool that adapts the passive monitoring principles identified in [14, 15, 16] specifically for the 3GPP/IEEE/SAE C-V2X protocol stack, enabling real-time diagnostic capabilities without requiring vendor-specific debug interfaces. Passive testing, as implemented in this tool, offers a distinct advantage: it observes the natural behavior of devices in a shared wireless medium without injecting artificial traffic that might alter the DUT's performance, and provides an automated wrapper that orchestrates the entire capture-to-analysis pipeline.

III. System Design

Fig. 1 shows the C-V2X interoperability testing tool is designed as an automated test orchestration framework. Its primary goal is to eliminate the manual complexity of managing multiple, vendor-diverse C-V2X devices (both OBUs and RSUs) during interoperability trials.

A. Orchestration Architecture

The software uses a centralized control pattern. A single workstation running the testing tool acts as the *test controller*, communicating with the DUTs over a local management network (typically Ethernet). The tool is written in pure Python for portability across operating systems, and utilizes PDM for deterministic dependency management. It leverages standard network protocols (SSH and SCP) to interact with the DUTs, ensuring compatibility with any Linux-based V2X stack without requiring the installation of custom agents on the vendor hardware.

B. Vendor Abstraction Layer

A core strength of the tool's design is its modular approach to vendor-specific differences. While different manufacturers use different interfaces, directory structures, and management commands, the tool abstracts these into pluggable adapter modules with a uniform interface. This architecture decouples the core orchestration engine, which remains device-agnostic, from the hardware-specific modules, which require knowledge of the internals of the device being managed. The current version of the software provides adapters for several commercial OBUs and RSUs from different manufacturers.

This design also simplifies the process of extending the tool to support a new vendor or device type. To do so, one only needs to implement a lightweight Python module that provides a small number of functions to prepare the device and start/stop the capture. If the device's software stack does not provide a native mechanism to capture V2X traffic on the sidelink interface, it can instead be configured to forward the relevant packets to the test controller over the management interface. The controller can then create a packet trace on behalf of the device.

By capturing data directly at the source, i.e., the C-V2X interface on the OBU/RSU, rather than using an external sniffer, the tool ensures that the collected traces represent exactly what the device sent and received. This is critical for interoperability testing, as it allows researchers to identify if a communication failure occurred at the radio layer or within the protocol stack of a specific vendor.

C. Automated Test Procedure

The tool utilizes a unified configuration system to define the operational parameters of each experiment execution, ensuring a deterministic and repeatable testing session. For each DUT, the user must specify the device type (OBU/RSU and vendor), the IP address to connect to the device, and any credentials required for authentication (e.g., password or SSH key). This device-specific metadata allows the orchestration engine to dynamically map each device to the correct SSH commands, file paths, and capture utilities. Additionally, users can configure the test duration to control the length of packet capture and the number of repetitions to facilitate automated batch testing and statistical consistency.

Fig. 2 shows the tool automates the lifecycle of an interoperability test run through a sequence of coordinated steps:

