Average Downstream Performance of Measured IEEE 802.11p Infrastructure-to-Vehicle Links

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***Abstract*—For the launch of intelligent transport systems (ITS), it is necessary to have detailed understanding of their performance. The draft standard IEEE 802.11p is the physical and medium access control layer (PHY/MAC) standard extension for wireless access in vehicular communications to IEEE 802.11. In order to evaluate its performance, we carried out an infrastructure-to-vehicle trial on a highway using an IEEE 802.11p prototype. This paper presents evaluation results of the average downstream performance of the PHY. Shadowing effects mainly caused by trucks lead to a strongly fluctuating performance of the link quality, especially for settings with long packet lengths and high vehicle speeds. The maximum achievable range, where the frame-success-ratio is continuously larger than 0.25, is about 700 m. The maximum data volume that can be transmitted when a vehicle drives by a roadside unit is achieved at low data rates of 6 and 9 Mbit/s.**

I. Introduction

Wireless transmissions from vehicle to infrastructure (V2I), and from vehicle to vehicle (V2V) are gaining more and more importance. Such systems, in general called intelligent transport systems (ITS), have the potential to reduce accident rates and to improve traffic efficiency and driving comfort. The importance is also highlighted by the European committee decision on the harmonized use of the $5875 - 5905$ MHz frequency band for safety-related applications of ITS [1] and by the final draft of the European Telecommunications Standards Institute (ETSI) standard [2]. The performance of ITS significantly depends on the communication technology that is used. In North America the technology for ITS is specified by the IEEE 1609 standard family, “Wireless Access in Vehicular Environments (WAVE)”. For the wireless link, the IEEE 802.11 standard [3] is currently being amended by Task Group P (TGp) to support vehicular communications. Before this standard is implemented in vehicular communication systems its performance needs to be evaluated, whether it complies with the strict requirements of ITS. Therefore, we carried out a V2I measurement campaign with an IEEE 802.11p prototype system on a highway in Austria.

In [4] measurements with standard IEEE 802.11a/b/g equipment in V2V and V2I scenarios show that the vehicle distance and availability of line-of-sight (LOS) are very important performance factors. Further they observe higher number of retransmissions for larger packet sizes and a reduced communication range for higher-order modulation schemes. The work in [5] investigates the performance of IEEE 802.11a with different bandwidths and compares measured V2V channel parameters with critical parameters of IEEE 802.11a/p. The most critical parameter they found is the packet length, because it is longer than the coherence time of the radio channel, especially when using the smaller bandwidth of 10 MHz in IEEE 802.11p compared with 20 MHz in IEEE 802.11a. In [6] the modifications of IEEE 802.11p related to IEEE 802.11a, in order to make the new standard IEEE 802.11p more robust in vehicular scenarios are presented. Several investigations deal with simulation based performance evaluations, e.g., [7], [8]. [7] concludes that in dense traffic scenarios IEEE 802.11p cannot ensure time critical message dissemination, because of long medium access control (MAC) queues and high end-to-end delays. In [8] simulations show that 90 % of successful communications were conducted at a distance of 750 m.

In our V2I measurements we investigated the physical (PHY) layer of IEEE 802.11p *without any MAC* layer functions, i.e., no retransmissions took place. This separate investigation of the PHY layer allows us to find out strengths and possibly point out improvements to the PHY layer protocol design to enable robust communications in real-world V2I scenarios.

The remainder of this paper is structured as follows. In Section II the type of V2I measurements, parameter settings, equipment, and scenarios are explained. Section III presents the measurement results, distinguishing effects caused by specific propagation environments, and effects due to the parameter settings chosen. Finally, Section IV concludes the paper.

