Directional Analysis of Vehicle-to-Vehicle Propagation Channels

Abbas, Taimoor; Kåredal, Johan; Tufvesson, Fredrik; Paier, Alexander; Bernadó, Laura; Molisch, Andreas

Published in:
IEEE Vehicular Technology Conference

2011

Link to publication

Citation for published version (APA):
Abstract—This paper presents a double directional analysis of vehicle-to-vehicle channel measurements conducted in three different traffic scenarios. Using a high-resolution algorithm, we derive channel parameters like Angle-of-Arrival (AOA), Angle-of-Departure (AOD), propagation delay and Doppler shift and identify underlying propagation mechanisms by combining these estimates with maps of the measurement sites. The results show that first-order reflections from a small number of interacting objects can account for a large part of the received signal in the absence of line-of-sight (LOS). This effect is especially pronounced in the two traffic scenarios where the road is not lined with buildings. We also found that the direction spread is low (and conversely that the antenna correlation is high) in such scenarios, which suggests that beam forming rather than diversity-based methods should be used if multiple antenna elements are available. The situation is reversed, however, in the third scenario, a narrow urban intersection, where a larger number of higher-order reflections is found to result in a higher direction spread.

I. INTRODUCTION

Vehicle-to-vehicle (V2V) communication systems have attracted a lot of interest in recent years due to their anticipated usefulness for traffic safety enhancement. Particularly, it is envisioned that future vehicles, equipped with radio transceivers, can share information about traffic dynamics with each other in order to facilitate driving and avoid accidents. Since the efficiency and the accuracy of such systems ultimately depends on the properties of the propagation channel, a lot of research effort has been spent on V2V propagation channels, usually with the intent of developing realistic simulation models (see e.g., [1], [2], [3]).

Although a number of propagation channel measurement campaigns have been performed in recent years (see e.g., [4], [5], [6], [7]), there are still many important aspects that have been little explored. First, the antenna impact is not well understood. Almost exclusively, the measurements conducted so far have been done with “regular” antenna arrays placed at an elevated position (above the vehicle roof). Neither the impact of design constraints nor antenna placement has been given much attention. Secondly, most measurement campaigns have been conducted under “general” traffic conditions, with cars driving either in convoy or in the opposite directions on the same road, e.g., on highways [4], [5] (a recent is found in [8], where signal obstruction due to vehicles is analyzed). In addition to such general traffic situations there are a number of application-specific scenarios where special propagation conditions apply, e.g., collision avoidance scenarios in street intersections or traffic congestion scenarios. These conditions are not well captured by the former standard measurement scenarios, and hence separate characterization of such scenarios is required.

Furthermore there is a lack of available results on directional properties of V2V channels in the literature; to the authors’ best knowledge there is only the paper by Pedersen et al., [9], which presents the angular spectra for convoy measurements. Analysis of directional properties is important for the assessment of multi-antenna capabilities, e.g., for evaluating the possible diversity gain, as well as to improve understanding of important propagation effects.

The current paper addresses these gaps of knowledge by presenting the results of extensive multiple-input multiple-output (MIMO) V2V channel measurements performed in Lund, Sweden. We present results of directional analysis for three application-specific scenarios and use these results to identify the underlying propagation mechanisms and analyze their impact on the total received power. We also evaluate the directional spread of the propagation channels in the different scenarios, and derive antenna correlation coefficients. The scenarios we study are: (i) an intersection scenario, (ii) a congestion scenario, and (iii) a controlled line-of-sight (LOS) obstruction between the vehicles moving on a highway. This paper partly extends the results of [10], where we presented power-delay profiles and root mean square (RMS) delay spreads (but no directional results) for different types of intersections.

