On the Applicability of Two-Ray Path Loss Models for Vehicular Network Simulation

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Abstract—**We discuss the applicability of simplified Two-Ray Ground path loss models to simulation-based performance evaluation studies of Inter-Vehicle Communication (IVC) protocols. We contrast this with the applicability of a more exact Two-Ray Interference model. A key result is that, in most cases, the commonly used simplified Two-Ray Ground models add no additional value compared to the most simple Free-space model – in particular in highway and suburban environments. We further argue that replacing a simplified with a fully featured Two-Ray Interference model can not only substantially improve the accuracy of simulation results but also allow capturing one notable artifact that becomes immediately visible in field tests, namely strong signal attenuation at short and medium ranges. We implemented the Two-ray Interference model within the Veins simulation framework and validated it using analytical predictions and field measurements. We show the impact of the more accurate Two-Ray Interference model, which only comes with negligible additional computational cost for simulation experiments.**

I. Introduction

The field of Inter-Vehicle Communication (IVC) is one of the most rapidly evolving areas, especially in wireless networking. Many approaches and protocols have been proposed and some are already on their way to standardization and commercial exploitation [1]–[3]. Outside of first large-scale field tests, for example in the scope of some huge European projects, most of the proposed concepts have been designed and evaluated with the help of simulation techniques.

Recently, much progress has been achieved to make simulation-based performance evaluation of vehicular networks more realistic, thus providing more insights into the behavior of, e.g., Vehicular Ad Hoc Networks (VANETs) [4], [5]. Among the big challenges in this field is the accurate modeling of physical radio communication, especially with focus on the IEEE 802.11p DSRC standard [6].

It has become a well-established fact that realistic path loss models are crucial to the quality of a wide range of VANET simulations [7]–[11]. Consequently, a model is preferable that accurately captures the signal attenuation, allowing to estimate the impact of radio range and contact duration.

This has prompted many recent simulation studies to suggest the use of a two-ray path loss model as a path loss baseline, with additional loss effects like shadowing caused by obstacles building on this [11]. We believe, however, that the use of the simplified *Two-Ray Ground* model as implemented in all major network simulation tools does not lead to a sufficient quality improvement.

Based on early findings shown in [12], we investigated the implemented path loss models in detail and validated the results based on own experiments on the road using off-the-shelf IEEE 802.11p radios. Backed by further results, collected during two independent measurement campaigns by other groups [13], [14] which used advanced laboratory equipment, we were able to validate the effects shown in our measurements. In particular, we analytically verified that simplified Two-Ray Ground models are of no benefit compared to the basic Free-space model.

We also go one step further and evaluate the impact of the used radio models on higher layer IVC protocols in highway and suburban environments. Based on our findings, we argue that using a fully featured and more exact *Two-Ray Interference* model allows researchers to capture artifacts of strong signal attenuation manifesting at short and medium ranges. These artifacts become visible in measurements and field tests and lead to divergent application layer behavior at different distances.

The detailed model is applicable in both highway and suburban environments where reflections at obstacles do not dominate radio propagation effects [13], [14]. At the same time, on modern hardware, the use of a Two-Ray Interference model (as opposed to a simplified Two-Ray Ground model) only comes with marginal added computational cost for simulation experiments.

The key contributions of this paper can therefore be summarized as follows:

- We show that the approximation of the signal attenuation using the Free-space or the simplified Two-Ray Ground model does not lead to the often assumed improvements in simulative performance evaluations of IVC protocols.
- We carefully validate the Two-Ray Interference simulation model based on analytical predictions, based on the results of two independent measurement campaigns by other groups [13], [14], and based on measurements on the road using off-the-shelf IEEE 802.11p DSRC radios.
- We conduct a comprehensive set of simulation experiments, showing the impact of different models (in particular of a fully featured Two-Ray Interference model) on key metrics such as neighbor count and Received Signal Strength (RSS).
- We strongly argue to abandon the widely used simplified Two-Ray Ground model in favor of a fully featured Two-Ray Interference model in simulative performance evaluations of protocols using IEEE 802.11p DSRC.

