A Tool for V2X Infrastructure Placement

Michael Klöppel-Gersdorf[a] and Joerg Holfeld[b]
Fraunhofer IVI, Fraunhofer Institute for Transportation and Infrastructure Systems, Dresden, Germany

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Abstract: V2X technology sees an increasing rollout all over Europe, for instance as part of the C-Roads initiative. These rollouts are put into operation with implementing several use cases like Traffic Signal Priority request (TSP) for public transport or emergency vehicles or the provision of Green-Light Optimized Speed Advisory (GLOSA). Depending on the use case, the placement of V2X communication equipment, like Road-Side Units (RSUs), is essential for successful implementation of services. In this paper, a tool for V2X planning is introduced, which allows the efficient and fast estimation of V2X communication ranges especially in densely developed areas, reducing the need for costly measurement campaigns. Predicted data is compared with the results of a real-world measurement campaign in the city of Chemnitz, Germany.

1 INTRODUCTION

A variety of Vehicle-to-Everything (V2X) services, like Green-Light Optimized Speed Advisory (GLOSA) or Traffic Signal Priority request (TSP), require Road-Side Units (RSUs) installed at signalized intersections. To provide services successfully, transmission of messages must be guaranteed over a certain distance, e.g., receiving eco-driving information only briefly before the stop line does not help. While V2X communication based on IEEE 802.11p or C-V2X can reach distances of more than 1 km under optimal conditions, these communication ranges are much reduced in high-density areas like city centers, due to shadow fading, reflections, etc. Although there is a wealth of literature on the optimal placement of RSU, e.g., (Astudillo León et al., 2024), they are generally inspired by cell radio planning, i.e., with the goal of serving a certain area with the least number of units, while still having enough bandwidth to allow the realization of the V2X services even considering a large number of connected vehicles. Signal attenuation due to buildings and foliage is generally ignored, although these have a significant impact on transmission, up to completely blocking communication (Young et al., 2014) (the measurements conducted only included frequencies up to 4.9 GHz, but similar effects are expected for the current V2X technology, which uses 5.9 GHz). In addition, placement is not considered to be near a signalized intersection. This contrasts starkly with the realities when planning equipment for services like GLOSA or TSP. Typically, an RSU is installed at every signalized intersection, as a direct connection to the traffic light controller is required to get signal phase information or influence the signal plan. Furthermore, bandwidth is not a direct consideration as the penetration with connected vehicles is rather low (typically less than 1 %) and no immediate growth is expected in the near to mid future.

The propagation of V2X in urban areas was already considered in (Granda et al., 2017), where a ray-launching method coupled with a ray-tracing software was used to simulate propagation. Interestingly, this paper suggests that a simple exponential path-loss (as used in this study) might not be sufficient to model all necessary propagation effects. A similar approach as described here was already introduced in (Otto et al., 2023), although that paper was concerned with the implementation of TSP and does not provide insight into the workings and quality of the predictions. What the presented tool has in common with the cited research is the usage of a path-loss model (Goldsmith, 2005) to model radio propagation.

The specific reason for the presented research is situated in a shift the way TSP is carried out in Germany. Currently, most public transport providers use R09 telegrams (Schemel et al., 1990) transmitted us-

[a] https://orcid.org/0000-0001-9382-3062
[b] https://orcid.org/0000-0002-1618-4241

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ing a digital modulation scheme at frequencies in the 146 MHz – 174 MHz bands, which are designated for analog radio in the European Union. Currently, a channel spacing of 20 kHz is used, but due to harmonization in the European Union, the channel spacing will change to 12.5 kHz until the end of 2028. Furthermore, a part of the previously used frequency spectrum will be dedicated to other usages in the future. As a significant amount of current radio hardware installed in public transport is not able to operate under the new conditions, there is a currently a shift towards using V2X (mainly based on ETSI ITS-G5 over IEEE 802.11p) communication to solve these problems (Gay et al., 2022).

When realizing TSP using ETSI compliant messages, there are currently at least three possible implementations:

1. Using the R09 container within the special vehicle container in the Cooperative Awareness Message (CAM),
2. using the R09 container inside the Signal Request Extended Message (SREM),
3. or using a continuous registration flow using the SREM and Signal Status Extended Message (SSEM).