The paper is organized as follows: In Section II the measurement setup is described in detail and the properties of three different scenarios are explained. The parameter extraction process is described in Section III, whereas the results, including the identified propagation mechanisms, are presented in Section IV. Finally, the summary and conclusions are presented in Section V.
II. CHANNEL MEASUREMENTS

A. Measurement Setup

V2V channel measurement data were recorded using the RUSK Lund channel sounder that performs switched-array MIMO measurements. The measurements were conducted over a 240 MHz bandwidth centered around 5.6 GHz, the highest allowed center frequency of the sounder. The measurements were performed using standard hatch-back style cars with roof mounted four-element antenna arrays, specifically designed for V2V communication [11]. The antenna height was 1.73 m. For each branch of this 4 × 4 MIMO configuration, the channel sounder sampled the complex time varying channel transfer function $H(f, t)$ every $\Delta t = 307.2 \mu s$ during 10 or 20 s. To keep track of the positions of the transmitter (TX) and receiver (RX) vehicles during the measurements, each vehicle logged the GPS coordinates and had videos, taken through the windshield. These data were also combined with the measurement data, in order to identify important scatterers in the post-processing.

B. Measurement Scenarios

The measurement data we study were collected in different traffic scenarios.

In the first scenario (intersection) the TX and RX, were approaching a four way intersection in an urban environment at a speed of 30 – 40 km/h (8 – 11 m/s); see Fig. 1(a). There were houses on both sides of the streets, which obstructed the LOS until the cars met in the intersection (in practice, the TX car stopped at a yield sign while the RX car drove by). The streets were narrow; the street width was 14 – 18 m. Moreover, there were several street lights and road signs in this scenario, and many parked cars along the streets, but few moving vehicles.

In the second scenario (congestion) the TX car had just entered a congested area on a two-lane highway (due to a road works further ahead forcing the two lanes to merge). The TX car was stuck in the right lane whereas the RX car was approaching from behind in the left lane at a speed of about 70 km/h (20 m/s); see Fig. 1(b). There were road signs, light poles, various objects and a multitude of other vehicles in this scenario; beside the large number of cars standing still in the TX/RX direction, there was also (moving) traffic in the opposite direction, including some trucks. There was a metallic fence on the outer (right) boundary of the road and the directions of travel were separated by a low concrete wall (approximately 0.5 m).

In the third scenario (obstructed-LOS) the TX and RX cars were moving in the same direction on the right lane on a two-lane highway at a speed of 110 km/h (30 m/s); see Fig. 1(c). There were trucks in front of as well as behind the TX/RX convoy, and the LOS path was obstructed by a tall van between TX and RX. The LOS path appeared when the van decided to change lanes. There were many vehicles (moving) in the opposite direction and there were a couple of road signs and overhead electrical power transmission lines with poles on the roadside. Finally, the directions of travel were separated by a low metallic fence.

III. PARAMETER EXTRACTION

We assume that the $4 \times 4$ channel matrix $H$ can be described by a sum of $L$ plane waves or multipath components (MPCs) where each wave $l$ is characterized by a complex amplitude $\gamma_l$, propagation delay $\tau_l$, and a Doppler shift $\nu_l$. We then model the channel transfer function at each temporal instant (snapshot) $t_s$ and frequency point $f_k$ by [12]

\[
H[t_s, f_k] = \sum_{l=1}^{L} e^{j2\pi\nu_l t_s} \begin{bmatrix} g^H_{TX}(\Theta_{TX,l}) & g^V_{TX}(\Theta_{TX,l}) \\ g^H_{RX}(\Theta_{RX,l}) & g^V_{RX}(\Theta_{RX,l}) \end{bmatrix} e^{-j2\pi\nu_l f_k},
\]

