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SOURCE:
[1]Institut für Nachrichten- und Hochfrequenztechnik, Technische Universität Wien, Vienna, Austria
[2]Department of Electrical and Information Technology, Lund University, Lund, Sweden
[3]Forschungszentrum Telekommunikation Wien (ftw.), Vienna, Austria
[4]Information Systems Lab, Stanford University, Stanford, USA
[5]Mitsubishi Electric Research Labs, Cambridge, USA

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Nicolai Czink[3,4], Charlotte Dumard[3], Fredrik Tufvesson[2],
Christoph F. Mecklenbräuker[1], Andreas F. Molisch[2,5]

[1]Institut für Nachrichten- und Hochfrequenztechnik
Gusshausstrasse 25/389
1040 Vienna
AUSTRIA
Phone: +43 1 58801 38951
Fax: +43 1 58801 38999
Email: apaier@nt.tuwien.ac.at

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[1]Institut für Nachrichten- und Hochfrequenztechnik, Technische Universität Wien, Vienna, Austria
[2]Dept. of Electric and Information Technology, Lund University, Lund, Sweden
[3]Forschungszentrum Telekommunikation Wien (ftw.), Vienna, Austria
[4]Information Systems Lab, Stanford University, Stanford, USA
[5]Mitsubishi Electric Research Labs, Cambridge, USA

apaier@nt.tuwien.ac.at

Parts of this TD were presented at the PIMRC'07 in Athens in September 2007, [1], and in the COST2100 TD(07)303, [2].

Abstract

This paper presents a description of an extensive vehicle-to-vehicle and vehicle-to-infrastructure channel measurement campaign conducted in the year 2007, in Lund, Sweden. We focused on 4× 4 multiple-input multiple-output (MIMO) measurements at a center frequency of 5.2 GHz with high Doppler resolution. One vehicle-to-vehicle measurement data set where the two vehicles are traveling in opposite directions on a highway is available for download from ftw.'s homepage *http://measurements.ftw.at/*. A description of *how to get access* and a detailed structure of these data is presented in this paper.

1 Introduction

Vehicle-to-vehicle (V2V) and Vehicle-to-infrastructure (V2I) (henceforth called V2X) communications are constantly gaining importance for road-safety and other applications. In order to design efficient V2X systems, an understanding of realistic V2X propagation channels is required, but currently, only few measurements have been published. In order to alleviate the current lack of measurement data, we carried out a V2X radio channel measurement campaign in the 5 GHz band in Lund, Sweden.

Three different scenarios, rural, highway, and urban, were investigated. First evaluation results from these measurements concerning the power-delay profile and the delay-Doppler spectrum can be found in [1], [2], [3], and [4]. In [5] and [6] we focused on the non wide-sense stationarity uncorrelated scattering (non-WSSUS) behavior of the V2V radio channel by investigating stationarity and coherence parameters. A novel geometry-based stochastic multiple-input multiple-output (MIMO) channel model is presented in [7] and [8].

The remainder of the paper is organized as follows: Section 2 gives a detailed description of the measurement setup, including channel sounder, antennas, and further equipment. In Section 3 the measurement vehicles are described. The measurement practice is explained in Section 4 followed by the measurement scenarios in Section 5. In Section 6 the file structure of the measurement data, which is available for download is explained.

2 Measurement Equipment

2.1 Channel Sounder

The measurements were done with the RUSK LUND channel sounder, manufactured by the company MEDAV, that performs MIMO measurements based on the “switched-array” principle [9]. The transmitted signal is generated in the frequency domain, based on a broadband periodic multi-frequency excitation, in order to guarantee a pre-defined spectrum over the whole bandwidth, and approximately a constant envelope over time. The input signal at the receiver (Rx) is correlated with this transmitted signal in the frequency domain resulting in the specific transfer functions. The transmitter (Tx) and Rx were synchronized via Rubidium clocks for accurate frequency synchronism and a defined time-reference. In this measurement campaign we used a center frequency of 5.2 GHz. Using the RUSK LUND channel sounder we were able to use a very high measurement bandwidth of 240 MHz, which results in an intrinsic delay resolution of $\Delta\tau = 4.2\,\text{ns}$. The test signal length, also called maximum delay, was set to $3.2\,\mu\text{s}$, which is equal to a maximum propagation path length of 959 m. For the measurements we used the maximum transmit power of 27 dBm.

