Performance Analysis of Vehicle-to-Vehicle Tunnel Measurements at 5.9 GHz

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***Abstract*—In this contribution, we discuss and analyze results from real-world performance measurements for IEEE 802.11p along motorway A22 near Vienna, Austria. More specifically, we evaluate the frame success ratio and goodput of the IEEE 802.11p physical layer for a vehicle-to-vehicle scenario in a tunnel. We report and discuss the observed frame success ratios and goodputs for radio channels between the transmit and the receive antenna with and without a line-of-sight component, and investigate the impact of the propagation environment and the traffic situation inside the tunnel.**

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 its surroundings and even to take appropriate action to secure the occupants, if an accident is forecasted. Besides the safety applications, intelligent transport systems (ITS) promise to enable several information and entertainment services including real-time traffic information, social networking, and media distribution.

The importance of having dedicated wireless communication between vehicles has been acknowledged by the Federal Communication Commission (FCC), resulting in a 75 MHz frequency band allocation at 5.9 GHz for the purpose of Dedicated Short Range Communications (DSRC) in vehicular environments [1]. A further step in targeting nation wide deployment of this technology was the development of the standard IEEE 802.11p [2], specifying the medium access control (MAC) and the physical layer (PHY) for future ITS systems. However, the fundamental characteristics of the physical channel still remain an open question for both industry and the research community. Therefore, to enable robust, efficient, and practical design and deployment of V2V and V2I communication systems, the reliable knowledge of radio channel propagation behavior is required.

A number of authors have performed measurements in the 5.2-5.3 GHz band. Authors of [3] conducted flat-fading narrow-band measurements of inter-vehicle transmission at 5.2 GHz. Authors of [4] and [5] focused on investigation of the power-delay profiles and the delay-Doppler spectra from measurements in urban environment with vehicles driving in opposite directions at 5.2 GHz. Further the indoor measurements in low-mobility environment at 5.3 GHz were reported in [6]. Results of a V2V radio channel measurement campaign at 5.6 GHz with realistic traffic situations where presented in [7]. Although the principles of channel impairment are similar, scattering and obstruction by various objects in the environment vary significantly with frequency.

Most of the measurements conducted inside the 5.9 GHz DSRC band were performed for urban, suburban, rural and highway scenarios in open areas [8], [9], [10], [11]. However, to the best of the authors' knowledge the performance of IEEE 802.11p based V2V communication has not yet been investigated in such specific propagation environments as tunnels. Therefore, we have carried out an extensive V2V measurement campaign in a realistic tunnel environment on the motorway. In this contribution we present the evaluation of the system performance under different propagation conditions such as line-of-sight (LOS), non-line-of-sight (NLOS) and realistic overtaking maneuvers, and analyze how these conditions affect the percentage of successfully received packets.

The remainder of this paper is organized as follows: Section II describes the deployed hardware, the system parameters and the measurement environment. In Section III the measurement results based on the frame success ratio (FSR) and goodput values are analyzed and the system performance in different vehicular scenarios is examined. Finally, Section IV provides concluding remarks.

II. Description of the Measurement Campaign

A. Experiment Design

A common purpose of most field measurements conducted with V2V communication environment is to get real world input for the development of suitable channel models. In this paper, our aim is rather to evaluate the measurements from a system point of view. The measurement campaign presented here was performed in the tunnel part of the motorway A22 in Austria during September 2010, within the ROADSAFE project [12]. The main objectives of this measurement campaign are to analyze the performance of a single-hop V2V wireless link and to investigate the dependence of link quality on the realistic propagation conditions. We had chosen 5880 MHz as the center frequency for this measurement campaign. As transmitter and receiver we have used two vehicles equipped with one node of CVIS platform each, which will be described in more detail in II-B. The transmitter was set to the broadcast mode and was constantly transmitting approximately

TABLE I
CONFIGURABLE TRANSMITTER PARAMETERS AND THEIR VALUES.

Parameter	Value
Transmitter power	16 dBm
Packet length	200 byte
Data rate	6 Mbit/s

1600 packets per second. The received and recorded signal has been post-processed in order to evaluated the received signal strength indicator (RSSI) and the amount of the successfully received and decoded packets. It is important to note that throughout this measurement no MAC layer functions have been used, i.e., there has been no uplink signaling of any kind.

