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# Stress Test Of Vehicular Communication Transceivers Using Software Defined Radio

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**Abstract**—Wireless vehicular communication is, in contrast to other terrestrial types of wireless communications, more dynamic in nature. Both the transmitter and the receiver are moving at high speeds relative to each other, which generates highly dynamic wireless channels. Such channels are characterized by short stationarity regions and large Doppler spreads [1]. Modem manufacturers face a challenge when designing and implementing equipment for such environments. Similarly, for testing and evaluation real-life measurements with vehicles are required, which often is an expensive and slow process. This paper tackles this problem by proposing a method for stress testing transceivers based on the design and implementation of a real-time wireless channel emulator for wireless vehicular communications using a software defined radio (SDR). The emulator together with the proposed test methodology enable quick on-bench evaluation of wireless modems. In the paper we also apply the test on two different IEEE 802.11p modem implementations and characterize the packet error rate performance for different Doppler-delay combinations.

**Keywords**—Vehicle-to-Vehicle, Channel Emulator, Software Defined Radio, USRP

## I. BACKGROUND

Vehicle-to-Vehicle (V2V) communications have been introduced, and standardized (IEEE 802.11p, WAVE) [2], in order to reduce accidents and enhance the driving experience. The functionality is achieved by exchanging co-operative road safety, traffic efficiency and other general purpose messages [3] in an ad-hoc configuration in the 5.9GHz band using IEEE 802.11p wireless modems. A real-time wireless channel emulator for wireless vehicular communications based on a software defined radio (SDR) enables quick on-bench evaluation of such wireless modems while providing a high degree of reconfigurability. The SDR used in this paper is an NI USRP-2943R [4] equipped with 2 Radio Frequency (RF) chains and an Xilinx Kintex-7 Field Programmable Gate Array (FPGA) programmable in LabVIEW, which allows real-time 2x2 MIMO or 1x1 full-duplex SISO channel emulation. This paper describes a 1x1 SISO channel emulator as the standard IEEE 802.11p does not utilize MIMO technologies. A multiple antenna extension of the emulator is though straightforward. For vehicular transceiver characterization we also propose a stress test that allows for a straightforward evaluation of modem capabilities. The stress test focuses on three important capabilities of vehicular modems; the ability to handle large Doppler spreads, the ability to handle short signal outages (e.g. due to ground reflections) and the ability to handle large delay spreads. We implement this stress test and characterize two different modem implementations using this methodology.

Earlier work on channel emulation has been done by a few

companies. National Instruments has developed an example application for a real-time MIMO channel emulator based on a vector signal transceiver (VST) [5]. Nilsson et al. in [6] describe a Multipath Propagation Simulator (MPS) that simulates the wireless channel using multiple antennas, long fiber-optic delay lines and phase shifters. A demo of another channel emulator based on SDR has been presented by M. Gurcan in [7]. Furthermore, Spirent [8] and Anite [9] also provide commercial solutions for channel emulation. However, to the authors best knowledge, such a platform based on SDR has not been previously openly developed and evaluated in the academic community.

## II. DESIGN & IMPLEMENTATION

### A. Model

Assuming that the wireless channel for shorter time intervals can be seen as wide sense stationary, it can be modeled as a tapped delay line, where the coefficients multiplying the output from each tap vary with time [10]. The impulse response of the channel can be modeled as:

$$h(t, \tau) = \sum_{i=1}^N c_i(t) \cdot \delta(\tau - \tau_i), \quad (1)$$

where  $N$  is the number of taps,  $c_i(t)$  is the time-dependent complex coefficient and  $\tau_i$  is the delay of the  $i$ th tap. For the stress test we apply a special case of this channel: a two-tap channel where both taps have equal amplitudes but where the Doppler shift and delay of the second tap is varied while logging the packet error rate (PER). The complex coefficient for the second tap is given by:

$$c_i(t) = \alpha \cdot e^{j2\pi f_{D_i} t}, \quad (2)$$

where  $\alpha$  is the amplitude and  $f_{D_i}$  is the Doppler shift.

