Modeling Vehicle-to-Vehicle Line of Sight Channels and its Impact on Application-Level Performance Metrics*

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ABSTRACT

We analyze the properties of line of sight (LOS) channels in vehicle-to-vehicle (V2V) communication. We use V2V measurements performed in open space, highway, suburban, and urban environments. By separating LOS from non-LOS data, we show that a two-ray ground reflection path loss model with effective reflection coefficient range fits the LOS channels better than the frequently used free space path loss model. Two-ray model is a better fit not only in open space, but also in highway, suburban, and urban environments. We investigate the impact of using the modified two-ray model on the application-level performance metrics: packet delivery rate, throughput, latency, and jitter. Our results show that considerable differences arise in application performance when using two-ray and free space channel models. For this reason, we advocate the use of the two-ray ground model with an appropriately chosen effective reflection coefficient range.

Keywords

Vehicle-to-Vehicle Communication, Measurements, Line of Sight Channels, Two-ray Ground Reflection Model

1. INTRODUCTION

Vehicle-to-vehicle (V2V) communications is envisioned to support new cooperative Intelligent Transportation Systems (ITS) applications. The currently most prominent technology for enabling V2V communication is the Dedicated Short Range Communications (DSRC). The DSRC devices operate at the 5.85-5.925 GHz band and implement the IEEE 802.11p wireless standard, specifically designed for automotive use [1]. V2V channel modeling has attracted considerable effort in recent years (see, for example, [2–5]). However, designing models that can be generalized to different environments (e.g., rural, highway, suburban, urban) is a difficult task. The authors in [6] discuss the importance of accurate simulation of V2V communication, which is particularly important for effective implementation of safety applications [7, 8]. Other studies (see, for example, [9]) point out that different terrain surrounding the roads can result in considerably different V2V channel characteristics. In terms of vehicular traffic conditions, the authors in [10] discuss the need for traffic-dependent modeling of V2V channels.

In this paper, we are interested in modeling line of sight (LOS) V2V links in open space, highway, suburban and urban environments and under different traffic conditions. We also study the impact of model selection on application level performance in terms of packet delivery, throughput, latency, and jitter. We start by analyzing the occurrence of LOS conditions on experimental datasets collected in previous measurement campaigns described in [11–13] (details described in Section 2). We use videos recorded during the experiments to distinguish the packets collected in LOS conditions in highway, suburban, and urban environments. Figure 1 shows that data received over LOS channels comprises between 25% and 82% of the data decoded at the receiver.

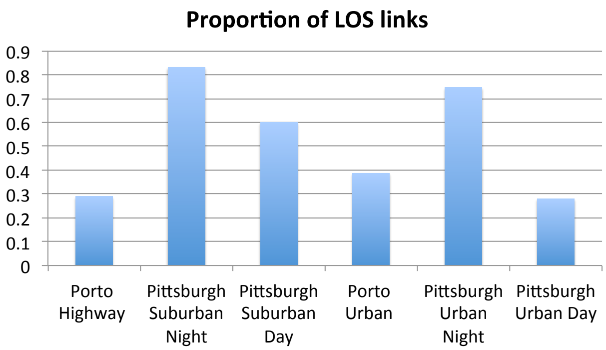

Figure 1: Measured proportion of LOS links in different environments.

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While the proportion of LOS channels could change considerably depending on the time of day and the specific environment [11], it is clear that LOS communication comprises a significant portion of the data. We note that the remaining channels are non-LOS, which occurs either due to the obstruction by static objects (e.g., buildings, trees) [14, 15] or mobile objects (other vehicles) [16]. In this paper, we focus exclusively on modeling the LOS channels.

By *separating* LOS channels from non-LOS channels in real VANET environments (suburban, urban, highway) under different vehicular traffic conditions (low and high density traffic), our study goes beyond the previous work ([17–19]) in the following aspects:

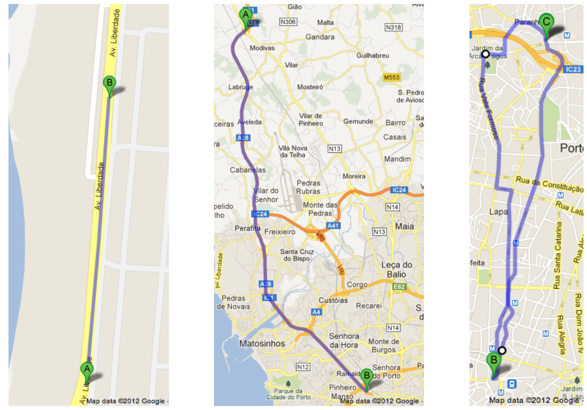
- We show that the two-ray channel model with effective reflection coefficient based on real-world measurements is preferable over the free space propagation model [20, Chap. 3.2] *not only in open space*, but also in *highway, suburban, and urban* environments; we also determine the traffic conditions under which the two-ray channel model is preferable over free space model;
- We illustrate the importance of channel modeling selection by comparing the differences in terms of application-level performance metrics when using the two-ray and free space channel model; the results show considerable difference in terms of latency, jitter, throughput, and packet delivery rate (PDR).