II. Measurements

A. Type of Measurements

In July 2009 we carried out V2I PHY trials on the highway A12 in Tyrol, Austria, within the REALSAFE project [9]. The measurement’s goal was to characterize the average downstream packet broadcast performance for a vehicle passing two roadside units (RSUs). Three nodes of the CVIS platform, [10], implementing the IEEE 802.11 TGp draft standard, were used for these performance measurements for a wireless channel centered around 5880 MHz with a bandwidth of 10 MHz. The two RSUs were installed at fixed locations on the highway with different antenna heights and configured as WAVE transmitters. The third CVIS platform was used as onboard unit (OBU) installed in a vehicle, and was configured as WAVE receiver with logging capabilities. There was no uplink signaling of any kind. Therefore, retransmissions were not used to increase reliability.

In order to investigate the behavior of the PHY layer, we filled the MAC service data unit (MSDU) of the transmitter with random data of specific length and transmitted this data over the wireless link. At the receiver we analyzed whether the frames could be decoded correctly, by checking the CRC-32 (cyclic redundancy check code). Further data, like the received signal strength indication (RSSI) values, number of received frames, time stamps of the frames, were logged with the Wireshark software tool at the receiver. Different packet length of the MSDU (0 Byte, 200 Byte, 787 Byte, and 1554 Byte) were investigated with a fixed data rate of 3 Mbit/s. Further we used all possible data rates (3 Mbit/s, 4.5 Mbit/s, 6 Mbit/s, 9 Mbit/s, 12 Mbit/s, 18 Mbit/s, 24 Mbit/s, and 27 Mbit/s) for our investigations with a fixed packet length of 200 Byte. All the different parameter settings were measured at two different vehicle speeds of 80 km/h and 120 km/h. Each measurement with the same parameter setting was repeated three times. The transmit power for the evaluations presented in this paper was set to 15.5 dBm (equivalent isotropically radiated power (EIRP)). The RSUs were transmitting continuously frames with the parameter settings mentioned above. With this setup we were able to receive frames at the OBU when we were entering the coverage area. The distance of the two RSUs was chosen large enough that there was no interference between the RSUs, i.e., there were two separated measurement setups with two RSUs. In this paper we focus on evaluation results from the RSU with the antenna mounted on the higher position.

B. Measurement Equipment

For both the RSUs and the OBU the CVIS platform was used. Each CVIS platform consists of a mobile vibration-proof PC equipped with a CVIS CALM M5 radio module, where the IEEE 802.11 protocol, including the TGp amendments, is implemented. The radio module was provided by Q-FREE in the framework of the European CVIS project [10]. The radio module is also equipped with a global positioning system (GPS) receiver, in order to log the location of the OBU and provide a global time stamp to both the OBU and the RSUs. As OBU antenna, the CVIS vehicle antenna [10] was used, which was also developed in the framework of the CVIS project. It was mounted with magnets on the roof of a VW Multivan at a height of 2 m. As RSU antenna we used a vertically polarized monopole with omni-directional antenna pattern and a nominal antenna gain of 9 dBi (SMARTEQ V09/54). For video documentation we used two digital cameras.

C. Measurement Scenario

As measurement scenario we chose the highway A12 in Tyrol, Austria. The RSU antenna was mounted on a metal pillar on the top of a highway gantry, 7.1 m above the road level (see Fig. 1). A low-loss cable connected the antenna with the CVIS platform, which was placed in a weather protection box close to the gantry at road level. The highway in the vicinity of the gantry is bordered by trees in both directions. There are two lanes in each direction. The lane divider consists of a waist-high concrete wall followed by bushes of the same height. The measurements were carried out in real traffic conditions for both driving directions (west and east) separately.

