Real-World Measurements-based Evaluation of IEEE 802.11p System Performance

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***Abstract*—In this paper, we discuss and analyze results from real-world vehicle-to-infrastructure (V2I) measurements in an IEEE 802.11p-based vehicular network. We compare measurements with different data rates and packet lengths and analyze their impact on system performance in terms of coverage range and throughput. Further we investigate influence of the driving direction on the system performance for different parameter settings and hardware components. Finally, we compare communication quality achievable with three different on-board unit antennas.**

I. Introduction

In recent years the idea of exchanging information between moving vehicles and roadside infrastructure 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 are able to retrieve information about traffic and road conditions enabling by that a variety of intelligent transportation systems (ITS) services such as automatic accident notification, vehicle condition reports, safety and driver assistance. Despite the seemingly large cost of deploying and maintaining the roadside infrastructure, V2I networks will clearly be a relevant component of future ITS applications. To carry out practical design of reliable roadside infrastructure-based communication systems, a deep understanding of the influence of every single system component and parameter is required.

Several research groups have considered vehicular communication aspects based on empirical measurement campaigns, in which impact of various system parameters, such as packet length, data rate, driving lane and vehicle speed were explored. The authors of [1] observed a negligible influence of the vehicle velocity on the communication range for different data rates and packet lengths. The results presented in [2] show that systems utilizing higher data rates, yield a reduced communication range.

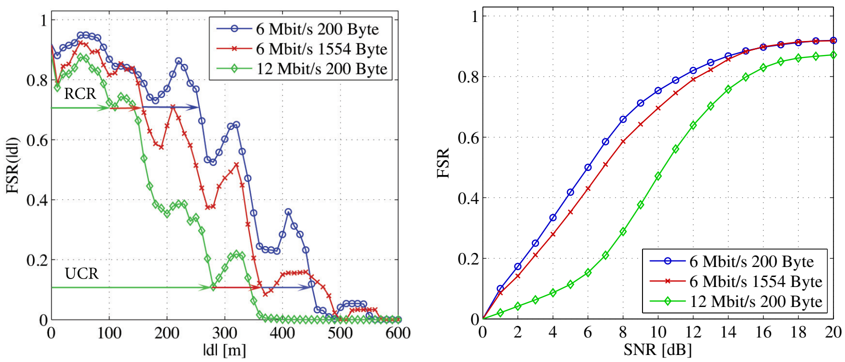
Other significant part of the measurement-based research activities in the field of V2I communications has been dealing with the effects introduced by the system components, such as antenna type and positioning, for both the on-board unit (OBU) and the roadside unit (RSU). With regard to OBU antenna, the authors of [3] considered different mounting positions and have concluded that a rooftop position yields the best performance in terms of lowest error ratios. Addressing the effects introduced by the antenna positioning related to the road geometry, the authors of [4] have shown that the system efficiency can be greatly enhanced by mounting RSU antenna at a higher position, above all the driving vehicles. Comparing the received signal strength (RSS) statistics for the RSU antennas mounted either on a mast next to the road, on a bridge above the road, or placed directly on the road surface the numerical results in [5] have shown that systems with RSU antennas mounted on the side of the road lead to the broader coverage range. Our previous field-tests [6] have shown that a 30% higher throughput and three times larger communication range can be achieved when using directional RSU antennas instead of omnidirectional. Further, we have shown that the influence of the environment and of the antenna mounting precision is larger for higher antenna gains.

However, the two types of experiments, the ones examining the system parameters and the ones considering system components have rarely been combined. Therefore, the main objective of the field study presented in this contribution is to analyze joint influence of different system parameters and components. Particularly, we search for system parameters that lead to the highest throughput and are more robust against change of the driving direction. Further we investigate if the influence of the driving direction can be reduced by an appropriate choice of the RSU antenna type and position. Finally we show that the OBU antennas having identical technical characteristics but different design lead to considerably different performance.

II. Experiment Design

All evaluations presented in this paper are based on V2I measurements performed on the highways S1 and A4 near Vienna, Austria within the ROADSAFE project [7].