In this measurement campaign we focused on time-variant channels. To achieve a high Doppler resolution, we had to choose the snapshot repetition rate properly. The snapshot time, i.e. the time over all $P = 16$ temporal multiplexed channels, is equal to $2 \times 4 \times 4 \times 3.2\,\mu\text{s}= 102.4\,\mu\text{s}$, where the factor 2 stems from the guard interval between consecutive snapshots used by the sounder. To obtain feasible file sizes but still allow for sufficient measurement time and high Doppler resolution, we set the snapshot repetition rate to $t_{\text{rep}} = 307.2\,\mu\text{s}$. Using $N = 32500$ snapshots, we could continuously measure for 10 s recording a file of 1 GB for each measurement. The maximum Doppler shift for a time-invariant channel can be calculated with

$$\nu_{max} = \frac{1}{2 \cdot t_{\text{rep}}}. \tag{1}$$

With these settings, the maximum resolvable Doppler shift is equal to 1.6 kHz, which corresponds to a maximum speed of 338 km/h.

As mentioned above the channel sounder yields the complex transfer functions

$$H(nt_{\text{rep}}, k\Delta f, p). \tag{2}$$

Such a transfer function imported into Matlab would have an overall array size of $32500 \times 769 \times 16$ ($N \times K \times P$). For calculations in Matlab, only parts of this matrices can be used, because of working memory limitations. With 769 frequency bins over 240 MHz the achieved frequency spacing is $\Delta f = 312.5\,\text{kHz}$. In (2), n is the time index, from 0 to $N - 1$, k is the frequency index, from 0 to $K - 1$, and p is the channel number, from 1 to P. Tab. 1 gives an overview of the main measurement parameters.

2.2 Antennas

On both link ends we used elements from uniform circular arrays of microstrip antennas. Fig. 1 shows the two antenna arrays. Each array consists of a circle (the Rx array consists of 4 circles) of 16 dual-polarized elements, from which we selected 4 symmetrically placed, vertically polarized elements. With the reference bearing 0° (as seen from a top view of the arrays) being in the direction of driving, the selected antenna elements were directed at 45°, 135°, 225°, and 315°. The directions of the main lobes of these elements were the same for both measurement vehicles and are described in Fig. 2. Each antenna array was mounted on top of a stack of Euro pallets, which, when mounted on the vehicle's platform, provided a total antenna height of 2.4 m above the ground (see Fig. 5). Tab. 2 presents the allocation of the channel numbers to the antenna elements.

Table 1: Measurement configuration parameters.

Center frequency, f_c	5.2 GHz
Measurement bandwidth, BW	240 MHz
Delay resolution, $\Delta\tau = 1/BW$	4.2 ns
Frequency spacing, Δf	312.5 kHz
Transmit power, P_{Tx}	27 dBm
Test signal length, τ_{max}	3.2 μs
Number of Tx antenna elements, M_{Tx}	4
Number of Rx antenna elements, M_{Rx}	4
Snapshot time, t_{snap}	102.4 μs
Snapshot repetition rate, t_{rep}	307.2 μs
Number of snapshots in time, N	32500
Number of samples in frequency domain, K	769
Recording time, t_{rec}	10 s
File size, FS	1 GB
Tx antenna height, h_{Tx}	2.4 m
Rx antenna height, h_{Rx}	2.4 m

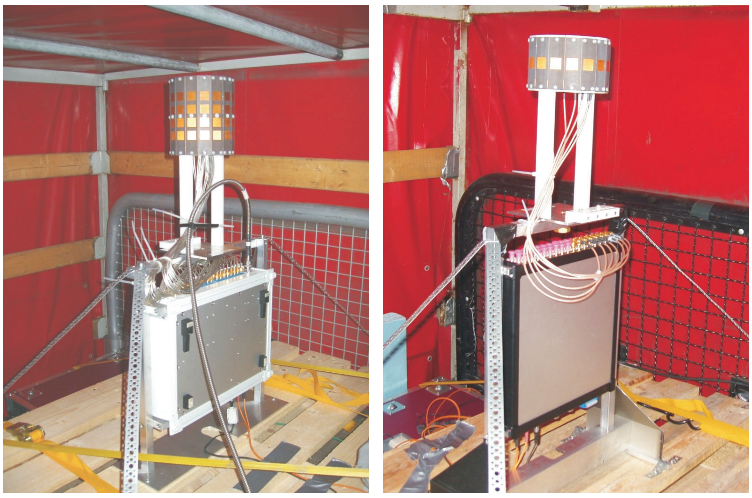


Figure 1: Antenna arrays — left Rx, right Tx

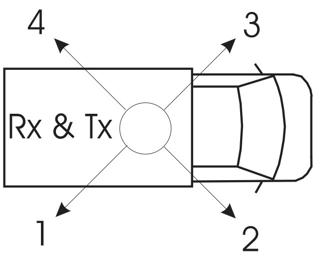


Figure 2: Direction of the main lobes of each antenna element for Rx and Tx

2.3 Route Documentation

To document the routes and scenarios during the measurements (traffic, weather, environment) we used two video cameras. Each camera was equipped with a fisheye lens, in order to capture a

