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Mikael G. Nilsson*†, Dimitrios Vlastaras*, Taimoor Abbas†, Björn Bergqvist†, and Fredrik Tufvesson*
*Lund University, Dept. of Electrical and Information Technology, Box 118, SE-221 00 Lund, Sweden
†Volvo Car Corporation, SE-405 31 Göteborg, Sweden
email: mikael.nilsson@volvocars.com

***Abstract*—Shadowing from vehicles can degrade the performance of vehicle-to-vehicle (V2V) communication systems significantly. It is thus important to characterize and model the influence of common shadowing objects like cars properly. For multilink systems it is essential to model the joint effects on the different links. However, the multilink shadowing effects in V2V channels are not yet well understood. In this paper we present a measurement based analysis of multilink shadowing effects in V2V communication systems with cars as blocking objects. In particular we analyze and characterize the joint large scale fading process for multilink communication at 5.9 GHz between four cars in a highway scenario. From our analysis it is found that the coherence time of the large scale fading process for different links can vary from a few seconds to minutes. The results show that it is essential to consider the correlation of the large scale fading processes as the correlation coefficients can have both large negative and large positive values. There is also a clear indication that multihop techniques provide an efficient way to overcome the issue with shadowed cars in V2V systems.**

***Keywords*—Vehicle-to-Vehicle, channel modeling, shadow fading, obstruction, large scale fading, multiple links, diversity, correlation**

I. Introduction

Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications have been introduced, and standardized [1], in order to reduce accidents and enhance the driving experience. Messages are exchanged over the dedicated 5.9 GHz band based on the establishment of ad-hoc networks, which can be highly dynamic in nature. The propagation channel at 5.9 GHz band is considered to be one of the most critical performance limiting factors for vehicular ad-hoc networks, due to high penetration losses, high mobility of vehicles, and antennas being close to the ground-level. Many studies have been performed and presented regarding channel characterization of the 5.9 GHz band using simulations, channel sounding equipment as well as 802.11p transceivers [2], [3].

V2V is particularly beneficial in the situations where visual line-of-sight (LOS) is obstructed by buildings or other vehicles. However, buildings and vehicles as physical obstructions induce additional propagation losses by blocking the LOS signals, which in turn reduces the communication range. In such an obstructed-LOS (OLOS) situation scattering and reflections from nearby objects, e.g., buildings, traffic signs, trucks and bridges, enable the signal reception [4].

The effect of vehicles as obstructions, which is of particular interest in this paper, is not yet fully understood. In the literature it is reported that a single vehicle on average can induce an additional fading of about 10-20 dB [5], [6] depending upon the shape, size and location of the obstructing vehicle. Moreover, it is found that this shadow fading is correlated and can be modeled with a Gaussian distribution [7]. Simulation results have shown that the shadowing leads to substantially reduced performance [8].

Most of the studies have considered communication between one transmitter (TX) and one receiver (RX), i.e. the single link case. A few studies have considered communication between one TX and several RX or vice versa, i.e. the multilink case. As pointed out in [9] it is essential to consider the properties of the joint shadowing process in *ad hoc* peer-to-peer channels. In this paper we aim to characterize those properties for V2V channels by a measurement based analysis of multilink shadowing effects in a highway scenario to see if multihop techniques, which e.g. are implemented in the ITS-G5 standard [10], can overcome the issue with shadowing by relaying the information via another car. The main contribution of the paper is the analysis of the coherence time and cross-correlation of the large scale fading processes for concurrent communication links, i.e., the multilink case. For the analysis we employ Maximum Likelihood (ML) estimation of the regression model to compensate for the influence of the noise floor on the estimated path loss exponent [11].

II. Measurement Description

Measurements are performed to capture the joint (simultaneous) behavior of the six possible links between four cars,

Fig. 1. All test cars (Volvo XC70, S60, XC90 and V70, respectively) lined up for the test scenario Convoy A.