The measurement campaign was carried out using the cooperative vehicle-infrastructure systems (CVIS) platform [8] as on-board unit (OBU) receiver. The CVIS platform is equipped with a CVIS communication architecture for land mobiles (CALM) M5 radio module implementing the IEEE 802.11p protocol and a global positioning system (GPS) receiver, which constantly logs the exact position of the device. The OBU was placed inside a test vehicle (a “Ford Galaxy”) and connected to one of the three OBU antennas under test. For evaluations presented in Sec. III-A, III-B and III-C CVIS vehicle rooftop antenna unit [9] was used. We will refer to it as **“OBU Antenna 1”** hereafter. In Sec. III-D we compare its performance to that achievable with other antennas referred to as **“OBU Antenna 2”** and **“OBU Antenna 3”**. The OBU antennas were mounted with magnets on the roof of the test vehicle at the height of approximately 1.7 m.



(a) FSR vs. absolute distance curves.

(b) FSR vs. SNR curves.

Figure 1: Performance comparison for different system parameters. System components: RSU Antenna 1; OBU Antenna 1.

We used two different platforms as RSU transmitters. For the measurements presented in Sec. III-A the same CVIS platform as for the OBU receiver was used. For all other measurements the transmitting RSU was an IEEE 802.11p standard compliant transceiver provided by Kapsch TrafficCom. In both cases the transmitter was placed inside a weather protection cabinet located close to the highway gantry, where it was connected to the mains and a local area network. It is important to note, that the packet generation rate was much lower for the latter transmitter, therefore the results of Sec. III-A should not be numerically compared with the remaining results. However a relative comparison is fair enough.

While the RSU was transmitting constantly in broadcast mode, the OBU was recording only within the expected coverage range, i.e., approximately 600 m before and after the RSU location. For each detected packet OBU records RSS, time and location where it was received and the result of a cyclic redundancy check (CRC), determining whether the detected packet was correctly decoded or not. Based on the results of CRC the frame success ratio (FSR) was calculated in the post-processing stage. FSR is a common metric used to characterize the performance of measured link for vehicular communications. It is defined as the number of packets that were successfully decoded by the receiver divided by the number of transmitted packets, during the time interval $T = \Delta/v$. Here, v is the velocity of the test vehicle and $\Delta = 10\,\mathrm{m}$, resulting in $0.36\,\mathrm{s} \leq T \leq 0.45\,\mathrm{s}$. Both the number of successfully decoded packets and the number of the transmitted packets were determined based on the MAC sequence number contained in the packet header. Fig. 1(a) shows an example of the FSR curves plotted vs. absolute distance from the RSU. Here, the FSR at absolute distance d is computed by averaging the FSR in the intervals $[-d-\Delta/2, -d+\Delta/2]$ and $[d-\Delta/2, d+\Delta/2]$.

All measurements were performed at a center frequency of 5.9 GHz in real traffic with a test vehicle speed between 80 and 100 km/h (22.2−27.8 m/s). The measurements were performed in both driving directions. The part of the measurements in which the test vehicle was driving directly under the RSU antenna will hereafter be referred as **"on RSU side"** and the measurements in which the test vehicle was driving in the other direction as **"opposite direction"**.

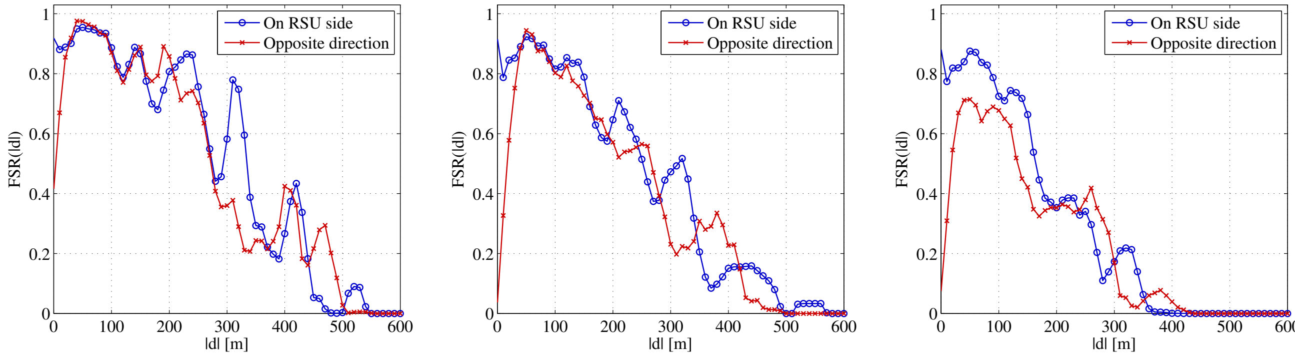
All results presented here were calculated as an average over at least 10 measurement runs.

