Simulating Non-Functional Communication Requirements in Automotive Software

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ABSTRACT

This paper proposes an approach to support the early validation of non-functional communication requirements in the development of automotive embedded software, particularly for Advanced Driver Assistance Systems (ADAS) that incorporate V2X (Vehicle-to-Everything) communication as a complementary input. The approach integrates the ns-3 network simulator as a systematic tool during the initial stages of the V-model, focusing on the data link layer, specifically the MAC and PHY sublayers, using the IEEE 802.11p protocol and its evolution, IEEE 802.11bd. Simulations are conducted in parallel with requirements elicitation, enabling the assessment and refinement of key parameters such as latency, reliability, packet loss, and communication range. By anticipating the analysis of these properties through simulation, the approach aims to reduce rework in later verification phases and improve the definition of system architecture. The ns-3 environment offers a reproducible, scalable, and low-cost solution for evaluating communication behavior under adverse conditions, contributing to more informed decisions early in the automotive software lifecycle.

KEYWORDS

Non-Functional Requirements Validation, V2X Communication, IEEE 802.11p/802.11bd Simulation, Automotive Embedded Software

1 Introduction

The increasing functional complexity of modern vehicles has expanded the scope of embedded software. Originally limited to control tasks within Electronic Control Units (ECUs), software now orchestrates critical domains such as vehicle connectivity and functional safety. Precise control of vehicle behavior depends on time-critical and reliability-related requirements, which demand rigorous handling from the early stages of software development.

Among the most complex features are Advanced Driver Assistance Systems (ADAS), which support functionalities such as autonomous emergency braking, adaptive cruise control, lane-keeping assistance, and blind spot monitoring. Executing these functions requires real-time perception and a reliable response to dynamic events, which in turn depend on the quality and availability of data within the vehicular environment.

V2X (Vehicle-to-Everything) communication has emerged as a key enabler to extend situational awareness beyond onboard sensors through the direct exchange of data between vehicles, roadside infrastructure, pedestrians, and backend systems. This distributed data exchange enables cooperative behavior among vehicular nodes, enhancing anticipatory capabilities and reducing uncertainty in scenarios with occlusions or limited visibility. Figure 1 illustrates the primary V2X communication links, including V2V (Vehicle-to-Vehicle), V2I (Vehicle-to-Infrastructure), V2P (Vehicle-to-Pedestrian), and V2N (Vehicle-to-Network), which constitute the core of next-generation vehicular connectivity [3].

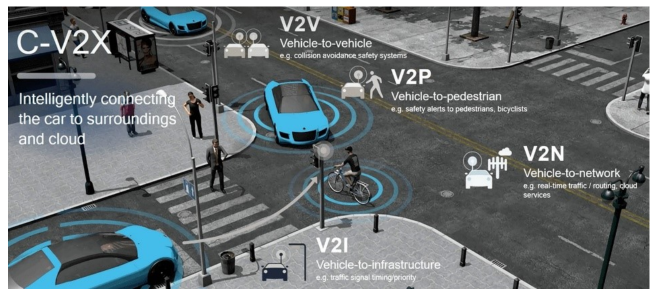

Figure 1: Illustrative example of V2X communication types: V2V, V2I, V2P, and V2N. Source: CT Engineering Group[3].

This paper proposes the use of the ns-3 network simulator to support the early validation of non-functional communication requirements in embedded systems with V2X capabilities. The approach leverages the IEEE 802.11p and IEEE 802.11bd protocols to evaluate key properties such as latency, reliability, packet loss, and communication range during the requirements definition phase. The objective is to reduce downstream rework and enhance the quality of software architecture in automotive systems.

2 Technical Background

2.1 Non-Functional Requirements

The reliability of automotive system functionalities is strongly dependent on non-functional communication properties such as latency, update rate, robustness under interference, and tolerance to packet loss. Klapez et al. [5] demonstrate that the IEEE 802.11p protocol, widely adopted in V2X applications, exhibits performance degradation under high vehicle density scenarios, with reduced throughput and increased losses in Cooperative Awareness Messages (CAMs), which periodically broadcast vehicle position and behavior to surrounding nodes.

Industry perspectives compiled by Martins et al. [7] further highlight that the early evaluation of such non-functional requirements is a recurring challenge in automotive software projects, especially in context-aware systems where communication constraints directly impact safety and performance. Their study indicates that current industrial practices often postpone the verification of these properties to later development stages, increasing the likelihood of costly rework—a limitation this work aims to address through simulation-based assessment.