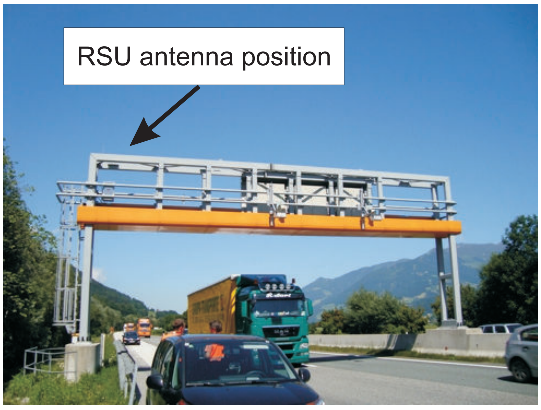

Fig. 1. Measurement scenario including RSU antenna position

III. Measurement Results

A. Definition of Performance Indicators

The *frame-success-ratio (FSR)* is defined as the number of frames that could be decoded with correct CRC-32 divided by the number of total transmitted frames during a time interval. We define the *achievable range* for the RSU on the interval where the FSR is permanently above a certain threshold. Based on a first evaluation of the FSR over distance for all measurement runs, we chose a threshold of 0.5 and 0.25. In Fig. 2 an example for the achievable range is depicted, where distance 0 m on the x-axis is the position of the RSU. Since we are using an omni-directional RSU antenna, the achievable range for the RSU is the overall range before and after the RSU. As *total data volume* we define the sum of all correctly received frames from the RSU multiplied by the packet length (MSDU length). The *achievable data volume* is calculated in the same way as the total data volume, but only the correct frames within the achievable range (FSR > 0.25), are considered. Furthermore we define the *theoretical data volume* as the number of transmitted frames from the RSU, when the OBU was inside the achievable range (FSR > 0.25), multiplied by the packet length.

B. Environment Effects

In this subsection, we analyze the impact of environment effects on the measured signal-to-noise ratio (SNR) and FSR.

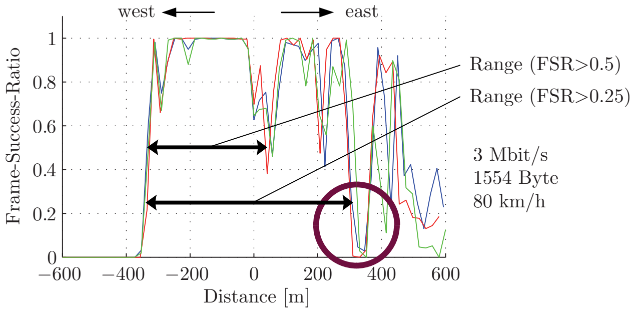

Fig. 2. Definition of achievable range and FSR fluctuation

We focus our attention on propagation effects that are caused by reflection, diffraction, focusing, and blocking of the traveling electromagnetic waves by objects between RSU and OBU. Thereafter, we investigate the impact of traffic on the performance of the system.

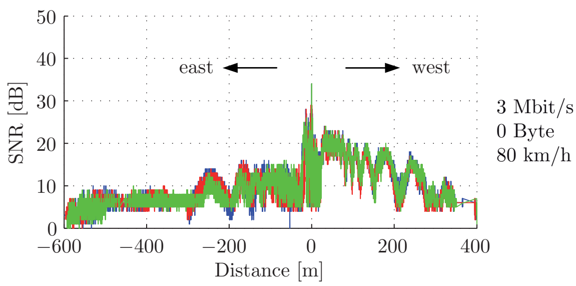

Fig. 3. SNR plot for vehicle driving west, transmit power 15.5 dBm

Figure 3 shows a characteristic SNR curve for a measurement run driving west. Three measurement runs with the same parameter settings were carried out and overlaid in the plot. The maximum SNR value is around 30 dB. The SNR curves for all runs show the typical large and small scale fading after passing the gantry, i.e., for positive distances. Surprisingly, the envelope of the SNR curve while approaching the gantry is 10 dB lower than after passing the gantry and lacks the typical small scale fading behavior. This unexpected behavior of the SNR curve is caused by the antenna pattern that is influenced by the metal pillars of the gantry. The antenna was mounted such that the metal pillars change the antenna pattern. Hence, the coverage range becomes unsymmetrical. For settings with higher-order modulation schemes, the unsymmetrical coverage range could be clearly identified.

