Accepted for presentation in: IEEE Vehicular Technology Conference (VTC-Spring), Helsinki, Finland, April 2021.

SDR-based Open-Source C-V2X Traffic Generator for Stress Testing Vehicular Communication

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***Abstract*—Cellular-Vehicle-to-Everything (C-V2X) communication is an essential component of future automated traffic systems. As vehicular communication is safety-critical, C-V2X is designed to be reliable and highly scalable. To analyze the C-V2X communication performance in experimental setups, a huge number of communication nodes are necessary, and those large setups become complex and expensive, and creating repeatable results in these huge experimental setups is hard.**
In research, communication system independent software-based traffic generators are often used to analyze the scalability of a communication system. However, these traffic generators are limited by the restrictions of the underlying communication technology. In this work, a Software-Defined Radio (SDR)-based open-source C-V2X traffic generator is presented. The traffic generator allows repeatable scalability experiments using fewer communication nodes by creating valid C-V2X communication traffic that mimics multiple C-V2X communication nodes. Experimental results using commercial off-the-shelf (COTS) C-V2X modems show that the achieved results correspond to the expected behavior. In addition, these experimental results are compared to the simulation results of our C-V2X simulator. The comparison shows that if the C-V2X traffic generator limits the channel resources, the PRR does almost exactly match the simulation results. The proposed C-V2X traffic generator's functionality is further confirmed by the very small difference in the Packet Inter-Reception time of only 0.4 % for around 250 vehicles.

I. Introduction

Cellular Vehicle-to-Everything (C-V2X) communication is specially designed for reliable and scalable communication to cope with the requirements of vehicular environments. To evaluate the performance of C-V2X for critical scenarios such as an inner-city intersection with many vehicles, mostly simulations like provided in [1] are used. To evaluate high load scenarios in laboratory setups, a huge number of nodes or strict constraints of time-frequency resources are necessary, as by design, severe performance limitations of C-V2X will only occur at high utilization of the wireless channel. The C-V2X standard does not contain operation under limited resources, so commercial off-the-shelf (COTS) C-V2X modems do not support configurations with limited frequency resources. Therefore the performance evaluation of COTS C-V2X modems requires a large number of those modems resulting in large, complex, and expensive laboratory setups. A C-V2X traffic generator that mimics the behavior of C-V2X modems to add traffic to the wireless traffic channel

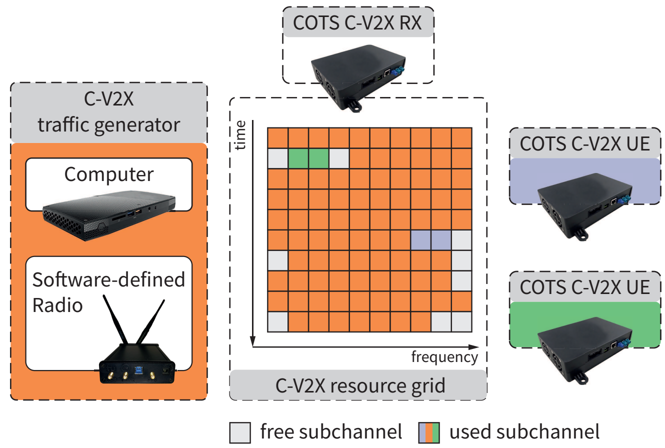


Fig. 1: System concept and experimental over-the-air setup using three COTS C-V2X UEs and the proposed C-V2X traffic generator. Note that one UE only acts as a receiver to not miss packages due to half-duplex conditions.

