On Roadside Unit Antenna Measurements for Vehicle-to-Infrastructure Communications

Veronika Shivaldova*, Alexander Paier†, Dieter Smely†, Christoph F. Mecklenbräuker*
*Institute of Telecommunications, Vienna University of Technology, Vienna, Austria
†Kapsch TrafficCom, Vienna, Austria
Contact: veronika.shivaldova@tuwien.ac.at

Abstract—**In this paper, we discuss and analyze results from real-world vehicle-to-infrastructure measurements in an IEEE 802.11p-based vehicular ad hoc network. For our experiments we have used six roadside units (RSUs) mounted on highway gantries equipped with five different antenna types. We compare the performance of directional and omnidirectional antennas and analyze performance improvements in terms of coverage range and throughput, achievable by using directional antennas. Our results show that the use of directional antennas yields substantial performance improvements in IEEE 802.11p-based networks. However, for high-gain antennas even more careful RSU antenna positioning with respect to the lane geometry is required.**

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 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 investigated roadside unit (RSU) antenna influence on the system performance in order to obtain antenna design guidelines for the downlink in V2I systems. Addressing the effects introduced by the antenna positioning related to the road geometry, the authors of [1] 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 [2] have shown that systems with RSU antennas mounted on the side of the road lead to the broader coverage range. The authors of [3] have considered an analytical V2I network model with omnidirectional RSU antennas, directional RSU antennas and antennas that can switch between the two modes. Numerical results have shown that the coverage range achievable in V2I networks with directional antennas is more than four times higher than with omnidirectional antennas. According to results in [4] deployment of directional antennas leads to sustainable RSS and coverage range enhancements, achieved by suppression of undesired multipath effects and frequency selective fading. In [5] the authors study the advantages and the theoretical limits achievable by adopting directional and smart antennas in ad hoc networks. They conclude that the antenna beam-width becomes an important factor when the suppression-ratio is not high enough to mitigate nearby interfering transmissions. The authors of [6] present a realistic cross-layer model, accounting for path-loss, shadowing, Rayleigh fading and incorporating effects of both the channel capture effect and the use of directional antennas. It has been shown that directional antennas outperform omnidirectional antennas in terms of throughput and the number of interfering users in systems with directional antennas is less than that in systems with omnidirectional antennas. Although numerous studies have explored aspects of RSU antenna type and placement based on simulation results, much effort still has to be invested in real-world experiments and measurements.

Our work described in this paper is based on the results of an extensive field measurement campaign on austrian highways with realistic measurement environments and traffic conditions. We present a performance evaluation of V2I measurements with different RSU antenna gains and types, which were placed in six different locations along the highway. More specifically, we analyze system performance in terms of RSS and packet reception probability achievable with different antennas. We investigate the performance increase in terms of coverage range and throughput when using higher gain directional antennas instead of omnidirectional antennas. Moreover, we emphasize the strong impact of precise RSU antenna positioning for high-gain directional antennas.

II. Experiment Design

We focus on the performance evaluation of different RSU antennas 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. The radio module inside each CVIS node includes

Table I
RSU ANTENNA CHARACTERISTICS

Antenna name	EIRP [dBm] / [mW]	Gain [dBi]	Antenna type	3 dB beamwidth hor./ver. [°]	Polarization	Mounting height [m]
Antenna 1	20.3/107.2	9	omnidirectional	omni/14	vertical	9.1
Antenna 2	12.8/19.1	6	directional	60/60	RHCP	7.1
Antenna 3	16.8/47.9	10	directional	35/35	RHCP	7.1
Antenna 4	19.8/95.5	13	directional	42/23	RHCP	7.1
Antenna 5	12.2/16.6	14	directional	40/30	vertical	7.1

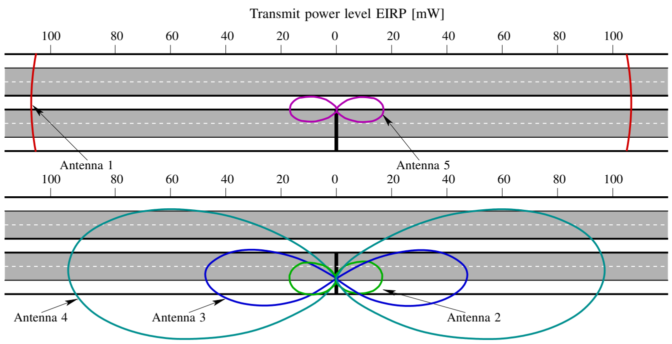


Figure 1. Antenna main beam patterns (in linear scale) and their positioning on the highway.