Two different IEEE 802.11p modem implementations have been evaluated by the channel emulator and the stress tests. Two modems, from now on denoted as modem group A, are early prototypes based on a modified IEEE 802.11a WiFi chipset, and therefore are not expected to perform optimally in a vehicular environment. The other two modems, from now on denoted as modem group B, are dedicated IEEE 802.11p modems and are expected to perform better. A two-tap delay line model,  $N = 2$ , was implemented on the FPGA of the SDR, where the first tap always remains at delay  $\tau_1 = 0$  ns and Doppler shift  $f_{D_1} = 0$  Hz. The second tap varies its delay in the range  $\tau_2 \in \{100 \dots 3400\}$  ns (corresponding to  $\{30 \dots 1020\}$  m) in 34 steps and its Doppler shift in the range  $f_{D_2} \in \{0 \dots 2000\}$  Hz (corresponding to  $\{0 \dots 366\}$  km/h) in 41

steps. Additionally, the amplitude is set to  $\alpha = 1$  for both taps, which generates a worst-case scenario. If the modems can manage such a scenario, they can manage weaker signals from the second tap as well, which serves as a reasonably good benchmark between different groups of modems. The ranges of the Doppler frequency shifts and delays were selected based on earlier studies and reasonable operation ranges in the parameter space. By moving the second tap to various points in the Doppler-delay domain, it is possible to log the packet error rate for each channel setting and characterize the modems' capabilities.

The choice of a two-ray channel with amplitude  $\alpha_1 = \alpha_2$  should be motivated. Two-ray channels are observed when there is a single strong reflection. In vehicular communications such a reflection may arise from the ground, a strong reflection from a bridge or a sign. In the case of a ground reflection, the Doppler shift of the second ray is expected to be  $f_{D2} \approx 0$  while the amplitude and delay are expected to be  $\alpha_1 \approx \alpha_2$  and  $\tau_1 \approx \tau_2$ , respectively. In the case of a strong reflection, e.g. from a sign, the Doppler shift of the line-of-sight (LOS) component is expected to be  $f_{D1} \approx 0$  for vehicles driving in convoy. However, the Doppler shift of the reflected ray  $f_{D2}$  is expected to be proportional to twice the speed of the vehicle. Meanwhile, the amplitude and delay of both taps are expected to be  $\alpha_1 \approx \alpha_2$  and  $\tau_2 \geq \tau_1$ , respectively. In case of a far reflection, the delay and amplitude are  $\tau_2 \gg \tau_1$  and  $\alpha_2 \ll \alpha_1$ , respectively in general, but with  $\alpha_2 \approx \alpha_1$ , as a worst case scenario that may arise when the LOS is blocked. All of these cases are covered using the approach in this paper.

### B. Overall System

The overall system consists of a laptop running LabVIEW, two modems and the SDR emulating the channel as shown in Fig. 1. A standard laptop with a PCI express card slot functions as the host computer, connecting to the SDR via an MXI cable. The host running LabVIEW is responsible for deploying FPGA bitfiles to the integrated FPGA and configures the RF-chains, i.e. sets active RF-chains, transmit power levels, received signal power reference levels, sampling rates, center frequencies and initializes active RF-chains. Furthermore, it is storing, post-processing and graphically displaying data from the SDR using target-to-host Direct Memory Access (DMA) First In First Out (FIFO) buffers.