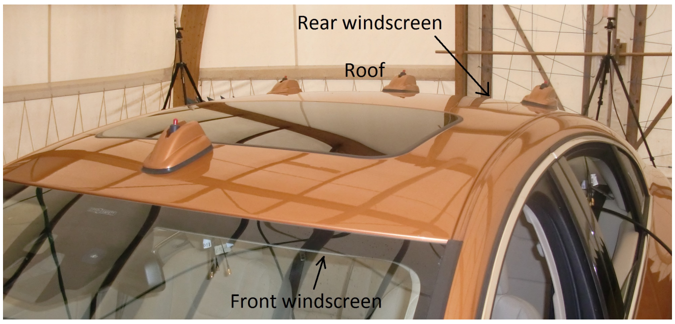

Fig. 2. The V2V antennas on the Volvo S60. Only front-windscreen, middle-roof, and rear-windscreen antennas were used during these measurements.

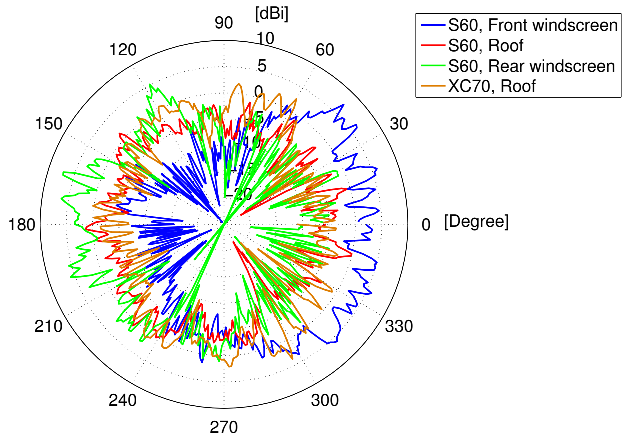

Fig. 3. Measured antenna pattern, mounted on the Volvo S60 and the Volvo XC70. The front of the cars is at 0°. The antenna pattern of the V70 and XC90 is similar as the presented XC70 since all these models have similar design of the roof area.

see Fig. 1, driving in the same direction on a highway. Measurements took place at *Rv 40* between Landvetter airport (lat N 57.68014, long E 12.31441) and Borås city (lat N 57.71958, long E 12.96809), Sweden. Four Volvo cars of different models were equipped with transceivers [12] from Kapsch TrafficCom AB using the communication standard IEEE 802.11p [1]. The antennas used in the test have been developed specifically for V2V communication. GPS coordinates and videos were recorded from each vehicle. Two major measurement scenarios were considered: Convoy and Overtaking car. For each scenario there were simultaneous LOS and OLOS links. OLOS is here defined as the situation where at least one car is in-between the RX and TX cars constituting the link nodes.

A. Measurement Setup

During the measurements each transceiver transmitted packets, bursts of pseudo random data with size and rate according to Table I. At the same time all the other transceivers were recording received packets. Each transceiver was connected via a coaxial cable to an antenna placed on the roof of a Volvo V70, XC70 and XC90. Inside a Volvo S60 two transceivers were placed, one connected to an antenna on the roof whereas transceiver number two, which had antenna diversity capability, was connected to two antenna elements placed inside the car at the front and rear windscreens, see Fig. 2. The second transceiver makes it possible to analyze the performance of antenna diversity and hidden antennas. All the antenna elements were omni-directional in the azimuthal plane, but the antenna pattern after mounting is certainly not, see Fig. 3. While many measurements were performed, some selected scenarios are presented and analyzed in this paper.

TABLE I. MEASUREMENT PARAMETERS

Parameter	Value(s)
Standard	IEEE 802.11p
Center frequency	5.9 GHz
Data rate	10 Mbit/s
Packet rate	10 Hz
Packet size	100, 500 and 1500 bytes every 100 ms.
S60 (mid size)	1 antenna at roof, height 145 cm, cable loss, 1.0 dB.
	1 at front windscreen and 1 at rear windscreen,
	both with the height 135 cm and cable loss 1.0 dB.
V70 (large size)	1 antenna at roof, height 155 cm. Cable loss, 3.5 dB.
XC70 (large size)	1 antenna at roof, height 160 cm. Cable loss, 3.5 dB.
XC90 (large SUV)	1 antenna at roof, height 178 cm. Cable loss, 3.5 dB.

