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Published in:
[Host publication title missing]

2010

Overview of Vehicle-to-Vehicle Radio Channel Measurements for Collision Avoidance Applications

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***Abstract*—In this paper we present an overview of a vehicle-to-vehicle radio channel measurement campaign at 5.6 GHz. The selected measurement scenarios are based on important safety-related applications. We explain why these scenarios are interesting from the aspect of radio propagation. Further we describe the power-delay profile and the Doppler spectral density of two situations especially suitable for collision avoidance applications: A traffic congestion situation where one car is overtaking another one, and a general line-of-sight obstruction between the transmitter and the receiver car. The evaluations show that in these situations the radio channel is highly influenced by the rich scattering environment. Most important scatterers are traffic signs, trucks, and bridges, whereas other cars do not significantly contribute to the multipath propagation.**

I. Introduction

Vehicle-to-vehicle (V2V) communications systems have recently drawn great attention, because they have the potential to reduce traffic jams and accident rates. V2V communications have also gained more importance because of the European committee decision on the harmonised use of the $5875-5905$ MHz frequency band for safety-related applications of intelligent transport systems (ITS) [1]. Examples of such applications include [2]:

- collision avoidance,
- emergency vehicle warning,
- hazardous location notification,
- wrong-way driving warning,
- co-operative merging assistance,
- traffic condition warning,
- slow vehicle warning, and
- lane change assistance.

The simulation and performance evaluation of existing systems like IEEE 802.11p, as well as the design of future, improved systems, requires a deep understanding of the underlying propagation channels. For this reason several V2V measurement campaigns have been conducted in recent years, see [3] for an overview. There are however, as pointed out in [3], a lack of knowledge in several aspects. First, most measurements conducted so far have been done with the transmitter (Tx) and receiver (Rx) cars driving either in convoy, or in opposite, parallel directions. The results of such investigations do not necessarily apply to many safety-critical V2V applications, e.g., collision avoidance in intersections, traffic congestions or when vehicles enter highways on entrance ramps. Second, few measurements have been conducted with an antenna mounting that is realistic from a car manufacturers point of view. The usual way of conduct is by using a ”regular” antenna array in an elevated position. Third, the impact of vehicles obstructing the direct path between Tx and Rx as well as the possible gains of using multiple antenna elements at Tx and/or Rx has been little explored.

In order to address these issues, and perform a realistic characterization of propagation channels for safety-related ITS applications a measurement campaign, called DRIVEWAY, was conducted in 2009. The key features of the measurements are the following:

- Measurements performed in traffic situations that are of particular interest for safety-related ITS applications, such as intersections, traffic congestion and merge lanes ([2], [4], [5])
- Realistic antennas, especially designed for vehicular usage and realistic antenna mounting
- Investigation of important propagation mechanism such as line-of-sight (LOS) obstruction
- Investigation of multiantenna benefits

This paper presents an overview of the measurement campaign, by describing the covered scenarios and discussing their properties from a propagation point-of-view. We also give a more detailed evaluation of two specific collision avoidance scenarios: a traffic congestion and a highway measurement where the LOS path of the radio signal is obstructed.

II. Measurements

A. Measurement Equipment

The measurements were performed using the RUSK LUND channel sounder that performs multiple-input multiple-output (MIMO) measurements based on the “switched-array” principle [6]. The channel sounder provides the sampled transfer function $H[m,q]$ with discrete time index m and discrete frequency index q. We were measuring with a bandwidth of 240 MHz at a center frequency of 5.6 GHz. This center frequency was the highest allowed by the channel sounder and

978-1-4244-2519-8/10/$26.00

considered close enough to the allocated $5.9\,\mathrm{GHz}$ frequency band for ITS in Europe for no significant differences to be expected. The transmit power was set to $27\,\mathrm{dBm}$, and the adjustable test signal length $3.2\,\mu\mathrm{s}$. The temporal sampling as well as time duration of the measurements were set for different measurements depending on specific conditions such as (Tx/Rx) car speed, but were on the order of hundreds of μs and $10 - 20\,\mathrm{s}$, respectively. Application-specific antenna modules were designed, [7], and integrated into the conventional mounting position for roof-top antennas on the rear part of the vehicles that we used (custom Volkswagen Tourans), see Fig. 1. Identical antenna modules were used for the Tx and Rx cars. Each antenna module consists of a four-element uniform linear array (ULA) with an interelement spacing of $\lambda/2$, see Fig. 2. The array consists of circular patch antennas that are excited in a higher-operational mode yielding terrestrial beam patterns with vertical polarization. To enable (future) directional estimation of the measurement data, the ULA orientation was chosen perpendicular to driving direction (thus implying a 90-degree rotation of the conventional antenna housing). Calibrated in-situ antenna measurements were taken in a large automated antenna measurement facility. Figure 3 shows the Rx unit of the channel sounder packed into the trunk of the car.