The rest of the paper is organized as follows. The measurements we used for channel modeling are described in Section 2. In Section 3, we analyze how a modified two-ray and free space channel models fit the measurements in different environments and under different traffic conditions. Section 4 discusses the impact of channel model selection on the application level performance metrics. Section 5 describes the related work, whereas Section 6 concludes the paper.

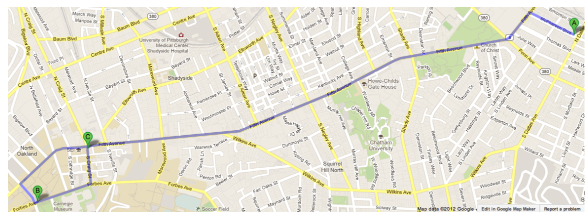
2. MEASUREMENT DATASETS

We used datasets collected in V2V measurement campaigns reported in [12] and [11]. The collected data and the videos of the experiments are freely available on the DRIVE-IN project website [21]. The measurements, utilizing IEEE 802.11p (DSRC) [1] radios, were performed in the following locations:

- Porto Open Space – 1 km route shown in Fig. 2(a). Approximate coordinates (lat,lon): 41.210615, -8.713418.
- Porto Highway – 13.5 km route shown in Fig. 2(b). Approximate coordinates (lat,lon): 41.22776, -8.695148.
  - Passenger car (short vehicles) experiments
  - Commercial van (tall vehicles) experiments
- Porto Downtown – 9 km route shown in Fig. 2(c). Approximate coordinates (lat,lon): 41.153673, -8.609913.
- Pittsburgh Suburban – 7 km route shown in Fig. 2(d). Approximate coordinates (lat,lon): 40.4476089, -79.9398574.
  - Daytime experiments (3 p.m. to 6 p.m.)
  - Nighttime experiments (11 p.m. to 2 a.m.)



(a) Porto Open Space. (b) Porto Highway. (c) Porto Downtown.



(d) Pittsburgh Suburban.

Figure 2: Experiment locations with indicated routes.

The transmitting and receiving vehicles were driven in the same direction and in normal traffic conditions according to the traffic rules on the road. The trailing vehicle was equipped with a videocamera, which was later used to separate the collected data according to the observed LOS conditions. One exception is the Porto Open Space measurement, which was controlled: the transmitting and receiving vehicles were the only two vehicles on an otherwise empty and flat road with the location selected so as to have minimal number of objects around the road. Measurements were performed between May 2010 and December 2011, all in mostly dry weather. Open Space, Highway, and Downtown experiments were performed in the afternoon hours (between 1 p.m. and 8 p.m.), whereas Suburban experiments were performed during nighttime (between 11 p.m. and 2 a.m.). Each vehicle was equipped with a NEC LinkBird-MX V3, a development platform for vehicular communications [22], complemented by Mobile Mark ECOM6-5500 omnidirectional antennas mounted on the roof of the vehicles. Details regarding the devices and DSRC parameter setup are shown in Table 1. Identical hardware setup and radio parameters were used in all experiments. Porto Urban, Porto Open Space, and Pittsburgh Urban experiments were performed with passenger cars, whereas Porto Highway was performed with two commercial vans. All passenger cars have a height of approximately 1.5 meters, which coincides with the statistical mean height for personal vehicles [16], whereas both

Parameter	Value
Channel	180
Center frequency (MHz)	5900
Bandwidth (MHz)	20
Data rate (Mbps)	6
Tx power (dBm)	10
Antenna gain Tx and Rx (dBi)	5
Cable and system loss, Tx and Rx (dB)	4
Beacon frequency (Hz)	10
Beacon size (Byte)	36

Table 1: Hardware configuration parameters

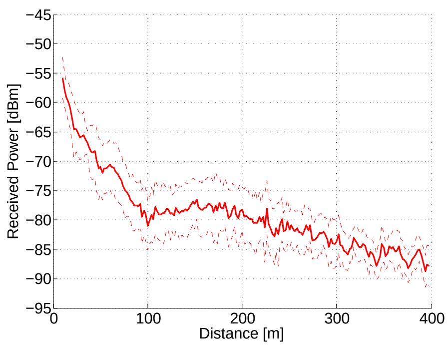


Figure 3: Received power in the Porto Open Space dataset. Measurement data is placed in two meter distance bins. Only bins with more than 40 data points are included. Dashed red lines represent one standard deviation around the mean received power for each bin.

vans have a height of approximately 2.5 meters. Additionally, we used the following measurements from [11] for determining the occurrence of LOS conditions only: Urban Pittsburgh (daytime experiments), Urban Pittsburgh (nighttime experiments).

3. MODELING THE V2V LOS CHANNELS

Due to the inherent structure of the environment where most V2V communication occurs – over the face of road surface – in case of LOS communication the propagation characteristics are likely influenced by at least two dominant rays from the transmitter to the receiver: optical LOS ray and ground-reflected ray. Figure 3 shows the received power as a function of distance for the Porto Open Space dataset. The shape of the received power curve indicates that the ground-reflected ray indeed interferes with the LOS ray. For this reason, we investigate in which environments and under which traffic conditions the two-ray ground reflection model [20, Chap. 3.] fits well the collected data.