B. Scenario Description

Two scenarios were considered during these highway measurements; Convoy and Overtaking Car, see Fig. 6 for details. *Rv 40* is characterized by low traffic in non-rush hours, guard rails in the middle of the road, some bridges, other structures, and with forest besides the road. The measurements are expected to characterize a normal to rich scattering environment.

1) Convoy Scenario: The convoy measurements were conducted with an average speed of 25 m/s (90 km/h). Two different convoy scenarios were measured with different positions of the cars to study obstruction losses due to different car sizes and reference measurements to achieve the path loss exponent for the *Rv 40* highway in the analysis, see Fig. 6, A and B.

2) Overtaking Car Scenario: This scenario is composed of a set of five sub scenarios going from C to G and then back to C, according to Fig. 6, where G is the steady state of F. Scenarios C to G are performed within a time duration of around one minute and are repeated several times.

There are several interesting scenarios from a relaying point of view: Relaying within a row of cars with obstruction from a small car (A), or with obstruction from a large car (B,C), relaying during overtaking with LOS to two cars (D, E, F, G), and all the transitions in between.

C. Data Processing

Each transceiver transmits packets with a 10 Hz repetition rate and the receivers report received signal strength (RSSI) in dB with a 1 dB resolution for successfully decoded packets. All transceivers are synchronized to GPS, meaning that they have a common time reference so that the time instants where the transmission failed and the number of missing packets can be identified. The knowledge of missing packets is used in the ML based estimations of the path loss exponent and the standard deviation of the large scale fading process to compensate for the influence of the (soft) sensitivity level of the receiver. It should be noted that both the absolute values of the simultaneous signal strengths and the joint distribution of the shadow fading process and its autocorrelation function are of interest for channel characterization and performance evaluations. For this specific measured scenario, of course the received signal strengths and the estimated packet error rates can be used directly, but for a realistic channel model with arbitrary distances between the vehicles one has to separate the correlated large scale fading process and the distance dependent path loss. The large scale fading is estimated by subtraction of the distance dependent path loss from the RSSI-value. On the RSSI-values and the estimated large scale fading we employ a sliding window (moving average) over 10 consecutive samples, i.e. the window has a length of 1 s. In the analysis we extract only one path loss exponent and reference value. The influence of obstruction by other cars is considered as a random time-correlated part of the large scale fading process.

III. Result and Discussion

The path loss exponent estimation is based on the measurement results from scenario Convoy A and B, in total 319,510 samples. A scatter plot of the received RSSI values, compensated with the cable losses, together with two regression models are found in Fig. 4. The first regression line, using ordinary Least Squares (LS) estimation, uses all samples with a reported RSSI value (i.e. all successfully decoded packets). The second one uses ML estimation to find the regression line taking the effect of censoring into account [13], i.e. missing RSSI values due to too low received power levels for the receiver. The ML estimation method also makes use of the information that the distance to transmitting car is known even though the data packets is not received correctly. The censoring due to lost packets does not occur at a fixed level. Instead, there is a soft censoring that occurs for data below RSSI values of -85 dBm (which is close to the sensitivity limit of the receivers specified by the manufacturer). For this reason, all data below -85 dBm are regarded as censored data in the analysis. We further neglect the probability of missed packets at RSSI values equal or larger than -85 dBm, which based on the log files is a good approximation. The ML method takes censored data into account and jointly estimates the path loss exponent, the standard deviation of the censored normal distribution and the intercept, PL_{d_0} corresponding to the mean path loss at a distance of 1 m. The path loss exponent for ordinary LS estimation is 1.52 and for the ML estimation the value is 2.02, which is used in the further analysis. The standard deviation is 5.0 dBm and 5.59 dBm respectively.