The vast majority of the measurements were 4×4 MIMO measurements. However, since the allowable sample rate of a switched-array system depends on the number of measured links, we also carried out a number of single-input single-output (SISO) measurements in order to sample the radio channel as fast as possible. The corresponding maximum resolvable Doppler shifts were $1.6\,\mathrm{kHz}$ (MIMO) and $78\,\mathrm{kHz}$ (SISO), respectively.

Fig. 1. The conventional antenna housing of a Volkswagen Touran.

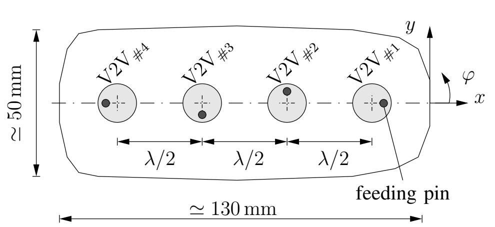

Fig. 2. Block diagram of the ULA. The driving direction is along the y-axis.

Fig. 3. The Rx car.

B. Measurement Scenarios

The following scenarios of importance for safety-related ITS applications were measured:

- **Road crossings**: The speciality of road crossings is that the LOS contribution of the radio signal between two cars approaching it (from perpendicular directions) may be obstructed for long durations. Thus, the success of a V2V link depends on the availability of other propagation paths, such as reflections from nearby buildings. To investigate the quality of such links and the importance of additional scatterers, we let the Tx and Rx cars approach four different four-way intersections from perpendicular directions:
  - Open area intersection: This suburban scenario is characterized by little to no buildings next to intersecting roads. No severe LOS obstruction is expected but the traffic situation is busy.
  - Obstructed LOS without surrounding buildings: The LOS path is blocked by a building until the cars meet in the intersection, but there are no buildings on the other sides of the intersection. There is no traffic, and we thus expect few additional scatterers to provide additional propagation paths.
  - Obstructed LOS with surrounding buildings and single-lane streets: There are buildings and parked cars on all sides of the intersection; these are expected to provide additional propagation paths. There is little traffic and no traffic lights.
  - Obstructed LOS with surrounding buildings and multi-lane streets: Similar to previous scenario, but with a larger intersection. There are traffic lights, busy traffic and each two-lane street has turn lanes (for left turns). Many additional propagation paths are expected, though their lifetime (visibility) may be short.
- **Merge lanes**: Similar to road crossings, an important aspect of this scenario is the possibility of an obstructed LOS path. These measurements were conducted with the Rx car driving on a highway whereas the Tx car was entering it from an entrance ramp.

- **Traffic congestion**: Traffic congestions are interesting due to their large number of involved vehicles, usually at low to zero speed. These radio links may thus be subject to LOS obstruction. It is also of interest to find out how many of the available scatterers (cars) that actually contribute to the received signal. We performed measurements for different congestion situations, such as when both cars are stuck in one, when one car stuck in congestion is overtaken by the other one, or when one car is approaching congestion where the other car is stuck.
- **Tunnel**: Tunnels potentially provide rich scattering environments, and we thus expect a more dense impulse response from these measurements that were conducted in the tunnel (following the Öresund bridge) between Denmark and Sweden. Both cars were driving in the same direction with different distances and a varying number of cars in between.

We also carried out an additional scenario, with no particular safety-application in mind: general LOS obstruction. The intention was, as pointed out in Sec. I, to alleviate the gap of general knowledge regarding V2V propagation channels. The goal of this scenario is to, in a controlled way, analyze the impact of an appearing/disappearing LOS path on the received signal. The measurements are conducted with both cars driving in the same direction on a highway, positioned such that trucks or other large vehicles are blocking the LOS during parts of each measurements. Ten to twenty measurement runs were made within each scenario, resulting in a total of about 140, which implies recording of more than 5 million MIMO impulse responses.

III. Measurement Results

In this section we give a thorough analysis of two selected measurements and analyze the contributing propagation paths in detail.