In addition to the unsymmetrical coverage range, an unexpected throughput drop caused by propagation effects occurred at a distance of 300 m after the gantry in direction east. The drop in throughput could be observed for different parameter settings, i.e., different power settings and modulation schemes, and irrespective of driving direction. Figure 2 shows an exemplary FSR curve, where the drop in performance is emphasized by a circle. Here, the driving direction was west, the data rate was 3 Mbit/s and (long) packets of 1554 Byte were transmitted. Our conjectures are that this throughput drop was most likely caused by LOS blocking, where the receiver hardware was unable to equalize rich multipath channels at low SNR.

Traffic has a severe influence on successful transmissions. Depending on the traffic situation, moving objects (cars, vans or trucks) that are blocking the LOS between RSU and OBU cause significant downstream performance differences. The range, transmit data volume and FSR of the measurement runs vary significantly. This effect is particularly significant at larger distances from the gantry at low SNR. Figure 2 shows a strong fluctuating FSR curve before passing the gantry, i.e., for positive distances. Comparing the video documentation with our data, we find that the antenna pattern effect, throughput dropping and traffic effects superimpose. The fluctuation increases at the borders of the coverage interval, where the SNR is low. On the other hand, the system performs well after passing the gantry, in an interval of about 200 m, where the performance is not influenced by the traffic and the SNR curve shows the typical fading behavior (see Fig. 3).

Long packet lengths and increased speeds are especially critical and lead to a strongly fluctuating performance of the WAVE system. Antenna patterns and the influence of the traffic need to be taken into account for site planning.

C. Parameter Setting Effects

In this subsection we investigate the influence of different parameter settings (packet length, data rate, and vehicle speed) on the achievable range and possible data volume, when the vehicle is passing the RSU.

1) Packet Length Test: Four different packet lengths (0 Byte, 200 Byte, 787 Byte, and 1554 Byte) were investigated at a fixed data rate of 3 Mbit/s. The vehicle speed for the evaluations in this subsection was 80 km/h. Figure 4 shows the achievable range for both definitions, FSR > 0.25 and FSR > 0.5, and both driving directions, west and east. The achievable range for FSR > 0.25 is by definition always larger than the achievable range for FSR > 0.5. We observe no influence of the packet length on the achievable range (using our range definition, Sec. III-A). The achievable range for FSR > 0.25 is always between 600 m and 700 m for both driving directions. Only the achievable range for FSR > 0.5 is slightly decreasing at long packet lengths for driving direction west. This can be explained by the more frequent FSR drops for long packet lengths, as mentioned in Sec. III-B.

The data volume of the correctly received packets, shown in Fig. 5, is increasing with increasing packet length and is similar for both driving directions. The total data volume is approximately 6 MB for a packet length of 200 Byte and approximately 10.5 MB for a packet length of 1554 Byte (retransmissions were not used, when packets were lost). The curves flatten at longer packets, because there is a packet length-independent gap between contiguous transmitted frames.

In Fig. 6 the achievable and theoretical data volume (including error bars), as defined in Sec. III-A, are shown. Both data volumes are increasing with increasing packet length. By taking the difference between the theoretical data volume and the achievable data volume, we can calculate how much data is lost during the transmission period. For driving direction east

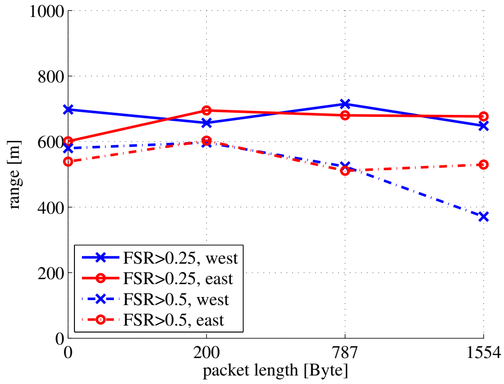

Fig. 4. Achievable range vs. packet length (80 km/h, 3 Mbit/s)