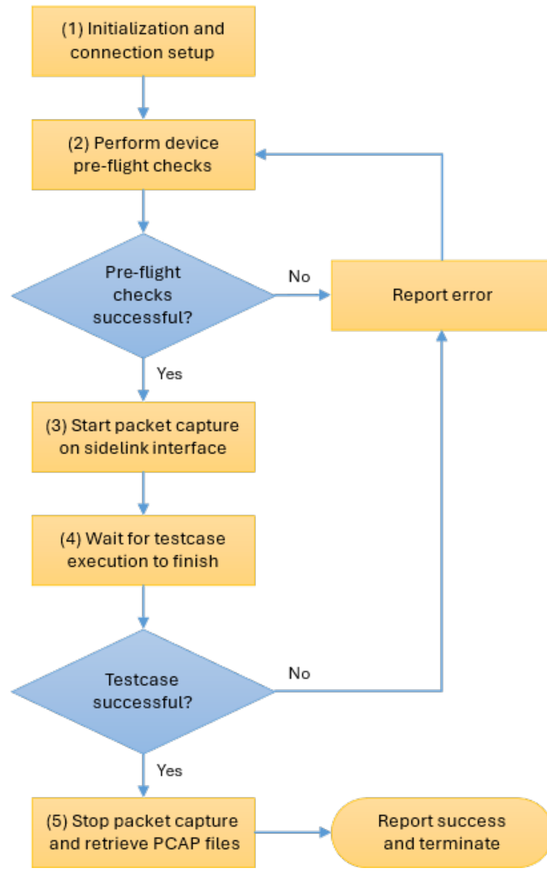

Fig. 2. Flowchart of the testing tool.

1) *Initialization*: The controller establishes concurrent SSH sessions with all participating OBUs and RSUs.

2) *Pre-flight Check*: The controller runs several basic sanity checks on each DUT, such as verifying proper GNSS synchronization and radio interface state, to ensure it is correctly configured and ready for testing.

3) *Synchronized Capture*: The tool triggers the native capture utility on each device (e.g., tcpdump or a vendor-specific logging tool) to monitor the PC5 sidelink interface. By initiating the packet capture almost simultaneously across all DUTs, the tool minimizes timing offsets between traces.

4) *Testcase Execution*: The test runs for a pre-defined duration, during which the OBUs/RSUs exchange V2X messages (BSM, MAP, SPaT, etc.) over PC5 according to their internal configurations.

5) *Data Retrieval*: Once the timer expires, the tool terminates the test execution and remote capture processes. It then uses SCP to pull the raw PCAP files back to the controller and stores them in a central location.

The resulting packet traces can be postprocessed and analyzed offline with any PCAP-compatible software such as Wireshark.

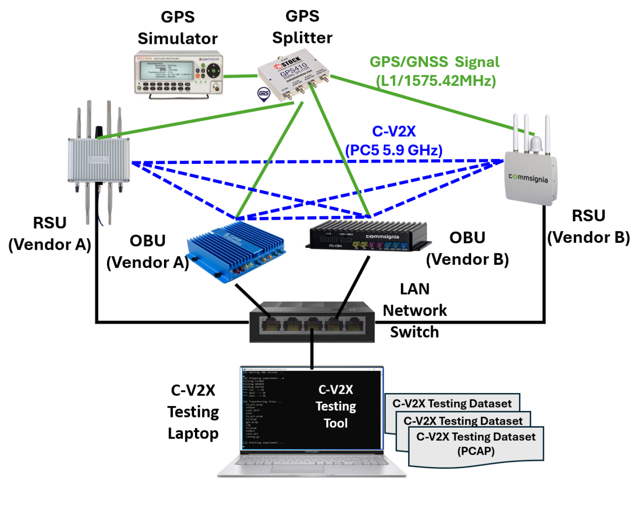

Fig. 3. C-V2X interoperability testbed setup.

IV. Testbed Setup

A typical testbed for the C-V2X Interoperability Testing Tool consists of a centralized orchestration environment that manages heterogeneous hardware units via a wired management network. This setup allows researchers to evaluate how different devices interpret and process V2X messages in real-time.

A. Hardware Components

Fig. 3 shows the C-V2X testbed that consists of three primary types of hardware components:

- One test controller: Any physical PC or virtual machine running the Python-based interoperability testing tool. It serves as the controller that executes the orchestration scripts and coordinates the entire testing campaign.
- One or more DUTs: Typically a mix of commercial OBUs and RSUs. To truly test interoperability, these units should be sourced from multiple different vendors.
- GNSS/GPS source: Since C-V2X requires precise timing for message synchronization and timestamping, all DUTs must be connected to either a live GPS antenna or a GNSS simulator to maintain a common clock.

