Using the Right Two-Ray Model? A Measurement-based Evaluation of PHY Models in VANETs

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ABSTRACT

We discuss the feasibility of simplified *Two-Ray Ground* path loss models, which are frequently used in simulation-based performance evaluation of Inter-Vehicle Communication (IVC) protocols. We first show that these models are of no benefit compared to the basic Freespace model. As an alternative, we propose a more exact *Two-Ray Interference* model. We substantiate this claim based on an extensive set of measurements on the road. We demonstrate that this model substantially improves the accuracy of the simulation of radio transmissions at negligible computational cost.

1. INTRODUCTION

Simulation is a key methodology to assess the performance of Inter-Vehicle Communication (IVC) protocols. Recently, much progress has been achieved to make vehicular networking simulations more realistic, thus, providing more insights into the behavior of, e.g., Vehicular Ad Hoc Networks (VANETs) [8]. Among the big challenges in this field is the accurate modeling of the physical radio communication. It has become a well-established fact that realistic path loss models are crucial to the quality of a wide range of IVC simulations [3]. Typically, the use of a two-ray path loss model is suggested, except in case of additional shadowing caused by obstacles [2]. We believe, however, that the use of the simplified *Two-Ray Ground* model as implemented in typical network simulation tools does not lead to a sufficient quality improvement.

We investigated the implemented models in detail and validated the results based on extensive experiments on the road. In this paper, we not only show that simplified Two-Ray Ground models are of no benefit compared to the basic Freespace model but also that the use of the more accurate *Two-Ray Interference* model as proposed in this paper leads to substantial quality improvements.

2. PATH LOSS MODELS

In network simulation, fading due to large-scale path loss, deterministic small-scale fading, or probabilistic attenuation effects is most commonly calculated as a sum of independent loss processes L_x [1, 5].

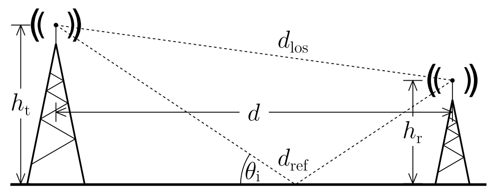


Figure 1: Simplified model of ground reflection causing signal interference at the receiver.

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

$$L_{\mathrm{freespace}}[\mathrm{dB}] = 20 \lg \left(4\pi \frac{d}{\lambda} \right). \tag{1}$$

However, more realistic treatment of the path loss takes the fact into account that radio propagation will commonly suffer from at least one notable source of interference, namely ground reflection, as illustrated in Figure 1. A physically more correct approximation [6] of path loss must therefore be based on the phase difference of interfering rays φ and a reflection coefficient $\Gamma_\perp$, leading to a *Two-Ray Interference* model,

$$L_{\mathrm{tri}}[\mathrm{dB}] = 20 \lg \left(4\pi \frac{d}{\lambda} \left| 1 + \Gamma_\perp e^{i\varphi} \right|^{-1} \right), \text{ substituting}$$

$$\varphi = 2\pi \frac{d_{\mathrm{los}} - d_{\mathrm{ref}}}{\lambda},\ \Gamma_\perp = \frac{\sin\theta_{\mathrm{i}} - \sqrt{\epsilon_{\mathrm{r}} - \cos^2\theta_{\mathrm{i}}}}{\sin\theta_{\mathrm{i}} + \sqrt{\epsilon_{\mathrm{r}} - \cos^2\theta_{\mathrm{i}}}},$$

$$d_{\mathrm{los}} = \sqrt{d^2 + (h_{\mathrm{t}} - h_{\mathrm{r}})^2},\ d_{\mathrm{ref}} = \sqrt{d^2 + (h_{\mathrm{t}} + h_{\mathrm{r}})^2},$$

$$\sin\theta_{\mathrm{i}} = (h_{\mathrm{t}} + h_{\mathrm{r}})/d_{\mathrm{ref}},\ \cos\theta_{\mathrm{i}} = d/d_{\mathrm{ref}}. \tag{2}$$

Apparently, this calculation is more complex than the much more simple calculation of path loss according to the Freespace model. Thus, e.g., Rappaport [6] helpfully illustrated how – for very large d and assuming perfect polarization and reflection – the calculation of interference between line-of-sight and reflected rays can be simplified to yield a path loss according to what is commonly termed the *Two-Ray Ground* path loss equation:

$$L_{\mathrm{trg}}[\mathrm{dB}] = 20 \lg \left(\frac{d^2}{h_{\mathrm{t}} h_{\mathrm{r}}} \right). \tag{3}$$

This has led many common network simulators (e.g., ns-2.34, ns-3.11, and INETMANET for OMNeT++) to pick up the Two-Ray Ground model as an option for simulating path loss in radio transmissions, using a cross-over distance d_c for switching between Equations (1) and (3) to yield

$$L_{\text{freespace/trg}}[\text{dB}] = \begin{cases} L_{\text{freespace}}[\text{dB}] & \text{if } d \leq d_c, \\ L_{\text{trg}}[\text{dB}] & \text{if } d > d_c. \end{cases} \quad (4)$$

Their cross-over distance can be derived to be

$$d_c = 4\pi \frac{h_{\text{t}} h_{\text{r}}}{\lambda}. \quad (5)$$

3. EXPERIMENTS ON THE ROAD

In order to investigate the applicability of the different path loss models for IEEE 802.11p transmissions, we first compare predictions by the simple Freespace model with measurements on the road taken during research for what was to become our computationally inexpensive empirical model of IEEE 802.11p radio shadowing in urban environments [7]. There, 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, 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 dBm value of Received Signal Strength (RSS). 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. Using the omnidirectional antenna, we then performed measurements under completely unobstructed channel conditions, in the middle of hayfields south of Erlangen.