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II. Path Loss Models

Following our earlier work on analytical validation of the impact of the Two-Ray Interference model [12], we investigate the basic foundations of the typically used path loss models in this section. We complete the discussion with an experimental validation of the analytical expressions and a focused argumentation on the impact of the choice of models.

A. Analytical Modeling of Radio Propagation

In network simulation, fading due to large-scale path loss, deterministic small-scale fading, and probabilistic loss effects is most commonly calculated as a sum of independent loss processes [15], [16]. Based on these terms L_x, on the transmit power of the radio P_t, and on transmit and receive antenna gains $G_{(t,r)}$, the receive power P_r can be expressed as

$$P_r[dBm] = P_t[dBm] + G_t[dB] + G_r[dB] - \sum L_x[dB]. \quad (1)$$

Path loss, which we focus on in this paper, is often estimated assuming free space propagation, taking into account only the distance d and the wavelength λ, yielding the *Free-space* model

$$L_{\text{freespace}}[\text{dB}] = 20\log_{10}\left(4\pi\frac{d}{\lambda}\right) \quad (2)$$

and empirical adaptations thereof that aim to account for non-ideal channel conditions by introducing an additional environment-dependent path loss exponent α, yielding

$$L_{\text{emp-freespace}}[\text{dB}] = 10\log_{10}\left(16\pi^2\frac{d^\alpha}{\lambda^\alpha}\right). \quad (3)$$

However, more realistic treatment of the path loss takes into account the fact that radio propagation will commonly suffer from at least one notable source of attenuation: constructive and destructive interference of a radio transmission with its own ground reflection. A physically more correct approximation [17] of path loss must therefore be based on the phase difference φ of two interfering rays, leading to a *Two-Ray Interference* model.

Following the notations in Figure 1, the length of the direct line of sight propagation path can be geometrically derived to be $d_{\text{los}} = \sqrt{d^2 + (h_\text{t} - h_\text{r})^2}$, and the length of the indirect, non line of sight path via ground reflection can be seen to be $d_{\text{ref}} = \sqrt{d^2 + (h_\text{t} + h_\text{r})^2}$. Based on the length difference of these paths and the wavelength, the phase difference of interfering rays can be derived as

$$\varphi = 2\pi\,\frac{d_{\text{los}} - d_{\text{ref}}}{\lambda}. \quad (4)$$

The attenuation of a polarized electromagnetic wave via reflection is commonly captured in a reflection coefficient, which is not only dependent on a fixed ε_r, but also on the incidence angle θ_i. For further computations, only its sine and cosine need to be known, both of which are straightforward to compute as $\sin\theta_\text{i} = (h_\text{t} + h_\text{r})/d_{\text{ref}}$ and $\cos\theta_\text{i} = d/d_{\text{ref}}$, respectively. Using these, the reflection coefficient can be calculated as

$$\Gamma_\perp = \frac{\sin\theta_\text{i} - \sqrt{\varepsilon_\text{r} - \cos^2\theta_\text{i}}}{\sin\theta_\text{i} + \sqrt{\varepsilon_\text{r} - \cos^2\theta_\text{i}}}. \quad (5)$$

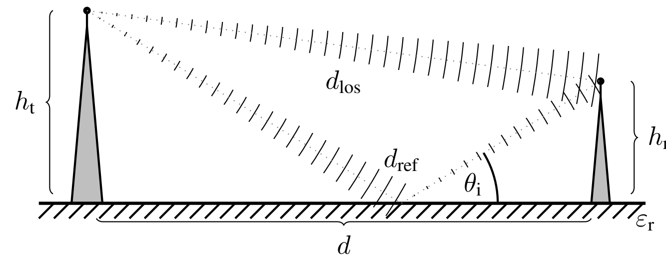


Figure 1. Conceptual model of ground reflection causing distance-dependent constructive and destructive signal interference effects at the receiver.

