A Computationally Inexpensive Empirical Model of IEEE 802.11p Radio Shadowing in Urban Environments

Christoph Sommer, David Eckhoff, Reinhard German and Falko Dressler
Computer Networks and Communication Systems
Dept. of Computer Science, University of Erlangen, Germany
{christoph.sommer,eckhoff,german,dressler}@informatik.uni-erlangen.de

***Abstract*—We present a realistic, yet computationally inexpensive simulation model for IEEE 802.11p radio shadowing in urban environments. Based on real world measurements using IEEE 802.11p/DSRC devices, we estimated the effect that buildings and other obstacles have on the radio communication between vehicles. Especially for evaluating safety applications in the field of Vehicular Ad Hoc Networks (VANETs), stochastic models are not sufficient for evaluating the radio communication in simulation. Motivated by similar work on WiFi measurements, we therefore created an empirical model for modeling buildings and their properties to accurately simulate the signal propagation. We validated our model using real world measurements in a city scenario for different types of obstacles. Our simulation results show a very high accuracy when compared with the measurement results, while only requiring a marginal overhead in terms of computational complexity.**

I. Introduction

Simulation is a key methodology in the development process of protocols for Inter-Vehicle Communication (IVC). Recently, much progress has been achieved in this field with respect to making such simulations more realistic, thus, providing more insights into the behavior of Vehicular Ad Hoc Networks (VANETs) [1], [2]. One of the open issues is related to the physical radio communication.

Typically used omnidirectional signal propagation models that assume exponential path loss are clearly not appropriate in the field of IVC if scenarios with buildings are to be investigated. Most importantly, the correct and realistic simulation of safety applications relies on an accurate evaluation of topology deficiencies and coverage [3].

Thus, a model that accurately captures the radio shadowing is preferable, which allows to estimate the impact of radio range and contact duration.

Central metrics for information dissemination in VANETs are a node's number of available neighbors and, more importantly, the variability in connectivity, which influences metrics such as neighbor lifetime, stability, and network rehealing times. Accurate modeling of, e.g., the radios' transmission range and packet error rates are crucial to arrive at realistic neighbor counts, as this metric is heavily influenced by the choice of path loss model.

Metrics like neighbor lifetime and network stability, however, can only be accurately simulated if the model also properly captures the effect of obstacles.

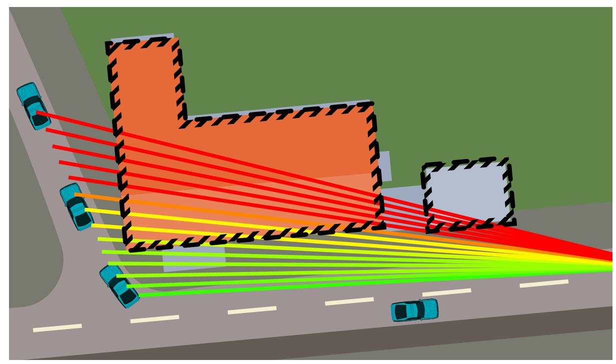

Figure 1. Deterioration of received signal strength (RSS) as a transmission is blocked by first one, then two buildings. Input parameters of the presented model are the buildings' geometries and the positions of both the sending and the receiving node.

As an example, the impact of obstacles is very evident when considering two vehicles that are driving on parallel roads separated by irregularly spaced buildings: here, channel conditions for transmissions between both nodes might quickly alternate between a near-perfect, lossless channel and strong (but predictable) shadowing.

It has thus become a well-established fact that realistic path loss models, which also capture effects like shadowing, are crucial to the quality of a wide range of VANET simulations [4]–[9], and it has been demonstrated that ray-tracing approaches can serve as an excellent approximation [6], [7], [10]–[12]. At the same time, however, the cost for preparing such scenarios was demonstrated to be high, sometimes prohibitively so.

As an alternative, stochastic models are used that describe the wireless channel characteristics quite well from a macroscopic point of view.