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 the CVIS vehicle rooftop antenna unit mounted on the roof of the test vehicle at the height of approximately 1.7 m. The CVIS CALM M5 antenna is a vertically polarized broadband (2 – 6.7 GHz) double-fed printed monopole with a radiation pattern close to that of an omnidirectional antenna, according to measurements in [9].

We used two different platforms as RSU transmitters. For the measurements described in Sections III-A and III-B we have used the same CVIS platform as for the OBU receiver. The transmitter platform was placed inside a weather protected cabinet close to the highway gantry, where it was connected to the mains and a local area network. The RSU was transmitting packets of 200 byte length at a data rate of 6 Mbit/s, corresponding to QPSK subcarrier modulation with code rate $1/2$. For the measurements presented in Section III-C, the transmitting RSU was an IEEE 802.11p standard compliant transceiver provided by Kapsch TrafficCom. For these measurements the RSU was again transmitting packets at data rate of 6 Mbit/s, but the packet length was 500 byte. Data rate of 6 Mbit/s was chosen according to the results in [10], as the one guaranteeing the most robust and reliable communication with RSU.

While the RSU was transmitting constantly in broadcast mode, the OBU was recording the received signal only during the time intervals when it was close to or inside the expected coverage range, i.e., approximately 1 km before and after the RSU location. The recorded by OBU data has been post-processed, in order to evaluate the RSS and the number of received packets together with the corresponding time and location information. Furthermore, a cyclic redundancy check was performed on the decoded data and based on that the frame success ratio (FSR) was calculated.

All measurements were performed at a center frequency of 5.9 GHz and were carried out in real traffic with a test vehicle speed between 80 and 100 km/h (22.2 – 27.8 m/s). The driving direction was chosen such that the test vehicle was driving directly under the gantry, on which the RSU equipment was installed. It is important to note that throughout the measurements no medium access control (MAC) layer functions were used, i.e., there was no uplink signaling of any kind.

We tested the performance of five different RSU antenna types, which were mounted on highway gantries in six different locations. The detailed characteristics of the antennas can be found in Table I[1]. In measurements with directional antennas there always were two identical antennas connected via a power splitter and mounted on the same gantry such that the signal was radiated in both directions of the highway. Fig. 1 shows a relative comparison of the equivalent isotropically radiated power (EIRP), horizontal antenna main beam pattern and antenna placement related to the road geometry for all antennas. The plots incorporate the EIRP and the width of the antenna's main lobe and are shown on linear scale. As shown in Fig. 1, Antenna 1 and Antenna 5 were mounted closer to the middle of the highway between the driving directions, while Antennas 2 to 4 were closer to the side of the road.

All results presented hereafter are based on sufficient number of repetitions and were calculated as an average over at least 10 measurement runs.

III. Experimental Results

A. Antenna Gain

In this subsection we focus on the discussion of the system performance in terms of communication range and throughput obtained by measurements with different RSU antennas.

A common metric used to characterize the performance of the measured radio link is the FSR. The FSR 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. 2 shows an example of the FSR curves plotted vs. absolute distance from

[1]Here, RHCP stands for right-hand circular polarization.

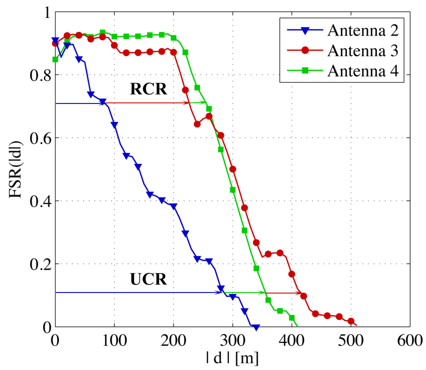


Figure 2. FSR performance achievable with different gain directional RSU antennas.

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 $[d-\Delta/2, d+\Delta/2]$. The blue, red and green curve represent the average FSR performance obtained in measurements with Antenna 2, 3 and 4, respectively.

In order to better summarize the obtained results in terms of the achievable coverage range we introduce the reliable communication range (RCR) and the unreliable communication range (UCR) as in [11], which are shown in Fig. 2. The RCR is the absolute distance from the RSU, within which the obtained FSR values are greater than 0.7, i.e., $\text{FSR}(d) > 0.7$ for all $d \leq$ RCR. The UCR is defined as the distance from the RSU, at which the FSR drops below 0.1, i.e., we have $\text{FSR}(d) < 0.1$ if $d \geq$ UCR. Therefore, the RCR represents the range over which high quality communications can be established, while for RCR $\leq d \leq$ UCR we expect a less reliable communication and for distances $d >$ UCR reliable communication with the RSU is not possible.

