Performance Evaluation of IEEE 802.11p Physical Layer Infrastructure-to-Vehicle Real-World Measurements

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***Abstract*—We evaluate the physical layer of infrastructure-to-vehicle communications from real-world measurements. For the measurements, a prototypical implementation of IEEE 802.11p was deployed in two roadside units (RSUs) along a highway in Austria. The required signal-to-noise ratio (SNR) for achieving a frame-error-ratio (FER) less than 0.1 is estimated from measurements for various configurations of data rate, packet length, and vehicle speed. Evaluations show that for a RSU with an antenna mounted at a low height (1.8 m) the required SNR depends on the packet length. This is not the case for a RSU, where the antenna is mounted higher (7.1 m). Further the averaged required SNR over all different parameter settings for the low RSU is 4.6 dB larger compared to the required SNR for the high RSU.**

I. Introduction

Wireless communications systems between vehicles and between vehicles and infrastructure are currently under development. With these systems, called intelligent transport systems (ITS), vehicles will communicate with each other and sharing information about their surroundings, hence the number of vehicle accidents and road deaths will decrease. The importance of such systems 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 and especially the reliability, which is of special interest for safety-related applications 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)". The Task Group P (TGp) is currently amending the physical layer (PHY) and medium access controll (MAC) layer of the IEEE 802.11p standard [3] to support vehicular communications. It is very important to evaluate the performance of this standard before it will be implemented, whether it complies with the strict requirements of ITS. Therefore, we carried out a vehicle-to-infrastructure (V2I) measurement campaign with an IEEE 802.11p prototype system on a highway in Austria.

In [4] field test with an IEEE 802.11p prototype are presented together with evaluations of the packet loss and latency. V2I measurements show that the vehicle speed (varied between 20 km/h and 100 km/h) does not really has an influence on the packet loss (about 30 %) and the latency (about 4 ms and 5 ms). The results in [5] show that with a standard IEEE 802.11a/b/g equipment in V2V and V2I scenarios the vehicle distance and availability of line-of-sight (LOS) are very important performance factors. A higher number of retransmissions for larger packet sizes and a reduced communication range for higher-order modulation schemes are observed in this paper. Beside the investigation of IEEE 802.11a performance for different bandwidths in [6], measured V2V channel parameters are compared with critical parameters of IEEE 802.11a/p. They found that the most critical parameter is the packet length, because it is longer than the coherences time of the radio channel (especially for the bandwidth of 10 MHz). Modifications of IEEE 802.11p related to IEEE 802.11a, in order to make the new standard IEEE 802.11p more robust in real-world vehicular scenarios are presented in [7]. A detailed explanation of an IEEE 802.11p prototype implementation is presented in [8]. First test on the road in order to find the best onboard unit (OBU) antenna position showed that the rooftop position yields the lowest error ratios. With this OBU antenna position communication ranges up to 1000 m in open area scenarios were achieved. [9] presents an IEEE 802.11p and IEEE 1609 implementation and results of the throughput, packet loss, and latency from performance measurements on the road. At a distance of more than 300 m the performance of these three indicators is decreasing rapidly.

In our V2I measurements we investigated the PHY 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 specific measurement results of the required signal-to-noise ratio (SNR) for a specific frame-error-ratio (FER) threshold of 0.1. Finally, Section IV concludes the paper.

II. MEASUREMENTS

An additional description of the measurements and results about the environmental effects on the measurement results and the coverage range and achievable data volume, passing the gantry, for various parameter settings (data rate, packet length) can be found in [10].