B. Network Configuration

Our approach utilizes a dual-network topology to separate the control plane from the data plane. The management network, typically implemented over an Ethernet LAN, connects each DUT to the test controller. This network is used exclusively for the tool's administrative tasks, such as establishing SSH sessions, sending start/stop signals, and retrieving PCAP files via SCP. The actual C-V2X communication network (PC5 sidelink) is the wireless over-the-air interface where the DUTs exchange safety messages (e.g., BSM, SPaT, MAP). The tool captures traffic directly from the internal buffers associated with this interface on each device. For more controlled and repeatable experiments, it is possible to connect the radio interfaces of the DUTs via RF cables. This also allows incorporating attenuators and/or channel emulators into the testbed in order to simulate more advanced real-world conditions. It is important to note that our software is independent from the physical layer (PHY) and radio configuration. Since the tool operates by capturing packets at the network layer, it remains agnostic to the underlying radio technology. Whether the devices are configured for LTE-V2X or NR-V2X, the tool functions identically. This makes the framework future-proof as the industry transitions from LTE to NR-based sidelink communication.

V. Experimental Testing and Results

A. V2X Interoperability Testing Scenarios

To validate the software's behavior, we considered three distinct testing scenarios that are relevant to interoperability testing of C-V2X PC5 communications. The three scenarios are:

- Vehicle-to-Vehicle (V2V): In this scenario, the tool orchestrated captures between two OBUs from different vendors. The primary focus was the successful acquisition of Basic Safety Messages (BSM).
- Vehicle-to-Infrastructure (V2I): This setup involved one OBU and one RSU. The test focused on the broadcast of Map Data (MAP), Road Side Alerts (RSA), Signal Phase and Timing (SPaT), and Traveler Information Messages (TIM) from the infrastructure to the vehicle.
- Simultaneous V2V and V2I: This involved a multi-node environment where multiple OBUs and RSUs were active concurrently. The message types involved in this test case were a combination of those in the two previous cases. This scenario validated that the tool is able to handle the increased complexity of a full connected intersection with multiple vehicles.

In all testing scenarios we employed a GSG-5 GNSS simulator to provide the GPS L1 signal to all OBUs and RSUs via GPS splitter in the test Lab. environment. This ensured proper clock synchronization across all devices using the GPS coaxial cables and sub-miniature version A (SMA) connectors. in the testbed. Batches of IEEE 1609.2 certificates were provisioned from two different vendors, each with their own trust anchor, to confirm correct message signing operations on the sender side and verification on the receiver side. The top half of Fig. 4 shows a diagram of the third test scenario (simultaneous V2V and V2I) with two OBUs and one RSU. All C-V2X devices were commercial off-the-shelf units. Note that other hardware configurations are possible and the tool itself can handle any combination of OBUs and RSUs as long as they are supported by the vendor abstraction layer, as explained in Section III.B. We configured the OBUs to broadcast BSMs at the standard frequency of 10 Hz, while the RSU was configured to transmit a set of MAP, SPaT, TIM, and RSA messages at a frequency of 1 Hz.

B. Experimental Results

The tool was successfully deployed and validated across the three interoperability scenarios described earlier (V2V, V2I, and simultaneous V2V/V2I). During this evaluation, the tool was run six times for each scenario, with varying physical topologies, and in each case it automatically captured packet traces of the LTE sidelink channel from all participating C-V2X devices, as designed. The resulting packet traces in PCAP