III. Experimental Results

A. Data Rate vs. Packet Length for higher Throughput

One of the objectives of this measurement campaign was to find a set of system parameters yielding the largest throughput at a constant transmit power of 10 dBm. We define throughput as a number of packets successfully decoded during one measurement multiplied by the packet length. One possible approach to achieve higher throughput is to increase the packet length, thereby decreasing the total amount of non-payload overhead. The main disadvantage of using the 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, since the CRC will fail even if there is a single bit error in the whole packet, given a certain bit error probability it is clearly more likely to see erroneous bits in a longer packets. Another possibility to achieve higher throughput is to use higher data rate. In this case the packet duration will be reduced, which allows to transmit more information in the same period and improves quality of the channel estimates, since the packets become shorter.

Previously our research group has investigated influence of different packet lengths (0 Byte, 200 Byte, 787 Byte, and 1554 Byte) and 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) on the performance of V2I communication. As shown in [1] throughput increase was obtained for both longer packets and higher data rates. However, coverage range was significantly reduced when using higher data rates, while almost no change in this respect was obtained when using longer packets. Therefore, in this measurement campaign we have considered two significantly different packet lengths, namely 200 Byte and 1554 Byte (the latter is the maximum packet length supported by the CVIS transmitter). In addition we have considered data rates of 6 Mbit/s and 12 Mbit/s, as the ones leading to the highest throughput in our previous measurements.



(a) 6 Mbit/s and 200 Byte. (b) 6 Mbit/s and 1554 Byte. (c) 12 Mbit/s and 200 Byte.

Figure 2: Influence of driving direction on the FSR performance for different system parameters. System components: RSU Antenna 1; OBU Antenna 1.

Fig. 1 shows average FSR vs. distance performance for different system parameters. Already from a visual comparison of these curves one can conclude that both the packet length extension and the data rate doubling lead to performance degradation in terms of packet reception probability and coverage range. In order to better summarize the obtained results in respect to achievable coverage range we introduce the reliable communication range (RCR) and the unreliable communication range (UCR) [10], calculated as shown in Fig. 1(a). The RCR is the absolute distance from the RSU, within which the obtained FSR values are greater than 0.7 and the UCR is defined as the distance from the RSU, at which the FSR drops below 0.1. Due to specific choice of the hardware components (set of directional antennas) and the way of installing them, in some of our measurements a distinct coverage gap in the closest vicinity of the RSU was obtained. This behavior is reflected by a drop of FSR curves in range $0\,\mathrm{m} \leq d \leq 30\,\mathrm{m}$, e.g., red curves in Fig. 2. However, this effect was neglected in calculation of RCR and UCR.

Table I: Comparison of system performance achievable for different system parameters. System components: RSU Antenna 1; OBU Antenna 1.

Direction	Parameter settings	Mean throughput [Mbit]	Mean RCR [m]	Mean UCR [m]
On RSU side	6 Mbit/s 200 Byte	67	250	430
	6 Mbit/s 1554 Byte	116	150	380
	12 Mbit/s 200 Byte	61	115	300
Opposite direction	6 Mbit/s 200 Byte	56	220	490
	6 Mbit/s 1554 Byte	97	150	440
	12 Mbit/s 200 Byte	48	80	300

