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[1]Institute of telecommunications, Vienna University of Technology, Austria
[2]Telecommunications Research Center Vienna (FTW), Vienna, Austria
[3]Kapsch TrafficCom AG, Vienna, Austria
[4]ASFINAG Maut Service GmbH, Klagenfurt, Austria

Overview of an IEEE 802.11p PHY Performance Measurement Campaign 2011

V. Shivaldova[1], A. Paier[3], T. Paulin[2], G. Maier[1], P. Fuxjäger[2], A. Alonso[1], D. Smely[3], B. Rainer[4],C. F. Mecklenbräuker[1]

Gusshausstrasse 25/389
1040 Vienna
AUSTRIA
Phone: +43 1 58801 78923
Fax: +43 1 58801 978923
Email: veronika.shivaldova@tuwien.ac.at

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V. Shivaldova*, A. Paier‡, T. Paulin†, G. Maier*, P. Fuxjäger†, A. Alonso*, D. Smely‡, B. Rainer§, C. F. Mecklenbräuker*

*Institute of Telecommunications, Vienna University of Technology, Vienna, Austria

†Telecommunications Research Center Vienna (FTW), Vienna, Austria

‡Kapsch TrafficCom AG, Vienna, Austria

§ASFINAG Maut Service GmbH, Klagenfurt, Austria

Contact: veronika.shivaldova@tuwien.ac.at

***Abstract*—In this contribution, we describe the measurement campaign that has been carried out on September 2011 along the highway A4 near Vienna, Austria, in order to evaluate the performance of IEEE 802.11p in realistic traffic environments. During this measurement campaign we have performed infrastructure-to-vehicle (I2V), vehicle-to-vehicle (V2V) and multihop measurements with three different test platforms as an onboard unit (OBU). Moreover we have also fulfilled I2V performance comparison tests with different OBU antennas.**

I. Introduction

In recent years the idea of exchanging information between moving vehicles and road-side infrastructures has attracted significant attention as a tool for reducing accident fatalities and facilitating traffic flow. Based on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, vehicles will be able to retrieve information about their surrounding and even to take appropriate actions to secure the occupants, if an accident is forecasted. This technology offers a broad range of applications including public safety, traffic control and infotainment. However to provide robust and efficient vehicular communication as well as to carry through practical design of reliable V2V and V2I communication systems, a deep knowledge of the underlying rapid channel propagation behavior is required. Therefore, much effort has to be invested in experiments, either through simulations or real world.

Several research groups have considered vehicular communication aspects based on empirical measurement campaigns. Some of them were focused on the effects introduced by the antenna positioning, on the signal propagation performance. In [1] it has been shown that the mounting position of the roadside unit (RSU) antenna has strong influence on the reliability of vehicular communication channels. It turns out that the system efficiency can be greatly enhanced by means of mounting RSU antenna at a higher position, above all the driving vehicles. Moreover, in [2] different on-board unit (OBU) antenna positions were considered. The authors concluded that a rooftop position yields the best performance in terms of lowest error ratios. Besides the investigation of antenna mounting position, a variety of system parameters, such as packet length, data rate, driving lane and vehicle speed were explored. The authors of [3] observed a negligible impact of the vehicle velocity on the communication range, also when analyzing the effects with different packet lengths and data rates. Furthermore, they concluded that the packet length has no influence on the achievable range, whereas the frame success ratio (FSR) shows a very strong fluctuation for longer packets. The results of the measurement campaign presented in [4] show that higher-order modulation schemes yield a reduced communication range. Several authors focused on the investigation of the power-delay profiles and the delay-Doppler spectra from channel sounding measurements in realistic vehicular environments, such as urban, sub-urban, rural areas, freeways or highways, as presented in [5], [6], [7]. Impairments to the system performance of IEEE 802.11p based I2V and V2V communications introduced by tunnel environments were analyzed in [8] and [9].