Table 2: Allocation between antenna elements and channel numbers

Rx element	**Tx element**	**Channel number**
1	1	1
2	1	2
3	1	3
4	1	4
1	2	5
2	2	6
3	2	7
4	2	8
1	3	9
2	3	10
3	3	11
4	3	12
1	4	13
2	4	14
3	4	15
4	4	16

Figure 3: Laser distance meter and video camera for documentation

field of view of about 150°. One camera was placed in the passenger compartment of the vehicle containing the Tx. The other camera was mounted in the back of the Rx transporter, where the vehicle's tarpaulin was opened at the back.

Global Positioning System (GPS) position data was directly available from the Tx and Rx of the channel sounder at a rate of one position sample per second. Moreover, we used one additional GPS system in order to record the actual speed of the Tx vehicle. This GPS system also provided a real-time display of the actual vehicle position.

In order to obtain a more accurate measurement of the distance between the vehicles, we also used a laser distance meter LD90-3100HS from Riegl Laser Measurement Systems GmbH. It was programmed such that it supplied the actual distance every 100 ms (and in some measurements every 200 ms). Fig. 3 shows the laser distance meter and one of the video cameras, which were mounted together on a monopod.

Figure 4: Measurement vehicle

Figure 5: Loading spaces with the measurement equipment — left Rx, right Tx

3 Vehicles

As measurement vehicles, we used two VW LT35 transporters (similar to pickup trucks), which are depicted in Fig. 4. The loading platform of the transporters were covered with a plastic tarpaulin to protect the measurement equipment and antennas against air stream (and possible rain), thus providing greater stability for the antennas. Since the height of the tarpaulin cover is larger than the driver's cabin, the antennas could be mounted on the loading platform in such a way that they could "see" over the driver's cabin (though we cannot exclude the possibility that waves reflected from the road, and thus arriving from an elevation angle smaller than 0 degree, might have been attenuated by the driver's cabin). Fig. 5 presents the measurement vehicles containing the channel sounders, batteries, and antennas placed on the loading space.[1]

[1]battery lifetime of the Rx equipment was extended by means of a petrol-driven power generator, which was also mounted on the loading space.

4 Measurement Practice

The measurement campaign was conducted during three days, and a total of 141 measurement runs were recorded.

In the Rx vehicle, one person acted as driver, another one controlled the channel sounder, and the third person wrote the measurement protocol. The Tx vehicle was steered by one driver, another person controlled the additional GPS-system and the laser distance meter with a laptop. The third person was responsible for the video documentation and pointing the laser distance meter onto the Rx vehicle using a telescope.

The laser distance meter was only used for V2V measurements in same direction. In this case the Tx vehicle followed the Rx vehicle. Consequently it was also possible to hold approximately the same distance between the vehicles during the measurement runs. Communication between the two vehicles was handled through walkie-talkies operating at a frequency of 446 MHz.

5 Measurement Scenarios

Three different scenarios, rural, highway, and urban, were measured. Satellite photographs of the scenarios can be found in [1] and [2].

In each scenario we carried out two kinds of V2V measurements: with the two measurement vehicles driving in (i) the same, and (ii) opposite directions. Vehicle speed and the distance between the vehicles was varied between different measurement runs in the range of $30 - 110\,\text{km/h}$ and $30 - 130\,\text{m}$, respectively. In the highway scenario, we also carried out V2I measurements, where the Tx was placed on a bridge above the road.