3.1 Two-Ray Ground Reflection Model – Background

The electric field (E-field) of the electromagnetic wave at the receiver can be calculated by accounting for existent contributing rays from all five propagation primitives: free space (LOS) transmission, reflection, diffraction, scattering, and transmission through material (e.g., walls) [23]. The resultant E-field magnitude, $|E_{TOT}|$ (in volts per meter), is calculated as follows:

$$|E_{TOT}| = |E_{LOS} + \sum_j E_{Refl_j} + \sum_k E_{Diffr_k} + \sum_m E_{Scatt_m}|, \tag{1}$$

where E_{LOS}, E_{Refl}, and E_{Diffr}, and E_{Scatt} are E-fields of LOS, reflected, diffracted, and scattered rays, respectively (note that free space transmission and transmission through material are mutually exclusive). Expanding eq. 1, we get

$$\begin{aligned} E_{TOT} = & \frac{E_0 d_0}{d_{LOS}} \cos\left(\omega_c\left(t - \frac{d_{LOS}}{c}\right)\right) \\ & + \sum_j R_j \frac{E_0 d_0}{d_j} \cos\left(\omega_c\left(t - \frac{d_j}{c}\right)\right) \\ & + \sum_k D_k \frac{E_0 d_0}{d_k} \cos\left(\omega_c\left(t - \frac{d_k}{c}\right)\right) \\ & + \sum_m S_m \frac{E_0 d_0}{d_m} \cos\left(\omega_c\left(t - \frac{d_m}{c}\right)\right), \end{aligned} \tag{2}$$

where E_0 is the E-field at a reference distance d_0 (in the antenna far field), ω_c is the angular frequency ($\omega_c = 2\pi f$), t is the time at which the E-field is evaluated, d_x represents distance traversed by ray x, R_j is the reflection coefficient of reflected ray j, D_k is the diffraction coefficient of diffracted ray k, and S_m is the scattering coefficient of scattered ray m.

The free space propagation model assumes the existence of only the LOS ray, i.e., the first term in Eq. 2. This simplification is done because calculating all reflected, diffracted, and scattered rays is a computationally expensive task. However, due to the inherent structure of the environment where V2V communication occurs – over the face of road surface – in case of LOS communication the propagation characteristics are most often influenced by at least two dominant rays: LOS ray and ground-reflected ray. For these two rays, the resulting E-field is equal to:

$$\begin{aligned} E_{TOT} &= E_{LOS} + E_{ground} \\ &= \frac{E_0 d_0}{d_{LOS}} \cos\left(\omega_c\left(t - \frac{d_{LOS}}{c}\right)\right) \\ &+ R_{ground} \frac{E_0 d_0}{d_{ground}} \cos\left(\omega_c\left(t - \frac{d_{ground}}{c}\right)\right), \end{aligned} \tag{3}$$

where E_{ground} is the E-field of the ground-reflected ray, R_{ground} is the ground reflection coefficient, and $d_{ground} = \sqrt{(h_t + h_r)^2 + d^2}$ is the propagation distance of the ground-reflected ray, where h_t and h_r is the height of the transmitting and receiving antenna, respectively, and d is the ground distance between the antennas (Fig. 4). Note that using the exact height of the antennas (h_t and h_r) is important, since a small difference in terms of either h_t or h_r results in significantly different interference relationship between the LOS and ground-reflected ray.

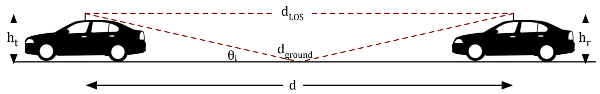


Figure 4: Two-ray ground reflection model.

When the originating medium is free space, the reflection coefficient R is calculated as follows for vertical and horizontal polarization, respectively [20, Chap. 3.]:

$$R_{||} = \frac{-\epsilon_r \sin\theta_i + \sqrt{\epsilon_r - \cos^2\theta_i}}{\epsilon_r \sin\theta_i + \sqrt{\epsilon_r - \cos^2\theta_i}} \quad (4)$$

and

$$R_{\perp} = \frac{\sin\theta_i - \sqrt{\epsilon_r - \cos^2\theta_i}}{\sin\theta_i + \sqrt{\epsilon_r - \cos^2\theta_i}}, \quad (5)$$

where θ_i is the incident angle, and ϵ_r is the relative permittivity of the material.

From E-fields in Eq. 2 and 3, the ensuing received power P_r (in watts) is calculated as follows (assuming unit antenna gain at the receiver):

$$P_r = \frac{|E_{TOT}|^2\lambda^2}{4\pi\eta}, \quad (6)$$

where λ is the wavelength and η is the intrinsic impedance (η =120π ohms in free space).