Comparing the FSR curves for measurements with different RSU antenna gains, we can first conclude that the UCR is almost doubled, when using Antenna 3 instead of Antenna 2 (4 dBi higher antenna gain). Even more important is the increase of the RCR by a factor of 5. A further 3 dBi increase of antenna gain (Antenna 4) did not yield a proportional coverage range extension. While the RCR was extended by 12 % compared to Antenna 3 and the FSR performance within this range is strictly greater, the average UCR was reduced by 15 %.

Additionally, for each measurement we have calculated the total throughput, defined as a number of packets successfully decoded during one measurement multiplied by the packet length. Table II compares the average range and throughput performance of Antennas 2 to 4. It can be seen that the largest throughput was achieved with Antenna 3, i.e., the 125 % average increase in throughput compared to Antenna 2. The average throughput of Antenna 4 is 12 % less than that of Antenna 3, irrespective of the 3 dBi increase of antenna gain.

We anticipate that the overall performance of systems with directional RSU antennas can be considerably increased by using antennas with higher gain. However, the performance growth is not strictly proportional to the antenna gain increase, since with increasing antenna gain the importance of precise antenna positioning is rising as well.

Table II
COMPARISON OF SYSTEM PERFORMANCE ACHIEVABLE WITH DIFFERENT RSU ANTENNAS.

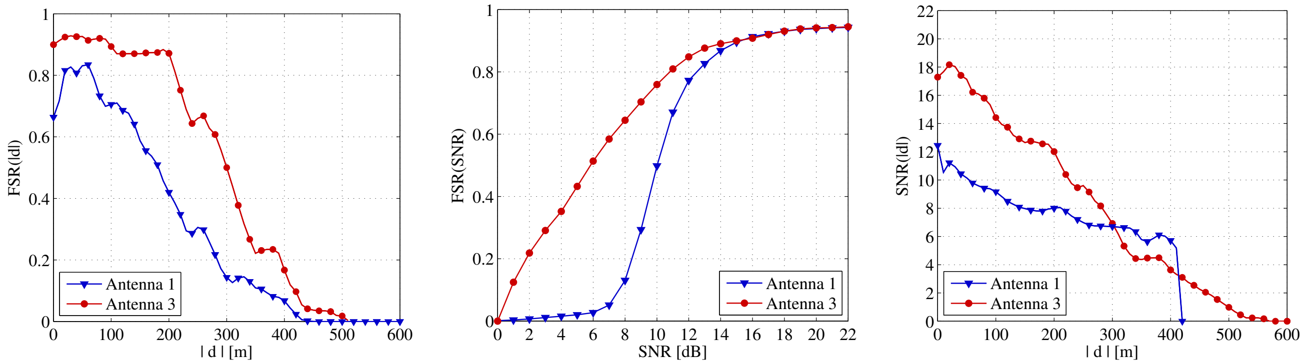
Used RSU equipment	Mean throughput [Mbit]	Mean RCR [m]	Mean UCR [m]
Antenna 2	28	45	290
Antenna 3	63	250	430
Antenna 4	56	280	370
Antenna 1	44	85	380

B. Directional vs. Omnidirectional Antenna

The comparison of directional RSU antennas with different antenna gains has shown that the best performance is achieved when using Antenna 3. Therefore we have repeated the experiment with an omnidirectional antenna (Antenna 1), whose gain is close to that of Antenna 3.

The average FSR performance of Antenna 1 and Antenna 3 is presented in Fig. 3(a). When using Antenna 1, we observe clear (up to factor of three) reduction of the range, in which reliable high quality communication with the RSU is possible. From the distinct gap between the two curves we observe that the packet loss probability in measurements with omnidirectional antenna is on average 20 % higher for the same distance between the RSU and the test vehicle. In fact the two curves never coincide for relevant FSR values, meaning that even under the best conditions, communication in systems with omnidirectional RSU antennas is 5 % to 10 % less reliable than that in the systems with directional antennas.