A. Type of Measurements

In July 2009 we carried out a measurement campaign, in order to investigate the downlink performance of the PHY of the draft standard IEEE 802.11p. This measurement campaign was part of the REALSAFE project, [11], and was carried out on the highway A12 in Tyrol, Austria. A vehicle, equipped with an OBU, was continuously passing two roadside units (RSU) that were installed next to the highway. While the RSUs were transmitting all the time, the OBU was recording the received orthogonal frequency division multiplexing (OFDM) frames, without sending any retransmissions, during the vehicle was passing the RSU. As center frequency 5880 MHz was chosen, which is the center frequency of the lower 10 MHz frequency band of the three frequency bands that will be used in Europe for intelligent transport systems (ITS), [12]. At the OBU, the received frames were checked if they can be decoded correctly, by analyzing the CRC-32 (cyclic redundancy check code). The Wireshark software tool was used, in order to log additional data, i.e., received signal strength indication (RSSI) values, number of received frames, and time stamps of the frames. The lengths of the transmitted RSU packets, which is in our case the length of the MAC service data unit (MSDU), were set to 0 Byte, 200 Byte, 787 Byte, and 1554 Byte. In the case of packet length 0 Byte the OFDM frame exists just of the PHY header. Further we used data rates of 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, which are all possible data rates of IEEE 802.11p. The speed of the OBU-vehicle was 80 km/h and 120 km/h. The transmit power of the RSUs was set to 16 dBm and 7.5 dBm, equivalent isotropically radiated power (EIRP), for the lower RSU and 15.5 dBm and 10.5 dBm, EIRP, for the higher RSU. For each parameter setup, three measurement runs were carried out.

B. Measurement Equipment

Three nodes of the CVIS platform, [13], implementing the IEEE 802.11p TGp draft standard, were used, two of them as RSUs and one as OBU. The CVIS platform consists of a mobile vibration- proof PC equipped with a CVIS CALM M5 radio module, developed by Q-FREE in the framework of the European CVIS project, [13]. The radio module is also equipped with a global positioning system (GPS) receiver, in order to provide a global time stamp to both the OBU and the RSUs and log the location for an accurate evaluation of the distance between the OBU and the RSU. The used OBU vehicular antenna was also developed in the framework of the CVIS project and was mounted with magnets on the roof of the vehicle in a height of 2 m. The RSU antennas were vertically polarized monopoles with omni-directional antenna patterns and a nominal antenna gain of 9 dBi (SMARTEQ V09/54). In order to record the environment and the traffic during the measurements, two digital cameras were used.

C. Measurement Scenarios

1) Scenario 1 (low RSU): Both measurement scenarios were on the highway A12 in Tyrol, Austria, with two lanes in each direction. The antenna at scenario 1, also called low RSU, was mounted in a height of 1.8 m next to the gantry (on the right side of the lane in direction west) on a snow protection wall. There is a noise protection wall at the border of the highway in both directions, see Fig. 1 (a). This scenario is referred as rich scattering scenario.

2) Scenario 2 (high RSU): At scenario 2, also called high RSU, the RSU antenna was mounted on the top of a gantry in a height of 7.1 m on the lane in direction west, see Fig. 1 (b). In contrast to scenario 1 there are no noise protection walls, but the highway in the vicinity of the gantry is bordered by trees, as shown in Fig. 1 (c).

III. MEASUREMENT RESULTS

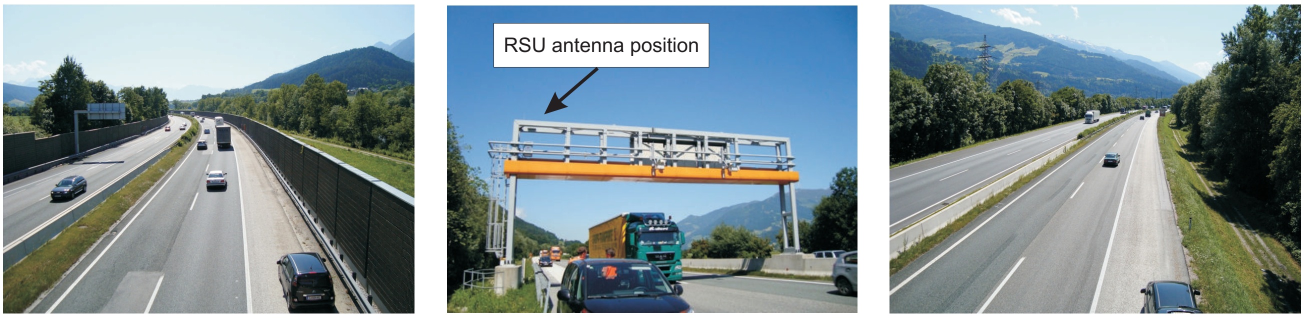
A. Definition of Performance Indicator

In this paper we analyze the FER versus the SNR for the different parameter settings, mentioned in Sec. II-A.