For the evaluation presented in this paper we have used constant MAC service data unit packet lengths of 200 byte and data rate of 6 Mbit/s. The transmit power level was set to 16 dBm. During the measurement campaign the vehicles with measurement equipment onboard maneuvered through realistic road traffic. The distance and the relative velocity between the two cars varied within certain limits. The inter-vehicle distance varies between 10 m and 100 m and the vehicles' speed was in range of $60 - 80$ km/h, depending on the actual traffic situation. Configurable transmitter parameters and their values used through out the measurement are summarized in Table I.

B. Measurement Equipment

Measurements were performed using a V2V prototyping platform equipped with a CVIS CALM M5 radio module, implementing the IEEE 802.11p protocol. The CVIS prototype systems were provided by Q-FREE in the framework of the European CVIS project [13]. The CVIS platform allows rapid prototyping of cooperative V2V and V2I applications and is largely based on open-source software components. Transmitter/receiver platforms were placed inside the test vehicles and connected to the CVIS vehicle rooftop antenna unit. The CVIS antenna pod contains five individual antennas for the different wireless access technologies such as for CALM M5, CALM 2G/3G, DSRC, WLAN and GPS. In our measurements only the CALM M5 and GPS antennas were connected for V2V communication and positioning respectively. The CVIS antenna for CALM M5 communication is a vertically polarized double-fed printed monopole and has radiation pattern close to isotropic, according to measurements in [14].

The transmitter antenna was mounted with magnets at the height of approximately 1.7 m on the roof of the first test vehicle (a "Ford Galaxy"), while the receiver antenna was mounted similarly but at height of 1.5 m on the roof of the second test vehicle (a "Peugeot 307").

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

C. Measurement Environment

The tunnel, in which the measurements were carried out is approximately 2 km long and has 3 lanes. In our experiments we have considered three different traffic scenarios:

1) **LOS scenario**: There was no obstruction between the transmit and the receive antenna blocking the LOS. Vehicles were driving on the same lane relatively close to each other (average separation 30 m).
2) **Overtaking scenario:** One of the test vehicles was overtaking the other. After the overtaking maneuver the inter-vehicle distance was larger as in the case of LOS scenario. Vehicles were still driving in the same lane, but LOS was occasionally blocked by other vehicles, depending on the traffic situation.
3) **NLOS scenario:** Vehicles were driving on different lanes with an average inter-vehicle separation of 80 m. The LOS was blocked during the whole measurement by vehicles passing between transmitter and receiver.

III. MEASUREMENT RESULTS

A. Frame Success Ratio and Signal-to-Noise Ratio Analysis

In this subsection we focus on the discussion of the system performance in terms of the signal-to-noise ratio (SNR) and the FSR. For each detection event a log entry is created on the receiver that contains the estimated values of the received signal and noise power level and the time stamp. The detection event can be caused by an actually transmitted packet, a corrupted packet or an interference source whose energy exceeds a given threshold. For all received packets that were successfully decoded a correct cyclic redundancy check (CRC) value and a MAC sequence number were additionally stored in the receiver log entry. The MAC sequence number is an integer $\mathrm{mod}(4095)$ counter value that is assigned to each packet of the transmitter and acts as a packet identifier.

The SNR values presented throughout this paper are calculated based on the signal and noise power values logged by the CVIS platform during the measurement. The method of SNR estimation performed by the CVIS platform still remains questionable and therefore the absolute SNR values might have a constant bias. However, the relative SNR values are accurate. The FSR is defined as the number of packets that were successfully decoded by the receiver (packets with correct CRC value and available MAC sequence number) divided by the number of transmitted packets, during a certain time interval. For evaluations presented in this contribution this time interval was set to 1 s. Since the actual transmission rate was not recorded in this measurement setup it is estimated based on the data available from the receiver as follows. The measurement data was divided into time intervals of 1 s and in each such time interval we only considered the first and the last successfully decoded packets along with their MAC sequence numbers and time stamps. The transmission rate for one time interval is thus given as the difference between the first and last MAC sequence numbers divided by the difference between their time stamps. Since the transmission rate for individual time intervals is not constant and varies within the certain limit ($\pm 1.5\,\%$) we have chosen a maximum value over all time intervals and used it as the approximated transmission rate for the whole measurement.

