Impact of Vehicles as Obstacles in Vehicular Ad Hoc Networks

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***Abstract*—A thorough understanding of the communications channel between vehicles is essential for realistic modeling of Vehicular Ad Hoc Networks (VANETs) and the development of related technology and applications. The impact of vehicles as obstacles on vehicle-to-vehicle (V2V) communication has been largely neglected in VANET research, especially in simulations. Useful models accounting for vehicles as obstacles must satisfy a number of requirements, most notably accurate positioning, realistic mobility patterns, realistic propagation characteristics, and manageable complexity. We present a model that satisfies all of these requirements. Vehicles are modeled as physical obstacles affecting the V2V communication. The proposed model accounts for vehicles as three-dimensional obstacles and takes into account their impact on the LOS obstruction, received signal power, and the packet reception rate. We utilize two real world highway datasets collected via stereoscopic aerial photography to test our proposed model, and we confirm the importance of modeling the effects of obstructing vehicles through experimental measurements. Our results show considerable obstruction of LOS due to vehicles. By obstructing the LOS, vehicles induce significant attenuation and packet loss. The algorithm behind the proposed model allows for computationally efficient implementation in VANET simulators. It is also shown that by modeling the vehicles as obstacles, significant realism can be added to existing simulators with clear implications on the design of upper layer protocols.**

***Index Terms*—VANET, vehicle-to-vehicle communication, simulation, signal propagation modeling, channel model**

I. INTRODUCTION

VEHICLE to vehicle (V2V) communication is proposed as the communication paradigm for a number of traffic safety, traffic management, and infotainment applications ([1], [2]). In V2V communication, due to the relatively low elevation of the antennas on the communicating vehicles, it is reasonable to expect that other vehicles will act as obstacles to the signal, often affecting propagation even more than static obstacles (e.g., buildings or hills), especially in the case of an open road. As noted in a recent survey on Vehicular Ad Hoc Network (VANET) simulators [3], state of the art VANET simulators such as NS-2 [4], JiST/SWANS/STRAW [5], and NCTU-NS [6], consider the vehicles as dimensionless entities that have no influence on signal propagation. One reason lies in the fact that realistic propagation models for such highly dynamic networks are generally deemed to be computationally expensive (e.g., ray tracing [7]), and mobile obstacles increase the complexity even further. Simplified stochastic radio models, which rely on the statistical properties of the chosen environment and do not account for the specific obstacles in the region of interest, are thus preferred for use in simulators, and are believed to offer reasonable approximations at low computational cost [8]. A recent study showed, however, that stochastic radio models do not provide good accuracy for typical VANET scenarios [9]. On the other extreme, topography-specific, highly realistic channel models (such as the one presented in [10]) yield results that are in very good agreement with the real world, albeit at a price. These models are computationally too expensive and bound to a specific location (e.g., a particular neighborhood in a city, such as in [10]) to be practically useful for simulations. For these reasons, such models are not implemented in VANET simulators.

Hence, there exists a need for accurate and efficient V2V channel models. To provide such a model, we incorporate vehicles as obstacles and present a method to analyze the existence of the LOS component of the signal for each communicating pair. The focus on the existence of the LOS component was motivated by the recent experimental V2V studies reported in [11] and [12]. These studies showed that, when existent, the LOS component of the signal carries orders of magnitude more power than the remaining components (e.g., due to reflection or diffraction). This was shown to be especially true for highway environments. We therefore analyze the data collected on Portuguese highways to show that, as physical obstacles, vehicles have a significant impact on signal propagation, by frequently obstructing the LOS between the communicating vehicles. Based on the (non-)existence of LOS, we implemented an efficient model for vehicles as obstacles and showed that for the proposed VANET communication standard, the Dedicated Short Range Communication (DSRC) [13], the signal attenuation due to the obstructing vehicles is significant. To further verify the predictions of the proposed model, we conducted empirical measurements which

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corroborated the results regarding the signal attenuation due to vehicles. Not modeling the vehicles as obstacles thus leads to unrealistic assumptions about the physical layer, and this was shown to have significant implications on the behavior of the upper layers of the protocol stack (e.g., [8], [14], and [15]).

Our main contributions are as follows.

1) By analyzing the real-world data, we *quantify* the impact of vehicles as obstacles on V2V communication in terms of LOS obstruction. The results show that the obstructing vehicles have a significant impact on LOS in both sparse and dense vehicular networks and should therefore be included in V2V channel modeling in order to obtain more realistic simulation results.
2) We develop a model for incorporating the vehicles as obstacles in VANET simulators. The model encompasses calculation of LOS obstruction, as well as a simple signal propagation model to characterize the effects of obstructing vehicles on the received signal power and the packet reception ratio. We confirm the validity of the results by performing empirical V2V measurements.
3) In order to make the proposed model suitable for implementation in VANET simulation environments, we designed it with the following characteristics in mind:
   - suitability for any VANET environment (e.g., urban, suburban, highway) with any vehicle density;
   - topology/location independence;
   - ease of implementation in VANET simulators; and
   - complementarity and compatibility with VANET signal propagation models for static obstacles (e.g., buildings, foliage, etc).

   The results obtained by employing the proposed model show that significant improvements can be obtained with regards to the realism of the simulation results, at the same time maintaining relatively low computational cost. The results also point out that the stochastic models that determine the overall, system-level additional attenuation due to vehicles are unable to adequately represent the impact of vehicles on the received signal power. For these reasons, we argue that a dedicated model for vehicles needs to be implemented in VANET simulators in order to increase the credibility of simulation results.

The rest of the paper is organized as follows. Section II describes previous work on channel characterization in V2V communication. The methodology for evaluating the impact of vehicles on LOS and signal behavior is described in Section III, whereas Section IV presents the requirements of the proposed model and the means to obtain the required data. The computational complexity of the algorithm proposed for implementation in VANET simulators is analyzed in Section V. Section VI highlights the obtained results. Finally, Section VII concludes the paper.

II. Related Work

Our approach towards V2V communication is based on the following hypothesis: the low heights of the antennas in V2V communication system suggests that other vehicles can act as obstacles for signal propagation, most notably by obstructing the LOS between the communicating vehicles. Numerous studies, both experimental and analytical (e.g., [16] and [17]), have shown that LOS and non-LOS (NLOS) scenarios must be separately modeled in VANETs, because the resulting channel characteristics are fundamentally different.

Several other experimental studies point out that other vehicles apart from the transmitter and receiver could be an important factor for the signal propagation (mainly by obstructing the LOS, thus decreasing the received signal power) and therefore should be included in channel modeling (e.g., [18], [19], and [20]).

Wang *et al.* in [21] analyzed the state of the art in V2V channel measurement and modeling. Based on the approach of modeling the environment (geometrically or non-geometrically), and the distribution of objects in the environment (stochastic or deterministic), three main types of models were identified: non-geometrical stochastic models, geometry-based deterministic models, and geometry-based stochastic models. Using this classification, we present an overview of the existing research on V2V communication and channel modeling with respect to vehicles as obstacles.

A. Non-Geometrical Stochastic Models

Otto *et al.* in [14] performed experiments in the 2.4 GHz frequency band in urban, suburban, and open road environments. Although the study focused on static obstacles such as buildings, the results showed a significantly worse signal reception on the same open road during the traffic heavy, rush hour period when compared to a no traffic, late night period. The measurements for the rush hour period showed a mean path loss exponent of 3.31 and a shadowing deviation of 4.84 dB, whereas in the late night period the mean path loss exponent was 3.1 with a shadowing deviation of 3.23 dB. The observed difference can only be attributed to other vehicles obstructing the signal, since all other system parameters remained the same.