The modems to be characterized are labeled as TX and RX, depending on if they act as transmitter or receiver. The TX modem is connected to one of the RF-chains, RF0, of the SDR with a 40 dB attenuator to prevent in the SDR. The signal is split to allow monitoring of the incoming signal using a spectrum analyzer. The received signal in the SDR is quantized to a 16-bit binary representation of In-Phase (I) and Quadrature (Q) components after the Analog-to-Digital Converter (ADC) and downconversion, as the ADC makes use of oversampling. Thereafter, the received signal is fed through the FPGA of the channel emulator. After channel emulation in the FPGA, the digital signal is upconverted and fed to the Digital-to-Analog Converter (DAC) to be transmitted through the other RF-chain, RF1, which is connected to the RX modem. The use of two separate RF-chains reduces leakage between receive and transmit signal tremendously, as the isolation between receiver

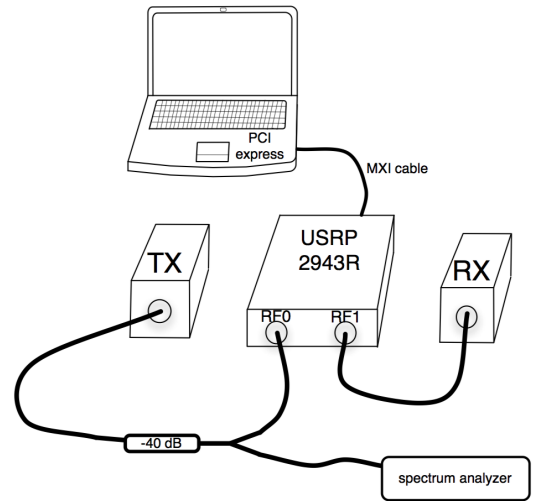


Fig. 1: The overall system including a laptop running LabVIEW, two modems under test and an SDR. The spectrum analyzer is used for monitoring purposes.

and transmitter on the same RF-chain is only 30 dB. A picture of the complete system can be seen in Fig. 2.

### C. Channel Emulation Core

Implementing a run-time configurable 2-tap delay line model on an FPGA-based SDR is achieved using a structure as shown in Fig. 4, where the input and output data are 32-bit complex values, consisting of 16-bit I and Q components, respectively. To move along the delay domain, an at run-time configurable varying length shift-register is used. Each tap delays the input by 100 ns, and as the branch to extract data from the shift register moves along the taps, relative delays from  $\tau_2 \in \{100 \dots 3400\}$  ns are achieved for the second tap whereas the first tap will not have any relative delay.

Movement in the Doppler domain is achieved by varying  $f_{D2} \in \{0 \dots 2000\}$  Hz in the complex exponential, eq (2), of the multiplier. Actual values to be used, are streamed from

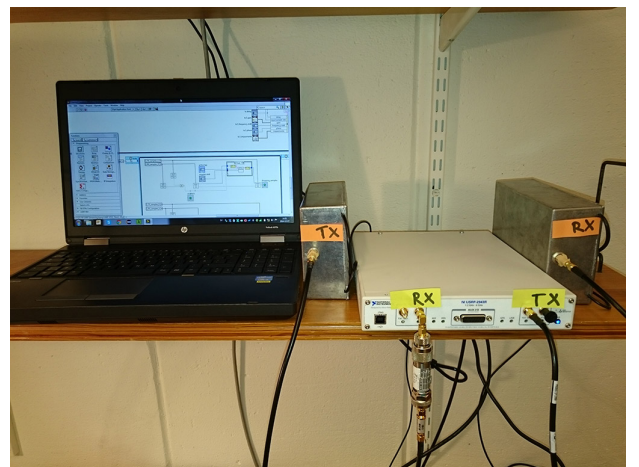


Fig. 2: The complete system operating on the bench.