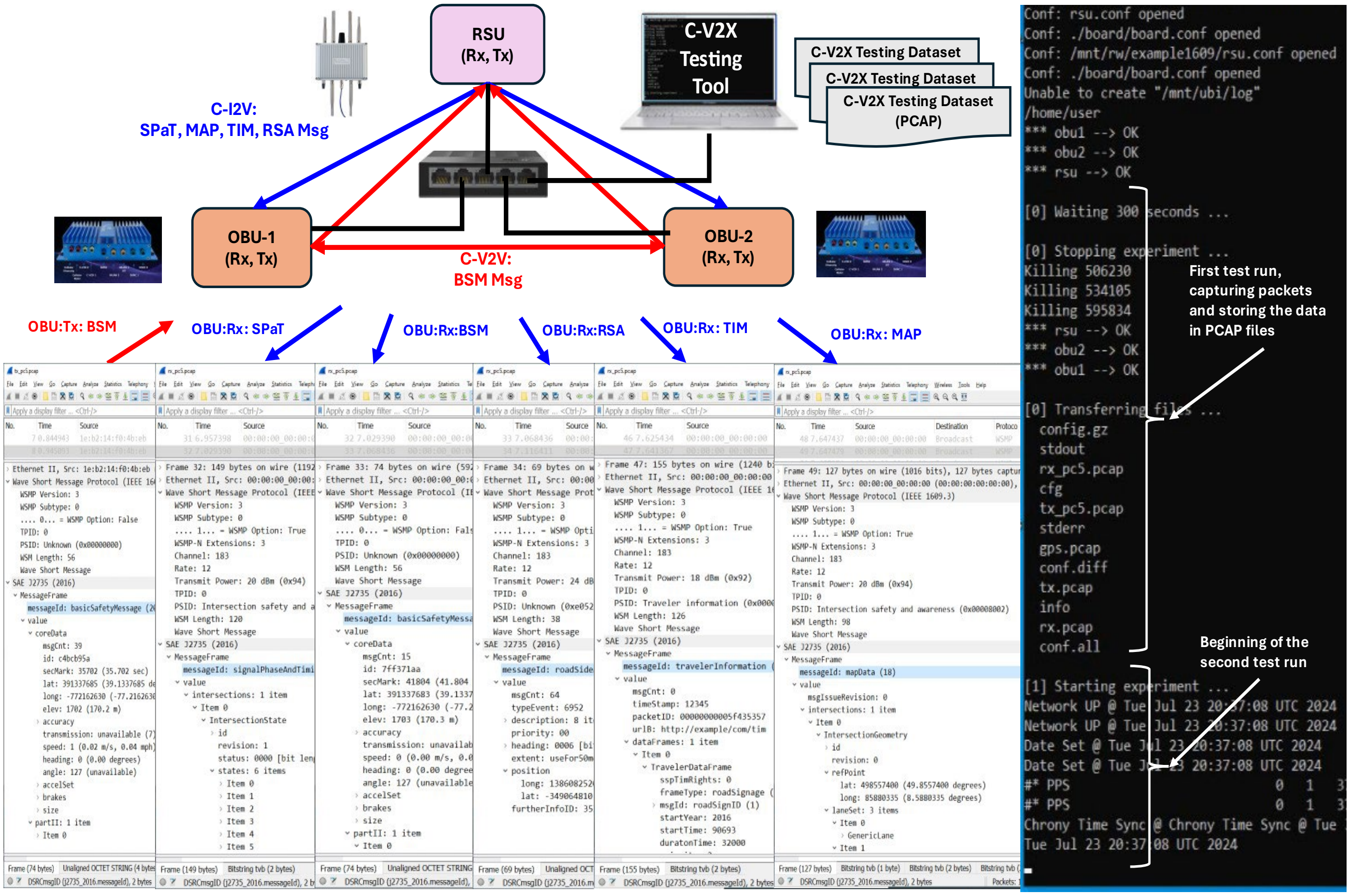

Fig. 4. Simultaneous V2V and V2I interoperability scenario and an example of tool execution.

format are publicly available at [18] and are further described in [19]. These datasets can be exported into the Packet Details Markup Language (PDML) format via Wireshark or Tshark, providing a structured XML representation of all message headers and fields, which can subsequently be processed by a V2X interoperability analysis and assessment tool such as [20]. Table 1 shows a summary of three V2X test cases.

Table 1. Summary of three V2X test cases.

Test case	V2V		V2I		V2V/V2I	
Number of V2X Devices	1 OBU	1 OBU	1 OBU	1 RSU	2 OBU	1 RSU
V2X Message Types	BSM	BSM	BSM	MAP, SPaT, TIM, and RSA	BSM	MAP, SPAT, TIM, and RSA
Generated Dataset Formats	PCAP and PDML		PCAP and PDML		PCAP and PDML	
Testing Duration (minutes)	3		3		3	
Repeating time	3		3		3	

VI. Discussion

The experimental results demonstrate that our C-V2X interoperability testing tool provides a reliable, scalable framework for multi-vendor protocol validation. Several important considerations emerged during the development and evaluation phases that warrant further discussion.