The first two methods have the advantage that the current logic for registration (based on four defined locations for pre-registration, registration, door-closed, deregistration) can still be employed, whereas the last method allows to use the whole movement profile of the public transport vehicle, allowing for a more tailored usage of resources. Outside of research projects, the third method is not being implemented in Germany at the moment. The first method requires the fewest channel resources, as the CAM must be sent regularly as required by the standard. A downside of this approach is that CAM do not hop using a geo-based broadcast mechanism. This complicates TSP, as the location for pre-registration can be located several hundred meters before the intersection and a direct communication between On-Board Unit (OBU) in the vehicle and the RSU at the signalized intersection is required. This problem can be overcome by the second implementation, as SREMs are allowed to hop and message flows can be organized, for example, with intermediate RSU.

In this paper, a tool for predicting V2X communication range is introduced which allows to estimate RSU positions at signalized intersections, considering surrounding building and allowing a sufficient range to fulfill the desired use cases. A comparison between real-world measurements and the modeling finalizes this publication.

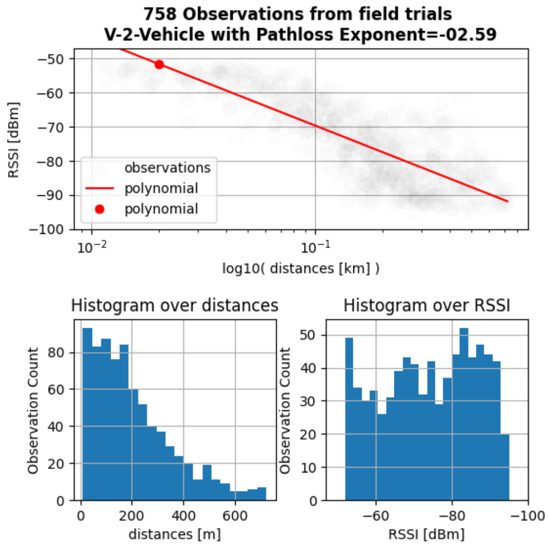

Figure 1: Measurements from test drives with RSSI vs RSU-OBU distance (top) and the histograms over distances and RSSI levels (below)).

The paper is organized as follows: The next section introduces the theoretical background for prediction of radio propagation and real-world measurements. Section 2.2 summarizes the findings, including a comparison between prediction and measured values. The paper is concluded in the last section.

2 METHODOLOGY

In the current iteration of the proposed tool, a user first identifies signalized intersections, which are to be equipped with RSU. In a second step, information of the desired coverage area (e.g., the registration points for public transport) have to be obtained. Last, the user has to manually position the potential RSU, considering constraints such as exiting posts, ductwork, maximum cable length, etc. The tool then uses a path-loss model as described below to predict V2X radio propagation and checks if reception levels are satisfactory for the given coverage area. If this is not the case, the RSUs have to be either moved to other positions or additional RSU have to be added.

2.1 Path-Loss Model and Link Budget

A simplified path-loss model according to (Goldsmith, 2005) is used to estimate reception levels caused by a RSU. This deliberately circumvents the modeling of reflections, shadowing, and fast fading effects. Obstacles due to traffic flows are also not considered and would require a statistical modeling. Typically, data packets are transmitted with a

Figure 2: Measurement setup used for data gathering. On the left is the RSU mounted on a mobile tripod, on the right is the vehicle used for measurements. The V2X antenna is visible on the top of the car.

robust and interference resistant modulation and coding scheme in accordance with the ITS-G5, so a V2X message can be reliably received within cell boundaries. The penetration density of the radio channel is not a limiting parameter due to the low traffic volume and small message size. A major focus was set to identify the Line-of-Sight (LOS) or Non-Line-of-Sight (NLOS) radio conditions between the transmitter and receiver geometry, the main source of obstructions being buildings. Therefore, the building locations were extracted from OpenStreetMap (OSM) as described in detail in the next section.