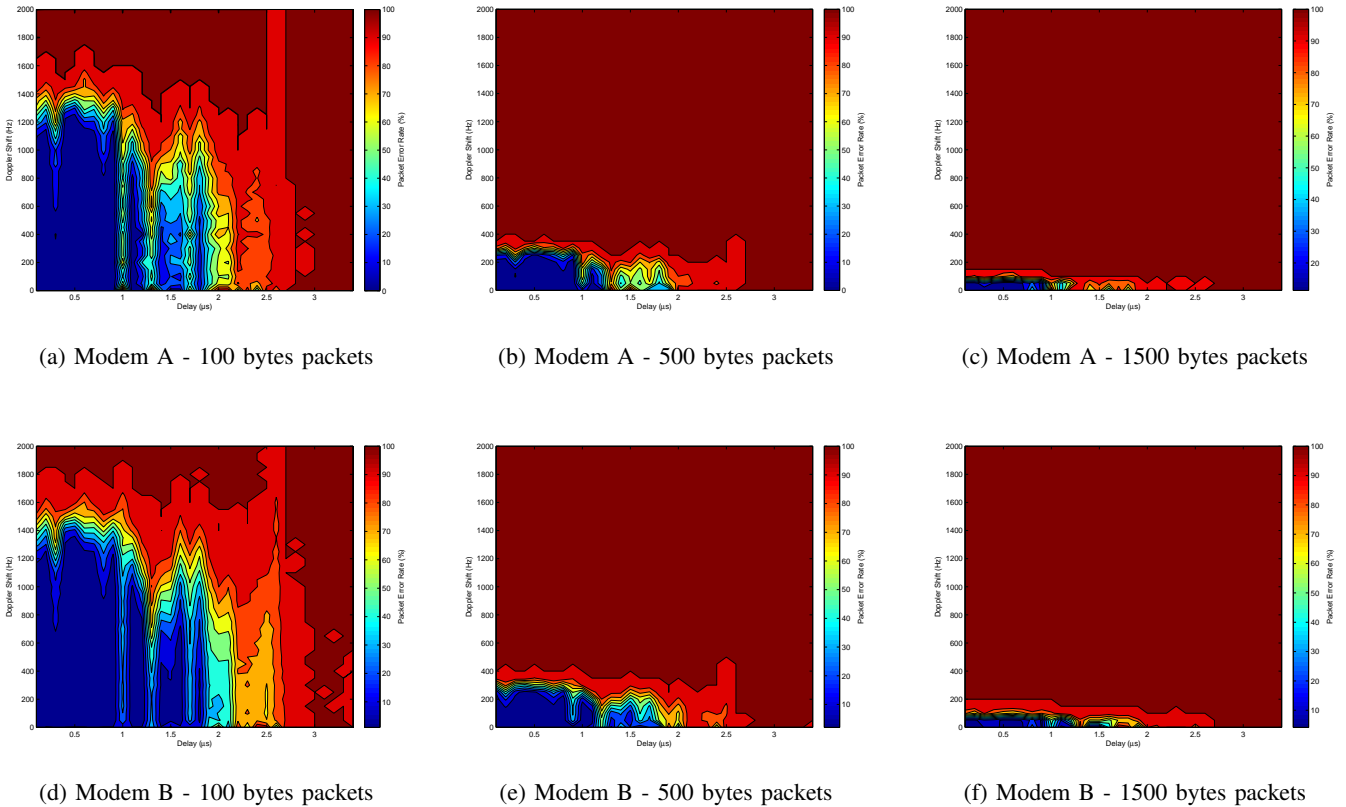


Fig. 3: Packet error rate for early prototype (A) and dedicated (B) IEEE 802.11p modems and different packet sizes. The early prototype modems were based on a modified IEEE 802.11a WiFi chipset.

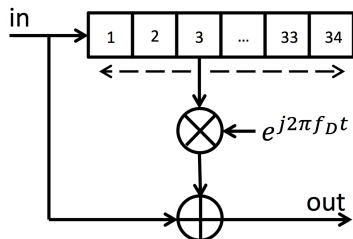


Fig. 4: Hardware implementation of a run-time configurable 2-tapped delay line model using a parameterizable shift register.

the host to the SDR using a host-to-target DMA FIFO during run-time.

Both signals, the first tap and the delayed, Doppler-shifted second tap are combined using a complex adder, efficiently implementing eq (1).