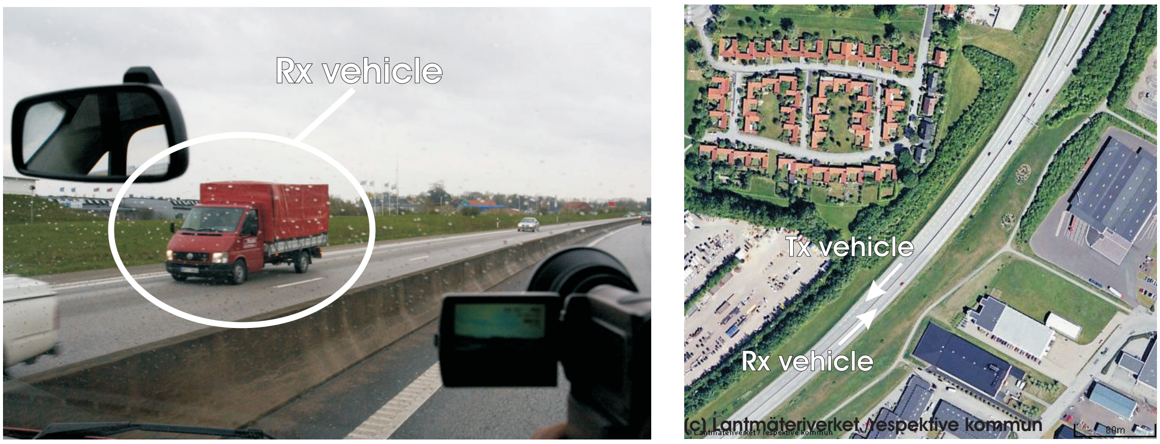
The measurement data that is offered for download is taken from one especially selected measurement run, where the vehicles were traveling in opposite directions on the highway E22 in the East of Lund. Each vehicle was traveling with a speed of about 90 km/h, which results in a relative speed of 180 km/h between the two vehicles. There was medium traffic on the highway (approximately 1 vehicle per second). Fig. 6(a) shows the Rx vehicle traveling on the opposite lane just before the vehicles were passing. The satellite photo of the highway scenario, Fig. 6(b), indicates that the Tx vehicle was heading in southwest direction while the Rx vehicle headed northeast. In the considered 10 s measurement run the two vehicles were passing after 7.5 s. In order to clarify the allocation between the channel numbers and the antenna elements from Tab. 2 the scenario in the case where the vehicles are approaching is depicted in Fig. 7.

6 File Structure

As mentioned in Chapter 2.1 the recorded file size in the MEDAV-format is 1 GB. We provide the measurement data in a standard Matlab-format [11] after using special import filters from MEDAV. After using this import filters the measurement data has a size of 6 GB. The Matlab array has 3 dimensions corresponding to following values

$$[Snapshots\,in\,time \;\times\; Frequency\,samples \;\times\; Channel\,numbers]. \tag{3}$$

The overall array would have a size of $32500 \times 769 \times 16$. Since there occur problems by importing such huge files in Matlab we divided the whole array in several manageable arrays. Each of the 16 channels is divided in 4 pieces over time which results in 64 separated files with a file size of approximately 95 MB. The first file of channel 1 (*V2V_Highway_ch1_1.mat*) covers the first 2.5 s of the transfer function, the second file of channel 1 (*V2V_Highway_ch1_2.mat*) covers the transfer



(a) (b)

Figure 6: (a) Photo of the highway from the passenger compartment, (b) satellite photo of the highway E22 in the east of Lund (source [10])

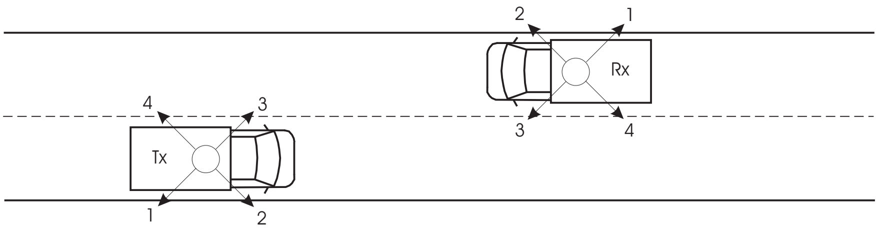


Figure 7: Antenna element direction of the main lobes in the case of approaching vehicles

function from 2.5 s until 5 s of the measurement run, and so on. Each file contains an array with the dimensions 8125×769.

7 Summary

The measurement data described in this paper is available for download at ftw.'s homepage *http://measurements.ftw.at/* under the following conditions:

- The data on this page may be used by anyone who has registered to our homepage, but only for scientific purposes.
- It is not allowed to share the data with third parties or any other subject that has not registered to our homepage.
- Within an affiliation the data may be shared with other employees who have registered to our website. The data must not be downloaded by each employee individually.
- The data is handed out without any support or guarantee.
- Any publication that uses at least parts of the measurements has to reference this paper, one of the papers mentioned on the homepage, and the URL of the homepage itself where the data can be found (*http://measurements.ftw.at/*).
  In addition a copy of the paper has to be sent to *measurements@ftw.at*

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