When evaluating the plausibility of measurements for this study, we used curve-fitting to match

$$L_{\text{emp-freespace}}[\text{dB}] = 10 \lg \left(16\pi^2 \frac{d^\alpha}{\lambda^\alpha} \right), \quad (6)$$

an empirical adaptation of the Freespace model, with our results and found a good correlation if a path loss exponent of $\alpha = 2.2$ is assumed [7].

As the use of the described Two-Ray Ground path loss model is commonly assumed to constitute the current state of the art for vehicular networking simulation, in this paper we explored its impact on simulation results.

Figure 2: Position of the omnidirectional antenna and GPS receiver on the roofs of the cars.

We started by calculating d_c when given typical values $h_{\text{t}} = h_{\text{r}} = 1.895$ m for transmitter and receiver antenna heights (corresponding to two passenger cars) and $\lambda = 0.051$ m for the used wavelength (corresponding to the IEEE 802.11p CCH center frequency of 5.890 GHz).

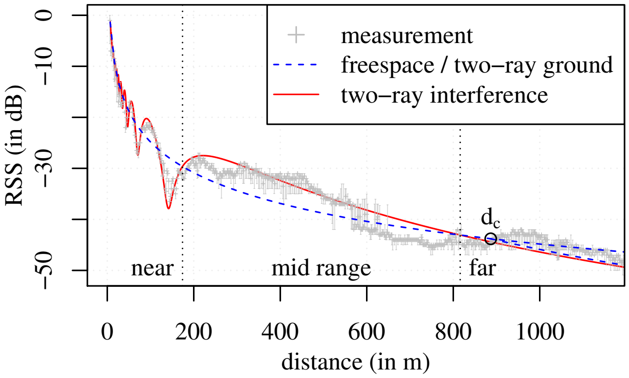
For these values, Equation (5) yields a value of $d_c = 886.6$ m. However, under realistic propagation conditions, IEEE 802.11p transmissions in urban areas are highly unlikely to ever reach that far [4, 7]. We must therefore conclude that VANET simulations based on common network simulators have, even when configured with a Two-Ray Ground model, in fact, been performed using the Freespace model only.

4. OBSERVATIONS AND RESULTS

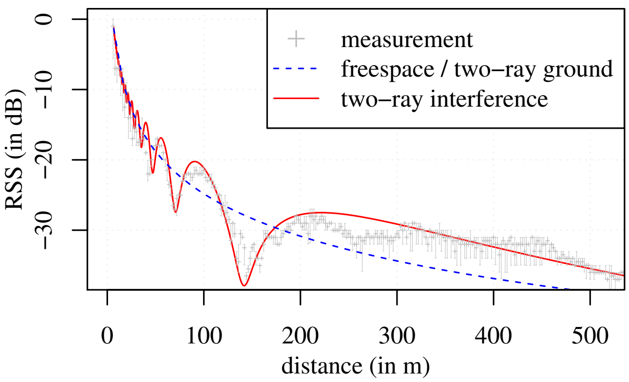
In this work, after illustrating the inapplicability of the simplified Two-Ray Ground model (which will only yield a different result compared to the standard Freespace model for improbably large distances d between sender and receiver), we now take this evaluation one step further and investigate the applicability of the Two-Ray Interference model, as given in Equation (2), for vehicular networking simulations.

Figure 3a illustrates the results of our investigation. We overlay a graph of our real-world measurements with predictions by three different path loss models: first, the Freespace model given in Equation (1); secondly, the Two-Ray Ground model given in Equation (4); finally, the Two-Ray Interference models given in Equation (2), plotted for an empirically determined $\epsilon_{\text{r}} = 1.02$.

Please note that the RSS values we gathered during measurements exhibit a peculiar irregularity: the used IEEE 802.11p platform never reported RSS values corresponding to −40 dB (measured at approx. 600 m); instead it seemed to report such values as either slightly higher or lower, thus reducing the fit between model and measurements. Still, the figure distinctly shows how little can be gained from substituting the Freespace model with the simplified Two-Ray Ground model in simulations of vehicular networks: even at transmission distances that border on being infeasible [4, 7], the difference in predicted RSS values is negligibly small.



(a) full 1.2 km



(b) first 300 m only

Figure 3: Received signal strength vs. distance between sender and receiver. Overlay of measurement results, predictions by the Freespace and Two-Ray Ground models, as well as predictions by the Two-Ray Interference model.

Focusing now on values gathered for more realistic transmission distances, for which we offer a slightly larger plot in Figure 3b, it can be seen that the Two-Ray Interference model captures path loss effects much more successfully than both the Freespace 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, as done in Equation (6), cannot compensate for these errors, further suggesting the use of 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 at approx. 150 m are, in fact, 10 dB worse than those at 200 m (and, thus, as bad as those at approx. 600 m) – a prediction that is confirmed in full by real-world measurement results.

5. CONCLUSION AND FUTURE WORK

In summary, it can be said that the proposed use of the Two-Ray Interference model leads to a substantially improved quality of the predicted path loss in vehicular environments. At reasonable transmission distances, the difference in predictions by the simplified Two-Ray Ground and Freespace models is zero or negligibly small. Moreover, the currently used models cannot capture complex path loss effects at small to medium transmission distances. In contrast, according to our measurement results, the Two-Ray Interference model leads to a better approximation for unobstructed scenarios.

In future work, we plan to integrate this model with our IEEE 802.11p radio shadowing model for urban environments, as part of our *Veins* vehicular network simulation framework [8], allowing us to investigate its impact on core network metrics.

6. REFERENCES

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