The relative change in signal strength due to constructive or destructive interference can then be modeled by amending Equation (2) with a simple correction term of the relative phase and magnitude of interference by the reflected ray, to yield

$$L_{\text{tri}}[\text{dB}] = 20\log_{10}\left(4\pi\frac{d}{\lambda}\left|1 + \Gamma_\perp e^{i\varphi}\right|^{-1}\right). \quad (6)$$

Obviously, this calculation is more complex than the much more simple calculation of path loss according to the Free-space model – and even more so if additional reflections [18] need to be considered.

However, at large distances, destructive signal interference effects will cause noticeably worse path loss than the Free-space model, making the effects impossible to ignore.

During the early days of simulative performance evaluation this has led researchers to wonder whether the model could be simplified. Indeed it has been demonstrated [17], how the calculation of interference between line-of-sight and reflected rays can be simplified for large distances d and assuming perfect polarization and reflection, to yield

$$L_{\text{trg,far}}[\text{dB}] = 20\log_{10}\left(\frac{d^2}{h_\text{t}h_\text{r}}\right). \quad (7)$$

This has led all of the most commonly used network simulators for simulative performance evaluation of IVC protocols to pick up what is commonly termed the *Two-Ray Ground* path loss model as an option for simulating path loss in radio transmissions, which uses a cross-over distance of both models d_c. Its value is defined as the distance where path loss according to both models breaks even and is used for choosing between Equations (2) and (7) to yield

$$L_{\text{trg}}[\text{dB}] = \begin{cases} L_{\text{freespace}}[\text{dB}] & \text{if } d \le d_c, \\ L_{\text{trg,far}}[\text{dB}] & \text{if } d > d_c. \end{cases} \quad (8)$$

Among these simulators are ns-2.35, ns-3.14, OMNeT++ INET 2.0.0, QualNet 5.1, and JiST SWANS 1.0.6. Most of these simulators have frequently been used for IVC protocol evaluations [19].

In the following, we investigate the applicability of these path loss models to the simulative performance evaluation of vehicular networks using IEEE 802.11p DSRC.

B. Experimental Validation

We first compare predictions by the simple Free-space model with measurements on the road, performed using off-the-shelf IEEE 802.11p DSRC radios. This field test was performed during research for what was to become our computationally inexpensive empirical model of IEEE 802.11p radio shadowing in urban environments [20]. 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 WSU platform, mounted in the trunk of an Audi A4 allroad quattro, configured to send Wave Short Messages (WSMs) on the Control Channel (CCH), i.e., at 5.89 GHz, in 200 ms intervals. On the receiver side, we logged for each packet its timestamp and sender position, as well as the receiver position and the reported dBm value of RSS.

We outfitted each car with a 5 Hz GPS receiver, which we used to log position information (along with the point dilution of precision) for sent and received packets. We further outfitted each car with an additional omnidirectional antenna, located next to its shark fin antenna assembly, at a height of 149.5 cm and a distance from the curb of 92 cm, as shown in Figure 2. Our measurements are thus not impacted by the high directionality characteristics of currently proposed, more streamlined antenna configurations [21].

As we show in the following, they are, however, impacted by imperfections in the metrics reported by our off-the-shelf radios. In order to make sure that the results we are presenting are not attributable to such artifacts, we validated the effects against (and found perfect agreement with) results collected using advanced laboratory equipment by two independent research groups [13], [14].

We performed measurements under completely unobstructed channel conditions, in the middle of hayfields south of Erlangen. In order to evaluate the plausibility of these measurements for our study, we first used curve-fitting (iteratively minimizing the sum of squared residuals using the Gauss-Newton algorithm) to match eq. (3). We found a good overall correlation [20], which validates the applicability of the presented path loss models in the examined scenario.