Cheng *et al.* in [22] performed measurements of the V2V channel in the 5.9 GHz frequency band and pointed out that vehicles as obstacles are the most probable cause for the difference in received signal power between the obtained experimental measurements and the dual slope piecewise linear channel model used in that study. Extensive measurement campaigns reported in [23] analyzed urban, suburban, and highway environments with two levels of traffic density (high and low). The measurements showed significantly differing channel properties in low and high traffic scenarios. Based on the measurements, several V2V channel models were proposed. The presented models are specific for a given environment and vehicle traffic density. A simple error model for V2V communication was presented in [24], where the authors differentiate the LOS and NLOS communication due to vehicles using a highly abstracted model where a threshold distance is used to separate the LOS and NLOS communication. As noted in the same paper, to achieve higher realism requires a more detailed channel model that differentiates between the LOS and NLOS communication induced by vehicles.

B. Geometry-Based Deterministic Models

A highly realistic model, based on optical ray tracing was presented in [10]. The model encompasses all objects in the analyzed environment (both static and mobile) and evaluates the signal behavior by analyzing the strongest propagation paths between the communicating pair. The model was compared against experimental measurements and showed close agreement. However, the realism of the model is achieved at the expense of high computational complexity and location-specific modeling. Even with the recent advances in optimizing the execution of ray tracing models [25], the method remains computationally too expensive to be implemented in VANET simulators. Additionally, detailed knowledge about the topology of the analyzed environment is necessary in order to accurately model the channel.

C. Geometry-Based Stochastic Models

Karedal *et al.* in [26] designed a model for the V2V channel based on extensive measurements performed in highway and suburban environments at the 5.2 GHz frequency band. The model distributes the vehicles as well as other objects at random locations and analyzes four distinct signal components: LOS, discrete components from mobile objects, discrete components from static objects, and diffuse scattering. Based on the obtained measurement data, a set of model parameters for the two environments is prescribed, and the non-stationarity of the V2V channel can be captured by employing a mobility model for the vehicles (it was shown in [27] that the wide-sense stationary uncorrelated scattering assumption does not hold for the V2V channel). Cheng *et al.* in [28] presented a MIMO channel model that takes into account the LOS, single-bounced rays, and double-bounced rays by employing a combined two-ring and ellipse model. By properly defining the parameters, the model can be used in various V2V environments with varying vehicle densities. Due to the static nature of the employed geometric model, the non-stationarity of the V2V channel cannot be captured.

With regards to the implementation of vehicles as obstacles in simulators, virtually all of the state of the art VANET simulators neglect the impact of vehicles as obstacles on signal propagation, mainly due to the lack of an appropriate methodology capable of incorporating the effect of vehicles both realistically and efficiently.

To the best of our knowledge, up to now there has been no study that focused on vehicles as obstacles by systematically quantifying their impact on LOS and consequently on the received signal power. Apart from quantifying the impact of vehicles, we present a computationally efficient model for the implementation of vehicles as obstacles in VANET simulators. Our model can be seen as a simplified geometry-based deterministic model.

III. Model Analysis

A. The Impact of Vehicles on Line of Sight

In order to isolate and quantify the effect of vehicles as obstacles on signal propagation, we do not consider the effect of other obstacles such as buildings, overpasses, vegetation, or other roadside objects on the analyzed highways. Since those obstacles can only further reduce the probability of LOS, our approach leads to a best case analysis for probability of LOS.

Figure 1 describes the methodology we use to quantify the impact of vehicles as obstacles on LOS in a V2V environment. Using aerial imagery (Fig. 1a) to obtain the location and length of vehicles, we devise a model to analyze all possible connections between vehicles within a given range (Fig. 1b). For each link – such as the one between the vehicles designated as transmitter (Tx) and receiver (Rx) in Fig. 1b – the model determines the existence or non-existence of the LOS based on the number and dimensions of vehicles potentially obstructing the LOS (in case of the aforementioned vehicles designated as Tx and Rx, the vehicles potentially obstructing the LOS are those designated as Obstacle 1 and Obstacle 2 in Fig. 1b).

The proposed model calculates the (non-)existence of the LOS for each link (i.e., between all communicating pairs) in a deterministic fashion, based on the dimensions of the vehicles and their locations. However, in order to make the model mathematically tractable, we derive the expressions for the microscopic (i.e., per-link and per-node) and macroscopic (i.e., system-wide) probability of LOS. It has to be noted that, from the electromagnetic wave propagation perspective, the LOS is not guaranteed with the existence of the visual sight line between the Tx and Rx. It is also required that the Fresnel ellipsoid is free of obstructions [7, Chap. 3]. Any obstacle that obstructs the Fresnel ellipsoid might affect the transmitted signal. As the distance between the transmitter and receiver increases, the diameter of the Fresnel ellipsoid increases accordingly. Besides the distance between the Tx and Rx, the Fresnel ellipsoid diameter is also a function of the wavelength.

As we will show later in Section IV, personal vehicle heights follow a normal distribution. To calculate $P(LOS)_{ij}$, i.e., the probability of LOS for the link between vehicles i and j, with one vehicle as a potential obstacle between Tx and Rx (of height h_i and h_j, respectively), we have:

$$P(LOS|h_i, h_j) = 1 - Q\left(\frac{h-\mu}{\sigma}\right) \tag{1}$$

and

$$h = (h_j - h_i)\frac{d_{obs}}{d} + h_i - 0.6r_f + h_a, \tag{2}$$

where the i, j subscripts are dropped for clarity, and h denotes the effective height of the straight line that connects Tx and Rx at the obstacle location when we consider the first Fresnel ellipsoid. Furthermore, $Q(\cdot)$ represents the Q-function, μ is the mean height of the obstacle, σ is the standard deviation of the obstacle's height, d is the distance between the transmitter and receiver, d_{obs} is the distance between the transmitter and the obstacle, h_a is the height of the antenna, and r_f is the radius of the first Fresnel zone ellipsoid which is given by

$$r_f = \sqrt{\frac{\lambda d_{obs}(d - d_{obs})}{d}},$$

with λ denoting the wavelength. We use the appropriate λ for the proposed standard for VANET communication (DSRC), which operates in the 5.9 GHz frequency band. In our studies, we assume that the antennas are located on top of the vehicles