3.2 Using the Two-Ray Ground Reflection Model in the Real World

Several previous studies concluded that the modified two-ray ground reflection channel model can be used to model LOS channels in V2V (e.g., [17, 18]). As pointed out previously in the literature (e.g., in [17]), the idealized two-ray model is an approximation of the actual V2V channel, since the reflection coefficient is affected by the antenna location, diffraction over the vehicle roof below antenna, and the roughness of the road, among other. For this reason, when calculating R_{ground}, we model the relative permittivity ϵ_r to obtain the *effective range of reflection coefficient values* across different incidence angles. To estimate ϵ_r, we used the Porto Open Space dataset (Fig. 3), as it was the environment most resembling the theoretical conditions for two-ray ground model (Fig. 4) – a flat empty road with very few nearby reflectors. We performed curve fitting by minimizing the square residuals, which yielded ϵ_r value of 1.003. This value is considerably lower from the ϵ_r for asphalt in the gigahertz range, which was measured to be between 1.5 and 6 (reported in [24] and [25], respectively). To explore this discrepancy, Fig. 5 shows the distribution of incidence angles for the Porto Open Space (other environments had similar distributions). Across the experiments, 90% or more data was received with θ_i below 10 degrees and 99% below 14 degrees. This is important since the antennas used in the experiments have the main lobe contained within 15 degrees

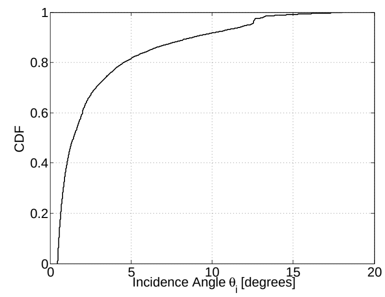
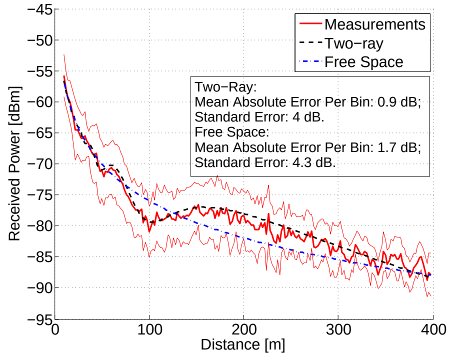


Figure 5: CDF of incidence angle θ_i for Porto Open Space dataset. Effective antenna heights of transmitter and receiver: 1.55 m and 1.57 m, respectively.

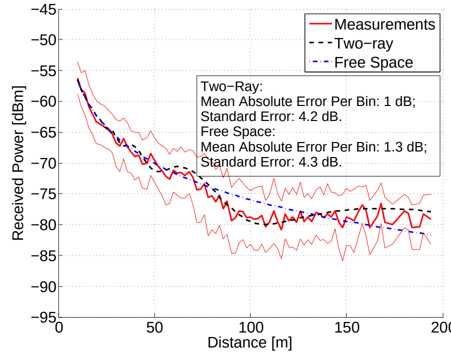
(in terms of elevation). Therefore, the reflected ray is received at approximately the same gain as the LOS ray, thus excluding the effect of the antenna gain on the magnitude of the reflected ray. The remaining variables that affect the propagation are the shapes of the transmitting and receiving vehicles and the surrounding environment. By modeling the received power using two-ray model, we hypothesize that the *reflection coefficient accounts not only for a single ground-reflected ray, but a range of rays* reflecting and diffracting off different parts of transmitting and receiving vehicle, such as roof below antenna, hood, or trunk. Combined with rays reflected and scattered off other objects (e.g., sidewalk and signposts), this results in the interference between these rays and the ground-reflected ray. From the perspective of the two-ray model, the combined effect of different rays manifests itself in the seeming reduction of the magnitude of the ground-reflected ray, since the reflection coefficient captures not only the ground-reflected ray, but also all the remaining reflected, diffracted, and scattered rays. By consequence, this reduces the value of ϵ_r that best fits the received power for the two-ray model. Similar line of reasoning when fitting the two-ray model to V2V communication was used by the authors in [17].

3.3 Comparing the Two-Ray Ground Reflection and Free Space Model with Measurements

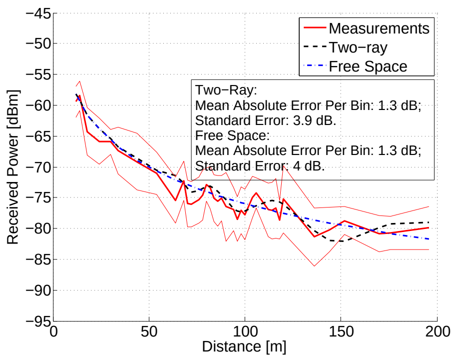
Figure 6 shows the received power measurements for LOS links in environments described in Section 2, compared with the two-ray and free space model. Not surprisingly, since it most closely matches the theoretical assumptions of the environment for the two-ray model, the Porto Open Space received power results in the best match with the two-ray model (Fig. 6(a)). Results for Pittsburgh Suburban where the experiments were performed during late night (11 p.m. to 2 a.m.) with very few vehicles on the road also show a good agreement with the two-ray model (Fig. 6(b)). It is interesting to observe the results for the same environments in a different time of day: Fig. 6(e) shows results in Pittsburgh Suburban environment during rush hour (between 3 p.m. and 6 p.m. on a working day). While the vehicles were driven on exactly the same route, the additional surrounding vehicles during rush hour created a considerably more dynamic propagation environment, thus resulting in a worse fit of the two-ray model for LOS links. Similarly, Fig. 6(c) and