(1)

where $H \in \mathbb{C}^{4 \times 4}$; $g^H_{TX}, g^V_{TX}$ and $g^H_{RX}, g^V_{RX}$ are $4 \times 1$ complex vectors representing TX and RX antenna responses, respectively. Furthermore, $\Theta_{TX,l} = (\theta_{TX,l}, \phi_{TX,l}), \Theta_{RX,l} = (\theta_{RX,l}, \phi_{RX,l})$ are angle-of-departure in elevation and azimuth, and angle-of-arrival in elevation and azimuth, respectively. Superscript $H$ and $V$ indicate horizontal and vertical polarization, respectively.
temporally sparse subset of the measurements data; every
estimating parameters using SAGE, we limit the analysis to a
scenarios, respectively. Due to the computational efforts of
1337
instants where non-LOS conditions apply.
The percentage of extracted power is generally lower for
some extent (for those time instants where the selected source
the extracted part may also contain diffuse contributions to
speaking this part also contains measurement noise. Moreover,
is not extracted by SAGE as
diffuse
noise and thus set to zero. We label the fraction of power which
noise floor with an additional
3
transfer functions were noise thresholded, i.e., anything below
transform of, the measured and the reconstructed, channel
evaluation, the mean squared amplitude of the inverse Fourier
LOS scenarios, respectively. For this power percentage eval-
in the intersection, every
1
68
MPCs account for
93
−
90%
−15
cases. We are further aided in the identification
due to errors in the positions of the TX and RX cars, we
are able to identify the likely propagation process in the vast
discrepancy between the coordinates of an actual object and
scatterers within the visibility range of the TX and RX can be
determined, and the accuracy of their coordinates depends on
their position relative to the TX and/or RX. Although a small
discrepancy between the coordinates of an actual object and
the location indicated by the estimated parameters is inevitable
due to errors in the positions of the TX and RX cars, we
are able to identify the likely propagation process in the vast
majority of the cases. We are further aided in the identification
process by the Average Power Delay Profiles (APDPs), which
are defined, for each time instant, as the averaged (over the
4 × 4 MIMO branches) squared magnitude of inverse Fourier
transform of the channel transfer function at that instant. Many
important MPCs show up as “lines” in the APDP, and the

IV. RESULTS

For each scenario and each time instant we plot the esti-
estimated propagation paths on the corresponding site maps
and then perform a measurement based ray-tracing from the
TX and RX, in order to identify the underlying propagation
mechanisms, e.g., if an object is found at (or more specifically
"sufficiently close" to) the intersection of the lines drawn in
the direction of the AOA from the RX and the direction of
the AOD from the TX for a certain MPC, and the geometric
length from TX to RX via this intersection matches the delay
estimate for the MPC, we consider a single-bounce reflection
from that object to be the underlying mechanism behind it.
In this process, the coordinates of the TX and RX are deter-
mined by combining recorded GPS and video data, whereas
the coordinates of moving scatterers are determined using
video data only. Obviously, only the coordinates of moving
scatterers within the visibility range of the TX and RX can be
determined, and the accuracy of their coordinates depends on
their position relative to the TX and/or RX. Although a small
discrepancy between the coordinates of an actual object and
the location indicated by the estimated parameters is inevitable
due to errors in the positions of the TX and RX cars, we
are able to identify the likely propagation process in the vast
majority of the cases. We are further aided in the identification
process by the Average Power Delay Profiles (APDPs), which
are defined, for each time instant, as the averaged (over the
4 × 4 MIMO branches) squared magnitude of inverse Fourier
transform of the channel transfer function at that instant. Many
important MPCs show up as "lines" in the APDP, and the