The RSU transmits with the highest allowed power of 23.0 dBm within the frequency band for V2X of 5.9 GHz. Due to the possible antenna positions at the masts, we consider a feeder loss of −2.5 dB and an omnidirectional modeled transmitting antenna with 2.0dBi gain. Geometric perspectives are taken into account in the antenna pattern, the distance between RSU and OBU, as well as the relative height of 5.0 m. Ultimately, distances greater than 750.0 m are not further modeled, as these are not typical in an urban environment. The RSUs and OBUs used are from the Cohda Wireless (see Section 2.3 below), which have a minimum reception level of −100.0 dBm, so that this parameter is used as a further termination criterion for the modeling.

The path-loss coefficient was determined from several measurement runs at various intersections and RSU masts in Chemnitz. The power losses were determined over the distance between the RSU and OBU. The path-loss coefficient results in the double-logarithmic representation as the slope of a regression line (see Fig. 1). During the measurement campaign, multiple situations occurred in which other road users

Table 1: The list of parameters for the link budget.

Link Budget Parameter	Value
Transmit Power	23.0 dBm
Feeder Loss	−2.5 dB
Omnidirectional RSU antenna	2.0dBi
Isotropic OBU antenna	0.0dBi
Height between RSU and OBU	5.0 m
Path-loss exponent	2.6
Reference distance	20.0 m
Reference offset	−74.1 dB
Penalty term for NLOS condition	−33.0 dB
Maximal transmission radius	750.0 m
Minimal OBU sensitivity	−100.0 dBm

crossed the direct line of sight and thus caused additional attenuation. In order not to weight such measured values and to remove the temporal bias by stopping at certain positions, the measurements were divided into segments of 10.0 m and only the median value of the upper 20% percentile of all Received Signal Strength Indicator (RSSI) was selected to avoid that obstacles downgrade the estimates. This assumption is regarded valid since a constant transmit power without a power control operates at the RSU side. Furthermore, positions with a distance closer than 10.0 m respectively RSSIs> -50.0 dBm are ignored. Finally, a path-loss coefficient of 2.6 dB per decade was estimated and used to model the propagation environment. The table 1 summarizes all the included parameters for the link budget.

2.2 Environmental Model via OSM

The decisive factor that influences the transmission / reception conditions is the building environment and the determination of the LOS and NLOS reception conditions. The layouts of the buildings listed in OSM were used for this purpose. The direct path from RSU to OBU was sampled every 10.0 m and their geocoordinates led to an Overpass-API query to determine if the point was located within a building. In the case of a building, the path was classified as NLOS and the additional path-loss of −33.0 dB was used as the penalty term. The value of the penalty term was not determined, only specified heuristically. OSM was also used to extract reception points on the roads used in the modeling.

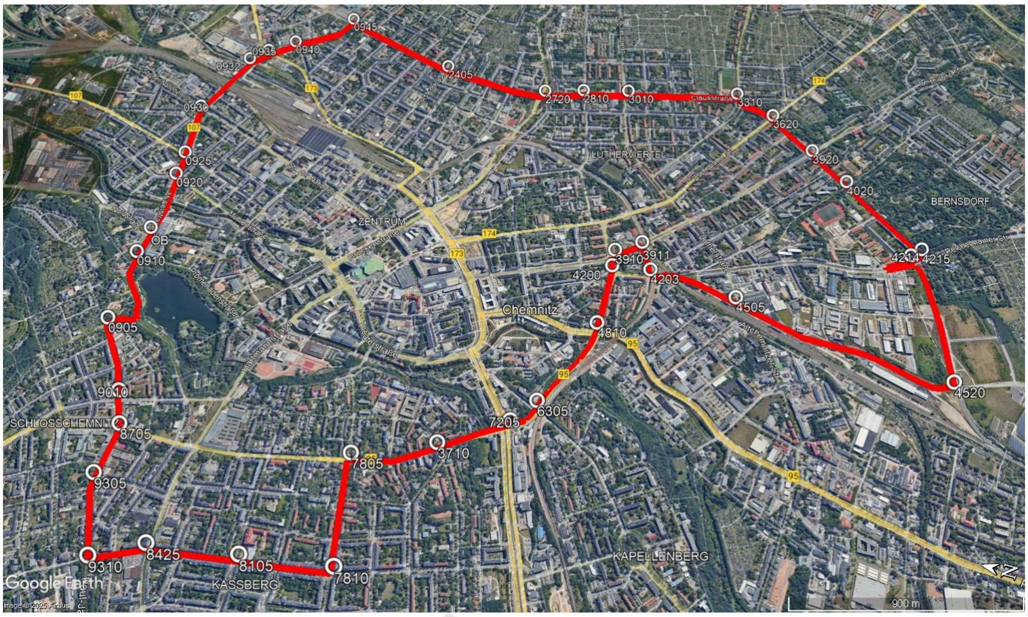

Figure 3: Route of the bus line 82 in Chemnitz, together with all (a total of 38) signalized intersections crossed by this line.