and, therefore, externally limits the available time-frequency resources can enhance those setups and reduce the number of modems necessary for performance evaluations. The system concept and experimental setup used in this paper is shown by Fig. 1
C-V2X communication is designed to take advantage of the periodic nature of cooperative vehicular communication (i.e., cooperative awareness messages, CAM). The sensing-based semi-persistent scheduling (SPS) algorithm for resource allocation uses control information that is transmitted by each UE to predict future resource usage and select transmission resources that are likely to be unused. The transmission of this control information is necessary to block resources as utilizing spectrum resources by random signals to limit the available resources externally will lead to artificial packet collisions that do not represent the actual performance of C-V2X communication in crowded scenarios. While the transmission of valid control information is important for the C-V2X traffic generator, the transmitted user-data can be filled with random bits. Also, precise time synchronization is vital for the C-V2X traffic generator. As C-V2X timing is based on GNSS (global navigation satellite systems), the traffic generator must include GNSS support to allocate valid subframes.
The creation of traffic for stress testing of communication

systems is often done by using application layer services such as iperf. However, as those applications are using the testing communication technology itself, the flexibility of the generated traffic is restricted by the communication technology. For C-V2X communication, for example, independent of the user traffic payload, the maximum channel usage is limited to one subframe every 20 ms. A complete usage of the spectrum resources will therefore need at least 20 COTS C-V2X modems. The SDR-based C-V2X traffic generator presented in this work creates the traffic on PHY-layer without restrictions of the transmission interval.

In this work, a Software-Defined Radio (SDR)-based open-source C-V2X traffic generator is introduced [1]. The software stack enhances the open-source LTE stack srsLTE [2]. PSCCH containing control information is transmitted to indicate used resources to COTS C-V2X modems to constrain the available time-frequency resources externally.

In the remainder of this paper, we build upon this motivation and explain the necessary basics and the underlying system design of the C-V2X traffic generator in Section II. Section III contains the experimental results of our C-V2X setup. Before concluding the paper in Section V, the experimental results are compared to simulations using our C-V2X simulator (Section IV).

A. Related Work

For traffic generators, software-based and hardware-based implementations exist. Specially designed hardware platforms are usually more precise and achieve better performance but are also more expensive, while software platforms are generally less precise but more flexible and cheaper or even open-source [3].

A software-based traffic generator is introduced in [4]. It is also compared to other software-based tools, but only the data rate is considered.

Another comparison of software-based traffic generators is presented in [5]. In contrast to [4] where a gigabit link is used for the comparison, the throughput over a 10 Gbps link is compared.

In [3] software-based packet-level traffic generators are analyzed and compared. Unlike the aforementioned research, multiple key performance indicators are analyzed. It is shown that software-based traffic generators suffer from internal and external interference. External interference is hereby defined as interference from other software processes on the same machine competing for processor resources, while internal interference is defined as interference between different tasks of the traffic generator such as time-stamping or calculations.

A distributed traffic generation for smart grid communication is presented in [6]. In an experimental setup, multiple traffic generators are used to analyze the behavior of the communication infrastructure and optimize an LTE cell for smart grid traffic.

[1] https://github.com/FabianEckermann/cv2x-traffic-generator

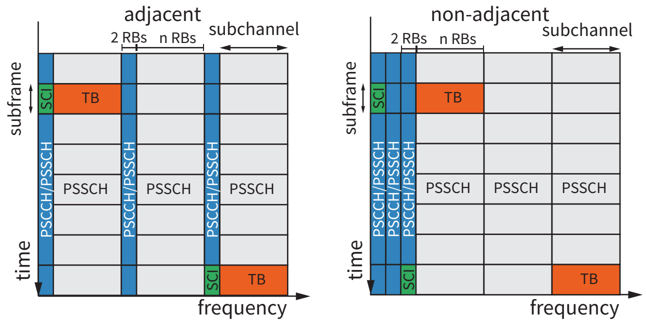


Fig. 2: C-V2X subchannelization schemes: Adjacent scheme (SCI and TB are transmitted in adjacent resource blocks) and Non adjacent scheme (resources are divided into PSCCH and PSSCH subframe pools).

All aforementioned traffic simulators are software-based and generate traffic on the packet-level. The C-V2X traffic generator presented within this work is hardware-based and creates traffic directly on the physical layer. This allows the traffic generator to violate the C-V2X standard by sending, for example, with a shorter transmission interval. This way, the traffic of multiple UEs is emulated.

As the C-V2X traffic generator uses an SDR as the radio front-end, it is also less expensive than COTS hardware traffic generators.