However, modeling the channel on a stochastic basis might lead to severe deviation from realistic behavior of single communications; thus, applications cannot be modeled accurately if single transmissions have a critical impact. This is, for example, the case for safety applications.

Thus, it appears that researchers have to choose between either going all the way and paying the cost associated with ray-tracing or ignoring many of the aforementioned effects.

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In this paper, we present an approach to fill this gap: based on results of extensive experiments we conducted using vehicles equipped with IEEE 802.11p radios, we highlight the shortcomings of traditional, non-ray-tracing models in capturing the effects that predictable shadowing can have on VANET applications. We present a novel, computationally inexpensive model which takes building geometry and the positions of sender and receiver into account (illustrated in Figure 1) and captures these effects. The model can easily be implemented to retrofit the path loss models of existing simulation tools to also respect shadowing effects[1].

The key contributions of this paper can be summarized as follows.

- We executed a wide range of experimental studies on the signal propagation of IEEE 802.11p/DSRC devices, measuring the effect of obstacles such as different buildings on the communication (Section III).
- Based on our findings, we developed a computationally inexpensive empirical obstacle model that can accurately capture shadowing effects in VANETs (Section IV).
- We finally executed an extensive set of simulation experiments, relying on 2.5D obstacle models as available in OpenStreetMap, to validate the simulation model with real world measurements using IEEE 802.11p-equipped cars (Section V).

II. Related Work

Common wisdom in wireless simulation tells us that transmissions are influenced by six main factors: free-space path loss, shadowing, reflection/absorption, fading, and Doppler shift/spread [13]. Such effects can be accurately reproduced by employing one of the many popular full-featured ray-tracing models available in the literature [7], [10]–[12], [14].

Yet, straightforward ray-tracing approaches do not scale to the number of simulated nodes and transmissions that is required in VANET scenarios, so models that rely on preprocessing steps [6] have been developed. Even for medium-scale simulation scenarios, however, these pre-calculation steps can be prohibitively time consuming (in this 2008 paper, it was reported that data pre-processing for a spatial resolution of $5\,m^2$ in a $4.56\,km^2$ scenario "took three days on a 50-node PC cluster and produced about 120 GB of output data").

Therefore, approaches have been developed that speed up ray-tracing by abstracting from individual buildings, instead modeling city blocks as a perfectly homogeneous cuboid of matter to derive an analytical model of shadowing [15], [16].

An evaluation [9] of such a model demonstrated that, aside from delivering the expected speedup, simulative results in general agree very well with experimental results. It also demonstrated, however, that the model abstracts away from some artifacts of real world wireless communication, namely short-lived transmission opportunities through gaps in buildings.

[1] An implementation for OMNeT++ and the *Veins* VANET simulation framework is available from http://www7.informatik.uni-erlangen.de/veins/

We therefore look towards models that can do without ray-tracing, but still capture predictable shadowing effects. The most straightforward approach that needs no ray-tracing computations, the use of an empirically determined, fixed path loss exponent depending on the city block in question [17] only captures the effect of obstacles in a scenario on a macroscopic level and, thus, does not capture predictable mesoscopic (i.e., smaller scale) effects, like variability of neighbor count.

By the same reasoning, purely stochastic models cannot alleviate this shortcoming. They model shadowing of individual transmissions as a random process, e.g., using a log-normal shadow fading [18] or an empirically generated list of 2-state Markov chains [5], hence they do not model predictable effects in radio propagation.

Models that apply different attenuation factors based on the relative position and heading of nodes [19] offer a convenient way to solve this issue, their biggest benefit being that they do not rely on geodata of buildings. If such geodata is available, however, the fidelity of simulations can be significantly improved. Models that rely on geodata are able to evaluate whether the direct line of sight between two vehicles is blocked, then apply perfect shadowing [20]–[24].