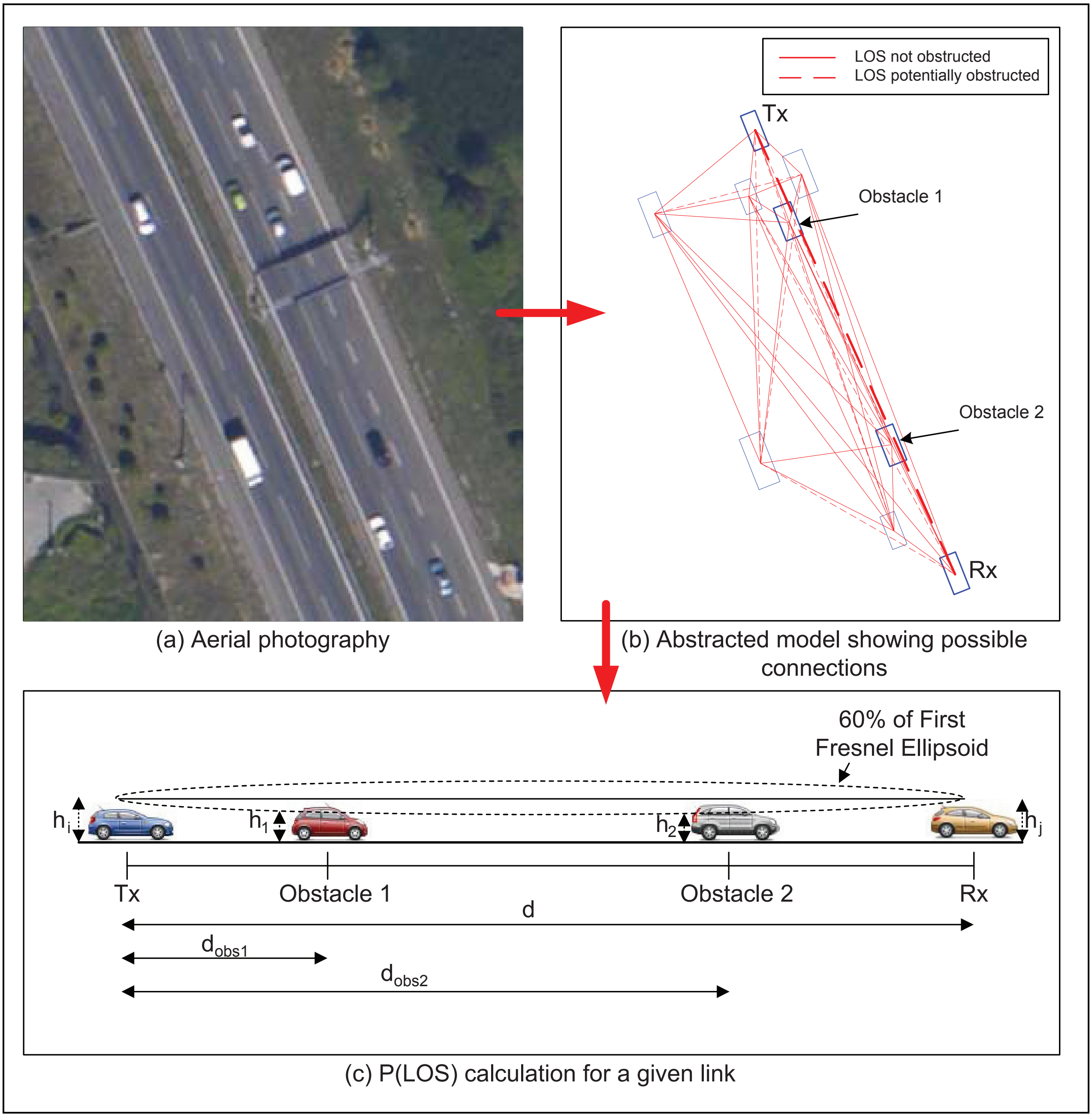


Fig. 1. Model for evaluating the impact of vehicles as obstacles on LOS (for simplicity, vehicle antenna heights (h_a) are not shown in subfigure (c)).

in the middle of the roof (which was experimentally shown to be the overall optimum placement of the antenna [15]), and we set the h_a to 10 cm. As a general rule commonly used in literature, LOS is considered to be unobstructed if intermediate vehicles obstruct the first Fresnel ellipsoid by less than 40% [7, Chap. 3]. Furthermore, for N_o vehicles as potential obstacles between the Tx and Rx, we get (see Fig. 1c)

$$P(LOS|h_i, h_j) = \prod_{k=1}^{N_o} \left[1 - Q\left(\frac{h_k - \mu_k}{\sigma_k}\right)\right], \qquad (3)$$

where h_k is the effective height of the straight line that connects Tx and Rx at the location of the k-th obstacle considering the first Fresnel ellipsoid, μ_k is the mean height of the k-th obstacle, and σ_k is the standard deviation of the height of the k-th obstacle. Provided that the heights of the obstacles are known beforehand (instead of being drawn from a normal distribution), equations (1) and (3) become deterministic (i.e., the result is zero in case of LOS obstruction and one otherwise).

Averaging over the transmitter and receiver antenna heights with respect to the road, we obtain the unconditional $P(LOS)_{ij}$

$$P(LOS)_{ij} = \int\int P(LOS|h_i, h_j)p(h_i)p(h_j)dh_i dh_j, \qquad (4)$$

where $p(h_i)$ and $p(h_j)$ are the probability density functions for the transmitter and receiver antenna heights with respect to the road, respectively.

The average probability of LOS for a given vehicle i, $P(LOS)_i$, and all its N_i neighbors is defined as

$$P(LOS)_i = \frac{1}{N_i}\sum_{j=1}^{N_i} P(LOS)_{ij} \quad (5)$$

To determine the system-wide ratio of LOS paths blocked by other vehicles, we average $P(LOS)_i$ over all N_v vehicles in the system, yielding

$$\overline{P(LOS)} = \frac{1}{N_v}\sum_{i=1}^{N_v} P(LOS)_i. \quad (6)$$

Furthermore, we analyze the behavior of the probability of LOS for a given vehicle i over time. Let us denote the i-th vehicle probability of LOS at a given time t as $P(LOS)_i^t$. We define the change in the probability of LOS for the i-th vehicle over two snapshots at times t_1 and t_2 as

$$\Delta P(LOS)_i = |P(LOS)_i^{t_2} - P(LOS)_i^{t_1}|, \quad (7)$$

where $P(LOS)_i^{t_1}$ and $P(LOS)_i^{t_2}$ are obtained using (5).

It is important to note that equations (1) to (7) depend on the distance between the node i and the node j (i.e., transmitter and receiver) in a *deterministic manner*. More specifically, the snapshot obtained from aerial photography provides the exact distance d (Fig. 1c) between the nodes i and j. While in our study we used aerial photography to get this information, any VANET simulator would also provide the exact location of vehicles based on the assumed mobility model (e.g., car-following [29], cellular automata [30], etc.), hence the distance d between the nodes i and j would still be available. This also explains why the proposed model is independent of the simulator used, since it can be incorporated into any VANET simulator, regardless of the underlying mobility model, as long as the locations of the vehicles are available. Furthermore, even though we used the highway environment for testing, the proposed model can be used for evaluating the impact of obstructing vehicles on any type of road, irrespective of the shape of the road (e.g., single or multiple lanes, straight or curvy) or location (e.g., highway, suburban, or urban[1]).

B. The Impact of Vehicles on Signal Propagation

The attenuation on a radio link increases if one or more vehicles intersect the ellipsoid corresponding to 60% of the radius of the first Fresnel zone, independent of their positions on the Tx-Rx link (Fig. 1c). This increase in attenuation is due to the diffraction of the electromagnetic waves. The additional attenuation due to diffraction depends on a variety of factors: the obstruction level, the carrier frequency, the electrical characteristics, the shape of the obstacles, and the amount of obstructions in the path between transmitter and receiver. To model vehicles obstructing the LOS, we use the knife-edge attenuation model. It is reasonable to expect that more than one vehicle can be located between transmitter (Tx) and receiver (Rx). Thus, we employ the multiple knife-edge model described in ITU-R recommendation [31]. When there are no vehicles obstructing the LOS between the Tx and Rx, we use the free space path loss model [32][2].