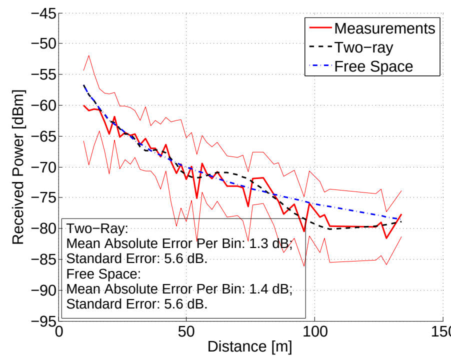
(a) Porto Open Space. Number of LOS data points: 61000. Average measured standard deviation: 3.3 dB.



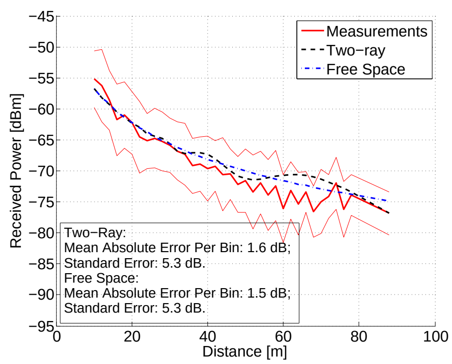
(b) Pittsburgh Suburban: Nighttime Experiments. Number of LOS data points: 11900. Average measured standard deviation: 4.1 dB.



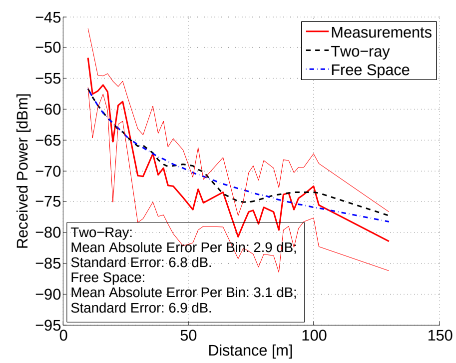
(c) Porto Highway: Tall vehicles. Number of data points: 3850. Average measured standard deviation: 3.6 dB.



(d) Porto Urban. Number of data points: 4400. Average measured standard deviation: 5.3 dB.



(e) Pittsburgh Suburban: Daytime Experiments. Number of LOS data points: 13400. Average measured standard deviation: 4.8 dB.



(f) Porto Highway: Passenger cars. Number of data points: 4820. Average measured standard deviation: 5.7 dB.

Figure 6: Comparison of received power collected during measurements with two-ray and free space model. Measurement data is placed in two meter distance bins. Only bins with more than 40 data points are included. Outer red lines represent one standard deviation around the mean received power for each bin.

Fig. 6(f) show results for Porto Highway environment with tall and short vehicles, respectively. Both experiments were performed in the 2 p.m. to 6 p.m. timeframe. The short vehicle experiments exhibit considerably more variations in terms of received power, presumably since the channel between lower antennas is more affected by reflections off surrounding vehicles. This results in an increased deviation from the two-ray model: as the number of reflections increases, the dominance of the LOS and ground-reflected ray reduces. On the other hand, the two-ray model represents the channel between tall vehicles better (Fig. 6(c)), since there are fewer significant reflecting rays reaching the tall mounted antennas.

Figure. 6(d) shows that the two-ray model fits the LOS data in Porto Urban environment slightly better than the free space model. Since in this environment the vehicles are continuously surrounded by nearby buildings that can create strong reflections, this implies that the ground-reflected ray is still a significant factor in path loss modeling for LOS channels in urban environments.

Overall, Fig. 6 shows that the two-ray model is able to capture the path loss of LOS links better than free space in all environments where the buildup of close-by surrounding objects that generate reflections is not considerable. Even when that is the case (e.g., Figs. 6(d), 6(e), and 6(f)), the proposed two-ray model performs similarly to free space model. However, in these environments, a model for LOS links that has a capability to account for additional reflections (e.g., ten-ray model in case of urban canyon [26]) is likely a better choice than two-ray or free space model.

Furthermore, since the reflection coefficients generated by $\epsilon_r = 1.003$ matches different environments well, we conclude that the underlying large scale path loss can be captured with a single instance of the two-ray model; in other words, the model does not need to be adapted to LOS links in a specific environment. This enables straightforward modeling of path loss for LOS channels in simulators: apart from the transmit and receive radio and antenna characteristics, the required information is limited to a single value of ϵ_r, heights of the antennas, and the distance between transmitter and receiver.

4. IMPACT OF CHANNEL MODEL SELECTION ON APPLICATION-LEVEL PERFORMANCE

Based on the results obtained in Section 3, in this section we study the impact of the channel model selection on application-level performance. To isolate the effect of the underlying LOS channel model, we focus on evaluating the performance of single-hop communication in terms of throughput, packet delivery rate (PDR), latency, and jitter. While PDR and latency are important for both real-time and delay-tolerant vehicular network applications [27], jitter and throughput are mainly relevant for real-time applications; one example of such application is overtaking assistance see-through system [28].