The results are derived according to the following: In vehicular communications the observed fading processes are non-stationary. Since we can assume that the process is stationary for a given period in time, which is labeled with the variable k, it is meaningful to represent its power spectral density as a function of time. In this sense, we compute an estimate of the local scattering function $\hat{C}_H[k;p,n]$ as in [8], which will allow us to calculate the time-variant power-delay profile (PDP) and Doppler spectral density (DSD). The ranges of the delay n and Doppler shift p are $\{0,\ldots,N-1\}$ and $\{-M/2,\ldots,M/2-1\}$ respectively, with $N = 256$ and $M = 128$. The absolute time m and the time index of the stationary region k are related by $m = Mk + m'$, where $k = 0\ldots\lfloor S/M\rfloor - 1$ and $m' = 0\ldots M-1$. The time-variant PDP

$$PDP[k;n] = \sum_{l=1}^{L}\sum_{p=-M/2}^{M/2-1} \hat{C}_H^{(l)}[k;p,n], \qquad (1)$$

and time-variant DSD

$$DSD[k;p] = \sum_{l=1}^{L}\sum_{n=0}^{N-1} \hat{C}_H^{(l)}[k;p,n], \qquad (2)$$

are obtained by summing the PDPs and the DSDs of all measured MIMO links $l = 1\ldots L$, with $L = 16$. In this paper we evaluate the PDP and DSD of two different scenarios. The number of temporal samples m of the measured channel transfer function $H[m,q]$ is $S = 32500$ for scenario 1 and $S = 65535$ for scenario 2, and the number of frequency samples q is $Q = 256$. In the first scenario the Tx car overtakes the Rx car in a traffic congestion situation, and the second scenario is a general obstructed LOS produced by a truck between Tx and Rx car.

A. Scenario 1: Traffic Congestion

In this scenario the Tx is stuck in a traffic jam on the right lane, whereas the Rx overtakes the Tx on the left lane. This situation is of special interest from the traffic safety point of view. It is a common reaction that a car stuck in a traffic jam on only one lane decides suddenly to change lane, sometimes without enough visibility. We analyze different scattering

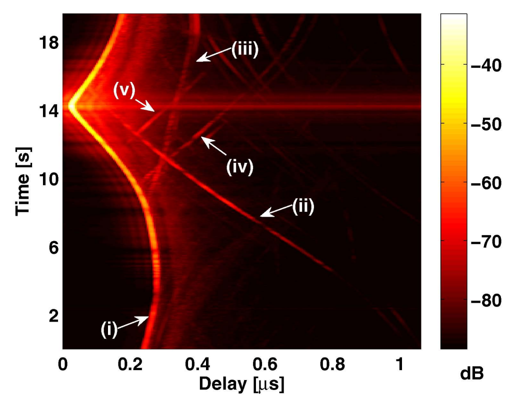

Fig. 4. PDP: Overtaking in traffic congestion.

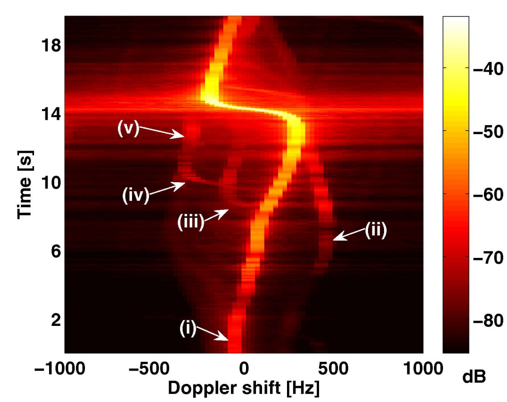

Fig. 5. DSD: Overtaking in traffic congestion.

contributions in the PDP and DSD, labeled in Fig. 4 and 5 from (i) to (v). Figure 6 shows a scheme of how the mobile and static scatterers are distributed. Contribution (i) corresponds to the LOS between the Tx and Rx car. In the beginning, the Rx stays on the right lane behind a large truck and moves to the left in order to overtake the Tx. We observe in Fig. 4 how the delay corresponding to this path gets slightly longer in the

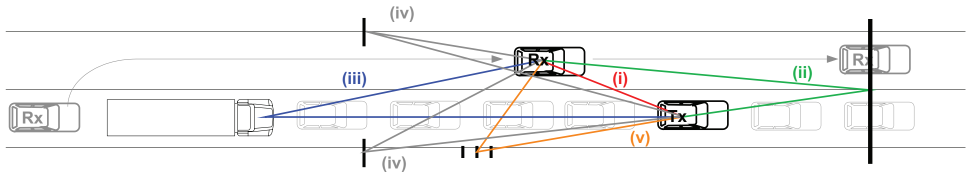

Fig. 6. Scatterers distribution for scenario 1.

beginning, because the Tx car is going faster than the Rx car. After some seconds the Rx car accelerates and therefore the delay gets shorter until the Rx overtakes the Tx at 14.3 s. At this time the delay is the shortest, corresponding to a distance between the cars of about 4 m. Since this is the minimum distance between the measurement cars the received power achieves its maximum at this time.

