Performance Evaluation of IEEE 802.11p Infrastructure-to-Vehicle Tunnel Measurements

V. Shivaldova*, G. Maier*, D. Smely‡, N. Czink†, A. Alonso*, A. Winkelbauer*, A. Paier*, C.F. Mecklenbräuker*
*Institute of Telecommunications, Technische Universität Wien, Vienna, Austria
†FTW Forschungszentrum Telekommunikation Wien, Vienna, Austria
‡Kapsch TrafficCom, Vienna, Austria
Contact: veronika.shivaldova@nt.tuwien.ac.at

***Abstract*—In this contribution, we discuss and analyze results from real-world performance measurements for IEEE 802.11p during September 2010 along the highway S1 near Vienna, Austria. More specifically, we evaluate the frame success ratio and goodput of the IEEE 802.11p physical (PHY) layer for a infrastructure-to-vehicle (I2V) scenario in a tunnel. We report and discuss the observed frame success ratios and goodputs for various PHY parameter settings and investigate the impact of the propagation environment and the traffic situation inside the tunnel.**

***Index Terms*—Vehicular communications, infrastructure-to-vehicle, measurements, road tests, tunnel, IEEE 802.11p.**

I. Introduction

Over the past few years intelligent transport systems (ITS) have gained wide popularity and importance in both academia and industry. This important technology offers a broad range of applications including public safety, traffic control and entertainment. However, most research projects focus their attention at public safety related applications, which promise to decrease the number of accidents, saving human lives. Vehicles can retrieve information about road condition, traffic situation and identify potential collisions, based on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications.

One of the first important steps in the process of the ITS integration in everyday life in Europe has been done in August 2008, when the Commission of European Communities has taken a the decision on the harmonized use of radio spectrum in the 5875–5905 MHz frequency band for ITS [1]. Moreover the European Conference of Postal and Telecommunications Administrations (CEPT) concluded in its report [2] that the whole 75 MHz band in the range from 5850 MHz to 5925 MHz may be used for ITS applications in the future, as long as they comply with certain emission limits. Thus, the frequency band allocated for safety-related ITS applications in Europe conforms to the spectrum used in other regions and in this manner contributes to global spectrum harmonization.

Besides the allocation of a protected frequency band, the definition of an ubiquitous communication technology between vehicles is an important issue. Wireless communication between vehicles is specified in an amended version of the IEEE 802.11a standard, known as IEEE 802.11p [3]. Since the original IEEE 802.11a standard is optimized for local area networks with low user mobility, it can barely handle fast fading conditions, resulting from the high mobility in vehicular networks. The amendments defined in IEEE 802.11p aim to provide interoperability between wireless devices that interact in rapidly changing communication environments, handling situations where transactions must be completed in a short time-frame. However, before the IEEE 802.11p-based technology will enter the market much effort has to be invested in simulations and field-test experiments, to ensure that ITS are able to meet the application requirements when being deployed in specific vehicular environments.

Several research groups have considered car communication aspects based on empirical measurement campaigns. Some of them were focused on system efficiency enhancement and current standard improvements. In [4] it has been shown that the mounting position of the roadside unit (RSU) antenna has strong influence on the reliability of vehicular communication channels. It turns out that the system efficiency can be greatly enhanced by means of mounting RSU antenna at the height higher that the largest vehicle. Moreover, in [5] different onboard unit (OBU) antenna positions were considered. The authors concluded that the rooftop position yields the best performance in terms of lowest error ratios. Besides the investigation of different test platforms, a variety of system parameters, such as packet length, data rate and vehicle speed were explored. The authors of [6] have observed a negligible impact of the vehicle velocity on the communication range with different packet lengths and data rates. Furthermore, they concluded that the packet length has no influence on the achievable range, whereas the frame success ratio (FSR) has shown a very strong fluctuation for longer packets. The results of the measurement campaign presented in [7] show that higher-order modulation schemes yield a reduced communication range. Several authors were evaluating communication channels in realistic vehicular environments, such as urban and rural areas or motorways, as presented in [8]. Sub-urban and freeway environments were investigated in [9].