We perform simulations using the NS-2.35 simulator [29], in which we implement the modified two-ray ground reflection channel model based on the findings of Section 3. We evaluate the impact of modeling the LOS channels with the modified two-ray model against the often used free space model [20, Chap. 3.2] in terms of the following four performance metrics:

- Throughput – the total amount of data successfully delivered to the destination vehicle within a given amount of time;
- Packet delivery rate (PDR) – the ratio of packets successfully delivered to the number of packets sent to the destination vehicle;
- Latency – the amount of time required for delivering packets to the destination vehicle;
- Jitter – the variability of latency, i.e., the difference between latency of two consecutive packets.

4.1 Simulation settings

Since we are interested in the impact that channel model selections has on application performance metrics, we set up a simulation scenario with only two vehicles, which assures that interference and routing protocol characteristics do not impact the communication. The vehicle in front constantly streams video traffic to the trailing vehicle. We opt for simulating video streaming because is enables analysis of all four performance metrics under investigation (throughput, PDR, latency, jitter). We assume that the video traffic is transmitted over Real-Time transport layer protocol (RTP) [30] and the communications between two vehicles lasts for 60 seconds. A realistic video traffic pattern is generated by the TES-based video traffic generator [31], which generates traffic that has the same first and second order statistics as the original MPEG4 trace it simulates. In terms of routing, note that because the simulated communication is single-hop, the choice of routing protocol is irrelevant. Physical and MAC layer mechanisms at both vehicles are implemented according to the IEEE 802.11p standard. The modified two-ray channel model and free space model are used as path loss models. According to the measurements in Porto Open Space environment, the variation around the mean power for LOS links – i.e., the small scale signal variation due to multipath – can be well modeled by a normal random variable (similar results for V2V links are reported in [32]). Therefore, atop the path loss, we add a normally distributed random variable with: a) zero mean and standard deviation of 3.3 dB (resembling Porto Open Space environment – Fig. 6(a)); and b) zero mean and standard deviation of 5.3 dB (resembling Porto Urban environment – Fig. 6(d)). Remaining parameters used in the simulations are provided in Table 2.

Receiver-based Auto Rate (RBAR) algorithm [33] is used as an adaptive modulation control scheme. RBAR adjusts the data rate based on the perceived signal-to-noise (SNR) value measured from the ACK packets. The SNR thresholds used in our simulations are described in [34] and given in Table 3.

4.2 Results

We first analyze the difference in rate selection between the modified two-ray model and the free space model with the

Table 2: Parameters used in the simulations to evaluate the impact of an accurate LOS channel model

Setting	Parameters	Values
Channel Model – Path Loss	Modified Two-ray (Eq. 3) Free Space (first term in Eq. 2)	$\epsilon_r = 1.003$
Channel Model – Fading	Normally distributed	$N(0, 3.3)$ & $N(0, 5.3)$ [11, 12]
PHY/MAC	Transmit power + antenna gains Antenna height of transmitting vehicle Antenna height of receiving vehicle	12 dBm 1.55 m 1.5 m

Table 3: DSRC data rate and SNR threshold [34]

SNR Threshold (dB)	5	6	8	10	13	15	20	N/A
Data Rate (Mbps)	3	4.5	6	9	12	18	24	27

fading that resembles Porto Open Space environment (standard deviation of 3.3 dB). Figure 7 shows the difference in terms of selected data rates over time when the two channel models are used for four source-destination distances. Observe that when the source and destination vehicles are close (e.g., 40 m apart – top plot of Fig. 7), the SNR values observed are usually larger than 20 dB for both two-ray and free space models and hence, most packets are transmitted at the rate of 27 Mbps (see Table 3). When the source-destination distance increases, the difference in the selected rate becomes more pronounced, since the observed SNR values are in the range of SNR thresholds shown in Table 3. For instance, observe in the second plot of Fig. 7 that the data rates selected when the modified two-ray model is used are most of the time lower than those selected when the free space model is used. At larger distances, the the mean data rate can vary by up to 5 Mbps – from an application standpoint, such disparity in simulated data rate might mean a difference between successful and unsuccessful transmission.

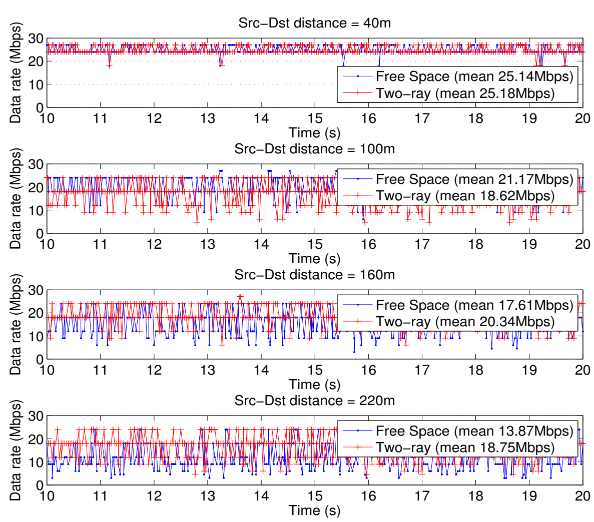


Figure 7: Instantaneous data rate used to transmit a packet for a given distance when the standard deviation of fading is 3.3 **dB.**

