Poster: Informing V2I Deployment Decisions Using Commercial Hardware-in-the-loop Testing

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***Abstract*—Vehicle-to-Everything (V2X) technologies are seeing significant growth as an element of smart cities and a more-interconnected digital world in the Internet of Things (IoT). As governing bodies like State Departments of Transportation (DOTs) contemplate Vehicle-to-Infrastructure (V2I) deployments, they need to know what V2I devices will perform best, both in general and in their specific jurisdictions. In this paper, we develop a method to test commercial, off-the-shelf (COTS) Cellular-V2X (C-V2X) roadside equipment (RSE) as a way to inform government deployment; this includes indoor and outdoor tests for thoroughness. While this method needs to be refined, it provides a strong basis for future DOTs to determine which devices will best meet their deployment needs.**

***Index Terms*—RSU, V2I, Hardware-in-the-loop V2X testing**

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I. Introduction

Vehicle-to-Everything (V2X) is a growing technology with great potential to reduce vehicular accidents and fatalities. That being said, it is quite a monetary investment for a government to deploy the necessary roadside equipment (RSE); they need to know that they are picking the best roadside unit (RSU) for their region. As government departments of transportation (DOTs) consider deployments of vehicle-to-infrastructure (V2I) devices, they must be informed about the performance of the various RSU options available to them.

In previous work, Cellular-V2X (C-V2X) device capabilities have been measured using computer simulations in [1] and [2], and while this provides scalability and performance estimations, simulations can't provide real-world data. Research that has been attempted outside of a virtual scenario has relied on open source, software defined radio-based solutions in [3], but this is limited by being non-commercial and not deployable at scale. Our work is unique because it performs hardware-in-the-loop testing on commercial, off-the-shelf (COTS) devices. It performs highly refined testing in an indoor environment and comparative measurement in an outdoor environment, pitting different COTS RSUs against each other.

Our goal is to build a methodology that DOTs and other organizations can mimic to run hardware-in-the-loop tests with different COTS RSUs and evaluate them for V2I deployment decisions. Our specific experiments for this poster serve to compare the communication ranges of various devices, but future applications can build off of this to compare any number of device traits. To this end, we develop methods to compare COTS RSUs to each other in head-to-head settings, specifically measuring V2X message reception rates. Our first set of experiments is in an indoor setting, using RF cables and shielded environments to see how well each device performs with manually adjusted attenuation values on each link. Our second set of experiments involves repeated performance testing of these devices in an outdoor environment.

Each of our experiments tests the performance of three COTS RSUs under identical receiving conditions (although the framework could be used for any number of COTS RSUs). We also used a C-V2X COTS On-Board Unit (OBU) to generate C-V2X traffic and Wireshark to analyze packet reception rates under various conditions. We present the experimental setup, the results of our methodology, and the open source code on GitHub [4] so that others can perform similar evaluations.

II. Indoor Experiment - Setup and Results

A. Methodology

The indoor experiments are performed using RF cables to connect the RSUs and the OBU, with a Mini-Circuits mesh attenuator [5] acting as a relay device. This allows us to control the signal strength between transmitter and receivers by manually changing the attenuation in each trial.

One issue we encountered is that these devices are prone to leaking RF signals over the air. This can produce both constructive and destructive interference with the over-the-wire signal, thus affecting the received signal strength despite the manually adjusted attenuation values. To overcome this, we place our transmitter and the receivers in RF-isolated environments. Figure 1 shows the entire indoor setup.

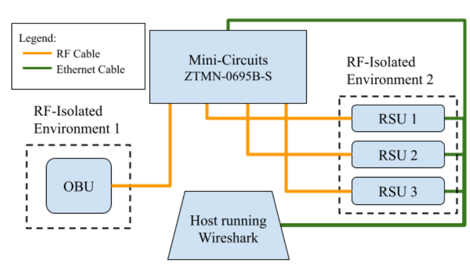

Fig. 1. A representation of the devices and connections in our indoor setup.

Each RSU has a programmable packet forwarding protocol, where it automatically transmits received V2X packets over an Ethernet connection. We program the RSUs to forward these all to a single host machine which, when running Wireshark, identifies which RSU forwarded a packet that it receives over the RF cable. This process allows us to identify when an RSU starts dropping packets because the attenuation gets too high.