Table I compares the average range and throughput performance for different parameter settings. Measurement results indicate that the throughput was increased by more than 70% when using longer packets, while doubling the data rate resulted in throughput decrease of up to 10%. Both higher data rate and longer packet length resulted in coverage range reduction. However, in case of longer packets RCR was reduced by 40% and UCR by 12%, while for higher data rate we obtain up to 55% and 30% decrease in RCR and UCR, respectively. Therefore in contrast to our expectations, shortening of the packet length by using a higher order modulation scheme resulted in overall performance degradation and no throughput increase was obtained. The reason for this is on one hand the fact that the typical V2I channels are much less time-variant than the V2V channels and therefore packet length has less influence on the quality of channel estimates. On the other hand use of higher order modulation schemes impose higher SNR requirements, as can be seen from Fig. 1(b).

Fig. 1(b) shows an average FSR vs. SNR performance for measurements with different parameters settings. We observe that when using longer packets the SNR requirements remain almost unchanged, since the blue and the red curves flow fairly close to each other and even coincide starting with 14 dB. On the other hand the FSR vs. SNR curve for the measurements with higher data rate is always strictly below the other curves. Moreover, based on the results presented on Fig. 1(b) we conclude that an up to 4 dB higher SNR is required to obtain the same FSR value when doubling the data rate. This is mainly because for a given value of SNR, the symbols of 16-QAM constellation have to be more densely spaced than the symbols of the QPSK constellation.

B. *Influence of Driving Direction*

We extend investigation of the performance dependance on system parameters comparing FSR vs. distance curves for different driving directions, presented in Fig. 2. The blue curves represent FSR performance of the measurements conducted on the RSU side, while the red curves correspond to the measurements performed in the opposite direction. As it was shown in our previous work [6], it is possible to infer the packet loss behavior of such V2I system only within the first 200 m from the RSU, where it is mainly influenced by the antenna characteristics. Comparing the measurements with different parameter settings within this essential distance interval, we clearly observe that the curves obtained in different driving directions with lower data rate (Fig. 2(a) and 2(b)) are more correlated than the curves for measurements with higher data rate (Fig. 2(c)). Particularly we obtain an up to 20 %

Table II: RSU antenna characteristics

Antenna name	EIRP [dBm] / [mW]	Gain [dBi]	Antenna type	3 dB beamwidth hor./ver. [°]	Polarization	Mounting height [m]	Mounting position on a gantry
RSU Antenna 1	16.8/47.9	10	directional	35/35	RHCP	7.1	on highway side
RSU Antenna 2	12.2/16.6	14	directional	40/30	vertical	7.1	in the middle of highway

loss in FSR due to driving direction change, when doubling the data rate. From the results summarized in Table I, we conjecture that the average throughput reduction due to driving direction is 16.5 % for lower data rate and 21.5 % for higher data rate. Regarding coverage the RCR was reduced by 31 % for higher data rate and only by 12 % for lower data rate. When using longer packets there was no difference in coverage range associated with the change of direction direction and the throughput was reduced by 16.5 % when driving in the opposite direction for both packet lengths.

C. *RSU Antenna Mounting Position*

As shown in Fig. 2 the FSR curves for measurements conducted in the opposite driving direction have a distinctive gap at $0 \leq |d| \leq 30\,\mathrm{m}$ for all system parameters. Our observations suggest that this explicit drop of the FSR in the close vicinity of the RSU is due to the specific choice of the RSU antenna type and even more importantly due to antenna mounting position with respect to the road geometry.

For the measurements presented in Sec. III-A and III-B we have used a right-hand circularly polarized (RHCP) antenna, detailed characteristics of which are provided in Table II and which for simplicity will be called **"RSU Antenna 1"** hereafter. Fig. 3[1] emphasizes the mounting position of this antenna related to the road geometry shown in yellow. From this schematic representation it follows that there is almost no gap in coverage when driving on the RSU side, while the coverage gap in the opposite direction is fairly large, which clarifies the FSR drop of the red curves in Fig. 2.