The SNR value is reported by the CVIS platform (analyzed with the Wireshark software tool) via the RSSI values. It is still a secret, how the CVIS platform measures/estimates the RSSI noise power and therefore the absolute SNR values provided in this paper can have a constant bias. However, the differences between the absolute SNR values of the different parameter settings are correct.

The FER is calculated by $\text{FER} = 1 - \text{FSR}$, where FSR is the frame-success-ratio. The 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. In order to get one FER value for each SNR value (in our measurements we got several different FER values for each SNR value), we take the median over the FER values. The main goal of this paper is to analyze the minimum required SNR for a FER value less than or equal to a threshold of 0.1. We calculate this required SNR for each measurement run and take the mean over the three repetitions with the same parameter setting. Theoretically the FER is monotonic decreasing with increasing SNR. In our measurements this is not always the case, but the FER is fluctuating over the SNR. In this case we define a second threshold at 0.2 and distinguish between following cases:

- If the FER vs. SNR curve is exceeding this threshold of 0.2 after dropping below 0.1, the next higher SNR value, where the FER is crossing 0.1, is chosen.
- If the FER vs. SNR curve is exceeding 0.1 after dropping below 0.1, but is staying below 0.2, the first SNR value, where the FER is crossing 0.1, is chosen.



(a) (b) (c)

Fig. 1. (a) Scenario 1 (low RSU), (b) mounting position of the high RSU antenna, (c) scenario 1 (high RSU)

Figure 2 depicts one example. The FER drops at first below 0.1 at point (i) (9.5 dB). This is not the valid required SNR, because the FER is exceeding afterwards the second FER threshold of 0.2, at point (ii). Point (iii) is the required SNR (17.5 dB), based on our definition, because the FER is staying below 0.2 afterwards. There is also a third point (iv), where the FER crosses the threshold of 0.1, but this is not the valid required SNR threshold, because between (iii) and (iv) the FER stays below 0.2.

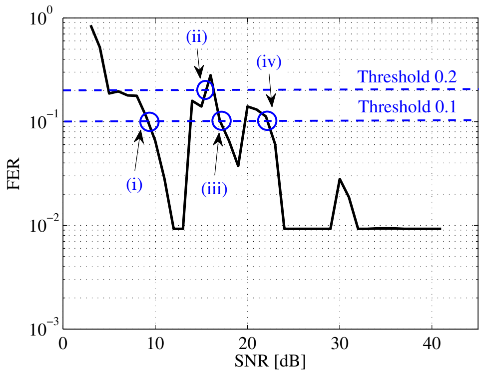


Fig. 2. Example of fluctuating FER

The lower bound of the FER, achievable with our way of calculation is based on the number of frames used for this calculation. This is depicted by the horizontal lines in Fig. 3 and Fig.7 at $1 \cdot 10^{-3}$ for the short packet length and in Fig. 4 and Fig. 8 at $9 \cdot 10^{-3}$.

In this paper we focus on evaluations of the higher speed, 120 km/h, of the OBU-vehicle.