To further investigate the FSR performance for directional and omnidirectional antennas, we have plotted FSR vs. SNR dependencies for both antennas, shown in Fig. 3(b). The SNR values are calculated based on the received signal strength indication values logged by the CVIS receiving 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 achievable for SNR $\geq$ 15 dB is equal for both antennas. However in the range 0 dB $\leq$ SNR $<$ 15 dB the FSR achievable for the same SNR values is always significantly higher for directional antenna. Notable is also the obvious difference in the slopes of these curves. While the curve for Antenna 3 is monotonically increasing over the whole SNR range, the FSR values achievable with Antenna 1 are close to zero if SNR $<$ 6 dB and the slope of the FSR curve for 6 dB $\leq$ SNR $\leq$ 15 dB is much steeper. A possible reason for this slope dissimilarity is the difference in the field distribution for antennas with directional and omnidirectional antenna patterns. The most straightforward illustration for this difference is shown in Fig. 3(c). Here, the averaged SNR values are plotted vs. the absolute distance from the RSU, where $\text{SNR}(d)$ is computed by averaging the SNR in the intervals $[-d-\Delta/2, -d+\Delta/2]$ and $[d-\Delta/2, d+\Delta/2]$. The



(a) FSR vs. absolute distance curves.

(b) FSR vs. SNR curves.

(c) SNR vs. absolute distance curves.

Figure 3. Performance comparison of directional and omnidirectional RSU antennas.

Table III
COMPARISON OF SYSTEM PERFORMANCE ACHIEVABLE WITH THE SAME RSU EQUIPMENT IN DIFFERENT LOCATIONS.

Used RSU	Mean throughput [Mbit]	Mean RCR [m]	Mean UCR [m]
RSU1	11	140	300
RSU2	14	140	400
RSU3	14	140	520
RSU4	16	145	720

most important point here is that the average SNR values for the same distance are considerably higher for measurements with Antenna 3. We furthermore observe an abrupt drop of the SNR curve for Antenna 1 at $d = 410\,\text{m}$, which in particular implies that the average SNR of the measurements with omnidirectional antenna was varying in the range $5\,\text{dB} \leq \text{SNR} \leq 12\,\text{dB}$ most of the time and SNR values below $5\,\text{dB}$ rarely occurred. This clarifies the fact that the FSR of the omnidirectional antenna for $0\,\text{dB} \leq \text{SNR} \leq 5\,\text{dB}$ in Fig. 3(b) is close to 0 and confirms that for $d \geq 410\,\text{m}$ communication with the RSU is no longer possible (cf. Fig. 3(a)). Finally we note that for measurements with an omnidirectional antenna even in the close vicinity of the RSU, the average SNR was varying between $10\,\text{dB}$ and $12\,\text{dB}$, which according to Fig. 3(b) results in maximum achievable FSR of 0.5 to 0.8, thereby verifying the results shown in Fig. 3(a).

As a final remark in comparison between directional and omnidirectional antennas, we state that the throughput achievable in systems with omnidirectional antennas is on average $30\,\%$ less than the throughput of systems with directional antennas, as can be seen from Table II.

C. Drawbacks of High-Gain Directional RSU Antennas

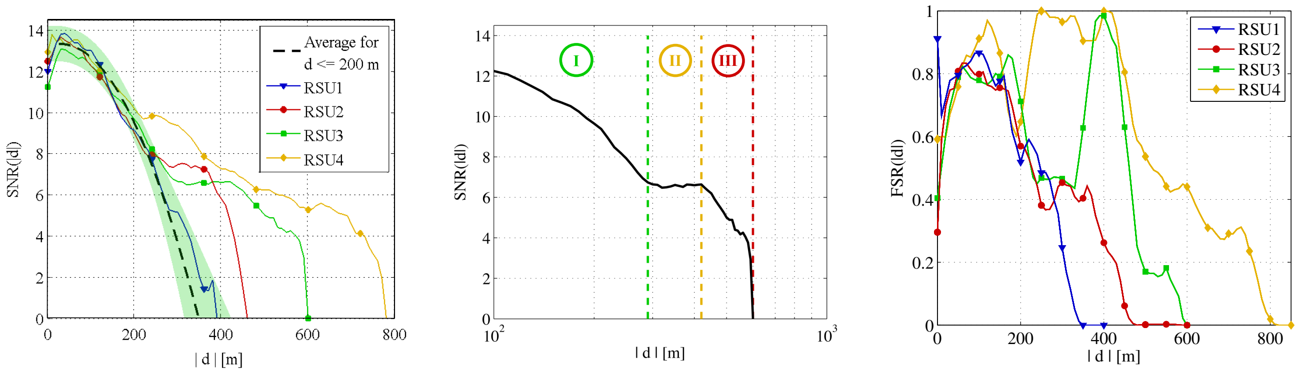
The results of the previous sections clearly show that directional antennas are more suitable for V2I communications than omnidirectional antennas and the use of higher antenna gains leads to increased throughput and coverage range. However with increasing antenna gain the precision of antenna positioning and influence of the environment becomes more important. In order to verify this observations we have performed a sequence of experiments with identically equipped RSUs using Antenna 5, placed in four different locations along the highway. This allows us to analyze the influence of road geometry and environment on the system performance. Regarding the measurement environment it is important to note that there was a noise protection wall on one side of the highway, starting exactly at the position of RSU2 and ending $120\,\text{m}$ after RSU4.