II. System Design

C-V2X communication is based on the Physical Sidelink Control Channel (PSCCH) and the Physical Sidelink Shared Channel (PSSCH), which are transmitted within the same subframe. In the frequency domain, the resources are organized in subchannels. Two subchannelization schemes have been defined, adjacent and non-adjacent mode (see Fig. 2), that are both supported by the C-V2X traffic generator. In adjacent mode, Sidelink Control Information (SCI) and user-data (Transport Block, TB) are transmitted in adjacent resource blocks (RBs). SCI always occupies the first two resource blocks of each subchannel, while the following TB can occupy several subchannels. In non-adjacent mode, the resource blocks are divided into pools, one pool for SCI and one for TB divided into subchannels, and the SCI pool resources are associated with TB pool resources.

As mentioned before, the transmission of a PSCCH that contains valid control information (e.g., SCI) is important for a C-V2X traffic generator. For C-V2X communication, SCI format 1 is transmitted in the PSCCH. The content of SCI format 1 is shown by TABLE I.

While the SCI is always Quadrature Phase Shift Keying (QPSK) modulated, the Modulation and Coding Scheme (MCS) transmitted within the SCI indicates the MCS of the PSSCH. However, as for the generation of C-V2X traffic the content of the PSSCH is dispensable, the MCS is hardcoded and the TB is filled with random data.

The 4 bit resource reservation value is derived from the resource reservation interval as defined in [7]. The *frequency*

TABLE I: SCI format 1 (32 bits)

PARAMETER	SIZE
priority	3 bits
resource reservation	4 bits
frequency resource location of initial transmission and retransmission	0-8 bits
time gap between initial transmission and retransmission	4 bits
modulation and coding scheme	5 bits
retransmission index	1 bit
reserved bits	7-15 bits

resource location of initial transmission and retransmission value is equal to the resource indication value (RIV) and describes the resources used for PSSCH transmission.
The RIV corresponds to a starting subchannel index $n_{\text{subCH}}^{\text{start}}$ and a length in terms of contiguously allocated subchannels ($L_{\text{subCH}} \geq 1$) [7]. It is calculated as follows:

$$\begin{aligned}&\text{if } (L_{\text{subCH}} - 1) \leq \lfloor N_{\text{subCH}}/2 \rfloor \text{ then}\\ &\quad \text{RIV} = N_{\text{subCH}}(L_{\text{subCH}} - 1) + n_{\text{subCH}}^{\text{start}}\\ &\text{else}\\ &\quad \text{RIV} = N_{\text{subCH}}(N_{\text{subCH}} - L_{\text{subCH}} + 1) +\\ &\qquad\qquad (N_{\text{subCH}} - 1 - n_{\text{subCH}}^{\text{start}})\end{aligned} \tag{1}$$

where N_{subCH} is the total number of subchannels in the resource pool.
The sensing-based SPS algorithm uses the transmission interval derived from the *resource reservation* field, as well as the *frequency resource location of initial transmission and retransmission* value of the SCI to select transmission resources that are likely to be unused.
The channel utilization of the C-V2X traffic generator presented in this work can be configured by a configuration file, that contains the starting subchannel index $n_{\text{subCH}}^{\text{start}}$ and the length in terms of contiguously allocated subchannels (L_{subCH}) for 100 subframes. These information is used to calculate the RIV and therefore the length of the PSSCH transmission. The transmission interval of each transmission is 100 ms so the 100 subframes are periodically send. It is important to note, that per subframe only one PSCCH and therefore only one transmission is send. However, as described before, the user-data can occupy several subchannel.
For the time synchronization of the C-V2X traffic generator, a Global Positioning System (GPS) module is added to the SDR so that transmissions can be aligned to the standardized subframe grid.