1) Single Knife-Edge: The simplest obstacle model is the knife-edge model, which is a reference case for more complex obstacle models (e.g., cylinder and convex obstacles). Since the frequency of DSRC radios is 5.9 GHz, the knife-edge model theoretically presents an adequate approximation for the obstacles at hand (vehicles). The prerequisite for the applicability of the model, namely a significantly smaller wavelength than the size of the obstacles [31], is fulfilled (the wavelength of the DSRC is approximately 5 cm, which is significantly smaller than the size of the vehicles).

The obstacle is seen as a semi-infinite perfectly absorbing plane that is placed perpendicular to the radio link between the Tx and Rx. Based on the Huygens principle, the electric field is the sum of Huygens sources located in the plane above the obstruction and can be computed by solving the Fresnel integrals [33]. A good approximation for the additional attenuation (in dB) due to a single knife-edge obstacle A_{sk} can be obtained using the following equation [31]:

$$A_{sk} = \begin{cases} 6.9 + 20\log_{10}\left[\sqrt{(v-0.1)^2+1} + v - 0.1\right]; \\ \quad \text{for } v > -0.7 \\ \quad 0; \text{ otherwise,} \end{cases} \quad (8)$$

where $v = \sqrt{2}H/r_f$, H is the difference between the height of the obstacle and the height of the straight line that connects Tx and Rx, and r_f is the Fresnel ellipsoid radius.

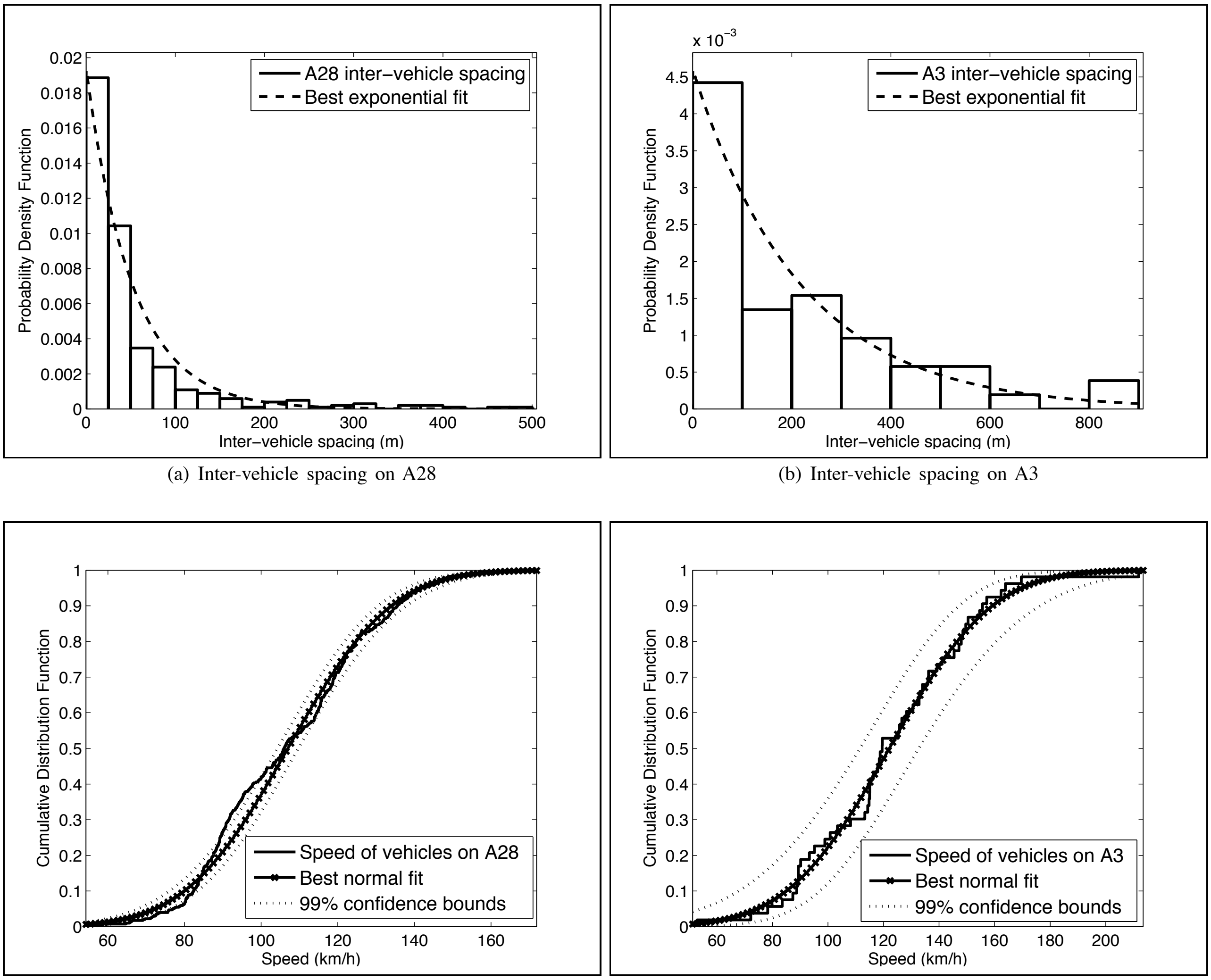
2) Multiple Knife-Edge: The extension of the single knife-edge obstacle case to the multiple knife-edge is not immediate. All of the existing methods in the literature are empirical and the results vary from optimistic to pessimistic approximations [33]. The Epstein-Petterson method [34] presents a more optimistic view, whereas the Deygout [35] and Giovanelli [36] are more pessimistic approximations of the real world. Usually, the pessimistic methods are employed when it is desirable to guarantee that the system will be functional with very high probability. On the other hand, the more optimistic methods are used when analyzing the effect of interfering sources in the communications between transmitter and receiver. To calculate the additional attenuation due to vehicles, we employ the ITU-R method [31], which can be seen as a modified version of the Epstein-Patterson method, where correcting factors are added to the attenuation in order to better approximate reality.

IV. Model Requirements

The model proposed in the previous section is aimed at evaluating the impact of vehicles as obstacles using geometry concepts and relies heavily on realistic modeling of the physical environment. In order to employ the proposed model accurately, the following physical properties are necessary: the exact position of vehicles and the inter-vehicle spacing; the speed of vehicles; and the vehicle dimensions.

[1]However, to precisely quantify the impact of obstructing vehicles in complex urban environments, further research is needed to determine the interplay between the vehicle-induced obstruction and the obstruction caused by other objects (e.g., buildings, overpasses, etc.).

[2]We acknowledge the fact that the free space model might not be the best approximation of the LOS communication on the road. However, due to its properties, it allows us to analyze the relationship between the LOS and non-LOS conditions in a deterministic manner.



(a) Inter-vehicle spacing on A28

(b) Inter-vehicle spacing on A3

(c) Speed distribution on A28

(d) Speed distribution on A3

Fig. 2. Speed and inter-vehicle spacing distribution on highways.