This paper presents results from an extensive measurement campaign evaluating the performance of the IEEE 802.11p physical (PHY) layer for an infrastructure-to-vehicle (I2V) tunnel scenario. We evaluate the system performance using various system parameter settings and investigate the impact

978–1–4244–9538–2/11/$26.00 © 2011 IEEE

of the propagation environment and the traffic situation inside the tunnel.

The remainder of this paper is organized as follows. The next section describes the measurement campaign in full detail. Specifically, we discuss the deployed hardware, the system parameters and the measurement environment. Section III presents the measurement results, which allow us to analyze specific propagation effects and various parameter settings. Finally, in Section IV we summarize the contribution of this paper.

II. Description of the Measurement Campaign

A. Experiment Design

This paper is focused on the evaluation of I2V measurements performed on the highway S1 in Austria during September 2010, within the ROADSAFE project [10]. The main objectives of this measurement campaign were to study propagation effects in a tunnel environment and to find the achievable communication range imposed by the tunnel with different parameter settings. We have used two CVIS platform nodes, which will be described in more detail in the next subsection. One of these nodes has been used as OBU and the other one as RSU. While the RSU was transmitting constantly, the OBU was recording the received signal just during the time intervals when we were approaching the expected coverage range, i.e., approximately 1 km before and after the RSU position. The recorded OBU signal has been post-processed in order to determine the number of received frames and to obtain a time stamp for each frame. Furthermore, we have evaluated the received signal strength indicator (RSSI) and we performed a cyclic redundancy check (CRC) on the decoded data to analyze whether the received frames have been decoded correctly or not. It is important to note that throughout this measurement no medium access control (MAC) layer functions have been used, i.e., there has been no uplink signaling of any kind.

We have used MAC service data unit (MSDU) packet lengths of 200 byte and 1554 byte, which we have tested in combination with different subcarrier modulation schemes, namely QPSK and 16-QAM, both with code rate $1/2$. For the evaluation presented in this paper the equivalent isotropically radiated power (EIRP) of the transmitter was set to 16 dBm. All measurements were performed at 5880 MHz and with an approximate vehicle velocity of 100 km/h. In addition, the measurements were performed on different lanes with multiple sets of system parameters. When driving to the east, we were passing directly under the RSU antenna. Since we did not change the mounting position of the RSU antenna, it was located across the motorway while we were driving in the other direction. Each measurement with the same parameter settings has been repeated three times.

B. Measurement Equipment

The measurement campaign was carried out using two nodes of CVIS 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 European CVIS project [11]. The objective of this project is to develop a harmonized technology for V2V and V2I communication, based on the international communications standard CALM, which provides interoperability between different car manufacturers and different roadside systems as well as infrastructure systems. The radio module inside each CVIS node includes a global positioning system (GPS) receiver, which constantly logs the exact position of the device. OBU antenna was mounted at the height of approximately 1.7 m on the roof of our test vehicle (a "Ford Galaxy").

The RSU CVIS node has been placed inside a weather protection case close to the highway gantry, where it was connected to the mains and a local area network. We have used two clockwise circularly polarized directional antennas with the nominal antenna gain of 6 dBi which were mounted on top of the gantry, at a height of approximately 7.1 m (see Fig. 1(b)). While the first antenna was radiating in the direction of the tunnel exit, as shown in Fig. 1(a), the second antenna was pointed in the opposite direction along the highway (see Fig. 1(c)). Both antennas were attached to a 3 dB power splitter followed by a 17 m long low-loss cable connecting them to the CVIS platform.

In addition we have used two digital cameras, in order to precisely document the environment and traffic situation during each measurement.