III. Experimental Results

To demonstrate the effect of the C-V2X traffic generator on C-V2X communication, the experimental setup as shown by Fig. 1 is used. A summary of the relevant C-V2X configuration parameters of this paper is depicted by TABLE II. An exemplary spectrum utilization of the experimental setup is shown by Fig. 3. It is shown that the COTS C-V2X UEs only utilize spectrum resources that are not allocated by the C-V2X traffic generator. For the validation results, the Packet

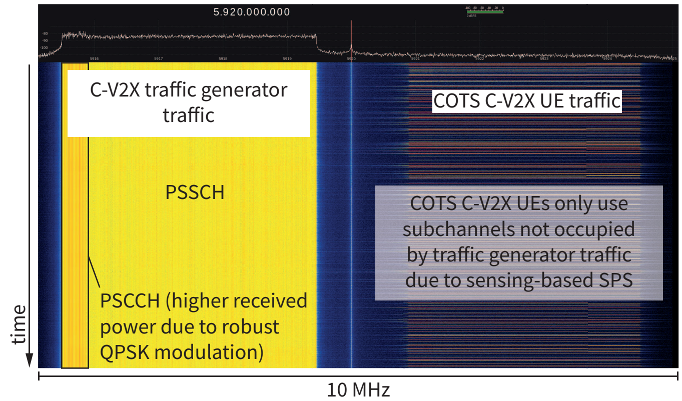


Fig. 3: Waterfall diagram of an exemplary spectrum utilization with C-V2X traffic generated by the C-V2X traffic generator and two transmitting COTS C-V2X UEs in the 5.9 GHz band. Note that the COTS UEs avoid spectrum utilized by the C-V2X traffic generator.

Reception Ratio (PRR) and Packet Inter-Reception (PIR) as specified in [8] are analyzed for different channel utilization of the C-V2X traffic generator given in percent of the maximum channel capacity.

- The PRR is calculated by X/Y, where Y is the number of transmitted packets and X is the number of successful packet reception among Y.
- The PIR describes the time between two successful receptions of two different successive packets transmitted from node A to node B.

For the distribution of the utilized resources by the C-V2X traffic generator, six different channel utilization schemes are used, as exemplarily shown by Fig. 4. The following parameters describe the channel utilization schemes:

- **contiguous subchannel**: If this is set, the resources are utilized such that as few subframes as possible are used, as all subchannels are contiguous.
- **contiguous subframes**: If this is set, all transmissions occur in contiguous subframes; otherwise, the subframes are shuffled.
- **random start**: The random start defines whether the starting subchannel index of the transmission is random.

Although the overall channel utilization is the same for each scheme, the amount of usable resources differs for transmissions that need more than one subchannel. This affects the impact on the C-V2X communication performance as shown for the communication reliability by Fig. 5.
In Fig. 5 the PRR of the two COTS C-V2X UE is measured for an increasing amount of channel utilization caused by the C-V2X traffic generator. As expected, for low C-V2X traffic

TABLE II: Validation parameters

C-V2X PARAMETERS	
sidelink frequency	5.9 GHz
sidelink channel bandwidth	10 MHz
resource blocks per subchannel	10

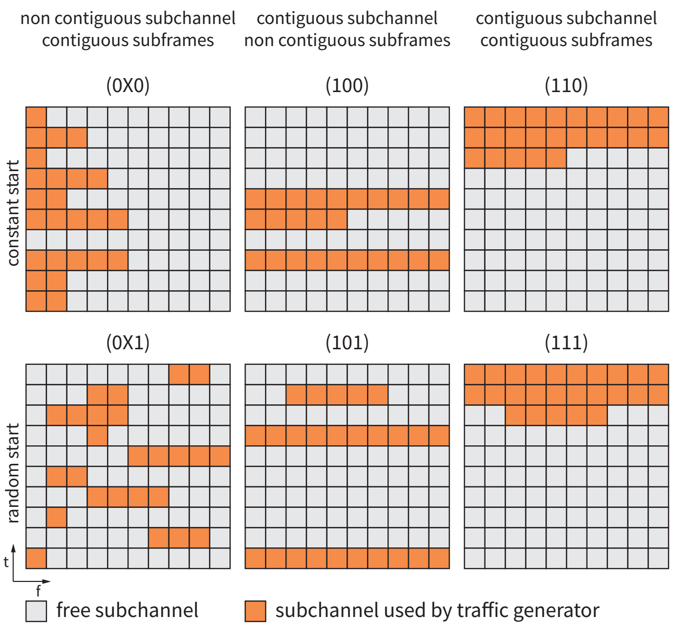


Fig. 4: Different C-V2X traffic generator configurations and the resulting channel utilization on an exemplary resource grid. The naming convention for the different configurations is based on their features, i.e., 100 translates to a configuration with contiguous subchannel, shuffled subframes, and aligned starting subchannel. Note that if the subchannels are not contiguous, the subframe order has no effect and is therefore marked with an X in the naming convention.