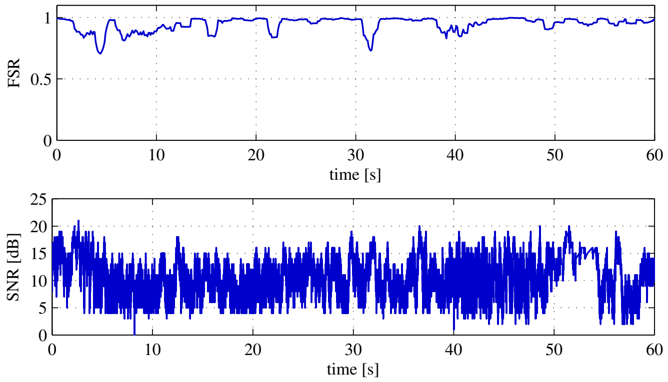

Fig. 1. SNR and FSR plots vs. time for LOS scenario.

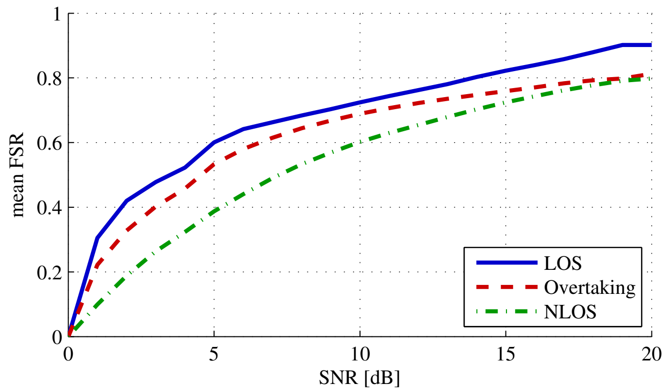

Fig. 2. Comparison of the SNR vs. mean FSR plot for different scenarios. Solid blue line corresponds to the LOS, dashed red line - to the overtaking and dash dotted green line - to the NLOS scenario.

Fig. 1 shows the resulting SNR and FSR curves plotted versus time for a typical LOS scenario. Both the SNR and the FSR curves show very smooth behavior without interruptions and remain within certain limits.

Based on the observations of the SNR curves for different scenarios we can conclude that the SNR values were varying in the range of $5-20$ dB in case of the LOS and the overtaking scenarios, while for the NLOS scenario the SNR values were on average 5 dB less. Considering the FSR curves we can infer that for both the LOS and the overtaking scenarios no interruptions were obtained for the whole duration of the measurement, although the FSR curve for LOS scenario was deviating significantly less, than the FSR curve for overtaking scenario. For measurements from the NLOS scenario, several intervals of low connectivity, where the FSR dropped below the threshold of 0.25, were obtained.

Fig. 2 compares the dependence of the mean FSR on the mean SNR for different scenarios. Here, the solid blue line corresponds to the LOS scenario, the dashed red line represents the data from the overtaking scenario and the dash-dotted green line depicts the NLOS case. Carefully note that the curves presented here do not approach the upper bound of the FSR even for the largest SNR value, since the mean FSR value is calculated based on a large amount of values.

Based on the observations from Fig. 2 we can conclude that for the same mean SNR values the highest FSR values were always achieved in the LOS scenario, which is as expected. However in case of the overtaking and the NLOS scenarios the FSR performance is on average only 6% and 12% worse, respectively. For lower SNR values the overtaking scenario curve is closer to those of the LOS scenario, while with growing SNR its performance deteriorates and is nearly the same as in NLOS conditions. For the LOS scenario the FSR of 0.5 is attained already by the SNR of 4 dB, which is true for approximately 90% of the measurement data. While for the overtaking and the NLOS scenario 1 dB and 4 dB increase of mean SNR is needed in order to assure the same packet loss of less than 50%, respectively. Furthermore, the LOS is the only scenario for which mean FSR vs. mean SNR curve saturates at around 0.9. Therefore, we can conclude that with the equipment used and the parameter settings given in Tab. I for an arbitrary high SNR it is not possible to achieve the average packet loss[1] of less than 10%, even if there are no obstacles blocking LOS between the transmitter and the receiver.