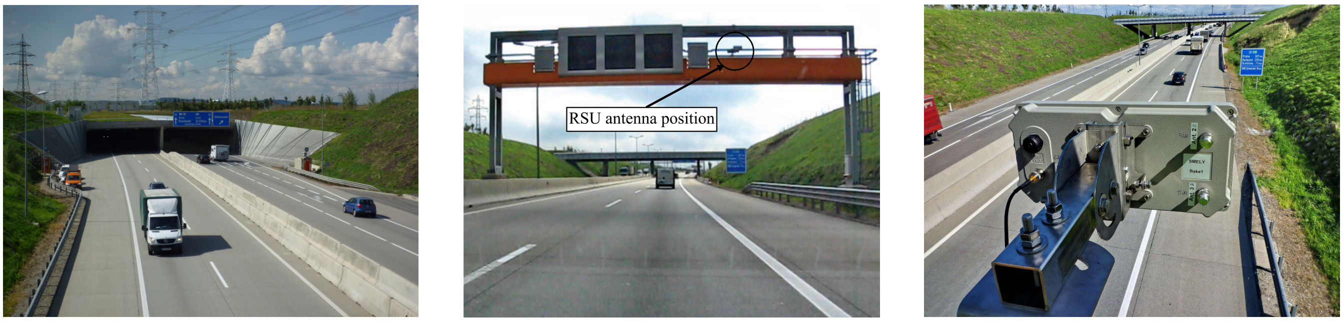
C. Measurement Environment

The measurement campaign took place on the highway S1 in Austria, having two lanes in each direction. There is a 300 m long tunnel, whose exit is at a distance of approximately 150 m from the gantry where the RSU was mounted. The highway was bordered with the grass-covered embankments from both sides creating kind of a canyon for the vehicle driving in the vicinity of the RSU, as shown in Fig. 1. There was also a bridge at a distance of approximately 140 m behind the RSU.

III. Measurement Results

A. Frame Success Ratio

In this subsection we focus on the discussion of the system performance in terms of signal-to-noise ratio (SNR) and frame success ratio (FSR) for measurements with different parameter settings. The SNR values are calculated based on the RSSI 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 provided in this paper 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 divided by the number of transmitted packets, during a certain time interval. In our case this time interval is defined as the amount of time required by the test vehicle to drive 10 meters. Since our vehicle was moving with a velocity of 100 km/h on average, the time interval for which we calculate the FSR is around 0.37 s. The number of



(a) View of the tunnel from RSU antenna position. (b) Mounting position of the RSU antenna. (c) RSU antenna and measurement environment.

Fig. 1. Measurement environment.

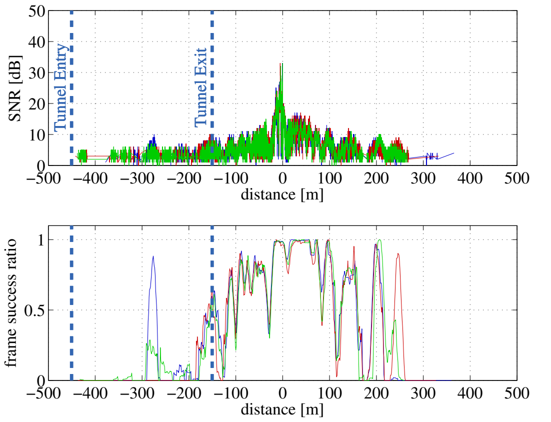


Fig. 2. SNR and FSR plots vs. distance. The test vehicle exiting the tunnel was passing directly under the RSU antenna at the distance of 0m. The data rate is 6 Mbit/s, the packet length is 200 byte, and the transmit power is 16 dBm. Repetitions of the measurement are indicated using different colors.

successfully decoded frames is determined by the result of the CRC of each frame.

Fig. 2 shows the resulting SNR and FSR curves plotted versus distance, where the origin of the abscissa corresponds to the position of the RSU. Negative values on the abscissa correspond to locations of the vehicle approaching the RSU from west towards east. The positive distances represent the vehicle locations after the RSU (this means that when we are exiting the tunnel, the OBU is passing directly under the RSU antenna at distance $d = 0\,\text{m}$). For this measurement we have used a data rate of 6 Mbit/s and a packet length of 200 byte. In Fig. 2, data recorded during three measurement repetitions using the same parameter settings is shown.

The maximum SNR value, which is around 33 dB, has been achieved directly in front of the RSU. For all measurement repetitions, SNR curves show typical large scale and small scale fading behavior after passing the gantry. However, the envelope of SNR curve at the negative distances lacks the large scale fading behavior. Particularly interesting is the behavior of the SNR curve inside the tunnel, where we observe just minor fluctuations and the SNR values remain below 10 dB.