In this contribution we present an overview of the recently performed vehicular measurement campaign, aimed to provide empirical values, which will help us to answer a broad range of relevant research questions. Using various OBU equipment we have performed I2V and V2V tests, and combination of both, resulting in the multi-hop tests. The rest of this paper is organized as follows: this section will be followed by a description of the measurement environment, specification of the deployed hardware and finally the design of the performed experiments. Section V provides some concluding remarks and outlines future research activities based on the collected measurement data.

II. Measurement Environment

The measurement campaign presented has been carried out on the highway A4 in Austria during September 2011, within the ROADSAFE project [10]. For I2V and multi-hop experiments we have installed five RSU transmitters, each equipped with two directional antennas. RSU antennas has been mounted on the highway gantries, such that the signal is equally radiated in both directions along the highway. The outmost RSUs are located 5.6 km apart. The distance between the first four RSUs has been chosen sufficiently large, so that their communication range do not overlap, while the communication range of the last two RSUs are intentionally overlapping. Exact positions of the RSUs and distances between them are summarized in Table I and shown on the map in Figure 1.

Fig. 1. Location of the RSUs along highway A4 (image source: Google Earth).

TABLE I
LOCATION AND DISTANCES BETWEEN THE RSUS.

RSU number	Latitude	Longitude	Distance to the next RSU
RSU1	48.166670	16.462694	2091 m
RSU2	48.154056	16.480135	1627 m
RSU3	48.147492	16.499415	1487 m
RSU4	48.142304	16.517775	598 m
RSU5	48.140295	16.522155	———

The part of the highway chosen for the experiments lies in the industrial area connecting the city of Vienna with the international airport of Vienna. This fact determines introduces three important characteristics of the measurement environment; considerably dense traffic, significant number of road signs and infrastructure units, but little vegetation in vicinity of the highway. Most of the highway track selected for measuring consists of three lanes, however there are some parts with two lanes only. Further important characteristic of the measurement environment, essential for signal propagation, is the noise protection wall on one side of the highway, starting exactly at the position of RSU3 and ending 120 m after the RSU5.

III. MEASUREMENT EQUIPMENT

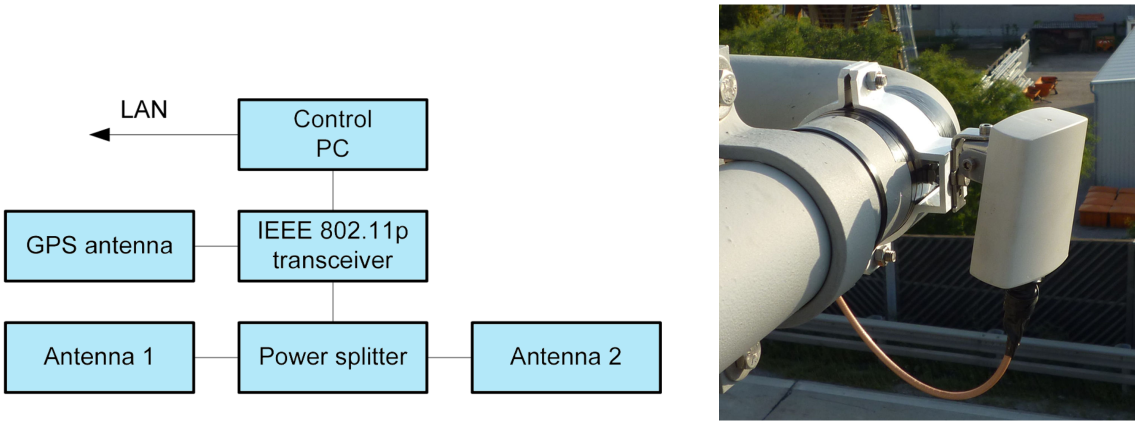
This section provides a detailed overview of equipment used in our measurement campaign, starting with the technical characteristics of the used RSU equipment and going through all the OBU receive platforms and antennas used.