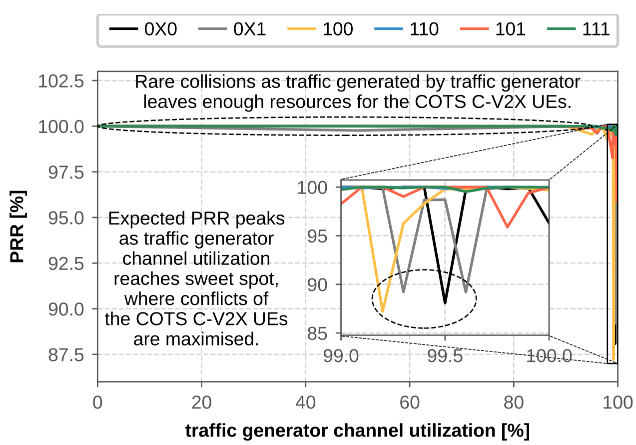


Fig. 5: PRR of the COTS UEs for increasing C-V2X traffic generator channel utilization. Note that only collisions between the COTS UEs are measured. Each measurement is based on more than 17.000 transmissions per channel utilization.

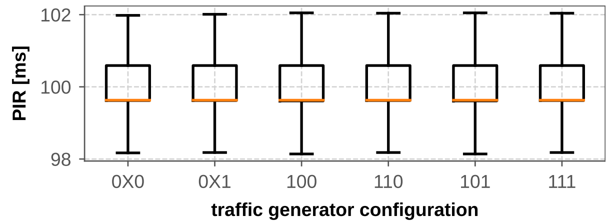


Fig. 6: PIR of the COTS UEs for the different C-V2X traffic generator configurations. For each measurement the results of all C-V2X traffic generator channel utilizations are combined (>300.000 transmissions per measurement).

generator channel utilization, the PRR is at around 100 %, as enough free subchannels are available for the COTS UEs, and therefore almost no collisions occur. However, for the most "random" channel utilization scheme (0X1), even at 50 % traffic generator channel utilization collisions occur, as due to the random channel utilization, the amount of sufficiently long contiguous subchannel might be low.

The sensing-based SPS standardized for C-V2X communication in [7] uses the average receive power of PSSCH transmissions that is lower than a given threshold to estimate free resources and randomly selects one of them for transmission. The number of free resources must hereby be at least 20 % of the available resources. To gather free resources, the receive power threshold is increased until the 20 % target is met.

This is also shown in the reliability results. If the traffic generator channel utilization is so high that the amount of free subchannel is not sufficient for the COTS UEs to select different resources, more collisions occur, and the PRR drops to around 90 %. This is the sweet spot, where the traffic generated by the traffic generator affects the communication as desired. If the traffic generator channel utilization is further increased, the PRR increases, as the transmission power of the SDR-based traffic generator is lower than the transmission power of the COTS UEs, and therefore the transmissions by the traffic generator are reused by the COTS UEs. The amount of collisions for this setup is limited, as collisions only occur if both COTS UE select resources at the same time, but for the sensing-based SPS, selected transmission resources are kept for a random number of transmissions, so concurrent resource reselections are rare. On the other hand, collisions remain until one of the UEs selects new resources.

For the more random channel utilization schemes (0X0 and 0X1), the PRR fluctuates more due to the random subchannel utilization.

The results of the PIR measurements are shown by Fig. 6. For the PIR analysis, all measurements from the previous reliability analysis are combined and grouped by their channel utilization scheme, resulting in more than 300.000 transmissions per group. It is shown that the PIR is not affected by the channel utilization scheme, and the median PIR is slightly below the 3GPP C-V2X PIR requirement of 100 ms defined in [9]. The maximum PIR is at around 102 ms, and the minimum PIR is at around 98 ms.