Considering the FSR curve, we can conclude that we achieve higher goodput in the open area part. We can see that for all measurement repetitions, the FSR is above 0.25 from $d^- \approx -130\,\text{m}$ to $d^+ \approx 120\,\text{m}$, yielding a coverage range of approximately 250 m around the RSU. Observe that the drop of the FSR at d^- is located shortly after the test vehicle exits the tunnel. We conjecture that this drop is caused by a significant change in the propagation environment and an increased number of multipath components, that could not be properly resolved by the receiver hardware. The drop of the FSR at d^+ is most likely due to destructive interference of the LOS path and the reflection from the bridge, which is located at $d \approx 140\,\text{m}$ (see Fig. 1(c)).

Furthermore, we have observed that the different measurement runs have shown similar behavior in the open area part. In contrast to this, the deviation from the average FSR inside the tunnel is fairly large. This fact brings us to the conclusion that the traffic has a significant influence on the number of successfully received frames inside the tunnel. This influence will be analyzed in the next subsection based on our video documentation.

B. Traffic Effects

As already mentioned before, the variance of the FSR for different repetitions of the same measurement is clearly larger inside the tunnel than outside the tunnel. This observation can be explained by the absence of the LOS component between the OBU and the RSU, and as a direct consequence, the signal propagating inside the tunnel is strongly dependent on the traffic situation. Based on the video documentation, we have analyzed the influence of the traffic density, the type of moving objects and the distance between the test vehicle and the next moving object inside the tunnel. We can subdivide the possible traffic situations inside the tunnel into three scenarios, where each scenario has a different impact on the FSR.

1) Traffic scenario 1 (low traffic density): A typical low traffic density scenario is shown in Fig. 3(a). This figure is an extracted frame of the video that corresponds to the measurement run, which is indicated in red in Fig. 2. During this measurement run there were just few cars inside the tunnel and all of them were separated from the test vehicle by a relatively large distance of at least 100 m. From the corresponding FSR plot we can conclude that such a propagation environment is rather unfavorable for the reception quality inside the tunnel. Although there were no obstacles blocking the LOS, the signal radiated by the RSU antenna in the tunnel is quite weak.

2) Traffic scenario 2 (truck ahead): An example of such a scenario is depicted in Fig. 3(b). In this case the traffic flow is more intensive compared to the "low traffic density" scenario, especially because of two trucks, which were driving approximately $200\,\mathrm{m}$ ahead of the test vehicle. While these trucks were approaching the exit of the tunnel they were acting as reflectors, so that the signal radiated by the RSU antenna penetrated deeper into the tunnel. The blue curve in the Fig. 2, corresponds to this traffic scenario. As we will see later, this scenario yields the best performance in terms of FSR inside the tunnel.

3) Traffic scenario 3 (blocked LOS): Fig. 3(c) shows the traffic situation, corresponding to the FSR curve indicated in green in Fig. 2. In this case there is a truck approximately $80\,\mathrm{m}$ ahead of the test vehicle. In contrast to the previous scenario, the truck has a negative influence on the signal propagation, since it is blocking not only the LOS between the RSU and the OBU at the tunnel exit, but also some dominant multipath components inside the tunnel. Therefore this scenario can be expected to be worse than scenario 1.

Based on the video analysis we can conclude that not only the traffic density itself, but also the position and size of the vehicles between the OBU and RSU is crucial for the system performance in terms of FSR inside the tunnel.

C. FSR versus SNR Analysis

In this subsection we compare the dependence of the FSR on the SNR for signals propagating inside the tunnel, i.e., $-450\,\mathrm{m} < d < -150\,\mathrm{m}$, with the propagation in the open area in the same distance from the RSU, i.e., $150\,\mathrm{m} < d < 450\,\mathrm{m}$. Fig. 4 shows the resulting FSR versus SNR curves. Here, solid lines correspond to the open area part and dashed lines correspond to the tunnel part. Different colors again represent different measurement repetitions. For the sake of clarity we show only one curve for the open area part (solid green line), since the measurement results in the open area are similar for all repetitions (cf. Fig. 2) as mentioned previously.

For the open area part we can see that the FSR saturates at a value close to 1 for an SNR of roughly $9\,\mathrm{dB}$. Furthermore, in the medium SNR regime, the slope of this FSR curve is steeper than in the tunnel part. In particular this implies that an increase in SNR causes a higher FSR increase in the open area part than inside the tunnel.