In 2022, the IEEE published a revised vehicular communication standard, IEEE 802.11bd-2022 [4], introducing enhancements to the MAC and PHY layers to meet more stringent requirements. The updated specification defines operating modes with higher throughput, improved receiver sensitivity, support for relative speeds up to 500 km/h, and backward compatibility with legacy devices operating outside of coordination domains. These enhancements aim to sustain performance under conditions of high traffic density and mobility, as required by cooperative vehicular applications.

2.2 Automotive Software Development

The development of automotive software typically follows the V-model, in which verification activities are conducted only after implementation and system integration phases. In systems that rely on communication, the lack of early validation of non-functional requirements increases the likelihood of late-stage defect detection and significantly raises correction costs. Liu et al. [6] advocate the adoption of incremental verification practices starting from the early phases of development. Their approach incorporates simulation as a mechanism to support the specification and refinement of requirements, thereby reducing rework and improving the reliability of downstream development stages.

3 Proposed Approach

This work proposes using the ns-3 simulator, an open-source platform for realistic MAC and PHY protocol modeling, to support early specification and validation of non-functional requirements in automotive embedded systems with V2X communication. The approach integrates simulation-based testing into the requirements definition phase of the V-model (Figure 2), enabling early, controlled evaluation of latency, packet loss rate, link reliability, and communication range. These parameters align with ISO/IEC 25010 sub-characteristics [1]: Time Behavior (latency, range), Fault Tolerance (packet loss, reliability), and Resource Utilization (bandwidth efficiency under varying loads). The goal is to reinforce requirement specification from the outset using quantitative evidence from simulated vehicular scenarios.

Unlike conventional workflows, where communication requirements are validated after software integration and physical testing, ns-3 enables reproducible, low-cost, scenario-controllable assessment of critical constraints in earlier stages. It supports fine-grained configuration of protocol stacks, including bandwidth, modulation schemes, medium access policies (EDCA), midamble density, and node topology.

This proposal addresses a gap in traditional requirements engineering, which often underestimates the systemic impact of communication failures in high-mobility and congested environments. Simulation-based validation can align with ASPICE and ISO 26262, strengthening compliance in safety-critical systems. The framework is extensible to diverse topologies, protocol variants, and abstraction levels, providing a scalable basis for continuous evaluation in cooperative driving systems. Integrating simulation into requirements elicitation and validation improves traceability between network-level behavior and software architecture, enhancing failure predictability and engineering maturity in V2X-dependent automotive software.

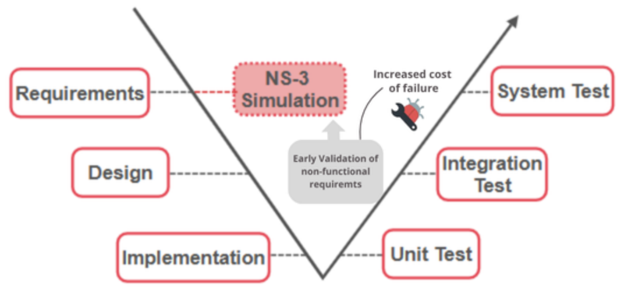

Figure 2: Ns-3 simulation during V-model requirements phase.

4 Methodology

The proposed methodology is based on the use of simulations within the ns-3 (Network Simulator 3) environment, focusing on the early validation of non-functional V2X communication requirements such as latency, packet loss, reliability, and communication range. The simulation model was developed across three complementary dimensions, described below.

4.1 Modeling the V2X Communication Stack in ns-3

The protocol stack was constructed using the `WaveNetDevice` module to represent both IEEE 802.11p and IEEE 802.11bd standards. The modeling of the MAC layer and multi-channel interface follows the implementation described by Bu et al. [2], which reproduces IEEE 1609.4 behavior in ns-3 with periodic broadcast of Cooperative Awareness Messages (CAMs). This structure enables accurate simulation of channel switching, MAC scheduling, and channel coordination mechanisms required in realistic V2X scenarios.

4.2 Physical Layer Configuration with Realistic Parameters

The PHY layer was configured to incorporate packet error rate (PER)-based models, following the methodology proposed by Reinoso-Chisaguano et al. [8]. Modulation schemes compliant with IEEE 802.11p and 802.11bd (BPSK, QPSK, QAM) were adopted, with sensitivity thresholds and transmission rates defined according to the IEEE 802.11bd-2022 amendment. This configuration aims to reflect real-world impairments due to high mobility, interference, and propagation dynamics in vehicular environments.