Each RSU consists of an IEEE 802.11p standard compliant transceiver provided by Kapsch TrafficCom, two directional antennas, a personal computer (PC) for controlling the transceiver, connected over ethernet and protection units (e.g., protection against overvoltage). Further there has been a GPS receiver installed, in order to deliver a sync pulse to the transceiver. The radio front-end of the IEEE 802.11p transceiver is connected via a power splitter to two directional antennas, mounted in a height of approximately 7.1 m above the road and pointing into both directions of the highway. The antenna gain of each antenna is 14 dBi resulting in a equivalent isotropically radiated power (EIRP) of approximately 12 dBm. The azimuth- and elevation-angle of the antennas has been set such that all lanes in both directions are covered. The remote control of the RSU was ensured by an ethernet connection to the local area network, which is provided to the gantries on the road. For these physical layer tests the RSUs has transmitted frames in broadcast mode.

In each test of this measurements campaign, we have used three different OBU receiver platforms, namely: CVIS platform, V2X MIMO testbed, USRP testbed.

The *CVIS platform* is equipped with the CALM M5 radio module, implementing the IEEE 802.11p protocol, which allows rapid prototyping of cooperative V2V and V2I applications and is largely based on open-source software components. The CVIS prototype systems were provided by Q-FREE in the framework of the European CVIS project [11]. The objective of the CVIS project is to develop a harmonized technology for V2V and V2I communication, based on the international communications standard CALM, which provides interoperability between different car manufacturers and vehicular technologies. The radio module inside each CVIS node includes a GPS receiver, which constantly logs the exact position of the device. Throughout the measurements campaign we have used two nodes of the CVIS platform, one as receiver in the I2V, V2V and multi-hop tests, and the other as transmitter for the V2V tests.

The *V2X MIMO testbed* consists of two external signal generators designated as clock source for the radio frequency (RF) frontend and a standard PC equipped with a Digital Signal Processor (Texas Instruments TMS320C6416 DSP), a Field Programmable Gate Array (XILINX Virtex 5 XC5VSX50T FPGA) module from Sundance [12], and a mimoOn RF frontend [13]. Throughout the measurement campaign the V2X MIMO testbed was configured as follows. Automatic gain control (AGC), time and frequency synchronization with maximum ratio combining (MRC) were implemented on the FPGA. Further details on the used algorithms can be found in [14]. The down sampled and compensated data was transferred via a First In - First Out (FIFO) memory on the FPGA, SDRAM on the DSP module to the harddrive. Due to the limited memory size and slow transfer rate between the individual parts of the testbed, a non-continuous data stream was recorded to hard disc drive.



(a) RSU block diagram.

(b) RSU antenna mounted at RSU2.

Fig. 2. RSU antenna.

The USRP testbed consists of the following components: RF-frontends, analog-to-digital conversion units, a common reference clock and the storage host PC. As RF-frontends we used XCVR2450 daughterboards (designed and manufactured by Ettus Research) which are quadrature receivers based on the MAXIM2829 chip. As analog-to-digital conversion units we used four USRP N210 which host the RF daughterboards. They are equipped with two 14bit analog-to-digital converters each (Texas Instruments ADS62P45) running at 100MSPS and a digital half-band filter to decimate the sample-rate down to 25MSPS in order to be able to reduce the total data-rate so that it does not exceed 1 Gbit/s which is the bandwidth of the the Gigabit-Ethernet bus that is used to transfer the sample-stream to the host PC. In order to be able to coherently sample the four streams the four USRP N210 units were provided with a common reference clock: A GPSDO unit that generated 1PPS outputs (needed to time-stamp the baseband-samples) and four synchronized low-noise+12 dBm 10 MHz Sine-Wave Outputs which were required to get phase-lock the local oscillators (LOs) in the RF-frontends. As a host system we used a standard x86 PC equipped with a single Quad-Gigabit-Ethernet NIC and a quad-core GPCPU running at 2.8 GHz. Using a combination of RAM-disks and SSDs we were able to sustain the required aggregate bandwidth of 3.2 Gbit/s for more than 100 seconds without interruption (the maximum length one snapshot).

Receiver/transmitter OBU platforms were placed inside the test vehicle and connected to one of the following OBU antennas, as shown in Figure 3: CVIS vehicle rooftop antenna unit, surface mount OBU antenna, planar OBU antenna.