While this approach suffices to reflect the impact of buildings on low power radio transmissions, however, they provide an overly simplistic abstraction if radio transmissions can be expected to penetrate into and through buildings.

These effects can be modeled by adjusting the unit disc model of propagation to switch to a smaller radius [25] if the line of sight of a transmission is blocked, by choosing a different path loss exponent [4] (evaluated for 2.4 GHz and found to be a reasonable fit for transmissions of over 60 m distance), or by employing a different propagation model altogether [26] for the transmission in question.

Such models go a long way to capture the impact of buildings on radio transmissions and represent shadowing in urban environments in a realistic fashion for low and medium powered radios. In scenarios with complex building geometries, or if radio transmissions can be expected to penetrate more than one building, however, basing the model on the presence or absence of line of sight alone does not suffice.

Advanced shadowing models hence determine for each transmission the number and the geometry of buildings intersected by the line of sight between sender and receiver. One example of such model applies for each obstacle intersected by the line of sight a random attenuation factor, e.g., chosen from a table of attenuation ranges at the target frequency stored for common materials [27].

However, for the aforementioned reasons, such approaches that introduce a stochastic model cannot capture predictable changes in path loss, although they better capture shadowing effects on a macroscopic scale.

These effects can be represented by reducing the received signal strength of transmissions by either a fixed attenuation factor per obstacle [28], per wall [29], or by applying a dual-slope path loss model using different path loss exponents for distance traveled through matter and in free space [13].

Figure 2. Position of the shark fin antenna assembly, omnidirectional antenna, and GPS receiver on the roof; installation of the DENSO WSU 802.11p radio in the trunk (inset).

To the best of our knowledge, though, no such model has been presented for IEEE 802.11p yet that considers the specific makeup of most buildings, especially in urban environments: depending on how far a transmission has to penetrate through a building's interior, the attenuation that it will experience varies slightly; in addition, a thick outer wall heavily attenuates transmissions.

III. Data Basis and Measurements

In order to establish the data basis for evaluating the applicability of the obstacle models presented in Section II for simulating the effect of predictable shadowing caused by buildings in urban areas, we conducted an extensive series of experiments in a wide range of scenarios, gathering log data from continuous IEEE 802.11p transmissions between cars.

The radio we employed was part of the DENSO wireless safety unit (WSU) platform, mounted in the trunk of an Audi A4 allroad quattro.

As the shark fin antenna assembly installed on the roof (at a height of 149.5 cm, 92 cm from the curb) was an early prototype with directionality characteristics geared towards communication with receivers in the front of the car, we further outfitted each car with an omnidirectional antenna mounted next to it, as shown in Figure 2.

The third piece of equipment that can be seen installed on the roof of the car is the 5 Hz GPS receiver; we used these to log position information with each transmission.

Alternating between use of the shark fin antenna assembly and the omnidirectional antenna, we then performed measurements under completely unobstructed channel conditions, in the middle of hayfields south of Erlangen, and in urban scenarios with residential or commercial buildings, tightly packed or loosely spaced, as well as old or new.

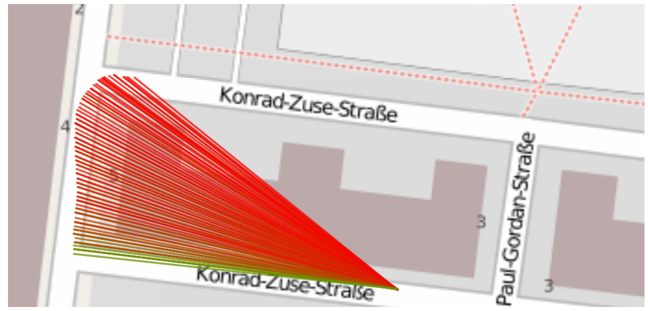

Figure 3. Use of geodata about road network and building geometry for the data correlation and verification step. Each line indicates one successful transmission between sending and receiving car, a line's color representing the measured RSS value.