A. On-Device Capture vs. External Air-Sniffing

A significant advantage of the tool's design is its reliance on internal passive capture rather than external air-interface sniffers (e.g., dedicated monitoring nodes). External sniffers may introduce their own packet loss, especially in high-density environments or near-interference sources, which can lead to false negatives where a message was correctly transmitted but not captured by the monitor. By capturing data directly at the OBU/RSU interface layer, our tool ensures that the resulting traces are a ground truth representation of what the device processed. This is also valuable for testing and diagnosing interoperability failures in which the radio hardware successfully receives a packet that the upper-layer application subsequently rejects or misinterprets.

B. Mitigation of the Observer Effect

Traditional active testing methods, which require injecting packets into the network to probe a device's response, inevitably alter the radio channel and can mask timing-sensitive issues. The purely passive approach of our tool maintains the integrity of the radio environment and minimizes interference. The tool's execution adds negligible overhead to the DUTs and, by acting as a silent listener, it facilitates controlled and reproducible experiments.

C. Scalability and Future-Proofing

The tool's radio-agnostic nature ensures its longevity as industry shifts from 4G LTE-V2X to 5G NR-V2X [21, 22]. Because the orchestration logic is independent of the underlying modulation and coding schemes, the same implementation used for current trials can be applied to 3GPP Release 16 and later hardware with minimal modification. Furthermore, the use of massively parallel SSH management allows the tool to scale from small lab tests to large-scale field tests involving dozens of nodes.

VII. Conclusion

As C-V2X technology moves toward wider adoption, the ability to ensure seamless communication across diverse hardware ecosystems is a prerequisite for public safety. This paper presented an automated, passive interoperability testing tool designed for synchronized, non-intrusive, packet-level data acquisition from commercial off-the-shelf OBUs and RSUs. By utilizing a modular, vendor-agnostic architecture, the tool successfully orchestrates multi-node testing scenarios without interfering with the sensitive radio environment.

Experimental validation confirms that the tool provides high-fidelity, ground-truth data, ensuring that retrieved packet traces accurately reflect real-world device behavior. The software's configuration-driven approach not only simplifies the management of heterogeneous OBUs and RSUs but also establishes a rigorous standard for scientific reproducibility in V2X research. Because the tool operates at the logical interface layer, it remains radio-agnostic and future-proof, providing a consistent testing approach as the industry transitions from LTE-V2X to NR-V2X and beyond. As such, this work enables researchers and engineers to verify that safety-critical messages are correctly understood across all hardware and software vendors in the C-ITS ecosystem.

Disclaimer

Certain commercial equipment, instruments, or materials, commercial or non-commercial, are identified in this paper in order to specify the experimental procedure adequately. Such identification does not imply recommendation or endorsement of any product or service by NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

References

[1] F. Arena and G. Pau, "An overview of vehicular communications," *Future internet,* vol. 11, no. 2, p. 27, 2019, DOI: 10.3390/fi11020027.

[2] J. Chang, S. G. Hatcher, E. Kuruvilla, K. Bare, M. Zaatari, C. Kain, I. McManus, A. Seshadri and K. Thompson, "Interoperable Connectivity - National V2X Deployment Plan Supplement," U.S. Department of Transportation, 2024.

[3] 5G Automotive Association, "The case for cellular V2X for safety and cooperative driving," 5G Automotive Association, 2016.

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

[5] 3GPP TR 23.285, "Architecture enhancements for V2X services," 3GPP.

[6] 3GPP TR 36.785, "Vehicle to Vehicle (V2V) services based on LTE sidelink; User Equipment (UE) radio transmission and reception," 3GPP.

[7] "IEEE Standard for Wireless Access in Vehicular Environments: Security Services for Application and Management Messages," *IEEE Std 1609.2-2022 (Revision of IEEE Std 1609.2-2016),* pp. 1-349, 2023.