B. Required SNR

1) Scenario 1 (low RSU): In Fig. 3 and 4 you can observe that the median FER is fluctuating much more at longer packet lengths. The reason for this is that the reported RSSI SNR of the CVIS box is based on the preamble of the OFDM frame. Since we have a time variant channel, the channel is changing much more at longer packet lengths. Therefore the SNR does not have so much influence on the FER, i.e., also at higher SNR there can occur errors, which leads to a more fluctuating FER versus SNR. In Fig. 5 it is shown

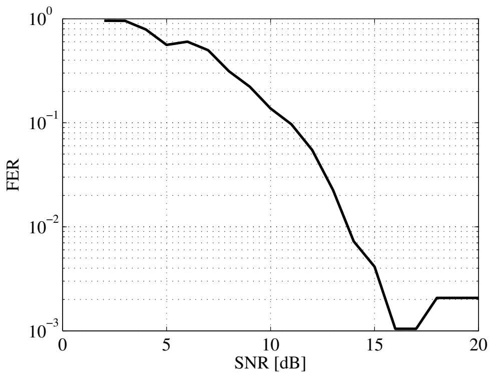


Fig. 3. Median FER vs. SNR for packet length 0 Byte at low RSU

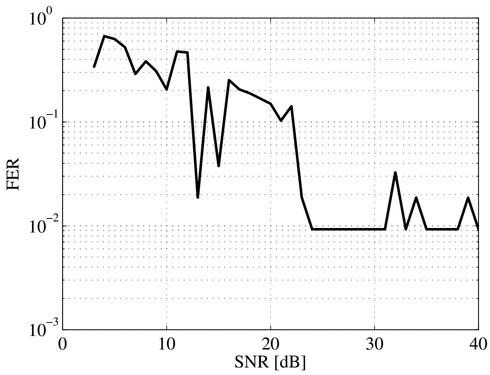


Fig. 4. Median FER vs. SNR for packet length 1554 Byte at low RSU

that the three shorter packet lengths (0 Byte, 200 Byte, and 787 Byte) do not have significant influence on the required SNR. Only the longest packet length shows a higher required SNR. There is a difference of 2.2 dB (mean over all packet lengths and both speeds for each driving direction) between the driving direction west and driving direction east, where the driving direction west shows a smaller required SNR. This is because the lanes in driving direction west are closer to the RSU compared to the lanes in driving direction east. If there are more lanes between the RSU and the OBU, there are more vehicles (cars as well as trucks) between them,

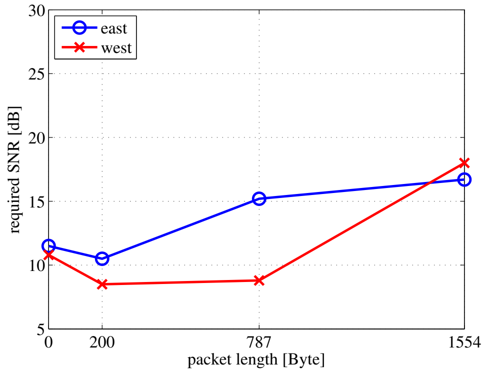


Fig. 5. Required SNR for variable packet lengths at low RSU, 120 km/h

which are blocking the LOS (remember that the RSU antenna height is only 1.8 m). The receiver is not able to cope these rich multipath channels. In Fig. 6 the influence of different data rates on the required SNR are shown. For the parameter settings used in this investigation, the packet length is 200 Byte and the data rate is 3 Mbit/s. It can be observed that the required SNR is increasing with increasing data rate. This is the expected result, because higher modulation schemes, which are used for higher data rates, need a higher SNR, in order to demodulate the received signal with the same error ratio. The mean difference of the SNR threshold between 27 Mbit/s and 3 Mbit/s is 15.4 dB. Similar to the observation for different packet lengths, there is a mean difference in the required SNR between the driving direction of 1.5 dB.