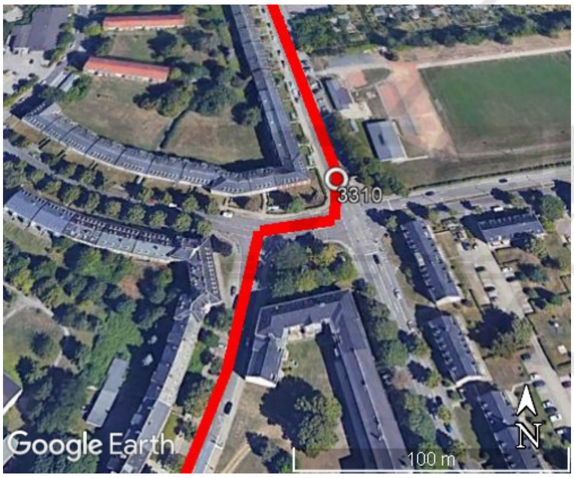

Figure 4: Example of one intersection, where manual measurements were conducted.

2.3 On-site Measurements

The measurement system for real-life measurements consists of an RSU mounted on a mobile post and an OBU mounted in a test vehicle. For both units, a Cohda MK5 was employed, which used a custom communication stack each (C4CART (Jacob et al., 2020)). The mobile RSU was modified for battery operation. Additionally, both OBU and RSU were equipped with cellular communication units to facilitate connection to a back-end server to allow real-time transmission of measurement data. In case of loss of mobile connectivity, measurement data can also be retrieved from recorded .pcap files.

As we are mainly interested in deploying TSP, a rather high vehicle (a Mercedes Vito) was used for the measurements, which is higher than a typical passenger vehicle. The complete measurement setup can be seen in Fig. 2.

For localization, the internal Global Navigation Satellite System (GNSS) modules of the respective units were used. These offer an accuracy of 2.5 m Circular Error Probable (CEP). For the measurements, the CAM were used, which were send according to the standard (ETSI EN 302 637-2 V1.4.1 (2019-04), 2019). This means that the RSU sends messages with 1 Hz, while the vehicle sends messages with 1 Hz – 10 Hz, depending on the dynamic state of the vehicle.

2.4 Limitations of the Model

Task of this evaluation is not an exact reproduction of the physical propagation behavior, but to get a solid idea of the placement of the RSUs. In particular, the cell borders need further visual inspections, since local obstacles might not be covered even in high-resolution maps. Furthermore, a constant height difference between sender and receiver is assumed (comp. Table 1), which is not always true due to the local topography. In addition, the low accuracy of 2.5 m CEP in the GNSS measurements potentially causes large differences between the reported and actual positions. Under some circumstances this leads to a wrong assignment of a NLOS connection, when comparing simulation with real world measurements.