To prove this assumption we have conducted experiments with different mounting position of the RSU antenna. In this case the RSU antenna was mounted on the other side of the gantry, exactly between the two driving directions. Since the antenna position and the tilt were changed, we have chosen antenna with slightly larger horizontal beamwidth in order to obtain comparably broad coverage range. Detailed characteristics of this antenna, called **"RSU Antenna 2"** hereafter, are provided in Table II. Analyzing schematic radiation pattern of the RSU Antenna 2 shown in Fig. 3 in green, we conclude that the signal is radiated more homogeneously along the highway and the coverage areas for both driving directions are more alike than in case of RSU Antenna 1.

Influence of the driving direction in systems with RSU antenna mounted in the middle of the highway between the driving directions is highlighted by Fig. 4 and Table III. Comparing blue curves on Fig. 4(a) and 4(b) we notice that the gap around the origin of the abscissa previously obtained for the opposite driving direction, i.e., in Fig. 2 is not present anymore and the curves look much more alike. The total throughput decrease due to driving direction measured in system with RSU Antenna 2 is only 6.5 % instead of 16.5 % obtained in case of RSU Antenna 1. However, the RCR was reduced by 12 % when driving in the opposite direction irregardless of RSU antenna type and mounting position.

[1]Carefully note that the radiation pattern shown in Fig. 3 is a purely schematic representation that does not take into account physical properties of the antennas and is only used for enabling better visualization.

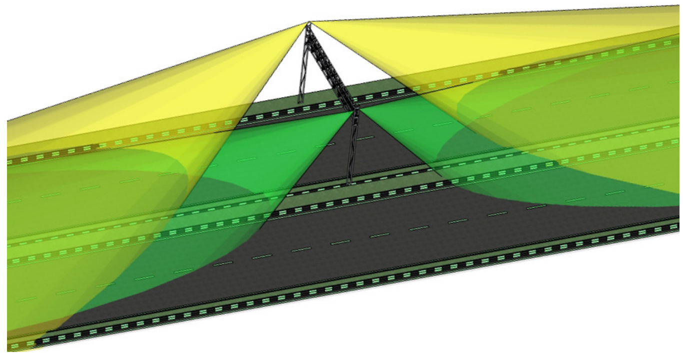
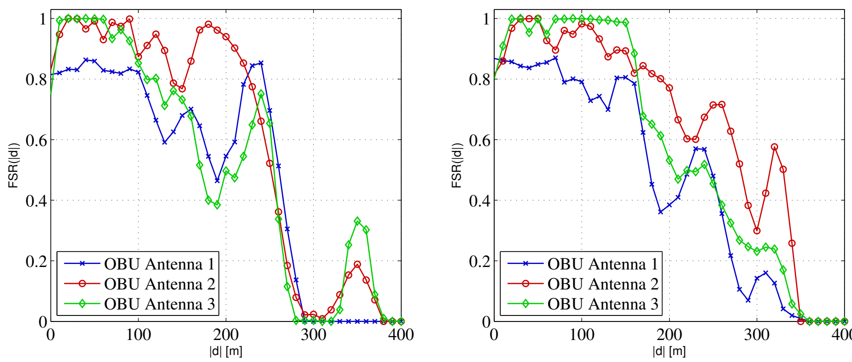


Figure 3: Schematic representation of different RSU mounting positions. The yellow color represents radiation pattern of RSU Antenna 1 and the green color of RSU Antenna 2.

D. *OBU Antenna Design*

Finally we repeat measurements with RSU Antenna 2, data rate of 6 Mbit/s and packet length of 500 Byte, however with different OBU antennas. For this purpose we have used two additional wideband OBU antennas, OBU Antenna 2 and OBU Antenna 3. Both of them have the same antenna characteristics as OBU Antenna 1, i.e., operate in $1.7 - 6$ GHz range with minimum peak gain (excluding amplification) of 5 dBi for the L1 signal band, are vertically polarized and allow for omnidirectional coverage in azimuth. Identical antenna mounting method, position on the test vehicle and cabling for all three OBU antennas were used. The purpose of this experiment was to show that OBU antennas with comparable technical characteristics, but different design lead to peculiarly large difference in performance.