The parameters of (1) for 50 MPCs are estimated using
the space-alternating generalized expectation-maximization
(SAGE) algorithm [13]. In order to reduce the computational
complexity, we use measurement data with a bandwidth of
20 MHz, out of the full 240 MHz, centered around 5.6 GHz,
and a temporal window of length 19.4 ms (64 snapshots). This
temporal window corresponds to a Doppler resolution of 52 Hz
and is selected based on the estimated stationarity time of the
channel (see [14] for details), which is 97.6 ms, 374.4 ms, and
1337.9 ms for the intersection, congestion and obstructed-LOS
scenarios, respectively. Due to the computational efforts of
estimating parameters using SAGE, we limit the analysis to a
temporally sparse subset of the measurements data; every 0.5 s
in the intersection, every 1 s in the other two. The 50 extracted
MPCs account for 68 − 90%, 83 − 98% and 68 − 94% of the
available power in the intersection, congestion and obstructed-LOS
scenarios, respectively. For this power percentage eval-
uation, the mean squared amplitude of the inverse Fourier
transform of, the measured and the reconstructed, channel
transfer functions were noise thresholded, i.e., anything below
noise floor with an additional 3 dB margin was considered as
noise and thus set to zero. We label the fraction of power which
is not extracted by SAGE as diffuse power, though strictly
speaking this part also contains measurement noise. Moreover,
the extracted part may also contain diffuse contributions to
some extent (for those time instants where the selected source
order is too high); this will be discussed further in the paper.
The percentage of extracted power is generally lower for
instants where non-LOS conditions apply.

Fig. 2. Results for the intersection scenario: (a) shows the relative power
contribution from different propagation mechanisms, only LOS and first-order
reflections are categorized explicitly; (b) shows some identified propagation
mechanisms in the time-delay domain (power-delay profile), dots indicate the
SAGE delay estimates for the five strongest MPCs.

Fig. 3. Results for the congestion scenario: a) shows the relative power
contribution from different propagation mechanisms, only LOS and first-order
reflections are categorized explicitly; (b) shows some identified propagation
mechanisms in the time-delay domain (power-delay profile), dots indicate the
SAGE delay estimates for the five strongest MPCs.
the propagation mechanisms into two different categories: the one stems from the body of the truck, whereas the other stems from the bonnet. There is, however, a small difference in the propagation distance which indicates they have very similar AOAs and AODs. There is, however, a small difference in the propagation distance which indicates they both stem from the same object, a truck behind the RX, since they are shown in Fig. 1. As an example of the identification process, consider MPC#5 in the intersection scenario in Fig. 1(a). This MPC is arriving at the RX from a direction where the only physical object is another vehicle (a van). In some cases, such as MPC#3, the interacting objects cannot be identified for certain, but we can say with high probability that a single-bounce process is not the underlying mechanism. Similarly in the congestion scenario (Fig. 1(b)), where there is a multitude of traffic around the TX/RX we can still identify important propagation mechanisms, e.g., MPC#2 which is a street light, using the fact that it is only object in the estimated direction that the measured geometric distance also matches the estimated delay. As a final example, consider MPC#3 and MPC#4 in the obstructed LOS scenario (Fig. 1(c)). We conclude that they both stem from the same object, a truck behind the RX, since they have very similar AOAs and AODs. There is, however, a small difference in the propagation distance which indicates the possibility that one signal is reflected from the bonnet whereas the other stems from the body of the truck.

Once the identification process is complete, we classify the propagation mechanisms into two different categories: the APDP can therefore be used to assess the temporal evolution of the propagation delay of those MPCs. APDPs for the three scenarios are shown in Fig. 2, 3, and 4, respectively. It is important to mention that the SAGE for some reasons cannot subtract the LOS completely and model the residue as specular paths. These paths cannot be tied to any of the described propagation mechanism and thus regarded as unclassified.

Sample plots of the identified MPCs at a certain time instant are shown in Fig. 1. As an example of the identification process, consider MPC#5 in the intersection scenario in Fig. 1(a). This MPC is arriving at the RX from a direction where the only physical object is another vehicle (a van). In some cases, such as MPC#3, the interacting objects cannot be identified for certain, but we can say with high probability that a single-bounce process is not the underlying mechanism. Similarly in the congestion scenario (Fig. 1(b)), where there is a multitude of traffic around the TX/RX we can still identify important propagation mechanism, e.g., MPC#2 which is a street light, using the fact that it is only object in the estimated direction that the measured geometric distance also matches the estimated delay. As a final example, consider MPC#3 and MPC#4 in the obstructed LOS scenario (Fig. 1(c)). We conclude that they both stem from the same object, a truck behind the RX, since they have very similar AOAs and AODs. There is, however, a small difference in the propagation distance which indicates the possibility that one signal is reflected from the bonnet whereas the other stems from the body of the truck.