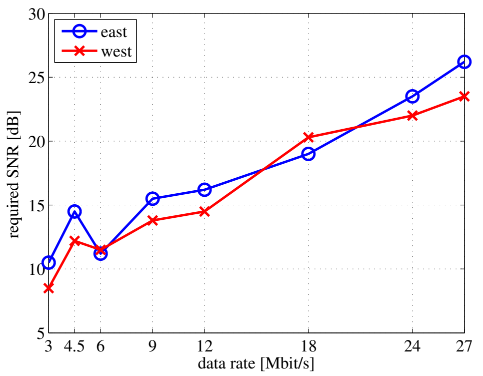


Fig. 6. Required SNR for variable data rates at low RSU, 120 km/h

2) Scenario 2 (high RSU): Compared to the FER curves from the low RSU, the FER curves from the high RSU are less fluctuating, see Fig. 7 and Fig. 8. The reason for this is that the radio channel between the high RSU and the OBU is less time variant compared to the radio channel between the low RSU and the OBU. In the case of the high RSU, other vehicles do not block the LOS as in the case of the low RSU, because the high RSU is mounted above the highway. The required SNR depicted in Fig. 9 shows no influence on the packet length. Also the driving direction has no influence on the required SNR. This is also a difference to the low RSU,

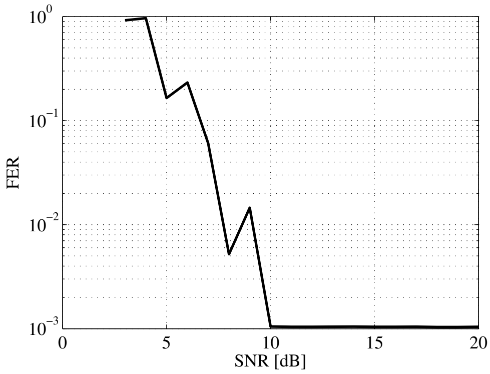


Fig. 7. Median FER vs. SNR for packet length 0 Byte at high RSU

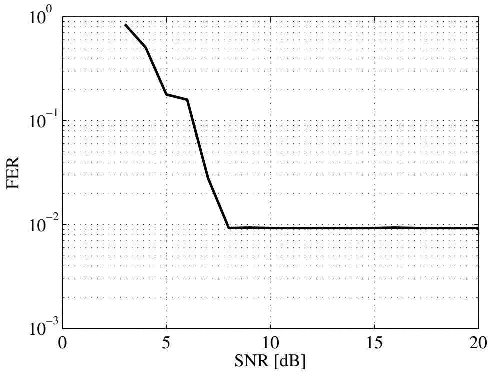


Fig. 8. Median FER vs. SNR for packet length 1554 Byte at high RSU

where the required SNR depends on the driving direction. The reason for this is again the mounting position of the RSU antenna, which is in this scenario above the highway. The vehicles do not block the radio propagation as much as with the low mounted RSU antenna. Figure 10 shows that the data

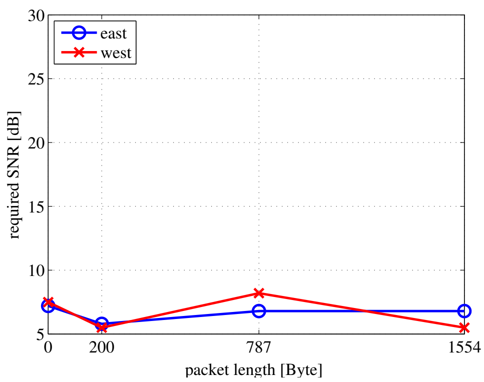


Fig. 9. Required SNR for variable packet lengths at high RSU, 120 km/h

rate has a large influence on the SNR threshold. For the highest data rate of 27 Mbit/s no required SNR could be calculated, because the FER stays always above 0.1. The mean difference between the SNR threshold at 24 Mbit/s and 3 Mbit/s for the speed of 120 km/h is 13.6 dB.