The coherence time is here defined as the time duration from the correlation peak ($\rho = 1$) to the time where the auto-correlation coefficient remains above 0.5. The auto- and cross-correlation calculation is based on the sample reflective correlation coefficient, where the mean is not subtracted in

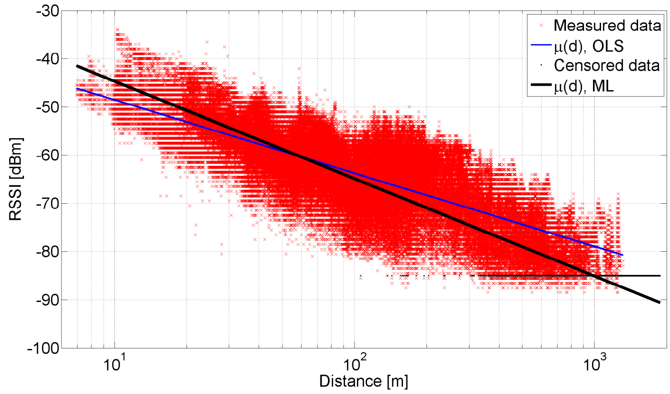

Fig. 4. Measured RSSI values from all cars for test scenario Convoy A and B. Estimated path loss with Ordinary Least Squares (OLS) and with the Maximum-Likelihood (ML) based estimation method.

the calculation of the correlation coefficient (1). The reason for using this measure instead of the conventional correlation coefficient is that the large scale fading process is a zero mean process with long time constants, and that further subtraction of local means from a shorter time series would highlight only short time correlation of small (random) variations instead of the correlation due to shadowing by other cars.

$$\rho_{xy} = \frac{\sum_i x_i y_i}{\sqrt{(\sum_i x_i^2)(\sum_i y_i^2)}} \quad (1)$$

One example result based from measurements in scenario Convoy A is shown in Fig. 5. As seen in the figure the coherence time for the multilink case can vary from a few seconds up to almost 2 minutes in this example. So even though that the transceivers transmits with a high repetition rate the receiving car can be shadowed in the range of minutes and will continuously have a significantly lower received power level compared to the value predicted by the path loss model.

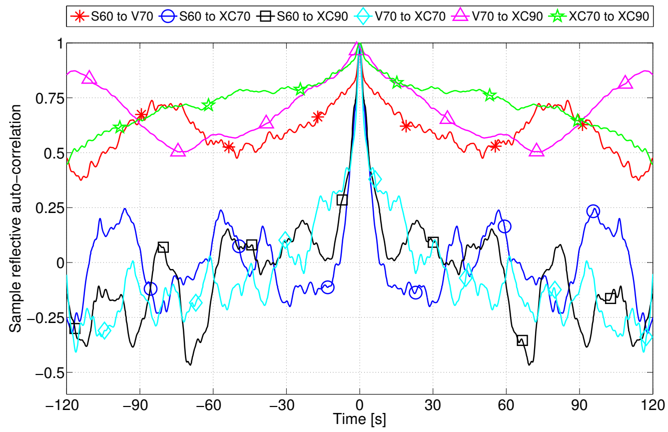

Fig. 5. One example of sample reflective auto-correlation for the measurement scenario Convoy A, where the cars first have fixed distances to each other and then in the end of this measurement example the Volvo XC70 increases the distance to the other cars.