As the use of the described simplified Two-Ray Ground path loss model is frequently assumed to constitute the current state of the art for vehicular networking simulation, we now explore its impact on simulation results. From Equations (2) and (7), the cross-over distance of both models can be derived to be

$$d_c = 4\pi \frac{h_\mathrm{t} h_\mathrm{r}}{\lambda}. \tag{9}$$

We calculate d_c when given typical values for transmitter and receiver antenna heights $h_\mathrm{t} = h_\mathrm{r} = 1.895\,\mathrm{m}$ (corresponding to the used cars and antennae) and $\lambda = 0.051\,\mathrm{m}$ for the used wavelength (corresponding to the IEEE 802.11p CCH center frequency of 5.890 GHz). For these values, Equation (9) yields a break even distance for the *Two-Ray Ground* model of

$$d_c = 886.6\,\mathrm{m}.$$

(a) One of the Audi A4 allroad quattro used for measurements

(b) Position of the omnidirectional antenna and GPS receiver

Figure 2. Photos documenting the vehicle body and antenna position.

However, under realistic propagation conditions, i.e., when attenuation by obstacles is considered, IEEE 802.11p DSRC transmissions in urban areas are highly unlikely to ever reach that far [20], [22]. We must therefore conclude that VANET simulations based on common network simulators have, even when configured with a simplified Two-Ray Ground model, in fact, been performed using the Free-space model only.

III. Impact on IVC Protocols

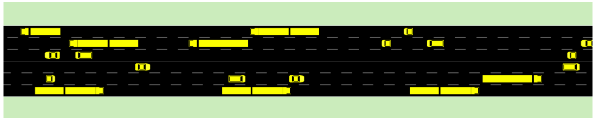
After illustrating the inapplicability of the simplified Two-Ray Ground model, we now take this evaluation one step further and investigate the applicability of the fully featured Two-Ray Interference model, as given in Equation (6), for vehicular networking simulations. In the following, we briefly describe the simulation model and the used parameters, before discussing the accuracy of the simulation model and its impact on higher layer IVC protocols.

A. Simulation Model and Parameters

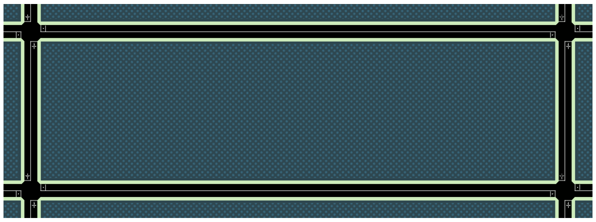
We implemented the presented path loss models as modules of the *Veins* [4] vehicular network simulation framework,[1] which is composed of the SUMO microscopic road traffic simulator and the OMNeT++ network simulation core (using MiXiM models for accurate simulation of lower layers).

We employ two basic scenarios for simulative analysis. The first scenario, a 1D Freeway depicted in Figure 3a, represents an average of 80 vehicles per km driving on all lanes of a perfectly straight 5 km stretch of freeway. Three lanes are running in each direction with no posted speed limit. The lanes are used by a mix of passenger cars and trucks (30 %), all using the *Krauss* vehicular mobility model, but configured for maximum speeds of $130 \pm 5\,\mathrm{km/h}$ and $80 \pm 20\,\mathrm{km/h}$, respectively, to produce small inhomogeneities in traffic. For the same reason, the vehicle lengths, acceleration/deceleration parameters, desired gaps to the leading vehicle, as well as drivers' responsiveness (defined by the Krauss model *dawdle* parameter) were varied.

[1] http://veins.car2x.org/



(a) 1D Freeway (depicted is a 150 m segment)



(b) 2D Grid (depicted is one city block)

Figure 3. Screenshots of the two types of scenarios simulated.