The *CVIS antenna pod* contains five individual antennas, for each of the different wireless access technologies: CALM M5, CALM 2G/3G, DSRC, WLAN and GPS. In our measurements, only the CALM M5 and GPS antennas were connected for signal reception and positioning, respectively. The CVIS antenna for CALM M5 communication is a vertically polarized double-fed printed monopole and has a radiation pattern close to isotropic, verified by measurements in [15].

The *surface mount antenna* is a wideband (1.7 - 6.0 GHz) antenna with omnidirectional radiation pattern, manufactured by 'Mobile Mark". Antenna performance is 5 dBi (peak gain) and has ground plane independent omnidirectional configuration. The antenna radome consists of plastic with a heavy metal base and threaded feed-thru. The bottom mounting plate is outfitted with a gasket for a watertight seal.

The *planar OBU antenna* radiates a vertically polarized field with an omnidirectional pattern, which could normally be obtained from a vertical monopole element. However, since a vertical monopole has a height of around one-fourth of a wavelength above the roof of the car, which is not aesthetically desirable, a novel design concept was used for this antenna. The design of the planar OBU antenna is based on electromagnetic equivalence between a vertical electric dipole and a horizontal magnetic loop, which are realized by a circular slot in the ground plane. The antenna is packaged into a molded plastic housing with integral magnets and can easily be installed on the vehicle roof.

While the CVIS vehicle rooftop antenna unit includes a built-in GPS antenna, which is directly connected to the receiver, we used an external GPS antenna for position logging in all tests with the surface mount OBU antenna and the planar OBU antenna.

For the set of experiments with the CVIS platform as receiver we mounted one of the above listed OBU antennas (a "Ford Galaxy") at the height of approximately 1.7 m on the roof of our test vehicle. For experiments with V2X MIMO and USRP testbeds we have used two or four surface mount antennas, respectively. In this case either all four antennas were placed on the outermost corners of the vehicle (a "Ford Focus") roof, or two of the OBU antennas were placed on the roof and the other two next to the side mirrors on both sides of the vehicle.

In addition we used two web cameras, installed in the front and at the back of the test vehicles, in order to precisely document the environment and traffic situation during each measurement.

(a) CVIS vehicle rooftop antenna unit. (b) Surface mount OBU antenna. (c) Planar OBU antenna.

Fig. 3. OBU antennas.

IV. Experiment Design

For I2V and multi-hop tests we have used the RSU equipment described in Section III. As transmitter for V2V tests we used a vehicle equipped with one node of CVIS platform connected to the CVIS rooftop antenna unit. In all experiments we have transmitted packets in broadcast mode with MAC service data unit (MSDU) packet of 500 byte in combination with a data rate of 6 Mbit/s, corresponding to QPSK subcarrier modulation schemes with code rate $1/2$. All measurements have been performed at 5900 MHz, with an approximate vehicle velocity of $80-100$ km/h. Each measurement with the same parameter setting (combination of the RSU and the OBU equipment) has been repeated at least three times. Further it is important to note that throughout this measurement no MAC layer functions have been enabled, i.e., there has been no uplink signaling of any kind.

During the measurement campaign the vehicles with the measurement equipment onboard maneuvered through realistic traffic. In I2V experiments the RSUs were transmitting constantly, while the OBUs were switched on just during the time intervals when we were approaching the expected coverage range. In most of our tests the RSUs with overlapping communication ranges (RSU4 and RSU5) were not simultaneously active, in order to avoid influence of possible collisions on the measured performance. However we have done several measurement runs where all RSUs were active and the incurred effects will be analyzed separately.

For V2V tests we have introduced and tested the following traffic scenarios:

- *Line-of-sight (LOS) scenario*: Test vehicles were driving on the same lane with average separation of 30 m and without other vehicles between the transmit and the receive antenna blocking the LOS.
- *Non-line-of-sight (NLOS) scenario*: Vehicles were driving on the same lane with an average intervehicle separation of 80 m. The LOS was blocked during the whole measurement by a truck and sometimes other vehicles passing between transmitter and receiver.
- *Overtaking*: In the beginning of this experiment vehicles were driving on the same lane, just as in the LOS tests. Afterwards the vehicle driving behind started an overtaking maneuver. During a short time interval the vehicles were driving side-by-side and finally the vehicle performing the overtaking returned back to the same lane. After the overtaking maneuver, vehicles were still driving in the same lane, but LOS was occasionally blocked by other vehicles, depending on the traffic situation.