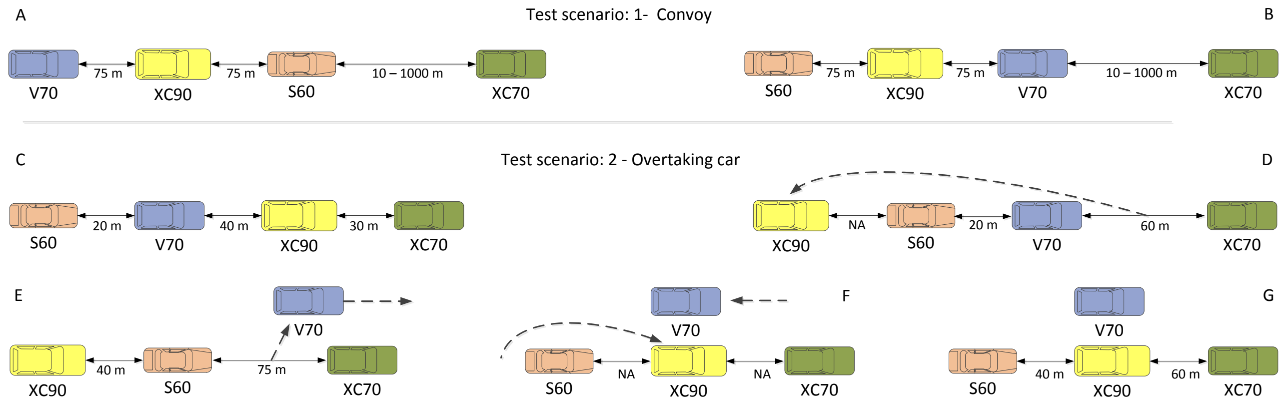

Fig. 6. Test scenarios 1 and 2. Distances are not correctly scaled.

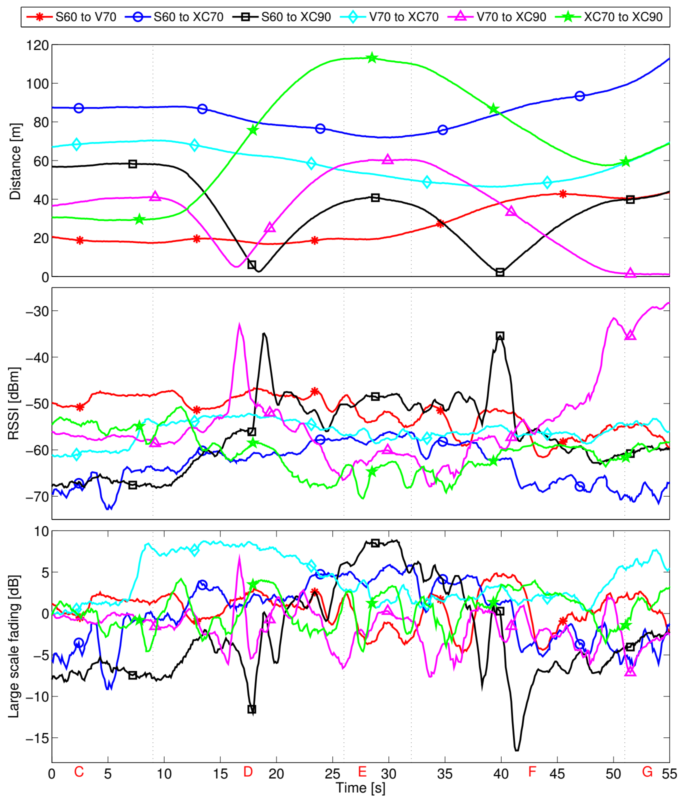

Fig. 7. Sub-plots from top to bottom showing, the distances between the cars, RSSI-values in the receiving car, and the large scale fading for the different links, respectively, as a function of time for the test scenario 2 - Overtaking Car. Five sub-scenarios are marked as C, D, E, F, and G, respectively.

The cross-correlation of the large scale fading process for the multilink case is, as mentioned before, important to understand and characterize for wireless communication systems using multihop techniques. We present one example from the measurements to show the importance of the cross-correlation coefficient. The used scenario is the Overtaking Car with the defined sub-scenarios; C: a stable convoy (0-9 s), D: the