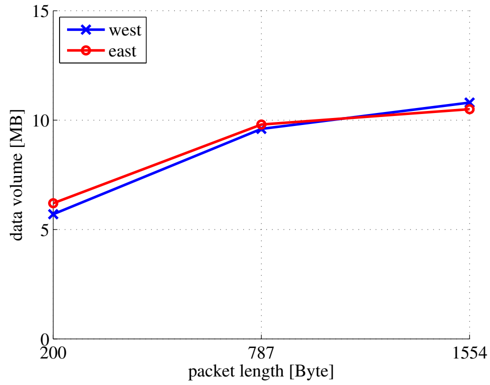

Fig. 5. Total data volume vs. packet length (80 km/h, 3 Mbit/s)

this data loss is increasing (0.7 MB, 1.5 MB, and 1.7 MB). For driving direction west such a behavior cannot be observed (0.6 MB, 1.4 MB, and 1.3 MB).

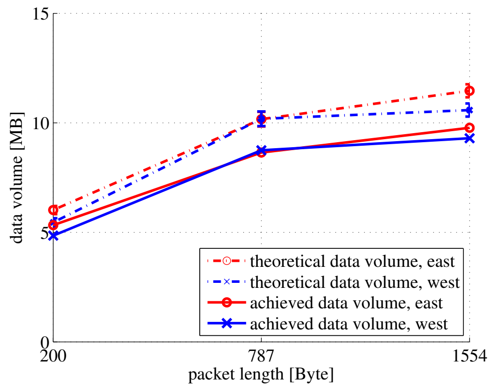

Fig. 6. Achievable/theoretical data volume vs. packet length (80 km/h, 3 Mbit/s)

2) Modulation and Coding Scheme Test: For this investigation all possible data rates of the IEEE 802.11 TGp draft, as described in Sec. II-A, were measured at a fixed packet length of 200 Byte and a vehicle speed of 120 km/h. In Fig. 7 the achievable range is plotted over the respective data rates. The achievable range is decreasing with increasing data rate. The same trend is observed for both driving directions and for both definitions of the achievable range (FSR > 0.25 and FSR > 0.5). The largest achievable range is approximately 720 m at a data rate of 4.5 Mbit/s and is decreasing to a range of smaller than 100 m for the highest data rate of 27 Mbit/s. The achievable range for FSR > 0.5 is only 10 m at this highest data rate. This behavior was expected, since higher-order modulation schemes need a higher SNR at the receiver in order to correctly decode the data.

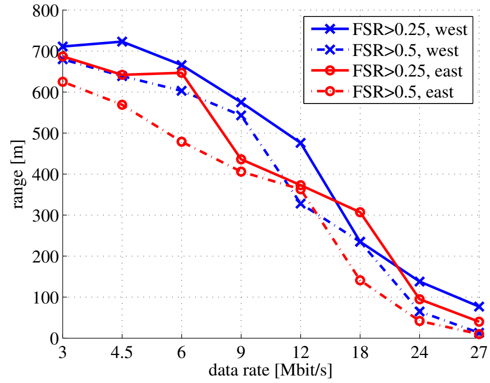

Fig. 7. Achievable range vs. data rate (120 km/h, 200 Byte)

Figure 8 shows the total data volume that is correctly received for both driving directions. The highest total data volume, for driving direction west, of 6.1 MB is achieved at a data rate of 9 Mbit/s. For driving direction east the maximum total data volume of 5.4 MB is achieved at data rates of 6 Mbit/s and 9 Mbit/s. Both data rates use quadrature phase shift keying (QPSK) modulation with different coding rates (1/2 and 3/4). These curves clearly show the impact of the data rate and the range. Higher data rates lead to a larger data volume, however, the range significantly decreases with higher data rates. This effect leads to an initial rise of the total data volume, with a strong eventual decrease.