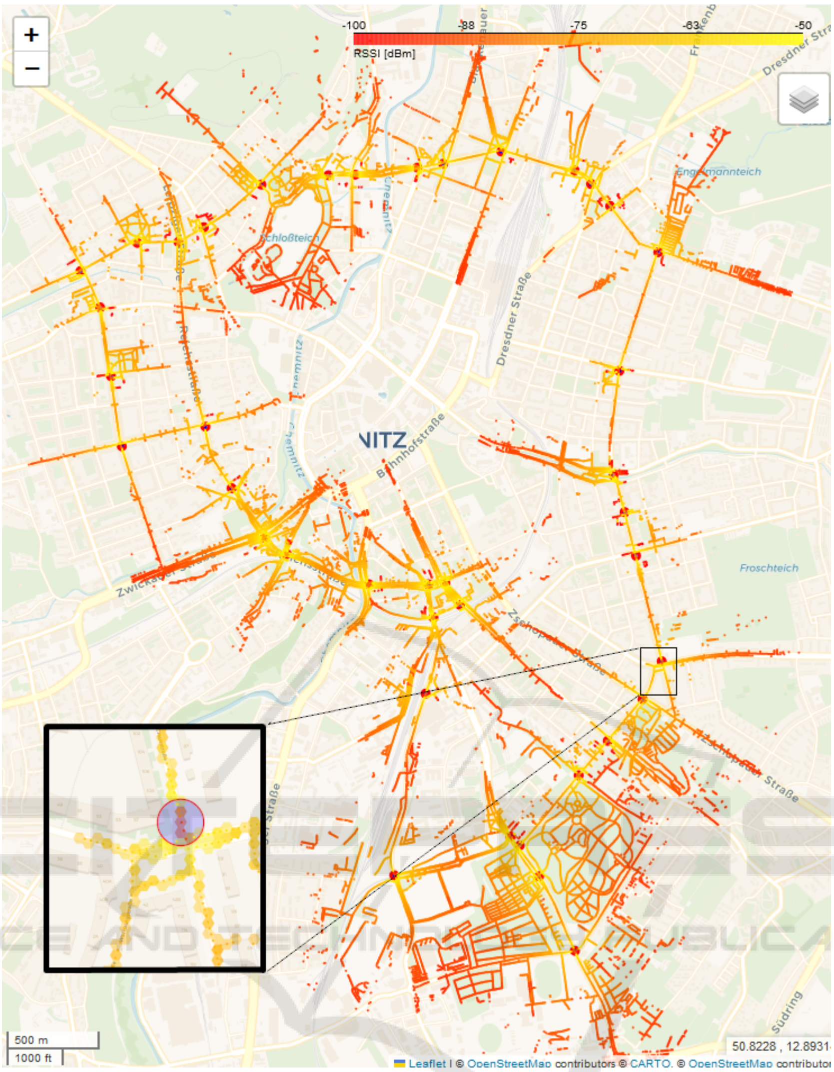

Figure 5: The proposed tool outputs the result as web page. Depicted are the prediction of RSSI levels at all signalized intersections connected to bus line 82 (compare Fig. 3). Enlarged, in the lower left corner, are the results for the intersection shown in Fig. 4. The red circle marks the position of the RSU. Overall, a good connectivity is predicted across the whole route, when using the current positions of RSU.

3 EVALUATION AND DISCUSSION

The proposed tool was used to plan the installation of RSU along the bus line 82 in the city of Chemnitz, Germany. This bus line crosses a total of 40 signalized intersections and crossings, where 38 traffic lights are equipped for prioritization (see Fig. 3). For all intersection RSU placement was evaluated using the tool using an estimated path-loss exponent. Of these intersections, 15 were considered critical, that is, the predicted range seemed insufficient to realize the intended use case, that is, the preregistration location was not covered or had only minimal radio coverage. One of these intersections is shown in Fig. 4. At this specific intersection, the bus line route does not follow the main road but instead takes a turn. As a result, one could expect a significant blockage of V2X communication due to buildings. Manual measurements were planned at these intersections to assess whether the placement of secondary RSU would be required. Due to road construction works, measurements could only be taken for 11 of the identified intersections. Consequently, these measurements were used to evaluate the accuracy of the predictions.

For evaluation, the measurement area was divided into hexagons. For a given position of the RSU, RSSI

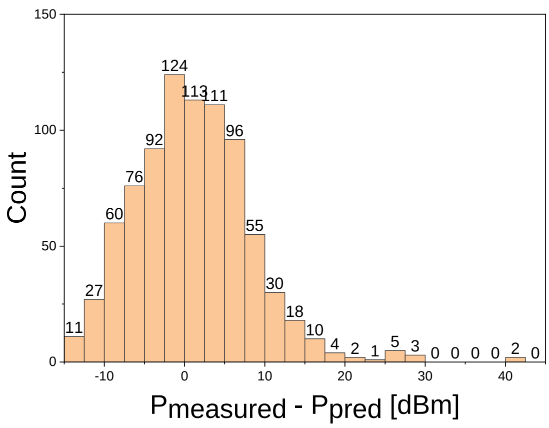

Figure 6: Comparison of real world measurements vs. the predictions. The mean difference is 0.99 dBm with a standard deviation of 7.35 dbm. Values on the right result from a too pessimistic modeling.