Average throughput and coverage range results for all RSUs are summarized in Table III[2]. Although the RSUs were identically equipped and operated, the measured performance was varying significantly for different locations, e.g., comparing performance of RSU1 and RSU4 we obtain $\sim 50\,\%$ difference in throughput and up to $250\,\%$ difference in UCR, while the RCR is almost equal for all the measurements.

To highlight the revealing difference in RSU performance, we show the SNR over distance measured by the receiver for each RSU in Fig. 4(a). Although the SNR curves seem to be quite different they in fact have a common tendency within $200\,\text{m}$ from the RSU. Based on the SNR values obtained from all RSUs within this range we have calculated a mean SNR vs. distance behavior represented in Fig. 4(a) by a black dashed curve and the corresponding $95\,\%$ prediction interval shown by the green shadowed area. We note that the only measured curve belonging to the $95\,\%$ prediction interval is the curve of RSU1, which is the only RSU located not in the vicinity of the noise protection wall. The SNR vs. distance curves of the other RSUs fall in to the green area only in the first $200\,\text{m}$, after which all curves flatten and the SNR remains nearly constant until it eventually drops rapidly.

Based on our observations the SNR behavior influenced by the noise protection wall, can be divided into three regions, each having a different slope and being caused by different propagation phenomena. These three regions are shown in Fig. 4(b), which represents the SNR vs. distance curve for RSU3 as in Fig. 4(a), however on a logarithmic scale. Within region I, the receiver has a direct line-of-sight (LOS) link to the transmitter and the SNR performance is mainly influenced by the antenna characteristics, e.g., antenna height, pattern

[2]Quantitative comparison of the results summarized in Table II and Table III is not possible, since not only the transmitting equipment, but also the parameter settings were different for these measurements



(a) SNR vs. distance curves for 4 identically equipped RSUs.

(b) Three specific ranges of the SNR vs. distance curve for RSU3 plotted in logarithmic scale.

(c) FSR vs. distance curves for 4 identically equipped RSUs.

Figure 4. Performance comparison of 4 RSUs identically equipped with Antenna 5, but differently located.

and the EIRP. Starting around 200 m the environment, such as the noise protection wall in case of these measurements, is essential for the signal propagation. We conjecture that the flattening of the SNR in region II is due to constructive interference introduced by the reflections from the metallic surface of the noise protection wall. With increasing distance between the transmitter and the receiver not only the phase of the reflections changes, introducing destructive interference, but also the number of multipath components increases. Therefore, we obtain an instantaneous drop of the SNR behavior in region III, where the receiver is no longer able to resolve the multipath components. All the effects described above are valid for RSU2 and RSU4 as well and do not only influence the mean SNR, but more importantly they strongly influence the FSR, as shown in Fig. 4(c). While within the first 200 m all curves are similar, the behavior changes drastically within region II where we obtain an extreme increase of the FSR measured for RSU3 and RSU4. We emphasize that the curves presented in Fig. 4 are based on 10 measurement repetitions and therefore the observed SNR and FSR dependencies are not random effects or artifacts.

IV. Summary and Conclusions

Based on the results of extensive real-world measurements, we have shown that directional antennas are more suitable for IEEE 802.11p-based V2I communications. The average throughput achievable in systems with directional antennas is 30 % higher and the range over which reliable communication with the RSU can be established is more than three times larger. We further have shown that by directional antenna gain increase of 4 dBi, the RCR can be increased by a factor of five and an average throughput gain of up to 125 % can be obtained. However, a further 3 dBi antenna gain increase did not yield further performance improvements, which underlines the fact that the use of high-gain directional RSU antennas imposes high requirements on the antenna positioning and placement. The analysis of measurements with identical equipment in different location has shown a strong influence of the environment on the overall system performance. From our results we infer that the signal propagation and packet loss behavior can be predicted based on the system parameters only within the first 200 m from the RSU, i.e., when the performance is mainly influenced by the antenna characteristics and the influence of propagation environment is negligible.

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