The straightforward way to survey this remarkable performance difference is to compare the FSR vs. distance curves for different OBU antennas presented in Fig. 4. Since the red and the green curves are strictly above the blue curve within the essential distance interval around the RSU, we conclude that both OBU Antenna 2 and OBU Antenna 3 have higher packet reception probability in both driving directions. Measurement results provided in Table III show that the throughput was increased by 30 % in both driving directions and RCR was extended by 16 % when driving on RSU side and by 20 % in the opposite direction, when using OBU Antenna 2 instead of



(a) FSR on RSU side.

(b) FSR in opposite direction.

Figure 4: FSR performance for different OBU antennas and RSU Antenna 2. System parameters: 6 Mbit/s; 200 Byte.

Table III: Comparison of system performance achievable with different OBU antennas and RSU Antenna 2. System parameters: 6 Mbit/s; 200 Byte.

Direction	OBU antenna	Mean throughput [Mbit]	Mean RCR [m]	Mean UCR [m]
On RSU side .	OBU Antenna 1	12.3	130	290
	OBU Antenna 2	16	210	350
	OBU Antenna 3	12.7	160	330
Opposite direction	OBU Antenna 1	11	115	280
	OBU Antenna 2	14.3	230	280
	OBU Antenna 3	11.3	140	275

OBU Antenna 1. In case of OBU Antenna 3 a 3 % gain in throughput and 22 % increase of RCR were achieved for both driving directions. Despite the marginal increase in throughput, deploying of OBU Antenna 3 can be highly recommended for safety-related application due to its high and fairly stable FSR performance in the close vicinity of the RSU.

IV. Summary and Conclusions

Based on the results of the extensive real-world measurements, we have shown that use of longer packets is more suitable approach for increasing throughput of IEEE 802.11p-based V2I communications than using higher data rates. An overall throughput increase of 70 % was obtained when using packets of 1554 Byte instead of 200 Byte. For measurements with data rate of 12 Mbit/s both the throughput and the coverage range were reduced by 10 % and 55 %, respectively, as compared to 6 Mbit/s. Moreover, change of the driving direction resulted in a much stronger performance degradation when increasing the data rate as when using longer packets. Change of the driving direction results in 16.5 % and 12 % loss in throughput and RCR for the lower rate and in 21.5 % and 31 %, respectively for higher rate. While throughput and coverage range reduction when driving in the opposite direction was the same for both packet lengths.

We have shown that the RSU antenna mounting position with respect to the road geometry has significant influence on the system performance and its dependance on the driving direction. In particular, it was possible to reduce the throughput loss due to change of the driving direction from 16.5 Mbit/s to 6.5 Mbit/s only. We conclude that, in order to obtain homogenous coverage on both driving directions around the RSU, transmitting antennas should be mounted rather in the middle of the highway than on a side. The analysis of measurements with three OBU antennas having comparable technical characteristics, but different design, has shown that the careful choice of the OBU antenna design allows for up to 30 % increase in the throughput and up to 20 % extension of the RCR.

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References

[1] 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.

[2] M. Wellens, B. Westphal, and P. Mähönen, "Performance evaluation of IEEE 802.11-based WLANs in vehicular scenarios," in *65th IEEE Vehicular Technology Conference (VTC 2007-Spring)*, April 2007.

[3] 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.

[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)*, November 2010.

[5] P. Loskot, "Antenna configurations for infrastructure-to-vehicle broadcast systems on motorways," in *11th International Symposium on Communications and Information Technologies (ISCIT)*, October 2011.

[6] V. Shivaldova, A. Paier, D. Smely, and C. F. Mecklenbräuker, "On roadside unit antenna measurements for vehicle-to-infrastructure communications," in *23d IEEE International Symposium on Personal, Indoor and Mobile Communications (PIMRC)*, September 2012.

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

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

[9] I. Jensen and J. Gamage, "CVIS vehicle rooftop antenna unit," in *6th ITS in Europe Congress & Exhibition*, 2008.

[10] J. Gozalvez, M. Sepulcre, and R. Bauza, "IEEE 802.11 p vehicle to infrastructure communications in urban environments," *Communications Magazine, IEEE*, vol. 50, no. 5, 2012.