TABLE I
ANALYZED HIGHWAY DATASETS

Dataset	Size	# vehicles	# large vehicles	Veh. density
A28	12.5 km	404	58 (14.36%)	32.3 veh/km
A3	7.5 km	55	10 (18.18%)	7.3 veh/km

A. Determining the exact position of vehicles and the inter-vehicle spacing

The position and the speed of vehicles can easily be obtained from any currently available VANET mobility model. However, in order to test our methodology with the most realistic parameters available, we used *aerial photography*. This technique is used by the traffic engineering community as an alternative to ground-based traffic monitoring [37], and was recently applied to VANET connectivity analysis [38]. It is well suited to characterize the physical interdependencies of signal propagation and vehicle location, because it gives the exact position of each vehicle. We analyzed two distinct data sets, namely two Portuguese highways near the city of Porto, A28 and A3, both with four lanes (two per direction). Detailed parameters for the two datasets are presented in Table I. For an extensive description of the method used for data collection and analysis, we refer the reader to [38].

B. Determining the speed of vehicles

For the observed datasets, besides the exact location of vehicles and the inter-vehicle distances, stereoscopic imagery was once again used to determine the speed and heading of vehicles. Since the successive photographs were taken with a fixed time interval (5 seconds), by marking the vehicles on successive photographs we were able to measure the distance the vehicle traversed, and thus infer the speed and heading of the vehicle. The measured speed and inter-vehicle spacing are used to analyze the impact of vehicles as obstacles while they are moving.

Figures 2a and 2b show the distribution of inter-vehicle spacing (defined as the distance between a vehicle and its closest neighbor) for the A28 and A3, respectively. The distribution of inter-vehicle spacing for both cases can be well fitted with an *exponential probability distribution*. This agrees with the empirical measurements made on the I-80 interstate in California reported in [39]. Figures 2c and 2d show the

TABLE II
PARAMETERS OF THE BEST FIT DISTRIBUTIONS FOR VEHICLE SPEED AND INTER-VEHICLE SPACING

Data for A28		
Parameter	**Estimate**	**Std. Error**
Speed: normal fit		
mean (km/h)	106.98	1.05
std. deviation (km/h)	21.09	0.74
Inter-vehicle spacing : exponential fit		
mean (m)	51.58	2.57
Data for A3		
Parameter	**Estimate**	**Std. Error**
Speed: normal fit		
mean (km/h)	122.11	3.97
std. deviation (km/h)	28.95	2.85
Inter-vehicle spacing : exponential fit		
mean (m)	215.78	29.92

TABLE III
PARAMETERS OF THE BEST FIT DISTRIBUTIONS FOR VEHICLE WIDTH AND HEIGHT

Personal vehicles	
Parameter	**Estimate**
Width: normal fit	
mean (cm)	175
std. deviation (cm)	8.3
Height: normal fit	
mean (cm)	150
std. deviation (cm)	8.4
Large vehicles	
Parameter	**Estimate**
Width: constant	
mean (cm)	250
Height: normal fit	
mean (cm)	335
std. deviation (cm)	8.4

speed distribution for the A28 and A3, respectively. The speed distribution on both highways is well approximated by a normal probability distribution. Table II shows the parameters of best fits for inter-vehicle distances and speeds.

C. Determining the vehicle dimensions

From the photographs, we were also able to obtain the length of each vehicle accurately, however the width and height could not be determined with satisfactory accuracy due to resolution constraints and vehicle mobility. To assign proper widths and heights to vehicles, we use the data made available by the Automotive Association of Portugal [40], which issued an official report about all vehicles currently in circulation in Portugal. From the report we extracted the eighteen most popular personal vehicle brands which comprise 92% of all personal vehicles circulating on Portuguese roads, and consulted an online database of vehicle dimensions [41] to arrive at the distribution of height and width required for our analysis. The dimensions of the most popular personal vehicles showed that both the vehicle widths and heights can be modeled as a normal random variable. Detailed parameters for the fitting process for both personal and large vehicles are presented in Table III. For both width and height of personal vehicles, the standard error for the fitting process remained below 0.33% for both the mean and the standard deviation. The data regarding the specific types of large vehicles (e.g., trucks, vans, or buses) currently in circulation was not available. Consequently, the precise dimension distributions of the most representative models could not be obtained. For this reason, we infer large vehicle height and width values from the data available on manufacturers' websites, which can serve as rough dimension guidelines that show significantly different height and width in comparison to personal vehicles.

V. COMPUTATIONAL COMPLEXITY OF THE PROPOSED MODEL

In order to determine the LOS conditions between two neighboring nodes, we analyzed the existence of LOS in a three dimensional space, as shown in Fig. 1 and explained in the previous sections. Our model for determining the existence of LOS between vehicles and, in case of obstruction, obtaining the number and location of the obstructions, belongs to a class of computational geometry problems known as geometric intersection problems [42], which deal with pairwise intersections between line segments in an n-dimensional space. These problems occur in various contexts, such as computer graphics (object occlusion) and circuit design (crossing conductors), amongst others [43].

Specifically, for a given number of line segments N, we are interested in determining, reporting, and counting the pairwise intersections between the line segments. For our specific application, the line segments of interest are of two kinds: a) the LOS rays between the communicating vehicles (lines colored red in Fig. 1b); and b) the lines that compose the bounding rectangle representing the vehicles (lines colored blue in Fig. 1b). It has to be noted that the intersections of interest are only those between the LOS rays and the bounding rectangle lines, and not between the lines of the same type. Therefore, we arrive at a special case of the segment intersection problem, namely the so-called "red-blue" intersection problem. Given a set of red line segments r and a set of blue line segments b, with a total of $N = r+b$ segments, the goal is to report all K intersections between red and blue segments, for which Agarwal in [44] presented an efficient algorithm. The time-complexity of the algorithm proposed in [44], using the randomized approach of [45], is $\mathcal{O}(N^{4/3} \log N + K)$, where K is the number of red-blue intersections, with space complexity of $\mathcal{O}(N^{4/3})$. This algorithm fits our purposes perfectly, as the red segments correspond to the LOS rays between the communicating vehicles and blue segments are the lines of the bounding rectangles representing the vehicles (see Fig. 1b).

To assign physical values to r and b, we denote v as the number of vehicles in the system and v' as the number of transmitting vehicles. The number of LOS rays results in $r = Cv'$, where the average number of neighbors C is an increasing function of the vehicle density and transmission range. The number of lines composing the bounding vehicle rectangles can be expressed as $b = 4v$, since each vehicle is represented by four lines forming a rectangle (see Fig. 1b). Therefore, a more specific time-complexity bound can be written as $\mathcal{O}((Cv' + 4v)^{4/3} \log(Cv' + 4v) + K)$.

Apart from the algorithm for determining the red-blue intersections, the rest of the proposed model consists in calculating the additional signal attenuation due to vehicles for each communicating pair. In the case of non-obstructed LOS the algorithm terminates, whereas for obstructed LOS, the red-blue intersection algorithm is used to store the number and location of intersecting blue lines (representing obstacles). The total number of intersections is given by $K = gr$, where g is the number of obstacles (i.e., vehicles) in the LOS path and is a subset of C. The complete algorithm for additional attenuation due to vehicles is implemented as follows.