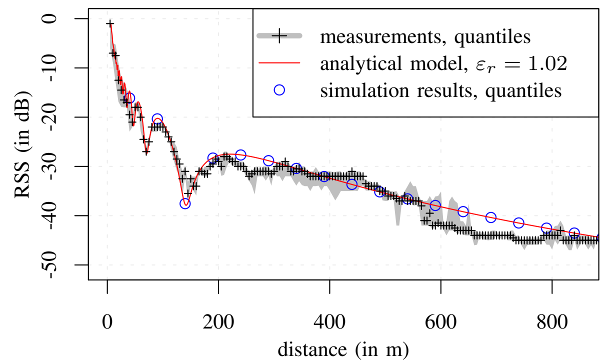


Figure 4. Measurement results of received signal strength vs. distance between sender and receiver (median, 1 %, and 99 % quantiles), overlaid with the calibrated Two-Ray Interference model and simulation results.

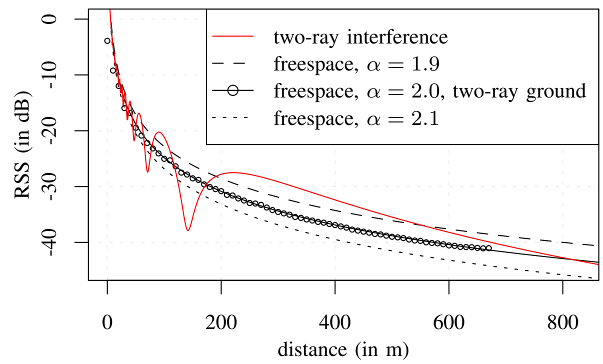


Figure 5. Model comparison for the Free-space model using different α values and the Two-Ray Interference model. For $d_c < 866.6$ m, results for $\alpha = 2.0$ and for the simplified Two-Ray Ground model are identical.

The second scenario, depicted in Figure 3b, simulates an average of 110 vehicles per km^2 in a classic Manhattan Grid type scenario of 5 km × 5 km with regularly spaced vertical and horizontal two-way (but single-lane) streets forming 270 m long and 80 m wide blocks. All intra-junction traffic is governed by right-of-way rules and a speed limit of 13 m/s is set.

On the network simulation side, we consider all vehicles to be equipped with an IEEE 802.11p DSRC radio and, thus, to participate in the vehicular network. Radios were configured to use the MiXiM default parameters, transmitting at 18 Mbit/s on a single channel. We implemented a frame error model that accurately matches the values reported in [23]. In order to eliminate border effects, we record statistics only for nodes in the center 1 km^2 region of interest.

We paid close attention to keep the path loss models computationally tractable. For the simulations reported in this paper, we observed a ±1 % difference in simulation run times for the empirical Free-space and Two-Ray Interference models, which can just as easily be attributed to secondary effects.

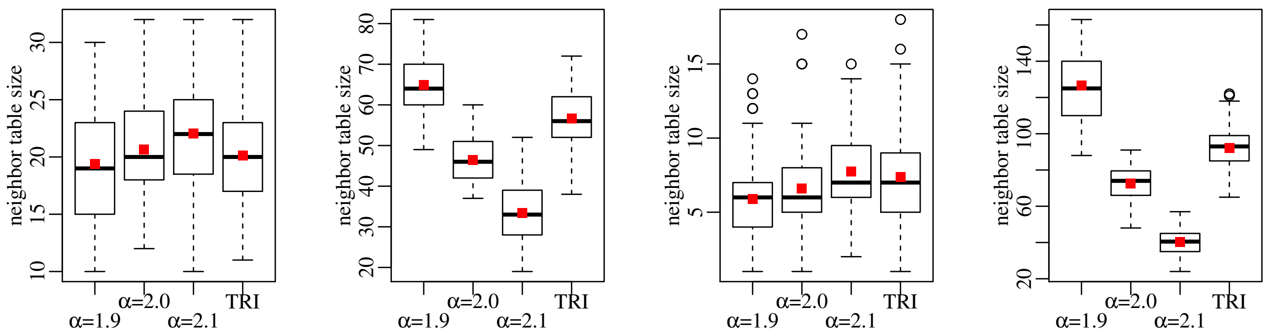
B. Model Validation and Comparison

In a first step towards studying the impact of these models, we validated both the analytical and the newly implemented Two-Ray Interference simulation models using an extensive set of field measurements. In Figure 4, we plot predictions by the analytical model together with our measurement results and a first set of simulation results obtained using the described simulation setup, relative to the maximum recorded RSS. We note that the analytical model matches real-world measurements well. Further, the simulation results match the analytical predictions, which gives us confidence for further evaluations.