4.3 Medium Access Parameter Evaluation

MAC layer evaluation included variations in contention window (CW) sizes and CAM message transmission intervals. These parameters were selected based on the analytical study by Sepulcre et al. [9], which investigates the impact of contention window tuning and channel bonding on the performance of IEEE 802.11bd networks. The study reports direct effects on communication latency and reliability, particularly under high-density node configurations, which are critical for V2X-enabled applications.

4.4 Pseudocode

Algorithm 1 outlines a generalized simulation structure for evaluating non-functional V2X communication requirements in ns-3.

It includes the configuration of IEEE 802.11p/802.11bd protocols, node mobility, periodic CAM message generation, and performance instrumentation via FlowMonitor to collect latency, jitter, packet loss, throughput, and delivery rate by distance.

The framework supports diverse topologies and traffic conditions, where X encompasses vehicles, infrastructure, pedestrians, and cloud systems. It provides a reproducible basis for controlled experiments under high mobility and congestion, enabling rigorous assessment of V2X communication performance.

Algorithm 1: Pseudocode

- $V2XProtocol$: Protocol to evaluate (`802.11p` or `802.11bd`)
- $NodeCardinalitySet$: Vehicular node quantities to simulate (*e.g.*, {2, 3, 4})
- $InterVehicleDistanceSet$: Set of pairwise distances between nodes (*e.g.*, {10, 50, 100, 150} m)
- $CAMInterval$: Periodicity of Cooperative Awareness Messages (CAMs)
- $PerformanceDataset$: Structured collection of metrics (delay, jitter, packet loss, throughput, delivery ratio)
- $Plots$: Graphs correlating metrics to parameters (node count, distance)

```
foreach distance ∈ InterVehicleDistanceSet do
    foreach nodeCount ∈ NodeCardinalitySet do
        // Simulation topology setup
        Instantiate nodeCount mobile nodes with static spacing via
          ListPositionAllocator;
        Assign constant velocity profile using
          ConstantVelocityMobilityModel;
        Initialize propagation model using YansWifiChannel;
        if V2XProtocol == 802.11bd then
            Apply extended PHY configuration: TxPower, Midambles,
              ReceiverSensitivity;
        else
            Apply IEEE 802.11p default PHY parameters;
        Configure MAC access via EDCA: (CWmin, CWmax, AIFS) for
          each AC (VO, VI, BE, BK);
        // Application and runtime instrumentation
        Deploy CAM broadcast application with periodicity
          CAMInterval;
        Enable data collection using FlowMonitor;
        Execute simulation with Simulator::Run();
        // Metric extraction
        Extract the following KPIs:
            Average communication delay;
            End-to-end packet loss rate;
            Jitter (delay variance);
            Aggregate throughput (Mbps);
            Delivery ratio relative to distance;
        Persist results for (nodeCount, distance) in
          PerformanceDataset;
Generate Plots from PerformanceDataset;
```

As a demonstrative application, Section 5 provides a script and output of a minimal scenario involving two mobile vehicles configured to communicate via UDP packets at varying distances. Although simplified, the example serves to demonstrate the operationalization of the elements described in the pseudocode for testing non-functional communication requirements.

5 Conclusion and Future Work

This work highlighted the need for early validation of non-functional requirements in automotive systems relying on V2X communication. The traditional V-model has limitations for real-time performance constraints, such as latency and link reliability, often delaying issue detection and increasing verification costs.

To address this, we proposed using the ns-3 simulator, with detailed IEEE 802.11p/802.11bd MAC and PHY modeling, to support the specification of communication requirements. The framework enables reproducible assessment of latency, packet loss, jitter, and throughput under diverse mobility and load conditions.

A minimal scenario demonstrated feasibility, showing the potential of simulation to detect inconsistencies before integration and refine non-functional requirements. Future work will extend to urban topologies, heterogeneous traffic, advanced medium access strategies, and integration with formal requirements tools for incremental verification in earlier V-model phases.

ARTIFACT AVAILABILITY

The simulation code and output of a minimal V2X scenario for testing non-functional communication requirements are available at https://github.com/LarissaPestana/SAST2025.

ACKNOWLEDGMENTS

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