In Fig. 5 the Doppler shift is negative in the beginning, when both cars are on the right lane and stuck in the traffic jam (the Tx car is going slightly faster than the Rx car). It increases towards positive values when the Rx starts overtaking. Between 3.5 and 14.3 s, the two cars are approaching (positive Doppler shift) and after 14.3 s on, the Rx drives away from the Tx (negative Doppler shift). At the end of the measurement, the Rx breaks due to a congestion also on the left lane and, as a result, the Doppler shift decreases to 0 Hz.

Path (ii) corresponds to a single bounce reflection produced by a big traffic sign placed ahead of both cars. This contribution occurs at 4.3 s. The Rx is not able to receive it earlier because there is a big truck blocking the signal coming from this direction. The maximum Doppler shift is 445 Hz, which implies a relative speed of 85 km/h. At this point, Tx and Rx are driving about 25 km/h and 60 km/h respectively.

The large truck standing in front of the Rx in the beginning of the measurement causes multipath contribution (iii) after the Rx overtakes the truck at 8.7 s. The maximum Doppler shift observed on this path corresponds to a relative speed of 17 km/h.

A similar phenomenon happens for paths (iv) and (v). They correspond to temporary traffic signs from a construction site at both sides of the road which contribute to the received signal as soon as they are left behind. Since both Tx and Rx are leaving these objects, the observed Doppler shift is negative and the delay increases.

The other cars present in the measurement do not have a significant influence on the wave propagation. They do not significantly contribute as scatterer and they do not shadow the LOS path. One reason is the antenna pattern and height of the vehicular antennas that are mounted on the roof of the measurement cars.

B. Scenario 2: General LOS Obstruction

In this scenario, see Fig. 8, the Rx drives in front of a truck at about 80 km/h and the Tx is behind this truck and drives at about 65 km/h. This is a typical situation of obstructed LOS, where the first path between Tx and Rx happens through diffraction on the roof surface of the truck. Figures 9 and 10 show the PDP and DSD observed for this scenario where we identify 5 different scattering contributions.

The first path corresponds to the obstructed LOS between Tx and Rx. Since the Rx drives faster than the Tx, the delay of this path grows with time. Noteworthy are three intervals in which the signal strength increases. The first interval starts at time 0 s and lasts until 3 s and corresponds to the time while there is a bridge between Tx and Rx. The same phenomenon happens during a second interval, between 4.5 and 5.5 s, when the Rx passes under a second smaller bridge and at 9.5 s, when the Tx drives under this bridge. The reflections produced by these objects contribute to increasing the received power at the Rx.

For the first path, the observed Doppler shift is slightly shifted towards negative values. The Rx drives between 10 and 15 km/h faster than the Tx, the observed Doppler shift is -63.5 Hz, well matching with a relative speed of 12 km/h. During the measurement run, the Tx decreases the speed about 5 km/h starting at 4 s, and therefore the Doppler shift of this first path gets more negative down to -89 Hz.

Path (ii) corresponds to a car that passes the Tx at 1.1 s. Normally we cannot notice any contribution from other cars driving beside Tx and Rx. In this case, since the overtaking takes places under the bridge, this path becomes stronger at that time. The Doppler shift associated to this path is 545 Hz, this leads to a relative speed of 105 km/h. Taking the Tx speed of 77 km/h and the Rx speed of 65 km/h into account, this third car should be driving at about 124 km/h. The third path stems from a reflection at the second bridge and shows a decreasing delay with time. It is visible until 4.5 s, Rx passes under the bridge, and has a Doppler shift of 735 Hz, corresponding to a relative speed to the bridge from both cars of 142 km/h.