We note that the RSS values we gathered during measurements exhibit a peculiar irregularity: a distinct drop in reported RSS values at −40 dB (measured at approx. 600 m), reducing the fit between model and measurements. A comparison with independent measurements collected using channel sounding equipment [13], [14] reveals this as an artifact (potentially due to discrete AGC at the receiver) induced by the off-the-shelf hardware used: both measurement campaigns were able to report data that fit the model even better.

In a second step, we compare the Two-Ray Interference model with the empirical Free-space model given in Equation (3), calibrated using different α values. In Figure 5, we overlay a graph of the different models. In order to increase the readability, we plot the analytical predictions for all the models and overlay those with simulation results for $\alpha = 2.0$ only; the other simulation runs match the analytical values with similar accuracy. As can be seen, none of the Free-space variants exactly matches the Two-Ray Interference curve. We explore the resulting effects when simulating higher layer IVC protocols in the next section.

Focusing now on values gathered for mid and short range transmissions, it can be seen that the Two-Ray Interference model captures path loss effects much more successfully than both the Free-space and the simplified Two-Ray Ground model. At mid distances, predictions by these simpler models consistently underestimate RSS values by more than −5 dB. Moreover, at small distances the prediction errors rapidly alternate between underestimating and grossly overestimating RSS values by as much as −5 dB and +10 dB. Thus, extending simpler models by a path loss exponent α, as in Equation (3), cannot compensate for these errors, further motivating the use of a fully featured Two-Ray Interference model.



(a) Freeway, near ($d < 174\,\mathrm{m}$) (b) Freeway, far ($d \geq 174\,\mathrm{m}$) (c) Grid, near ($d < 174\,\mathrm{m}$) (d) Grid, far ($d \geq 174\,\mathrm{m}$)

Figure 6. Distribution of nodes' neighbor table sizes (considering either only near or far neighbors). Results from the 1D Freeway and 2D Grid scenarios (1 Hz beacon interval), plotted for three empirical adaptations of the Free-space path loss model, as well as for the Two-Ray Interference model.

Of particular note is the fact that the simplified Two-Ray Ground model fails to capture an important effect: the proposed Two-Ray Interference model predicts that, in the presented scenario, RSS values recorded approximately 140 m away from the sender are, in fact, 10 dB worse than those at 200 m – and, thus, as bad as those at approximately 600 m.

This prediction is due to the Two-Ray Interference model's consideration of destructive signal interference by the signal components reaching the receiver via both direct line of sight and ground reflection. Again, the prediction is confirmed in full by real-world measurement results.

C. *Impact on Higher Layer IVC Protocols*

After examining the low-layer effects of the presented models in terms of RSS (which, under unloaded conditions, is related to packets' Signal to Interference and Noise Ratio (SINR) and, thus, packet loss) we now investigate how these low-layer effects might impact higher layer IVC protocols by means of simulations.

For the sake of example, and following the most recent IEEE 802.11p DSRC recommendations [6], we employ a simple protocol that sends periodic *Hello* beacons at a configurable frequency of 1 Hz to 100 Hz (the standard allows beacon frequencies of up to 10 Hz), and uses received beacons to maintain neighbor tables. Whenever a node receives a *Hello* beacon from another node for which no entry in its neighbor table exists yet, it creates a new entry containing the last time of contact. Similarly, it uses received beacons to update the last time of contact for existing entries of nodes. Any neighbor table entry that is not updated during three beacon intervals is considered expired and is removed.