In the multi-hop tests, source (RSU) was broadcasting messages, just as in case of I2V tests. In addition we had two OBU-equipped vehicles driving one behind the other. One of these vehicles acted as a relay and the other as a destination. The messages transmitted by the RSU were received at the relay and if possible at the destination (direct link). The only significant difference between relay and destination is that after receiving the message the relay decodes, processes and stores it, and after that encodes and forwards it to the destination (relay link), while the destination simply stores all received message. In order to be able to easily differentiate at the destination whether the received message was coming via the direct or the relay link the packet identifier (MAC sequence number) of the message forwarded from the relay remained unchanged, but the MAC address of the transmitting RSU was overwritten by the MAC address of the relay. The main idea of these measurements is to analyze the increase of the coverage range and the total throughput, introduced by using a multi-hop link instead of the single-hop link. For multi-hop tests we have done experiments with various distances between relay and destination and also changed the relative position of both vehicles to the RSU, such that in some tests the relay vehicle was driving ahead the destination vehicle, and the other way around.

V. Conclusions and Outlook

In this contribution we presented an overview of the recently performed measurement campaign at 5.9 GHz. The samples obtained with the V2X MIMO and the USRP testbeds are currently being analyzed in a postprocessing mode. Further we will analyze the influence of the OBU antenna mounting position on the overall system performance in both I2V and V2V types of communications.

The information collected with the CVIS receiver is currently being analyzed based on the following performance indicators: received signal strength indicator, FSR, throughput and coverage range. We will compare the link performance for the upcoming WAVE (wireless access for vehicular environments) technology for V2V communications in scenarios with LOS between transmitter and receiver, with LOS being occasionally blocked and without a LOS component. Based on the output of the first evaluations we plan to analyze statistical properties of V2V channels in terms of gap and burst distributions. These statistical values will be used to develop state-based models of vehicular channels, that could be a valuable input for future research in the field of vehicular communications.

Results of I2V measurements will be analyzed based on the same performance indicators as in case of V2V measurements. First of all we will compare performance of RSUs related to coverage range and achievable throughput. Since all RSUs were equally equipped, the comparison of their performance will allow us to analyze the influence of the environment around the highway (e.g., presence of the noise protection wall), road infrastructure and the RSU position on highway (e.g., situated around the curve as RSU1 and RSU2 or on the straight part of the highway as RSU3). Further we will compare impact of the used OBU antennas on the system performance.

As it has been shown in the results of our previous measurement campaigns [9] the connectivity in vehicular environments is almost immediately strongly degraded with loss of LOS between transmitter and receiver. Moreover it has been shown in [8] that the number of active nodes (vehicles), their position and size have a significant impact on network connectivity as well as the blocking probability of the wireless channel. In this context, the need for more sophisticated inter-vehicle networks arise, where arbitrary data can be transferred among vehicles and reliably disseminated within certain geographical regions with low latency. One possible way to disseminate information within a VANET (vehicular ad-hoc network) would be a one-to-all communication, where each vehicle that receives a message retransmits it to the neighboring vehicles. This insures lower blocking probability and guarantees that as many vehicles as possible receive the message. However for city scenarios or in highway traffic the intervehicle network is quite populated and by using a one-to-all communication concept the channel could easily be congested due to the big number of forwarders. Therefore, communication systems have to apply intelligent repeating mechanisms in order to prevent the network from being overloaded. The presented description of the measurement campaign is, to the best of authors knowledge, the first campaign, using multi-hop experiments in vehicular communications. Although in our experiments we had just a single relay link, measured data will provide us with the first estimate of coverage range and throughput extension, achievable by means of cooperative transmission techniques. This data will be definitely a valuable input for research activities in the fields of medium access control and dissemination algorithms. In our future work we will address the connectivity challenge in more detail.

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