Algorithm 1 Calculate additional attenuation due to vehicles

```
for i = 1 to r do
  [coord] = getIntersect(i) {For each LOS ray in r, obtain the location of intersections as per [44]}
  if size([coord]) ≠ 0 then
    att = calcAddAtten([coord]) {Calculate the additional attenuation due to vehicles as per [31]}
  else
    att = 0 dB {Additional attenuation due to vehicles equals zero.}
  end if
end for
```

The function $getIntersect(\cdot)$ is based on the aforementioned red-blue line intersection algorithm [44], and has complexity $\mathcal{O}((Cv' + 4v)^{4/3} \log(Cv' + 4v) + gr)$, whereas the function $calcAddAtten(\cdot)$ is based on multiple knife-edge attenuation model described in [31] with time-complexity of $\mathcal{O}(g^2)$ for each LOS ray r. It follows that the time-complexity of the entire algorithm is given by $\mathcal{O}((Cv' + 4v)^{4/3} \log(Cv' + 4v) + g^2 r)$.

In order to implement the aforementioned algorithm in VANET simulators, apart from the information available in the current VANET simulators, very few additional pieces of information are necessary. Specifically, the required information pertains to the physical dimensions of the vehicles. Apart from this, the model only requires the information on the position of the vehicles at each simulation time step. This information is available in any vehicular mobility model currently in use in VANET simulators.

VI. Results

We implemented the model described in previous sections in Matlab. In this section we present the results based on testing the model using the A3 and A28 datasets. We also present the results of the empirical measurements that we performed in order to characterize the impact of the obstructing vehicles on the received signal strength. We emphasize that the model developed in the paper is not dependent on these datasets, but can be used in any environment by applying the analysis presented in Section III. Furthermore, the observations pertaining to the inter-vehicle and speed distributions on A3 and A28 (Fig. 2) are used only to characterize the behavior of the highway environment over time. We do not use these distributions in our model; rather, we use actual positions of the vehicles. Since the model developed in Section III is intended to be utilized by VANET simulators, the positions of the vehicles can easily be obtained through the employed vehicular mobility model.

TABLE IV
$\overline{P(LOS)}$ for A3 and A28

Highways			
	Transmission Range (m)		
Highway	100	250	500
A3 $\overline{P(LOS)}$	0.8445	0.6839	0.6597
A28 $\overline{P(LOS)}$	0.8213	0.6605	0.6149

We first give evidence that vehicles as obstacles have a significant impact on LOS communication in both sparse (A3) and more dense (A28) networks. Next, we analyze the microscopic probability of LOS to determine the variation of the LOS conditions over time for a given vehicle. Then, we used the speed and heading information to characterize both the microscopic and macroscopic behavior of the probability of LOS on highways over time in order to determine how often the proposed model needs to be recalculated in the simulators, and to infer the stationarity of the system-wide probability of LOS. Using the employed multiple knife-edge model, we present the results pertaining to the decrease of the received power and packet loss for DSRC due to vehicles. Finally, we corroborate our findings on the impact of the obstructing vehicles and discuss the appropriateness of the knife-edge model by performing empirical measurements of the received signal strength in LOS and non-LOS conditions.

A. Probability of Line of Sight

1) Macroscopic probability of line of sight: Table IV presents the values of $\overline{P(LOS)}$ with respect to the observed range on highways. The highway results show that even for the sparsely populated A3 highway the impact of vehicles on $\overline{P(LOS)}$ is significant. This can be explained by the exponential inter-vehicle spacing, which makes it more probable that the vehicles are located close to each other, thus increasing the probability of having an obstructed link between two vehicles. For both highways, it is clear that the impact of other vehicles as obstacles can not be neglected even for vehicles that are relatively close to each other (for the observed range of 100 m, $\overline{P(LOS)}$ is under 85% for both highways, which means that there is a non-negligible 15% probability that the vehicles will not have LOS while communicating). To confirm these results, Fig. 3 shows the average number of neighbors with obstructed and unobstructed LOS for the A28 highway. The increase of obstructed vehicles in both absolute and relative sense is evident.

2) Microscopic probability of line of sight: In order to analyze the variation of the probability of LOS for a vehicle and its neighbors over time, we observe the $\Delta P(LOS)_i$ (as defined in equation (7)) on A28 highway for the maximum communication range of 750 m. Table V shows the $\Delta P(LOS)_i$. The variation of probability of LOS is moderate for periods of seconds (even for the largest offset of 2 seconds, only 15% of the nodes have the $\Delta P(LOS)_i$ greater than 20%). This result suggests that the LOS conditions between a vehicle and its neighbors will remain largely unchanged for

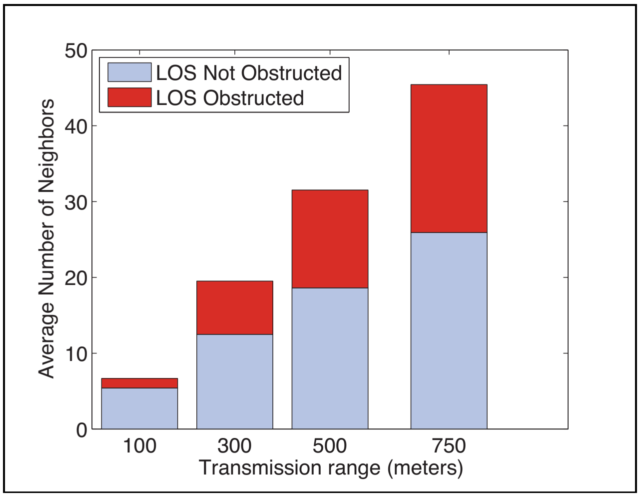


Fig. 3. Average number of neighbors with unobstructed and obstructed LOS on A28 highway.

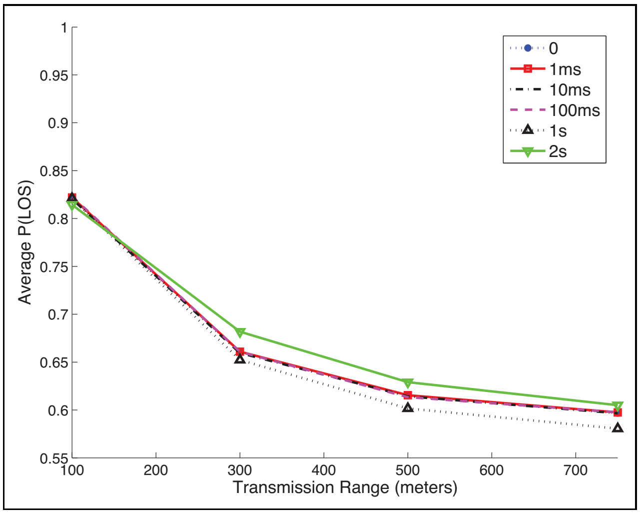


Fig. 4. $\overline{P(LOS)}$ vs. observed range for different time offsets

TABLE V
VARIATION OF $P(LOS)_i$ OVER TIME FOR THE OBSERVED RANGE OF 750 M ON A28.

Time offset	$\Delta P(LOS)_i$ in %			
	< 5%	5-10%	10-20%	>20%
1ms	100%	0%	0%	0%
10ms	99%	1%	0%	0%
100ms	82%	15%	3%	0%
1s	35%	33%	22%	10%
2s	31%	25%	29%	15%

a period of seconds. Therefore, a simulation time-step of the order of seconds can be used for calculations of the impact of vehicles as obstacles. From a simulation execution standpoint, the time-step of the order of seconds is quite a long time when compared with the rate of message transmission, measured in milliseconds; this enables a more efficient and scalable design and modeling of vehicles as obstacles on a microscopic, per-vehicle level. With the proper implementation of the LOS intersection model discussed in Sections III and V, the modeling of vehicles as obstacles should not induce a large overhead in the simulation execution time.