Figure 8 shows the application-level performance in terms of the four metrics for each source-destination distance in scenarios where the two LOS channel models are used with lower fading (standard deviation of 3.3 dB). It is important to note that while the models generate similar results in terms of the total amount of data transferred, the two-ray model results in 30% decrease in terms of packet latency and jitter. This result emphasizes the importance of underlying LOS channel model selection; such difference in latency and jitter would considerably change the perceived performance of real-time applications. It is worth pointing out that the main reason for the difference in latency and jitter arises from the fact that the two LOS channel models estimate different received power and hence, based on the estimates, different data rates are selected.

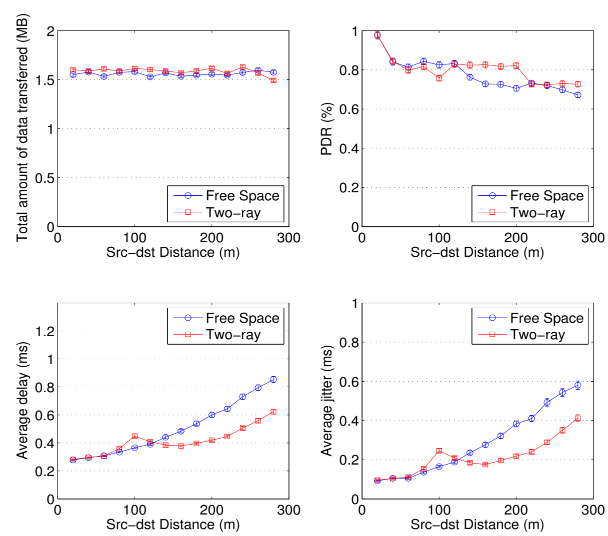


Figure 8: Application performances in terms of throughput, packet delivery rate, latency, and jitter when different LOS channels are used. The standard deviation of fading: 3.3 **dB.**

Figures 9 and 10 show the data rates and all four performance metrics with stronger fading effect (i.e., standard deviation of 5.3 dB, representing the Porto Urban environment). Because of stronger fading, one can observe larger variance in terms of data rate used even when the source-destination distance is small (see top plot of Figure 9). While the mean selected data rate is similar, the increased variance leads to noticeable difference in all four performance metrics, as s shown in Fig. 10. This phenomenon is however not surprising because with 5.3 dB fading standard deviation, the fluctuation in the received power can cause the "step-up" or "step-down" in terms of data rate. In addition, when SNR value is small (i.e., the source-destination distance is large), the effect of large fluctuation becomes even more significant. This is because the SNR thresholds of low data rates are spaced tightly (e.g., SNR thresholds of the lowest two data rates differ by only 1 dB). Based on the aforementioned observations, it is therefore clear that the choice of channel modeling and parameter values are critical as they provide significant difference in terms of application-level performance.

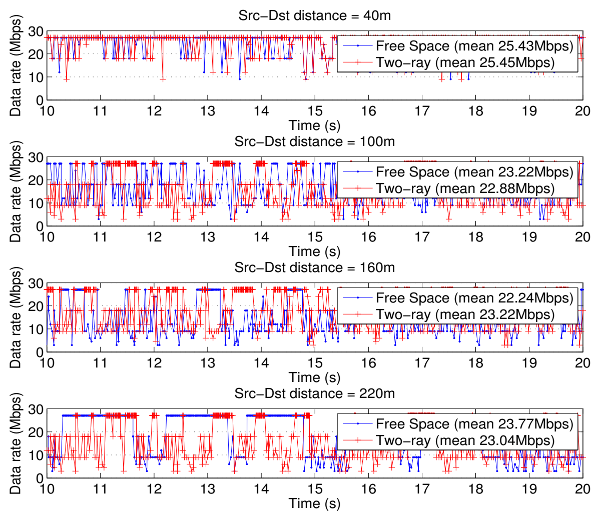


Figure 9: Instantaneous data rate used to transmit a packet for a given distance when the standard deviation of fading is 5.3 **dB.**

5. RELATED WORK

Kunisch and Pamp in [17] perform V2V measurements in rural, highway, and urban environments. They observe that the path loss in rural and highway environment is better matched by a modified two-ray model than the free space model, which is in line with our findings. On the other hand, contrary to our results, the authors find that in urban area the two-ray model did not match the measurements well. This discrepancy might be due to the inclusion of any non-LOS V2V communication in their measurements, since the measurement data was not separated in LOS and non-LOS. Similar study was performed by Karedal et al. in [35], where measurements in rural, highway, suburban, and urban environments are analyzed. Two ray model best matched the path loss profile of the measurements in rural environment, where vehicular traffic was very light. Our observations on the impact of vehicular traffic corroborate these findings. The remaining scenarios contained non-negligible amount of measurements collected in non-LOS conditions, which were not isolated (the authors point out that they "let the possibility of occasional shadowing be inherent in the subsequent models"). In a similar study, Cheng et al. in [18] perform measurements in rural and highway environments and con-