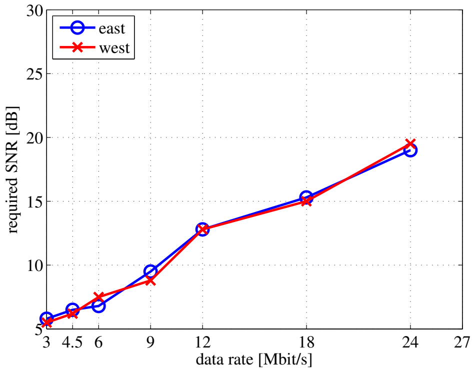


Fig. 10. Required SNR for variable data rates at high RSU, 120 km/h

IV. Conclusions

We evaluate and discuss the required SNR for the specific FER threshold of 0.1 from IEEE 802.11p PHY performance measurements, carried out on an Austrian highway. The RSUs were set up in "broadcast" mode, which means that there were no acknowledgments from the OBU and therefore no retransmissions from the RSUs.

Different packet lengths showed negligible influence on the required SNR for the high RSU, while for the low RSU the longest packet length increases the required SNR. This is explained by the radio channel being more time variant for the low RSU due to shadowing vehicles between the RSU and the OBU. On the other hand, the choice of data rate shows a significant influence on the required SNR in both scenarios, low RSU and high RSU. For the low RSU, the mean difference between the required SNRs for the highest data rate and the lowest one is 15.4 dB. For the high RSU the mean difference between the data rate of 24 Mbit/s and 3 Mbit/s is 13.6 dB (for the highest data rate of 27 Mbit/s there exists no required SNR, because the FER is always larger than the threshold of 0.1). The driving direction shows no influence on the required SNR in the case of the high RSU. For the low RSU, however, the driving direction does affect the required SNR. The mean difference of the required SNR is 1.7 dB. This is explainable by vehicles blocking the LOS between the RSU and the OBU in driving direction east, which results in a higher required SNR. Comparing the high RSU and the low RSU, the required SNR is always smaller in the case of the high RSU, with a mean difference over all parameter settings of 4.6 dB.

Based on these observations, we strongly recommend a mounting position of the RSU antenna at a height larger than the highest vehicles. This results in a more reliable vehicular communications channel that is especially of importance for safety related applications.

Acknowledgment

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References

[1] "Commission 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] ETSI ES 202 663, "European profile standard for the physical and medium access control layer of intelligent transport systems operating in the 5 GHz frequency band," final draft ETSI ES 202 663 v1.1.0, November 2009.

[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] C.-S. Lin, B.-C. Chen, and J.-C. Lin, "Field test and performance improvement in IEEE 802.11p V2R/R2V environments," in *IEEE International Conference on Communications, IEEE Vehicular Networks & Applications Workshop*, Cape Town, South Africa, May 2010.

[5] 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.

[6] L. Cheng, B. E. Henty, R. Cooper, and D. D. Stancil, "A measurement study of time-scaled 802.11a waveforms over the mobile-to-mobile vehicular channel at 5.9 GHz," *IEEE Communications Magazine*, vol. 46, pp. 84–91, May 2008.

[7] D. Jiang and L. Delgrossi, "IEEE 802.11p: Towards an international standard for wireless access in vehicular environments," in *IEEE 67th Vehicular Technology Conference*, May 2008, pp. 2036–2040.

[8] D. Carona, A. Serrador, P. Mar, R. Abreu, N. Ferreira, T. Meireles, J. Matos, and J. Lopes, "A 802.11p prototype implementation," in *Intelligent Vehicles Symposium (IV), 2010 IEEE*, La Jolla, CA, USA, June 2010.

[9] K.-Y. Ho, P.-C. Kang, C.-H. Hsu, and C.-H. Lin, "Implementation of WAVE/DSRC devices for vehicular communications," in *Computer Communication Control and Automation (3CA), 2010 International Symposium on*, vol. 2, May 2010.

[10] 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 *IEEE International Conference on Communications, Workshop on Vehicular Connectivity*, Cape Town, South Africa, May 2010.

[11] https://portal.ftw.at/projects/realsafe.

[12] "ECC decision of 14 March 2008 on the harmonised use of the 5875-5925 MHz frequency band for intelligent transport systems (ITS)," ECC Dec. (08)01, March 2008.

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

[14] D. Faetani, "IEEE 802.11p physical layer performance analysis of infrastructure-to-vehicle real world measurements," 2010.