Once the identification process is complete, we classify the propagation mechanisms into two different categories: the LOS path, single-bounce interactions (with buildings, traffic, road signs, street lights, and parked cars, and the concrete wall/metallic fence that separates the directions of travel on the highway) are used in all scenarios. In the obstructed-LOS scenario we split the traffic category into three sub-categories: trucks in front and behind the TX/RX, a van between the TX/RX and other traffic. Lastly, we use a category labeled "unclassified plus higher order reflections account" for both higher-order reflections and for the MPCs that cannot be tied to a specific propagation mechanism. This category will also contain a small amount of diffuse power extracted by SAGE.

Before we study how the received signal is composed, we add antenna influence to the extracted path weights. This way, the weights can be related to the energy that is not extracted by SAGE (see Section III). We thus have:

\[
\alpha_l = \sum_k g_{TX}^H \odot [ g_{RX}^H g_{RX}^V ] [ \gamma_l^{HH} \gamma_l^{HV} ]^2 \]

where, \(\gamma_l^{HH},\gamma_l^{HV}\) and \(\gamma_l^{VV},\gamma_l^{HV}\) represent the co-polarized and cross-polarized estimated complex path gains of extracted MPCs, respectively whereas the variable \(k\) and the operator \(\odot\) refer to the number of channels and the Khatri-Rao product respectively. Finally, the contribution from each propagation mechanism in total received power is calculated as,

\[
P_j = \frac{\sum_{l \in S_j} \alpha_l}{\sum_k \alpha_l},
\]

where \(P_j\) is the power contribution corresponding to the \(j^{th}\) MPC category \(S_j\). The results (see (a) of Fig. 2, 3, and 4) show that first-order interactions often dominate in the absence of LOS; they account for up to 70%, 90% and 65% of the total received power in the intersection, congestion and obstructed-LOS scenarios, respectively. Furthermore, we find that very few MPCs stem from other traffic in the intersection and congestion scenarios. This is mainly due to the antenna...
arrangements we use. The mounting of the antenna close to the car roof only allows for a limited gain below the azimuth plane. Therefore, other regular (sedan-type) cars are not "seen" by the antennas. Taller vehicles, on the other hand, are often found to constitute good scatterers. This is evident in the obstructed-LOS where the trucks and van surrounding the TX/RX account for the majority of the received signal.

The azimuth direction spread [15] is an important measure that indicates what level of spatial diversity can be anticipated. A direction spread of unity indicates that the signal arrives at the receiver uniformly spread over all directions, whereas a direction spread of zero implies that the signal arrives from a single direction. For all three scenarios, we derive the azimuth RMS direction spread at the receiver as,

\[
\sigma_{\text{ang}} = \sqrt{\sum_{l=1}^{L} e^{j \phi_{R,l}} \mu_{\text{ang}}^2 P_{\text{ang}}(\phi_{R,l})},
\]

where

\[
\mu_{\text{ang}} = \sum_{l=1}^{L} e^{j \phi_{R,l}} P_{\text{ang}}(\phi_{R,l}),
\]

and \( P_{\text{ang}}(\phi_{R,l}) \) is the normalized azimuth angular power spectrum. The direction spread is calculated with and without antenna influence and the results are shown in Fig. 5. Taking antenna influence into account, we find that the direction spread is higher in the intersection scenario because of the congested surrounding. This is in contrast to the other two scenarios where the signal is mainly composed of a small number of MPCs within a small angular range, and hence the average direction spread is low. However, the direction spread is high when removing antenna influence which encourages potential use of multi-antenna arrangements to exploit the diversity gain (see Fig. 5).

Finally, we derive the correlation coefficients between the different branches of our measured MIMO system. The corre-

\[\text{REFERENCES}\]