IV. COMPARISON TO SIMULATION RESULTS

To further evaluate the results achieved within this work, the results are compared to simulations using the C-V2X simulator presented in [1]. For the comparison, the PRR and the PIR metrics are used. To match the analysis metrics, the C-V2X traffic generator channel utilization is translated to a corresponding number of vehicles (N_{ue}) by:

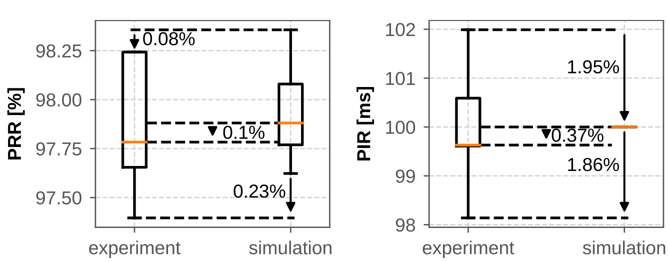
$$N_{ue} = T_{rrp} \frac{N_{subch}^{sl} U_{tg}}{N_{subch}^{tx}}, \tag{2}$$

where T_{rrp} is the resource reservation period in subframes, N_{subch}^{sl} is the number of sidelink subchannels, U_{tg} is the channel utilization of the traffic generator and N_{subch}^{tx} is the number of subchannels used per transmission.

The PRR comparison for 250 vehicles is shown by Fig. 7a. Since the PRR for low channel utilization is around 100 %, the focus of the comparison is on the effective number of vehicles, where the generated traffic provokes conflicts for the COTS C-V2X UEs. For the comparison, the C-V2X traffic generator results of the different configurations are combined, as for real-world measurements, all kinds of channel utilization schemes can occur. The combined PRR for the experimental setup is at around 98 % and almost exactly matches the simulation results. This shows that the proposed C-V2X traffic generator can realistically restrict the time-frequency resources of the wireless communication channel by valid C-V2X traffic.

In Fig. 7b the PIR of the traffic generator setup and the C-V2X simulator are compared. Opposed to the PIR results shown by Fig. 6 where the traffic generator channel utilization per traffic generator configuration are combined, here the traffic generator configurations per traffic generator channel utilization are combined. The combined median PIR is at around 97.75 ms. The PIR of the C-V2X simulation results is almost constant at 100 ms and, as shown in [1] only for the 0.1 % and 99.9 % quantiles, differences are visible. The difference between simulation and experimental results of less than 0.4 % again show that the results are plausible.

It must be noted that within this work, only two COTS C-V2X modems are used in addition to the C-V2X traffic generator. If the number of COTS C-V2X modems is increased, the scalability of the C-V2X communication can be further analyzed while still using fewer COTS modems compared to a setup without a traffic generator.



(a) Packet reception ratio. (b) Packet inter-reception.

Fig. 7: Comparison of the C-V2X traffic generator results and C-V2X simulator results from [1] (static scenario) for 250 vehicles. For the experimental results, more than 100,000 transmissions are evaluated.

V. CONCLUSION

In this paper, we presented an SDR-based open-source C-V2X traffic generator for stress testing vehicular communication. The C-V2X traffic generator creates valid C-V2X traffic to mimic a multitude of C-V2X communication nodes, so for example, a scalability analysis needs fewer C-V2X modems, whereby experimental setups become smaller, less complex, and less expensive. The experimental results prove that the presented C-V2X traffic generator works as expected. In addition, these experimental results are compared to simulations from our C-V2X simulator. It is shown that the PRR of the experimental results using the proposed C-V2X traffic generator almost exactly matches the simulation results if the resources are restricted. The functionality of the proposed C-V2X traffic generator is further confirmed by the minimal PIR difference of only 0.4 % for around 250 vehicles. In future work, we will further evaluate the C-V2X traffic generator using more C-V2X modems. In addition, we will use amplifiers to increase the transmission power of the SDR front-end to match the COTS C-V2X modems.

ACKNOWLEDGMENT

Part of this work has been supported by Deutsche Forschungsgemeinschaft (DFG) within the Collaborative Research Center SFB 876 “Providing Information by Resource-Constrained Analysis”, project B4.

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