### III. STRESS TEST

The TX and RX modems to be characterized were connected as described above. For both sets of modems, once the channel emulator started emulating the channel, the transmitter (TX) started transmitting packets with sequence numbers and dummy payload. On the receiver (RX) side, the sequence numbers were collected and the packet error rate was calculated

based on the number of missing sequence numbers. Once the receiver monitored and stored the PER for a certain Doppler-delay combination, new channel parameters were loaded to the channel emulator and a new PER calculation was performed.

TABLE I: Test scenarios

Scenario nr	Modem group	Over-the-air packet size
1	Modem A	100 bytes
2	Modem A	500 bytes
3	Modem A	1500 bytes
4	Modem B	100 bytes
5	Modem B	500 bytes
6	Modem B	1500 bytes

The test scenarios of the two modem implementations, as specified in Table I, were evaluated in order to characterize the modems and examine the influence of different packet sizes on the packet error rate. In each scenario 200 packets per second were transmitted, resulting to a worst case utilization of

$$\frac{200 \text{ packets/s} \cdot 1500 \text{ bytes/packet} \cdot 8 \text{ bit/byte}}{6.0 \text{ Mbit/s}} = 40\%$$

of the link capacity, thus not congesting the link. Each channel configuration lasted 3 seconds. Therefore, 41 Doppler shifts · 34 delays = 1394 possible Doppler-delay combinations were evaluated in 3 s · 1394 combinations = 70 minutes for each scenario, which is a relatively fast evaluation time for on-

bench stress tests. Further measurement parameters are given in Table II.

TABLE II: Measurement parameters

Parameter	Value
Link capacity	6 Mbit/s
Center frequency	5.9 GHz
Emulated channel bandwidth	10 MHz
Sampling rate	40 MS/s
Resolution in the delay domain	100 ns
Resolution in the Doppler domain	50 Hz
Number of transmitted packets per channel	600

#### IV. RESULTS

The results of the stress test are shown in Fig. 3. Several observations can be made based on these results.

Firstly, the packet error rate increases with increased packet size which is quite intuitive since the channel estimates are based on the pre-amble in each packet; the larger the packets are the bigger time is required for transmission. However, increased packet size does not influence the packet error rate if the Doppler shift is  $f_{D2} \approx 0$  Hz, as expected.

Secondly, modem implementation B performs slightly better for increased Doppler shifts for delays above  $1 \mu\text{s}$ . However, with increased packet size that improvement becomes insignificant and both implementations of modems perform similarly.

Thirdly, the packet error rate for both modem implementations increases dramatically in the proximity of  $1.3 - 1.9 \mu\text{s}$  which coincides with the length of the IEEE 802.11p OFDM cyclic prefix of  $1.6 \mu\text{s}$  [11] (which corresponds to 480 m propagation delay).

Overall, the performance of both groups of modems decreases significantly with increased packet size. Generally acceptable good performance with a PER  $< 10\%$  is only achieved with small packet sizes.

#### V. CONCLUSIONS

A real-time wireless channel emulator based on a software defined radio (SDR) for evaluating the performance of modems for wireless vehicular communications using the 802.11p protocol has been proposed and implemented. Based on the implementation, a way of performing simple stress tests of modems for vehicular communication has been presented. Tests with both early prototype modems and dedicated vehicular modems have been performed and their packet error rate (PER) performance has been characterized.

Despite our expectations, the dedicated modems did not impose a significant improvement over the early prototype modems in the stress tests, only marginal improvements at higher delays were seen. Those improvements might had been larger, if the second tap was attenuated compared to the first tap. Both groups of modems performed well at smaller packet sizes. Thus, it may be concluded that safety critical messages should be kept as small as possible, without duplicated information. Unfortunately, that is not currently the case as information such as latitude, longitude, elevation,

speed and heading is duplicated in both the CAM [12] and GeoNetworking [13] layers of the Cooperative Awareness Message (CAM) packet.

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