Our results also show a saturation of the FSR starting at SNR $\approx 9\,\mathrm{dB}$ inside the tunnel. However, the FSR saturates at a value which is far from 1 and, more importantly, this value is dependent on the traffic situation inside the tunnel. We can see that the maximum FSR inside the tunnel differs by a factor of up to 2 for the different measurement repetitions depending on the traffic. Moreover, observe that the saturated FSR values are qualitatively consistent with our analysis of the traffic effects in the previous subsection.

D. Goodput Analysis

One of the objectives of this measurement campaign was also to find a set of system parameter settings, which yields

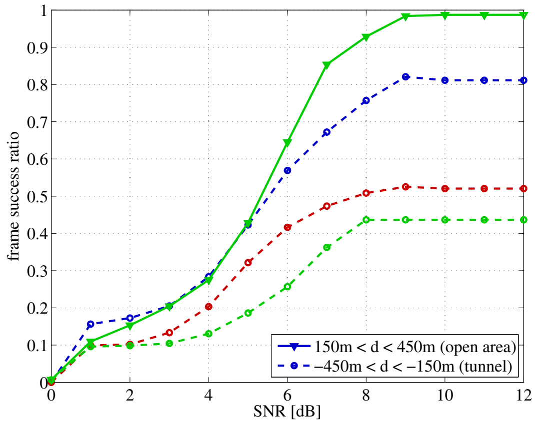


Fig. 4. SNR vs. FSR plots. The test vehicle is driving on the right lane heading eastward. The data rate is 6 Mbit/s, the packet length is 200 byte, and the transmit power is 16 dBm. Repetitions of the measurement are indicated using different colors.

maximum total goodput at a transmit power of $6\,\mathrm{dBm}$. Table I shows the corresponding results, in terms of data rate and packet length.

We note that the goodput vs. distance behavior is very similar to the FSR vs. distance curves depicted in Fig. 2, since the test vehicle velocity is approximately constant at $100\,\mathrm{km/h}$.

As shown in [4], the packet length has only negligible influence on the minimum SNR required to achieve FSR ≥ 0.5. Therefore, in this measurement campaign we have considered two significantly different packet lengths, namely $200\,\mathrm{byte}$ and $1554\,\mathrm{byte}$. Increasing the packet length is a simple approach to achieve higher throughput by simply decreasing the total amount of transmitted non-payload overhead. The main disadvantage of longer packets is that the quality of the preamble-based channel estimates is getting worse the longer the packet duration is. This is especially true in strongly time-variant vehicular channels. Furthermore, given a certain bit error probability, it is clearly more likely to see erroneous bits in a larger packet than in a short packet. Since the CRC will fail even if there is only a single bit error in the whole packet, this implies that the number of packets which have to be discarded due to CRC failure will increase with the packet length. The results of our measurements, summarized in Table I, indicate that the negative effects of larger packets outweigh the positive effects, i.e., the total goodput cannot be increased by simply increasing the packet length.

The results of our measurements show that the increase of the data rate by means of using higher order modulation schemes, is a more suitable approach for increasing the total goodput. Particularly, we have compared the total goodput achievable with QPSK and 16-QAM at a packet length of $200\,\mathrm{byte}$. We found that it is possible to achieve up to $60\,\%$ gain in goodput by doubling the data rate. This is primarily due to increased amount of packets recorded by the OBU. Since the amount of payload data per OFDM symbols doubled when going from QPSK to 16-QAM, the number of OFDM symbols necessary for a given packet length is reduced. Thus, the transmission duration for each packet is reduced, yielding

(a) Low traffic density.

(b) Truck approx. 250 m ahead of the test vehicle.

(c) LOS at the tunnel exit blocked by the truck driving approx. 80 m ahead of the test vehicle.

Fig. 3. Various traffic situations in the tunnnel.

TABLE I
GOODPUT ACHIEVABLE WITH DIFFERENT PARAMETER SETTINGS.