3) Stochastic properties of line of sight in mobile vehicular network: Figs. 2a and 2b show that a Poisson process with parameter α can be used to describe the distribution of vehicles on highways at a given time t. It is reasonable to assume that, for a vehicular traffic in the free-flow phase, the rate of change of the parameter α over time is quite slow, thus the Poisson process can be considered homogeneous for a certain amount of time. This allows us to utilize one of the key properties of homogeneous Poisson processes, namely stationary increments, which says that if two road segments are of the same length, the probability distribution function of the number of vehicles over those segments is equal [46]. Therefore, one can conclude that for a certain period of time, the probability distribution function of the number of vehicles on two road segments will only depend on the size of the segments. Based on the homogeneity assumption, applying this property on the same segment of the road but at different times results in identical probability distribution for the number of vehicles. Therefore, it is expected that the $\overline{P(LOS)}$ over the observed road segment will not change over time, as long as the arrival rate α remains constant.

In order to confirm these results, we performed tests using two snapshots of A28 highway taken on the same road interval 5 seconds one after another. By inferring the speed and heading of the vehicles from the snapshots, it was possible to accurately interpolate the positions of the vehicles for 1 ms, 10 ms, 100 ms, 1 s, and 2 s offsets from the first snapshot.

The obtained results showed that the average inter-vehicle spacing remains invariant for the observed time offsets, thus confirming the first-order stationarity of the underlying Poisson process. Similarly, Fig. 4 shows that for various communication radii (100 - 750 m), the $\overline{P(LOS)}$ does not change for the observed time offsets. Therefore, we can conclude that $\overline{P(LOS)}$ remains constant on the observed road interval as long as the arrival rate of the generating Poisson process remains constant. Thus, the presented $\overline{P(LOS)}$ results hold for both the instantaneous V2V communication as well as for V2V communication over time (i.e., for moving vehicular network).

B. Received Power

Based on the methodology developed in Section III, we utilize the multiple knife-edge model to calculate the additional attenuation due to vehicles. We use the obtained attenuation to calculate the received signal power for the DSRC. We employed the multiple knife-edge model for its simplicity and the fact that it is well studied and often used in the literature. However, we point out that the LOS analysis and the methodology developed in Section III can be used in conjunction with any channel model that relies on the distinction between the LOS and NLOS communication (e.g., [24] or [47]).

For the A28 highway and the observed range of 750 m, with the transmit power set to 18 dBm, 3 dBi antenna gain for both transmitters and receivers, at the 5.9 GHz frequency band, the results for the free space path loss model [32] (i.e., not including vehicles as obstacles) and our model that accounts for vehicles as obstacles are shown in Fig. 5. The

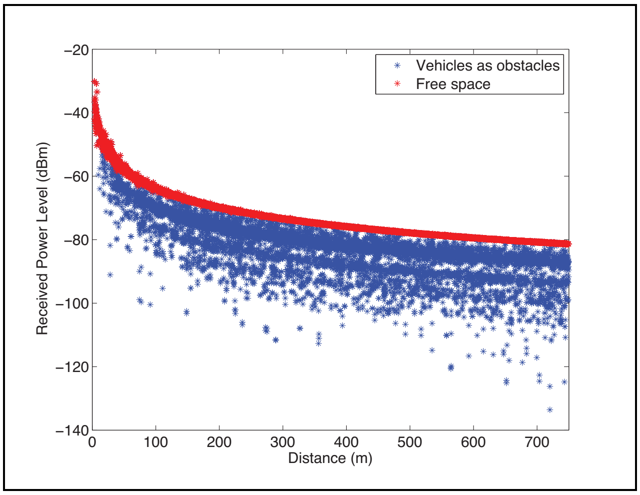


Fig. 5. The impact of vehicles as obstacles on the received signal power on highway A28.

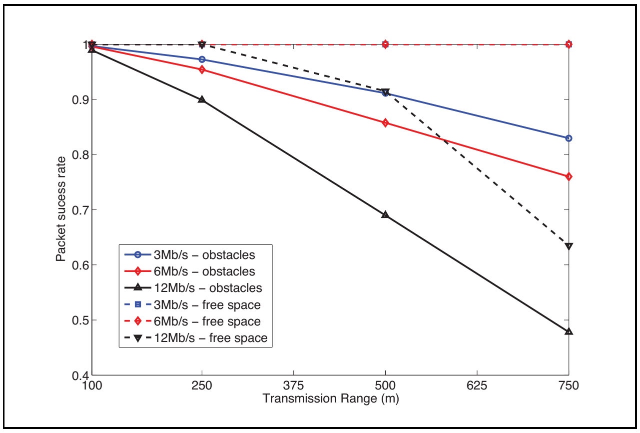


Fig. 6. The impact of vehicles as obstacles on packet success rate for various DSRC data rates on A28 highway.

TABLE VI
REQUIREMENTS FOR DSRC RECEIVER PERFORMANCE

Data Rate (Mb/s)	Modulation	Minimum sensitivity (dBm)
3	BPSK	−85
4.5	BPSK	−84
6	QPSK	−82
9	QPSK	−80
12	QAM-16	−77
18	QAM-16	−70
24	QAM-64	−69
27	QAM-64	−67

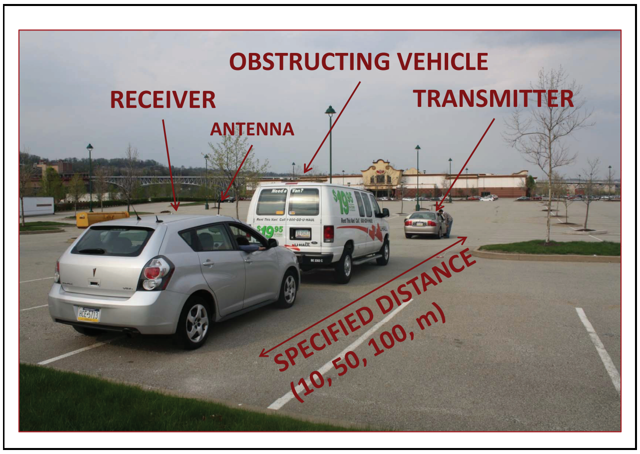


Fig. 7. Experiment setup.

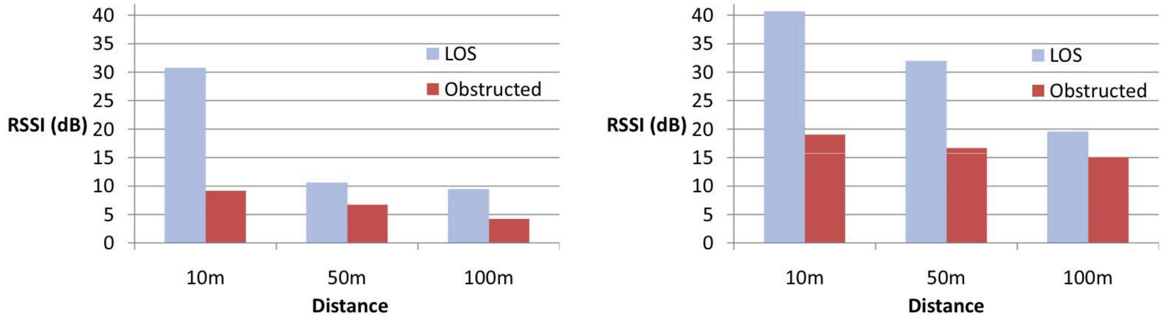
average additional attenuation due to vehicles was 9.2 dB for the observed highway. The large spread in received power at different (but fixed) distances between transmitter and receiver puts into perspective why it is very difficult to use conventional statistical channel models (such as Rayleigh, Ricean, Nakagami, etc.) for quantifying the impact of vehicles as obstacles. Indeed, while the *average* additional attenuation due to impact of vehicles as obstacles is 9.2 dB, the spread in RSSI at fixed distances (e.g., at 50 m or 100 m) can be as large as 30 dB.