B. *Complimentary Cumulative Distribution Function Analysis*

In order to analyze the probability of the packet loss for different propagation scenarios in more detail we have calculated the complimentary cumulative distribution function (CCDF) of the FSR, which is shown in Fig. 3. The CCDF indicates the probability of the FSR results to be above a certain level. Each scenario is represented by its own line style and color. For LOS and overtaking scenarios the CCDF curves for FSR below 0.5 are equal. Further we can conclude that for these scenarios the probability to lose more than 50% of packets is only around 10%. NLOS scenarios exhibit approximately 4 times higher FSR values compared to LOS scenarios. This approves our observation in III-A that for the LOS scenario, a packet loss of more than 50% is obtained for SNR values less than 4 dB, which is true only for 10% of the measurement data.

For FSR values higher than 0.5 the CCDF curve of the overtaking scenario is always slightly below the LOS scenario curve. This particularly implies that the higher the FSR is, the lower the probability is to achieve it with the overtaking scenario as compared to the LOS scenario.

The probability of successful packet transmission for the NLOS scenario is always lower than in other scenarios, since the vehicles were not driving in the same lane and LOS component is continuously blocked by a truck or several vehicles. While for LOS and overtaking scenario the FSR is always higher than 0.25 (CCDF ≈ 1), which particularly implies that there were no interruptions in transmission and the FSR curve never drops below 0.25, for NLOS such interruptions occurred around 10% of the measurement time.

C. *Goodput Analysis*

The SNR vs. FSR and CCDF curves introduced in previously has shown that the link performance in terms of

[1]Carefully note that the average packet loss should not be confused with the absolute individual FSR values presented on Fig. 1.

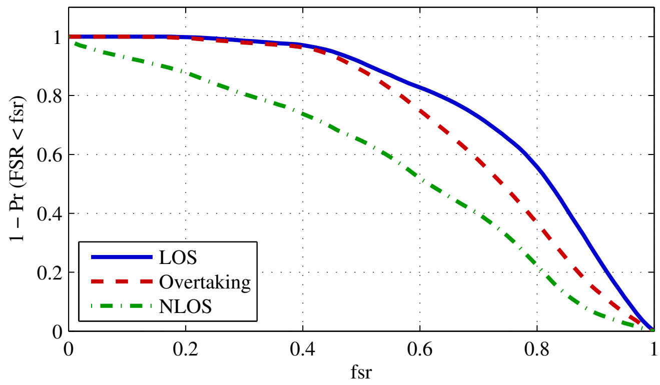

Fig. 3. CCDFs of the FSR for different scenarios. Solid blue line corresponds to the LOS, dashed red line - to the overtaking and dash dotted green line - to the NLOS scenario.

TABLE II
GOODPUT ACHIEVABLE IN DIFFERENT PROPAGATION SCENARIOS.

Scenario	Goodput
LOS	1.8 Mbit/s
Overtaking	2 Mbit/s
NLOS	1.3 Mbit/s

successfully transmitted packets for the overtaking scenario is only slightly worse than in case of LOS, while the performance in NLOS conditions is significantly worse. In order to further validate this tendency we introduce the goodput in this subsection. Goodput is calculated as a number of successfully decoded packets during one measurement multiplied by the packet length, which is 200 byte (equivalently 1600 bit) in our case, and divided by the measurement duration. The average total goodput values calculated for different scenarios are shown in Tab. II.

Since for the measurements a constant data rate of 3 Mbit/s was used, we can conclude that in the LOS case around 67% of packets were successfully transmitted to the destination. For measurements with blocked LOS between the transmitter and the receiver the link performance decreases considerably and only 43% of information is available at the receiver.

IV. CONCLUSIONS

We presented the experiments of V2V communication at 5.9 GHz inside a tunnel and evaluated the performance in various settings. We also compared the link performance for up-coming WAVE technology in scenarios with LOS between transmitter and receiver, with LOS being occasionally blocked and without LOS component. For the LOS scenario the FSR is nearly constant and most of the time it is above 0.8. For the scenario in which the LOS was occasionally blocked the FSR was fluctuating significantly more, but the link performance was almost as good as in case of continuous LOS measurements. For NLOS measurements we have frequently obtained the interruptions where the FSR dropped below 0.25. Furthermore, the link performance was shown by an average packet loss of above 50%. Therefore, we can conclude that connectivity is almost immediately strongly degraded with loss of LOS.

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