Data rate (Mbit/s)	Packet length (byte)	Total goodput (Mbit)
6	200	27
6	1554	22
12	200	43

a higher quality of the preamble-based channel estimates and increasing the total amount of recorded packets in each measurement repetition. However, note that this increase in the total goodput comes at the price of a reduced coverage range, induced by the higher SNR requirements of 16-QAM compared to QPSK.

Thus, analyzing the trade-off between the data rate, the packet length and the resulting total goodput, we can conclude that for IEEE 802.11p-based ITS applications it is beneficial to keep the packet length rather short and to use higher order modulation schemes.

IV. CONCLUSIONS

We have evaluated the performance of IEEE 802.11p technology for an I2V scenario in a tunnel which features distinctive radio propagation effects. We reported and discussed the obtained transmission errors and the goodput.

Our measurement results indicate that the instantaneous traffic situation severely impacts the reception of the transmitted data, most dominantly inside the tunnel. The positions and sizes of the vehicles between the OBU and the RSU are of much higher significance than the density of the surrounding traffic.

For medium SNRs in the open area environment, we observe that an SNR *increase* results in a stronger enhancement of the FSR when compared to the tunnel environment. Additionally, we have evaluated the goodput achievable with various PHY parameter settings. It was shown that the use of higher order modulation schemes, while keeping the packet length constant, is more beneficial to the total goodput, than an increase in packet length.

ACKNOWLEDGMENT

This work was carried out within COST 2100 partially funded by the Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility and the FTW project ROADSAFE within the Austrian COMET framework. The financial support by the Federal Ministry of Economy, Family and Youth and the National Foundation for Research, Technology and Development is gratefully acknowledged. We acknowledge Kapsch TrafficCom for supplying the RSU antennas and the Federal Ministry for Transport, Innovation, and Technology of Austria (BMVIT) for granting a test license in the 5.9 GHz band.

REFERENCES

[1] "Commision decision on the harmonised use of radio spectrum in the 5875-5905 MHz frequency band for safety-related applications of intelligent transport systems (ITS)," 2008/671/EC, August 2008.

[2] CEPT, "Report from CEPT to EC in response to the Mandate on the harmonised radio spectrum use for safety critical applications of Intelligent Transport Systems (ITS) in the European Union," CEPT report 20, December 2007.

[3] IEEE 802.11p, "Draft standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements: Wireless access in vehicular environments," IEEE P802.11p/D9.0, September 2009.

[4] A. Paier, D. Faetani, and C. F. Mecklenbräuker, "Performance evaluation of IEEE 802.11p physical layer infrastructure-to-vehicle real-world measurements," in *Third International Symposium on Applied Sciences in Biomedical and Communicational Technologies (ISABEL) 2010*, November 2010.

[5] M. Shulman and R. Deering, "Third annual report of the crash avoidance metrics partnership april 2003–march 2004," Nat. Highw. Traffic Safety Admin. (NHTSA), Washington, DC, January 2005.

[6] A. Paier, R. Tresch, A. Alonso, D. Smely, P. Meckel, Y. Zhou, and N. Czink, "Average downstream performance of measured IEEE 802.11p infrastructure-to-vehicle links," in *2010 IEEE International Conference on Communications (ICC 2010)*, May 2010.

[7] M. Wellens, B. Westphal, and P. Mähönen, "Performance evaluation of IEEE 802.11-based WLANs in vehicular scenarios," in *IEEE 65th Vehicular Technology Conference*, April 2007, pp. 1167–1171.

[8] G. Grau, D. Pusceddu, S. Rea, O. Brickley, M. Koubek, and D. Pesch, "Characterisation of IEEE802.11p radio channel for Vehicle-2-Vehicle communications using the CVIS platform," CAWS internal report, http://www.aws.cit.ie/personnel/PersonalMain.php, Tech. Rep., 2010.

[9] J. Singh, N. Bambos, B. Srinivasan, and D. Clawin, "Wireless LAN performance under varied stress conditions in vehicular traffic scenarios," in *Vehicular Technology Conference, 2002. Proceedings. VTC 2002-Fall. 2002 IEEE 56th*, vol. 2. IEEE, 2002, pp. 743–747.

[10] https://portal.ftw.at/projects/roadsafe.

[11] http://www.cvisproject.org.