In each scenario, we configured one car to broadcast its current position in 200 ms intervals by sending Wave Short Messages (WSMs) on the Control Channel (CCH), i.e., at 5.89 GHz. On the receiver side, we logged for each packet its timestamp and sender position, as well as the receiver position and the dBm value of received signal strength (RSS).

In a first step we correlated the log data we recorded with the position and 2.5D shape of buildings (i.e., their outline and height). For this we used OpenStreetMap geodata and satellite imagery, overlaying as shown in Figure 3 the log data on top of the road network and building outlines using a custom application based on the OpenLayers API. We visualized transmissions by drawing the line of sight corresponding to each, using color coding to indicate the attenuation it experienced.

Thus, we were able to verify the accuracy of data and associate with each recorded RSS value the two metrics required for a validation of the non-ray-tracing models mentioned in Section II: the number of exterior walls intersected by the line of sight between sender and receiver and the length of this intersection.

In a second step, we examined the plausibility of RSS measurements by comparing results from the unobstructed scenario to expected values from an analytical model, based on the simple free space path loss model and adapted to include a path loss exponent α, as given in Equation 1 (where λ is the wavelength and d is the distance between sender and receiver). For $\alpha = 2$, this model explains the attenuation that a wireless transmission experiences based solely on antenna aperture and the spread of energy on a two-dimensional disc.

$$L_{freespace}[dB] = 10 \lg \left(\frac{16\pi^2}{\lambda^2} d^\alpha \right) \quad (1)$$

Figure 4 illustrates how measurement results match up reasonably well with this (simplistic) model if a path loss exponent of $\alpha = 2.2$ is assumed: results are shown in the form box plots: for each data set, a box is drawn from the first quartile to the third quartile, and the median is marked with a thick line; additional whiskers extend from the edges of the box towards the minimum and maximum of the data set, but no further than 1.5 times the interquartile range.

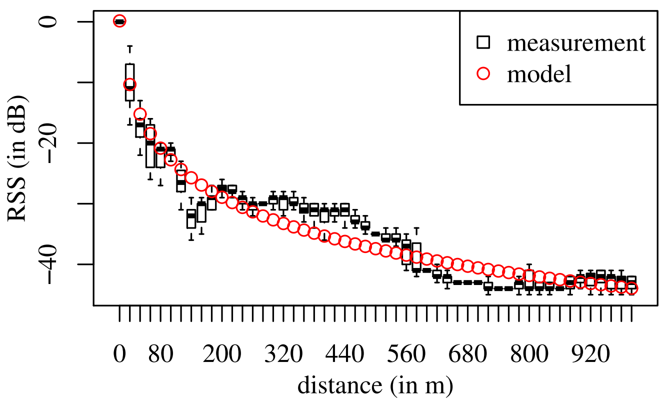

Figure 4. Free space path loss model (red circles) vs. measurement data in the unobstructed scenario for a path loss exponent of $\alpha = 2.2$.

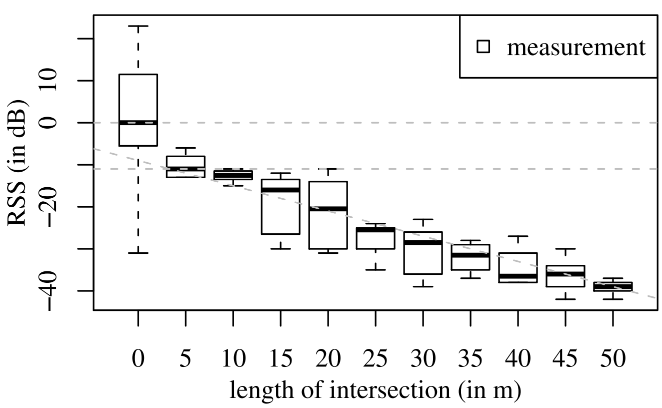

Figure 5. Sharp drop and continuous decline in measured RSS as the length of building penetrated increases.