The fourth path appears shortly after the Tx leaves the first

Fig. 7. Aerial of measurement scenario 2. ©2009 Google-Map data

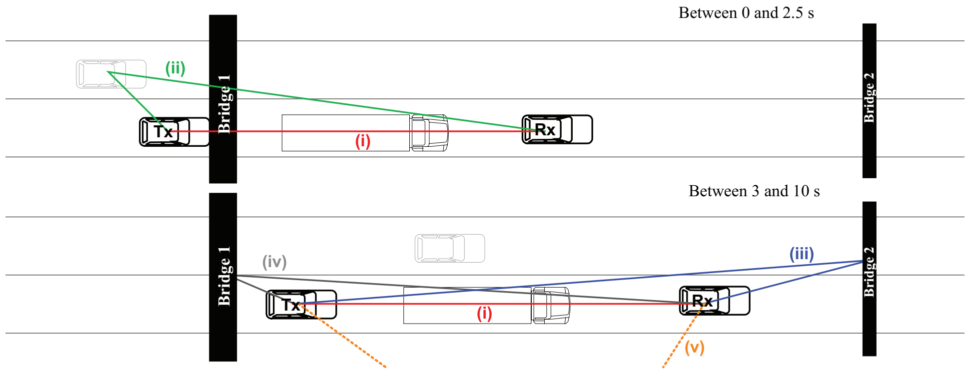

Fig. 8. Scatterers distribution for scenario 2.

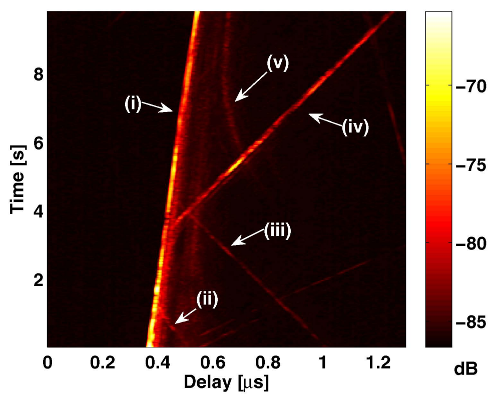

Fig. 9. PDP: Obstructed LOS.

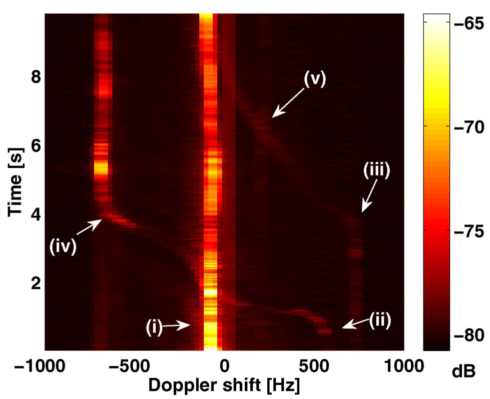

Fig. 10. DSD: Obstructed LOS.

bridge, and it is produced by a reflection on this bridge. The delay increases with time and the Doppler shift is $-700\,\mathrm{Hz}$. The observed Doppler shift of path (iv) is smaller in magnitude than the one for path (iii) because at $4\,\mathrm{s}$ the Tx reduces its speed below $60\,\mathrm{km/h}$.

In Fig. 7 we observe a large building about 100 meters off the road. This building causes the fifth contribution. Since it is an object placed far away from the Tx and Rx, the changes on the delay and Doppler shift are smoother. The shortest delay of this path is $0.65\,\mu\mathrm{s}$ with a travelled distance of $195\,\mathrm{m}$.

IV. Conclusions

This paper gives an overview about a recently conducted vehicle-to-vehicle radio channel measurement campaign using the RUSK LUND channel sounder. Different main situations, based on the importance for safety-related intelligent transport system (ITS) applications, were chosen. The paper presents the power-delay profile and the Doppler spectral density for two different scenarios. In the first one the Rx car overtakes the Tx car in a traffic congestion situation, and the second scenario is an obstructed line-of-sight (LOS) caused by a truck between the Tx and Rx cars. In such scenarios the multipath contributions are produced by big metallic surfaces. An important finding is that the most significant scatterers are traffic signs, trucks, and bridges. Other cars do not significantly contribute to the multipath propagation. One reason for this is that we used realistic vehicular antennas mounted on the roof of the measurement cars and their resulting antenna pattern. In both investigated scenarios, it is possible to detect the signal between Tx and Rx also when there is no direct LOS. This is especially beneficial for collision avoidance situations.

Acknowledgement

The measurement campaign was partly funded by a COST2100 short term scientific mission. The work of L. Bernadó is supported by the Vienna Science and Technology Fund (WWTF) in the FTW project COCOMINT. This work was carried out in cooperation with the FTW project ROADSAFE and the Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility.

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