[8] "IEEE Standard for Wireless Access in Vehicular Environments (WAVE): Networking Services," *IEEE Std 1609.3-2020 (Revision of IEEE Std 1609.3-2016),* pp. 1-210, 2021.

[9] SAE International Technical Standard, "V2X Communications Message Set Dictionary, SAE Standard J2735_202409," SAE International, 2024.

[10] OmniAir Consortium, "C-V2X Certification," [Online]. Available: https://omniair.org/product-certification/c-v2x-certification/. [Accessed 12 March 2026].

[11] ETSI TS 103 192-2, "Intelligent Transport Systems (ITS); Testing; Interoperability test specifications for ITS V2X use cases; Part 2: Test Suite Structure and Test Purposes," ETSI, 2022.

[12] J. Anderson, T. English, K. Shain, S. Niemer, B. Hicks and B. Mangel, "Test Plan for V2X Interoperability Testing," 15 November 2024. [Online]. Available: https://www.its.dot.gov/_astro/Final_V2X_Interoperability_TestPlanAS_TESTED.Bq8OBuTa.pdf. [Accessed 12 March 2026].

[13] E. Y. Song and K. B. Lee, "Interoperability test of IEEE 1451.5 standard-based wireless," in *2010 International Conference on Measuring Technology and Mechatronics Automation*, 2010, DOI: 10.1109/ICMTMA.2010.846.

[14] E. Y. Song, K. B. Lee and F. Proctor, "Testing system for IEEE 1451.5-802.11 standard-based wireless sensors," in *2014 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) Proceedings*, 2014, DOI: 10.1109/I2MTC.2014.6860865.

[15] E. Y. Song, K. B. Lee, G. J. FitzPatrick and Y. Zhang, "Interoperability test for IEC 61850-9-2 standard-based merging units," in *2017 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2017, DOI: 10.1109/ISGT.2017.8086084.

[16] E. Y. Song and K. B. Lee, "Hardware-In-The-Loop (HIL) Simulation-based Interoperability Testing Method of Smart Sensors in Smart Grids," in *2024 IEEE 7th International Conference on Industrial Cyber-Physical Systems (ICPS)*, 2024, DOI: 10.1109/ICPS59941.2024.10640022.

[17] E. Y. Song and G. J. FitzPatrick, "Interoperability test for IEEE C37.118 standard-based phasor measurement units (PMUs)," in *2016 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2016, DOI: 10.1109/ISGT.2016.7781240.

[18] E. Song, D. Pesavento and Y.-S. Li-Baboud, "C-V2X Interoperability Testing Datasets," 2024. [Online]. Available: https://data.nist.gov/od/id/mds2-3541. [Accessed 12 March 2026].

[19] E. Song, D. Pesavento and Y.-S. Li-Baboud, "C-V2X Interoperability Testing Datasets: Description and Use," NIST Technical Note (TN) 2315, National Institute of Standards and Technology, 2024, DOI: 10.6028/NIST.TN.2315.

[20] E. Song, D. Pesavento, T. Roth and T. Wong, "C-V2X Interoperability Analyzer Software Tool: Description and Use," NIST Technical Note (TN) 2339, National Institute of Standards and Technology, 2025, DOI: 10.6028/NIST.TN.2339.

[21] D. Garcia-Roger, E. E. González, D. Martín-Sacristán and J. F. Monserrat, "V2X Support in 3GPP Specifications: From 4G to 5G and Beyond," *IEEE Access,* vol. 8, pp. 190946-190963, 2020, DOI: 10.1109/ACCESS.2020.3028621.

[22] M. Harounabadi, D. M. Soleymani, S. Bhadauria, M. Leyh and E. Roth-Mandutz, "V2X in 3GPP Standardization: NR Sidelink in Release-16 and Beyond," *IEEE Communications Standards Magazine,* vol. 5, no. 1, pp. 12-21, 2021, DOI: 10.1109/MCOMSTD.001.2000070.