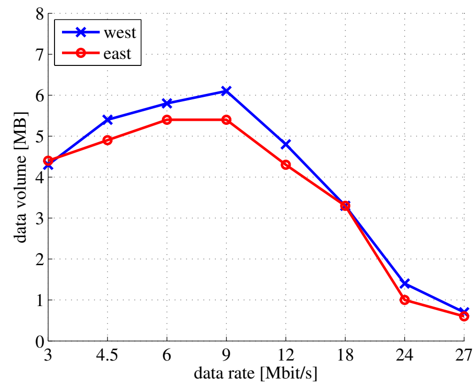

Fig. 8. Total data volume vs. data rate (120 km/h, 200 Byte)

In Fig. 9 the theoretical and achieved data volume are shown. The data loss, difference between theoretical and achieved data volume, is between 0.2 MB and 1.7 MB. No influence of the data rate on this loss is observed. As for the total data volume the maximum achieved data volume is observed at 6 Mbit/s (direction east) and 9 Mbit/s (direction west). The reason for the decreasing behavior of the theoretical data volume after a specific data rate is due to its definition based on the achievable range. This range is decreasing with increasing data rate.

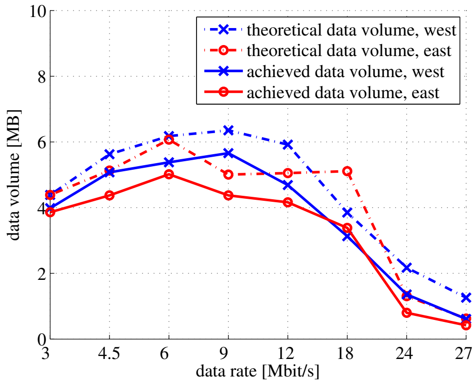

Fig. 9. Achievable/theoretical data volume vs. data rate (120 km/h, 200 Byte)

3) Vehicle Speed Test: The packet length test measurements were carried out at a vehicle speed of 80 km/h, as presented in Sec. III-C1, and 120 km/h. We observed no influence of the speed on the achievable range for different packet length. The total data volume is smaller in the case when the vehicle is driving 120 km/h. The average difference over packet length and driving direction between the higher speed, 120 km/h, and lower speed, 80 km/h, is 2.5 MB. The main reason for this difference is that in the case of the higher speed, the vehicle is passing the RSU faster. Therefore, there is less time to transmit data from the RSU to the OBU.

For selected data rates (3 Mbit/s, 6 Mbit/s, 9 Mbit/s, and 12 Mbit/s) we repeated the modulation and coding scheme test with a vehicle speed of 80 km/h. As for the packet length test we observed no significant influence of the speed on the achievable range. Also the total data volume over data rate showed the same behavior as in the packet length test for different speeds. The total data volume is on average 1.9 MB smaller, considering the higher speed, which is proportional to the shorter time span, in which the vehicle is in the range of the RSU.

IV. Conclusions

WAVE performance measurements for vehicle-to-infrastructure links were carried out on an Austrian highway. The RSUs were set up in "broadcast" mode, which means that there is just a one-way link from the RSU to the OBU. Hence, we did not allow retransmissions.

Environment effects, such as antenna height, electromagnetic wave propagation effects, and traffic were found to have a severe impact on the performance of WAVE. Shadowing effects caused by trucks lead to a strongly fluctuating transmission performance, particularly for settings with long packet lengths and higher speeds. Furthermore, the RSU antenna pattern was found to be strongly influenced by its surrounding (metallic) environment. To avoid a resulting unsymmetrical coverage range, improved antenna designs are necessary. Unexpected throughput drops, caused by the poor IEEE 802.11 pilot pattern design and by the equalizer capabilities of the receiver hardware, were observed for environments with rich multipath channels at low SNR.

The maximum coverage range of approximately 700 m, for a FSR > 0.25, was achieved at a data rate of 3 Mbit/s. Different packet lengths showed no influence on the achievable range, however the FSR showed a very strong fluctuation for long packets. The total correct received data volume, when the vehicle was passing the RSU, was increasing from 6 MB for a packet length of 200 Byte to 10.5 MB for a packet length of 1554 Byte. By investigating the influence of different data rates, we observed a decreasing achievable range with increasing data rate (approximately 700 m at 3 Mbit/s to smaller than 100 m at 27 Mbit/s). The maximum correct received total data volume was achieved at low data rates of 6 Mbit/s and 9 Mbit/s.

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