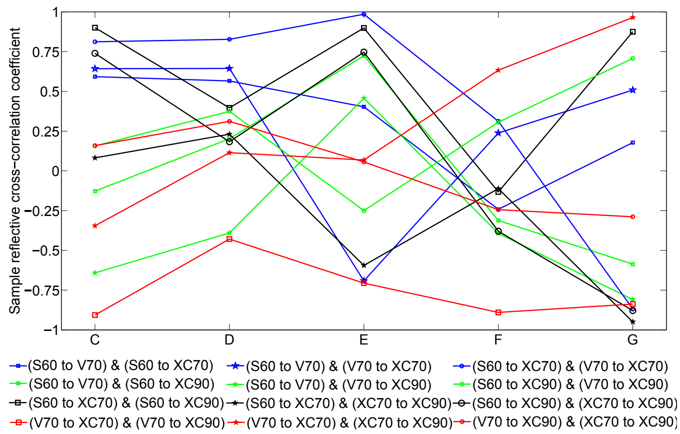

Fig. 8. Sample reflective cross-correlation coefficient ($t = 0$) for the measurement scenario Overtaking Car. The color coding representing different subsets; Blue: S60, V70, and XC70, Green: S60, V70, and XC90, Black: S60, XC70, and XC90, Red: V70, XC70, and XC90.

movement of the XC90 from position 2 to position 4 (9-26 s), E: another almost stable convoy and then the V70 is changing lane and moves ahead (26-32 s), F: movement of the XC90 from position 4 to position 2 with the V70 to the left (32-51 s), and G: stable setup of sub-scenario F. The distances between the cars, RSSI-values in the receiving cars and the large scale fading for the different links are presented in Fig. 7. The links between two cars are assumed to be reciprocal. In Fig. 8 the sample cross-correlation coefficient ($t = 0$) from 12 out of 15 values are presented. The last three, which are not presented,

TABLE II. SCENARIO G, LARGE SCALE FADING (LSF) AND SAMPLE CROSS-CORRELATION COEFFICIENT (X-CORR).

Communication link	LSF	X-corr
S60 to V70	Neutral	0.51
V70 to XC70	Very good	
S60 to XC90	Bad	-0.88
XC70 to XC90	Neutral	
S60 to XC70	Very bad	NA

are the links involving all cars without a common node.

To exemplify the advantages of multihop the communication links, S60 to V70, S60 to XC70, S60 to XC90, V70 to XC70, and XC70 to XC90 are considered in the sub-scenario G. Further, it is assumed that the V70 and the XC90 are attempting to relay a package from the XC70 to the S60. In the Table II the values of the large scale fading and the sample reflective cross-correlation coefficients are briefly summarized. The link between the S60 and the XC70 is bad due to obstruction by the XC90. The link between the S60 and the XC90 is not that good either due to antenna pattern; the S60 roof antenna elevation angle is around 10° and the XC90 is quite tall. By using links that receive signals with high concurrent received power levels the communication system can overcome the issue with shadowed cars. Looking at the large scale fading and the cross-correlation coefficient, the Table II suggests that it is better to use the V70 as the relaying car compared to the XC90 since the links communicating with the V70 have positive cross-correlation coefficients. Similar analyses have been made for all sub-scenarios but are not presented in this paper due to space constraints. Similarly, no results from the front and rear windscreen antennas in the S60 are presented in this paper.

IV. Summary and Conclusions

In this paper we have presented initial results of a measurement based analysis on multilink shadowing effects in a highway scenario using V2V communication at 5.9 GHz. The focus in the analysis has been on joint characterization of the large scale fading processes, more specifically the coherence time of the large scale fading process and the sample reflective cross-correlation coefficient for the multilink case. The coherence time can vary from a few seconds up to almost 2 minutes when four cars are driving in a convoy on the highway. So even though that the transceivers transmit with a high repetition rate the receiving car can be shadowed in the range of minutes and will experience long periods with received power levels being much lower than predicted by the path loss model only. Multihop techniques, which e.g. are implemented in the ITS-G5 standard, can overcome this issue by relaying the information via another car. Analysis of the sample reflective cross-correlation coefficients between all links in our setup shows that there are simultaneous positively and negatively correlated links. By using links between cars that receives signals with high power the wireless communication system can overcome the issue with shadowed cars. The measurements give a clear indication that this approach can be successful.

V. Acknowledgement

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