Figure 5 gives an exemplary illustration of the results we gathered, plotting samples of the RSS versus the length of the calculated section of intersection between line of sight and a building. From this (and, likewise, from measurements we conducted in other scenarios, both with and without use of the omnidirectional antennas), we observe that RSS values drop sharply as soon as the line of sight is blocked and continue to decrease as the length of the intersection of line of sight and building increases. It is clear that this behavior can not be accurately reproduced by considering only the *attenuation per wall* nor by only considering *attenuation per meter of penetration*. Rather, it appears that both factors need to be considered.

IV. Obstacle Model

As presented in the previous sections, simulating path loss in urban environments to capture predictable shadowing effects seems to require more complex models than *attenuation per wall* or *attenuation per meter of penetration* approaches.

In theory, precise modeling of radio propagation in urban environments is possible by using a ray-tracing approach with a fine enough granularity and an extremely detailed geodata base, but (as shown in related work) the computational effort to employ this approach for large scale VANET simulations is prohibitively high. In a similar vein, modeling effects such as reflection and diffraction requires geodata with a level of detail that is unlikely to be available at the required scale.

Thus, our motivation was to develop a model that only relies on building outlines, which are commonly available in modern geodata bases, and thus needs to abstract from reflection and diffraction effects. Furthermore, in order to keep the model computationally inexpensive, it considers the line of sight between sender and receiver only; it disregards any objects blocking, e.g., parts of the first Fresnel zone.

This way, simulations that make use of the model scale very well, the calculation of intersection between all lines of sight and all buildings being its most expensive step. Finding these intersections, however, can easily be supported using caching and binary space partitioning approaches [13] to solve this step in $\mathcal{O}(n^2 \log n)$ time. Furthermore, depending on the employed simulation framework, this process can also be treated as a *red and blue line segments* intersection problem, for which algorithms that run in $\mathcal{O}(n \log n)$ time have been proposed [30].

Because of the simplifications made regarding physical effects, the model needs to be carefully checked against real-world measurements to examine its validity for the envisioned application. Still, aside from mesoscopic path loss effects, i.e. shadowing, the model is envisioned to accurately represent both macroscopic and microscopic effects.

Analogous to those in related work [13], [28], [29], we thus envision our model to be a generic extension of well-established fading models. In general, these can be expressed in the form of Equation 2, where P are the transmit (or receive) powers of the radios, G are the antenna gains, and L are terms capturing loss effects during transmission.

$$P_r[dBm] = P_t[dBm] + G_t[dB] + G_r[dB] - \sum L_x[dB] \quad (2)$$

Common models of large-scale path loss, of deterministic small-scale fading, or of probabilistic attenuation effects can then be written as components L of Equation 2 and, thus, chained to calculate the compound attenuation. Equations 3 and 4 illustrate this for the examples of two-ray ground path loss and log-normal shadow fading, respectively.

$$L_{tworay}[dB] = 10 \lg \left(\frac{d^4 L}{h_t^2 h_r^2} \right) \quad (3)$$

$$L_{lognorm}[dB] = 10 \lg (X_\sigma) \quad (4)$$

We extend the general model shown in Equation 2 by contributing another term L_{obs} to be used for each obstacle in the line of sight between sender and receiver: based on the observations presented in Section III, deriving its structure (illustrated in Equation 5) is straightforward:

$$L_{obs}[dB] = \beta n + \gamma d_m \quad (5)$$

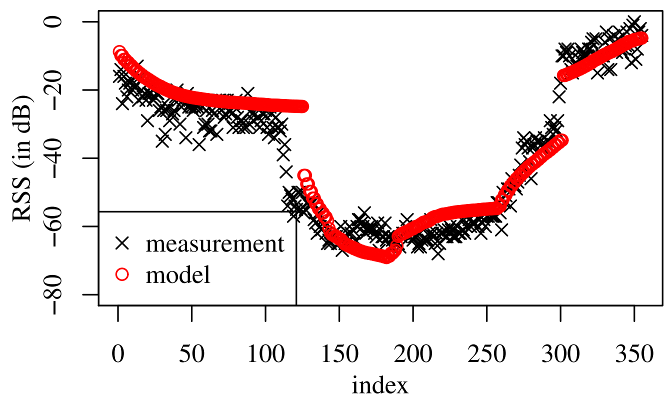

Figure 6. Measured and calculated RSS values for a countryside warehouse.