In the experiment, a trial is run for 15 minutes at a constant attenuation value. We count how many packets are received from each RSU during that time and divide it by the number expected (the OBU transmits ten V2X messages every second, so we expect around 9000 received messages from each RSU during the trial). We then modify the attenuation value and repeat for the next trial.

B. Analysis

After all the trials have been run, we are able to see at what attenuation value each RSU starts to lose reception, eventually losing it entirely. We have the rate of 90% set as the safety minimum for each device, and so we are able to identify the "knee" of the graph as the point where the reception rate drops below that safety limit. Figure 2 shows the results from one such experiment.

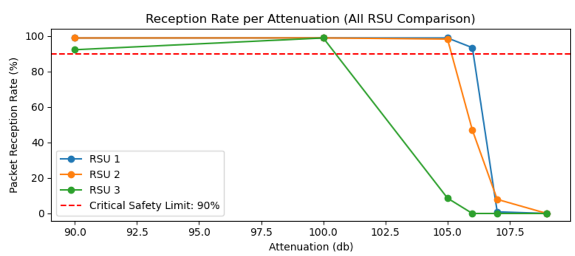

Fig. 2. The results from running all three RSU's against each other over multiple trials. Each dot represents the RSU's performance during a given trial, when a specific attenuation was applied for 15 minutes. Note the "knees" where the reception rates drop below the critical safety limit.

Depending on how many ports are available on the mesh attenuator, additional tests can be run to represent different scenarios. In our lab, we have a spare port that we hook a software-defined radio into to test each RSU's vulnerability to on-channel and off-channel interference. Overall, the indoor method allows for multiple different additional experiments to be performed beyond pure performance comparisons.

III. Outdoor Experiment - Setup and Results

A. Methodology

For the outdoor experiments, we use a road that is typical of where deployments for these devices would take place for our partnering DOT (in our case, a long, straight road). We station the RSUs at one end of the road and then drive a vehicle away from them with the OBU transmitting V2X messages ten times a second. In this case, we do not have a constant change in signal strength as the distance increases, but we are instead able to record the vehicle's progress and determine at what time it reaches successive intersections. As we again use Wireshark to track packet reception rates, we cross reference time marks with how far away the vehicle has gotten; we can then show how that reflected in the packet reception rates (see Figure 3).

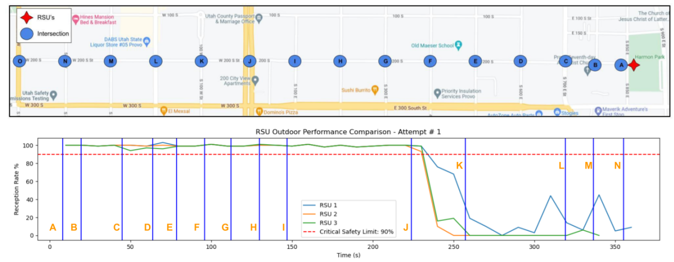

Fig. 3. (Top) The route taken by the vehicle while driving away from the RSU's; each intersection is labeled with a letter. (Bottom) The results from a single trial of running all three RSU's against each other in the outdoor environment; the blue lines indicate when each intersection was crossed in the time domain, matching the labels from the (Top) image.

IV. Assessment of Effectiveness and Future Work

Our research initiative is to determine the best-performing RSE for a state-wide V2I deployment. We desire to accomplish this using hardware-in-the-loop testing on COTS RSUs with the specific task of determining communication range. We present in this paper our methods of providing identical RF conditions to each RSU being tested and seeing how they perform in receiving from a COTS OBU.

We are confident in the potential of these methods and the results they have already yielded; in fact, our work is already being considered by a state DOT in their own V2I deployment decision making process. While refinements to the methodology will be made over time, the methods themselves already show great promise.

This set of tests is a relatively new method for large-scale testing of COTS devices as DOTs and other organizations are preparing for large V2I deployments in their jurisdictions. Future work will involve refinement of the testing process, but it could also include using these indoor and outdoor testing methods to determine other attributes of these devices over RF connections, such as resistance to interference and performance of different messages types.

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