levels were predicted (see Fig. 5 for an example). These were compared against the RSSI measured during the test drive. In case there was more than one measurement per hexagon, the 80% percentile of all measurements was used. This was done to exclude certain cases of NLOS, e.g., if communication was blocked by another vehicle. For evaluation, 841 predicted values were compared with measurements, where the measured values were retrieved from all intersections included in the measurement campaign. The result of this comparison can be seen in Fig. 6. The difference between measured and predicted values usually lies between $-15\,\text{dBm} - 20\,\text{dBm}$, with some outliers greater than 25 dBm. These outliers could be traced to an erroneously assigned NLOS connection. This is due to the inaccuracy in GNSS, i.e., the reported position resulted in NLOS connection, but the real position had LOS.

Generally, modeling differences larger than 0 dBm do not cause problems, as long as all registration points are still covered (for the case of TSP), as this means that the actual connection was even better than predicted. Values smaller than 0 dBm are more concerning. Detailed investigations have shown that these values appear mainly near the submitting station, which means that some propagation properties of the radios are not fully considered by the path-loss model. As reception levels near the radio are typically very high, this does not cause an issue for the overall tool.

Although previous research (Eltahir, 2007) has shown that the choice of the radio propagation model has a significant impact on the results of the simulations, our results actually validate the choice of a simple path-loss model with a penalty term for NLOS connections, at least if used for V2X infrastructure planning. Compared to the ray-launching method proposed by Granda et al. (Granda et al., 2017), a similar mean error was achieved (0.99 dBm here vs. 1.75 dBm). In contrast, their method achieves a much lower standard deviation (2.54 dBm) versus 7.35 dBm. Although the results obtained using the ray-launching method are more accurate, ray-launching requires ray-tracing software and hardware, which are rather expensive to obtain and to operate, whereas the proposed algorithm runs on an office notebook. Given that V2X planning is mainly contracted by public communities, the offset in costs could justify the use of a less accurate model, especially if the results are still good enough for the desired task.

4 CONCLUSIONS & OUTLOOK

Taking real-world measurements for 11 of the 38 signalized intersections required two people and a day of work. Measurement of all intersections would have taken nearly a week. In comparison, generating the predictions took less than twenty minutes on an office notebook, most of this computation time. In general, the proposed approach leads to a significant decrease in planning RSU placement. Furthermore, it was shown that the model was able to sufficiently predict real-world radio propagation. Although the comparison was performed using IEEE 802.11p, it can be equally used for C-V2X as the physical propagation and radio frequencies are the same for both technologies.

However, there are some limitations of the current approach. It works best when the local path-loss exponent can be accurately estimated, which still relies on real-world measurements. This is necessary, as this exponent can vary wildly given the local circumstances, for example, (Goldsmith, 2005) cites measured path-loss exponents between $2.7 - 6.5$. On the other hand, already existing RSU could help with this part by comparing reception levels with the position reported in the CAM by connected vehicles already on the road today. Furthermore, currently a constant difference between the height of RSU and OBU are assumed. Although the model could also handle varying height differences, this would complicate the computations, e.g., buildings would need to be checked for NLOS connections, but also the ground, especially in hilly regions.

The current approach relies on OSM data. Since this is an open-source effort, the quality of the data differs. For some regions in Germany, for example, Saxony, there exists a digital height model with 25 cm resolution, which is captured from flight data. In addition to the higher accuracy, these data also contain information on larger plants and their spread.

In the future, machine learning is planned to be used for propagation prediction. Given enough training and meta-data, it is assumed that some kind of neural net can estimate the path-loss exponent/propagation sufficiently. This would eliminate the need to determine a path-loss exponent. In addition, in the current iteration, the position of the RSU is still determined by hand. In a future iteration, this position could also be computed using optimization algorithms, which could consider constraints like the distance to the traffic light controller (depending on transmission technology, for example not longer than 100 meters for Power-over-Ethernet (PoE)) and physical restrictions on placement.

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