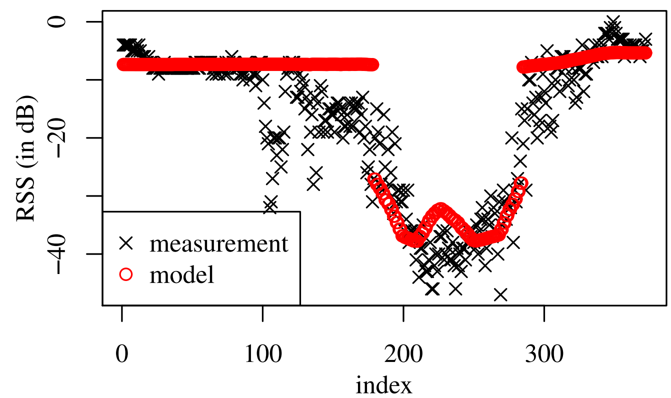

Figure 7. Measured and calculated RSS values for a suburban house.

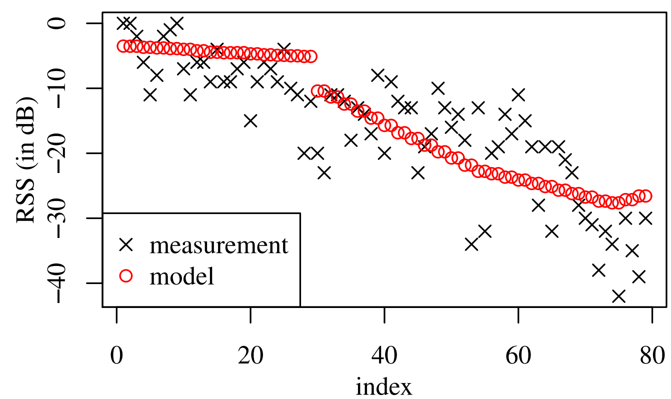

Figure 8. Measured and calculated RSS values for a light construction house.

L_{obs} is intended to capture the additional attenuation of a transmission due to an obstacle, based on the number of times n the border of the obstacle is intersected by the line of sight and the total length d_m of the obstacle's intersection. The first of the two calibration factors, β, is given in dB per wall and represents the attenuation a transmission experiences due to the (e.g., brick) exterior wall of a building. The second calibration factor, γ is given in dB per meter and serves as a rough approximation of the internal structure of a building.

This parameterization allows the model to be intuitively adjusted to represent different kinds of buildings in urban settings. In the following, we present an evaluation of this model, along with empirically determined values for parameters β and γ.

V. Evaluation

We evaluated how well the shadowing model presented in Equation 5 can capture the predictable changes in path loss caused by buildings: we combined it with the generic and free space path loss models shown in Equations 1 and 2 to arrive at Equation 6.

$$P_r[dBm] = P_t[dBm] + 10 \lg \left(\frac{G_t G_r \lambda^2}{16\pi^2 d^\alpha} \right) - \beta n - \gamma d_m \quad (6)$$

In order to determine to what extent changes in measured RSS could be explained by this model, we examined whether parameters β and γ could be fitted so that analytical results would match up with measured ones. Parameter fitting was performed by iteratively minimizing the sum of squared residuals using the standard Gauss-Newton algorithm [31] until the algorithm converged, based on a tolerance threshold of 1×10^{-5}.