The size of nodes' neighbor tables can thus serve as a convenient indication of both the stability of connections in a network, as well as of nodes' degree of reachability, as dictated by the quality of radio links.

We differentiate between two classes of entries in nodes' neighbor tables: those made by nodes in the immediate vicinity and those made by nodes farther away. As the threshold between both classes, we select a distance of $d = 174\,\mathrm{m}$, corresponding to the second to last break-even point of the Free-space and Two-Ray Interference models, as was illustrated in Figure 5.

We plot distributions of neighbor table sizes in Figure 6, corresponding to our sample protocol operating with a beacon interval of 1 Hz in either the 1D *Freeway* or the 2D *Grid* scenario, respectively. 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. Data points outside the range of box and whiskers are considered outliers and drawn separately. Finally, the mean is plotted as a small red square.

We start by investigating how the choice of the Free-space empirical path loss parameter α influences nodes' neighbor table sizes. Unsurprisingly, a smaller value of α leads to less path loss over distance (cf. Figures 6b and 6d) and, thus, to larger neighbor tables, although this effect is compensated by network congestion at closer distances (cf. Figures 6a and 6c) and if beacon intervals of 10 Hz and 100 Hz are employed (results not depicted).

We thus turn our attention to the more interesting question of to what extent different empirical adaptations of the Free-space model can reproduce network topology effects observed for the Two-Ray Interference model.

Figure 6a seems to indicate that, for the 1D *Freeway* scenario, one might be able to approximate topology dynamics in the network by using $\alpha = 2.0$. However, Figure 6b makes it very clear that a model thus parameterized is, at the same time, very bad at capturing topology dynamics more than 174 m away. Here, a value of $\alpha \approx 1.95$ might be a much better match.

Comparing this, however, to results obtained in the 2D *Grid* scenario plotted for distant neighbors in Figure 6d, it becomes clear that this value of α is still too high to capture effects in this scenario, suggesting smaller values of α – an observation that is turned on its head by the results plotted in Figure 6c, which seems to suggest the exact opposite: a value of $\alpha = 2.1$.

Thus, it becomes clear that no single parameterization of the empirical Free-space model can approximate the higher-layer effects predicted by the Two-Ray Interference model.

In fact, core metrics of network topology dynamics are consistently over- or underestimated, depending on the road layout in general and individual transmission distances in particular. Taken together with the minimal impact on run time performance, these results strongly suggest to employ the Two-Ray Interference model in place of the simplified Two-Ray Ground model for path loss in vehicular networks.

IV. Conclusion and Future Work

We argue that the use of the detailed Two-Ray Interference model substantially improves the quality of the predicted path loss in vehicular environments. We integrated the model into our *Veins* vehicular network simulation framework [4] and validated it based on predictions of the analytical foundations as well on extensive sets of real-world measurements (both by us, using off-the-shelf IEEE 802.11p DSRC radios and by two independent groups [13], [14], using laboratory equipment) which we believe substantiates the claims significantly.

We conducted an extensive set of simulation experiments to estimate the impact of the Two-Ray Interference model both on signal level and on higher layer IVC protocols. As an important side effect we note that the overall simulation time is only negligibly impacted by the more complex model.

Conclusions drawn from the presented simulation experiments can be summarized as follows: The Free-space and Two-Ray Ground models cannot capture complex path loss effects at small to medium transmission distances (in fact, at realistic distances both models deliver the same results). In contrast, according to our measurement results, the Two-Ray Interference model leads to a better approximation for unobstructed scenarios. Most importantly, neither the Free-space model nor the simplified Two-Ray Ground model can be calibrated in a way that is accurate both for short range communication as well as for long range transmissions.

The demonstrated short-range effects are of particular concern for the many modern protocols that seek to trade few long range transmissions for multiple short range transmissions [24]. They are prevalent in all scenarios where reflections on buildings do not dominate radio propagation effects, i.e., in typical highway and suburban environments.

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