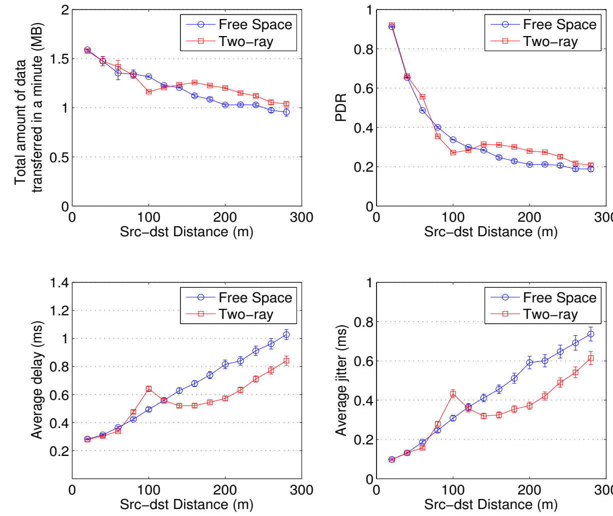


Figure 10: Application performances in terms of throughput, packet delivery rate, latency, and jitter when different LOS channels are used. The standard deviation of fading: 5.3 **dB.**

clude that the two-ray model fits well the path loss of the measurements. All three studies have one point in common – whenever the collected measurement data was predominantly of LOS type, the modified two-ray model fits the path loss well. The analysis we perform in Section 3 corroborates this finding and goes beyond it by looking at the different environments in more detail. By separating the LOS data, we show empirically that: a) the fit of the two-ray model to V2V LOS data gets better the less cluttered the environment becomes; and b) the two-ray model fits the LOS data even in unexpected environments, such as suburban and urban.

The above studies focused on modeling the path loss for V2V channels, without dealing with the repercussions of the channel model selection on upper layer performance metrics (i.e., MAC, network, and application performance). To that end, Sommer et al. in [19] perform experiments in an open space environment and fit the measured path loss to a modified two-ray model with a comparable value of relative permittivity (ϵ_r=1.02) to the one we obtained (ϵ_r=1.003). Based on the modified two-ray model, the authors evaluate the difference in terms of the number of neighboring vehicles when using the modified two-ray and the free space models with varying path loss exponent. The results show that there is a notable difference in the number of discoverable neighbors when using different channel models. Tan et al. in [36] performed V2V measurements in urban, rural, and highway environments at 5.9 GHz. The authors distinguish LOS and non-LOS communication scenarios by coarsely dividing the overall obstruction levels. Their results showed significant differences with respect to delay spread and Doppler shift in case of LOS and NLOS channels (NLOS was often induced by trucks obstructing the LOS). In terms of network-level performance, the authors conclude that different channel conditions result in considerably varying transmission time (i.e., latency). Separating LOS and non-LOS communication is important for correct modeling of V2V channels [37]. The authors of [38] and [39] propose analytical models based on the collected measurement data. Both models enable fine-grained separation of V2V communication based on the LOS conditions. In a comprehensive study, Gozalvez et al. in [40] analyze the impact of different channel models proposed within the scope of WINNER project [41] on the V2V communication performance. The authors conclude that the selection of the correct channel model is critical for realistic evaluation of safety applications and routing protocol performance.

To the best of our knowledge, this is the first study that: a) modeled the V2V LOS channels exclusively by separating LOS from non-LOS communication using experiments performed in different real-world environments; b) analyzed LOS channels with different vehicular traffic conditions; and c) assessed the impact of LOS channel model selection on throughput, PDR, latency, and jitter.

6. CONCLUSIONS

We analyzed V2V LOS channels in open space, highway, suburban, and urban environments. By utilizing V2V measurements performed in these environments and by separating the LOS from non-LOS communication using the video recordings of the experiments, we establish that the modified two-ray ground reflection model is a better match for LOS channels than the often used free space model, in particular when the number of surrounding objects (either mobile – other vehicles, or static – buildings or similar) that generate additional reflections is low. In all environments, the modified two-ray model results are comparable to or better than the free space model.

Based on our findings, we perform simulations to explore the impact of LOS channel model selection in terms of application level performance. Specifically, we analyze the behavior of throughput, packet delivery rate, latency, and jitter when modified two-ray model and free space model are used. Considerable differences arise in the simulated results, particularly in terms of delay, jitter and packet delivery rate. This result emphasizes the importance of using the correct channel model for LOS links. Since in terms of computational complexity the two channel models are equally simple to implement (the only additional information required for the two-ray model are the transmitting and receiving antenna heights), we advocate the use of modified two-ray model for simulating V2V LOS channels.

As noted in [19], state-of-the-art vehicular network simulators (e.g., Jist/SWANS [42], NS-2 [29], NS-3 [43], etc.) use a simplified version of the two-ray model that makes several assumptions, which make it essentially equal to free space channel model for realistic V2V communication distances (up to a kilometer). To that end, based on our findings, we will make available for the research community the code that implements the modified two-ray channel model for NS-2 simulator.

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