Figure 6 shows the results of this process for a representative set of measurements in the countryside. Here, we circled a free-standing warehouse, obtaining parameters of $\beta = 9.2\,\text{dB}$ per wall and $\gamma = 0.32\,\text{dB/m}$. We observe that β and γ are within the expected range and, in general, computed values for the attenuation match the values we measured quite well. The plotted values also demonstrate that the model only considers the line of sight, rather than the first Fresnel zone, between sender and receiver: the smooth decrease of measured RSS values that can be observed as the line of sight is not yet crossing the first corner (but the building's intersection with the Fresnel ellipsoids is starting to increase) at around index 125 is replaced by a sudden drop in RSS values in the analytical model.

Another effect can be observed in Figure 7, which shows results from measurements of driving around three quarters of a house in a suburban area (the fitting of model parameters resulted in similar values of $\beta = 9.6\,\text{dB}$ per wall and $\gamma = 0.45\,\text{dB/m}$). We observed that in our measurements, computed and measured RSS values diverge under specific constraints (in this example: at around index 220). Closer examination of the traces reveals that this corresponds to transmissions that have their line of sight passing straight through one of the corners of the house – as our model doesn't capture this effect, it overestimates RSS values in these cases.

For the vast majority of the collected data, this parameterization of $\beta \approx 9\,\text{dB}$ and $\gamma \approx 0.4\,\text{dB/m}$ resulted in our model fitting the experimental results quite well. But even though measurements like this were the most common type, it needs to be said that there are, of course, some types of buildings that could not be represented well using the default values of β and γ.

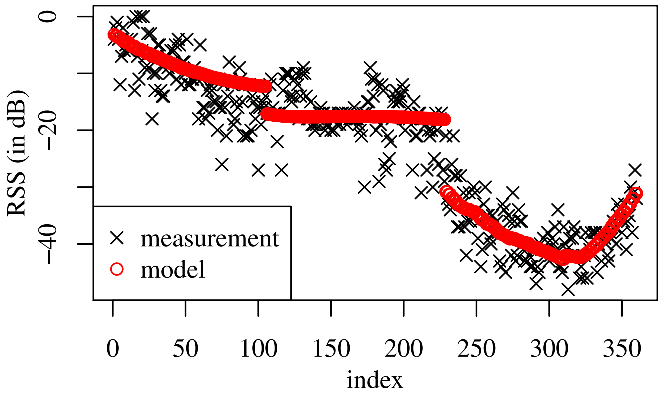

Figure 9. Measured and calculated RSS values for an urban residential home and garage, using per-building parameterization.

One such example can be seen in Figure 8: here, we show measurements taken from a lightly built house. While the model is able to represent the attenuation characteristics of this type of building, its parameters are unlike those of standard ones, now taking values of $\beta = 2.4\,\mathrm{dB}$ per wall and $\gamma = 0.63\,\mathrm{dB/m}$.

However, if we allow such per-building parameterization the presented model works equally well for heterogeneous scenarios. Figure 9 illustrates the results we achieved when measuring transmissions intersecting an urban residential home and its garage, the scenario sketched in Figure 1. Adding another term for the second building to Equation 6 and choosing $\beta_1 = 2.38$ and $\gamma_1 = 0.1$, as well as $\beta_2 = 6.26$ and $\gamma_2 = 0.41$ for home and garage, respectively, enabled us to model this scenario equally well.

VI. Conclusion

We presented a computationally inexpensive model for IEEE 802.11p/DSRC radio shadowing in urban environments. In particular, the presented model allows to accurately estimate the signal attenuation of the wireless radio transmission by obstacles such as buildings. With the help of available 2.5D models of buildings (e.g., from OpenStreetMap), our model allows to very efficiently estimate realistic path loss values for ongoing radio communication. Our model has been empirically calibrated using an extensive set of measurement data and integrated with our simulation framework *Veins* for evaluating VANET applications. We think that the model is of particular importance if safety applications are to be investigated, because traditional stochastic models are not able to measure the effects of a specific radio transmission properly.

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