Using the minimum sensitivity thresholds as defined in the DSRC standard (see Table VI) [48], we calculate the packet success rate (PSR, defined as the ratio of received messages to sent messages) as follows. We analyze all of the communicating pairs within an observed range, and calculate the received signal power for each message. Based on the sensitivity thresholds presented in Table VI, we determine whether a message is successfully received. For the A28 highway, Fig. 6 shows the PSR difference between the free space path loss and the implemented model with vehicles as obstacles for rates of 3, 6, and 12 Mb/s. The results show that the difference is significant, as the percentage of lost packets can be more than 25% higher when vehicles are accounted for.

These results show that not only do the obstructing vehicles significantly decrease the received signal power, but the resulting received power is highly variable even for relatively short distances between the communicating vehicles, thus calling for a microscopic, per-vehicle analysis of the impact of obstructing vehicles. Models that try to average the additional attenuation due to vehicles could fail to describe the complexity of the environment, thus yielding unrealistic results. Furthermore, the results show that the distance itself can not be solely used for determining the received power, since even the vehicles close by can have a number of other vehicles obstructing the communication path and therefore the received signal power becomes worse than for vehicles further apart that do not have obstructing vehicles between them.

C. Empirical Measurements

We performed measurements in order to prove the validity of our hypothesis regarding the effect of vehicles on the received signal strength. To isolate the effect of the obstructing vehicles, we aimed at setting up a controlled environment without other obstructions and with minimum impact of other variables (e.g., other moving objects, electromagnetic radiation, etc). For this reason, we performed experiments in an empty parking lot in Pittsburgh, PA (Fig. 7). We analyzed the received signal strength for the no obstruction, LOS case, and the non-LOS case where we introduced an obstructing vehicle (the van shown in Fig. 7) between the transmitter (Tx) and the receiver (Rx) vehicles. The received signal strength was measured for the distances of 10, 50, and 100 m between the Tx and the Rx. In case of the non-LOS experiments, the



(a) 2.4 GHz. (b) 5.9 GHz

Fig. 8. RSSI measurements: average RSSI with and without the obstructing vehicle.

TABLE VII
DIMENSIONS OF VEHICLES

Vehicle	Dimensions (m) Height	Width	Length
2002 Lincoln LS (TX)	1.453	1.859	4.925
2009 Pontiac Vibe (RX)	1.547	1.763	4.371
2010 Ford E-250 (Obstruction)	2.085	2.029	5.504

obstructing van was placed in the middle between the Tx and the Rx. We performed experiments at two frequency bands: 2.4 GHz (used by the majority of commercial WiFi devices) and 5.9 GHz (the band at which spectrum has been allocated for automotive use worldwide [13]). For 2.4 GHz experiments, we equipped the Tx and Rx vehicles with laptops that had Atheros 802.11b/g wireless cards installed and we used 3 dBi gain omnidirectional antennas. For 5.9 GHz experiments, we equipped the Tx and Rx vehicles with NEC Linkbird-MX devices [49], which communicate via IEEE 802.11p [13] wireless interfaces and we used 5 dBi gain omnidirectional antennas. In both cases, antennas were mounted on the rooftops of the Tx and Rx vehicles (Fig. 7). The dimensions of the vehicles are shown in Table VII, and the height of the antennas used in both experiments was 260 mm. The transmission power was set to 18 dBm. The Atheros wireless cards in laptops as well as IEEE 802.11p radios in LinkBird-MXs were tested beforehand using a real time spectrum analyzer and no significant power fluctuations were observed. The central frequency was set to 2.412 GHz and 5.900 GHz, respectively, and the channel width was 20 MHz. The data rate for 2.4 GHz experiments was 1 Mb/s, with 10 messages (140 B in size) sent per second using the ping command, whereas for 5.9 GHz experiments the data rate was 6 Mb/s (the lowest data rate in 802.11p for 20 MHz channel width) with 10 beacons [49] (36 B in size) sent per second. Each measurement was performed for at least 120 seconds, thus resulting in a minimum of 1200 data packets transmitted per measurement. We collected the per-packet Received Signal Strength Indication (RSSI) information.

Figures 8a and 8b show the RSSI for the LOS (no obstruction) and non-LOS (van obstructing the LOS) measurements at 2.4 GHz and 5.9 GHz, respectively. The additional attenuation at both central frequencies ranges from approx. 20 dB at 10 m distance between Tx and Rx to 4 dB at 100 m. Even though the absolute values for the two frequencies differ (resulting mainly from the different quality radios used for 2.4 GHz and 5.9 GHz experiments), the relative trends indicate that the obstructing vehicles attenuate the signal more significantly the closer the Tx and Rx are. To provide more insight into the distribution of the received signal strength for LOS and non-LOS measurements, Fig. 9 shows the cumulative distribution function (CDF) of the RSSI measurements for 100 m in case of LOS and non-LOS at 2.4 GHz. The non-LOS case exhibits a larger variation and the two distributions are overall significantly different, thus clearly showing the impact of the obstructing van. Similar distributions were observed for other distances between the Tx and the Rx at 2.4 and 5.9 GHz.

In order to determine how well the knife-edge model fits our measurements, we calculated the additional attenuation due to the knife-edge diffraction model for the given parameters: distances between the Tx and the Rx of 10, 50, and 100 m, location of the obstructing van, the dimensions of the vehicles, 2.4 GHz and 5.9 GHz frequency band, 3 dBi and 5 dBi antenna gains, and 18 dBm transmit power. The difference between the measurements and the knife-edge model was negligible at 100 m (e.g., 0.17 dB for 100 m at 2.4 GHz) and increased with the decrease of distance between the Tx and Rx (e.g., 1.2 dB for 50 m distance at 2.4 GHz and 10+ dB at 10 m). The knife-edge model approximates the real world measurements fairly well at longer distances between the Tx and Rx; however, it is too optimistic with regards to the additional attenuation at shorter distances (e.g., 10 m). Therefore, the results reported in the Section VI pertaining to the received power can be regarded as an upper bound. To model the received power at shorter distances more accurately, appropriateness of other structures for vehicles (e.g., cylindrical or wedge) should be explored.

VII. CONCLUSIONS

We proposed a new model for incorporating vehicles as obstacles in VANET simulation environments. First, we analyzed the real world data collected by means of stereoscopic aerial photography and showed that vehicles as obstacles have a significant impact on LOS obstruction in both dense and sparse vehicular networks, and should therefore be included in V2V channel modeling. Then, based on the concepts of computational geometry, we modeled the vehicles as three-dimensional objects that can act as LOS obstructions between

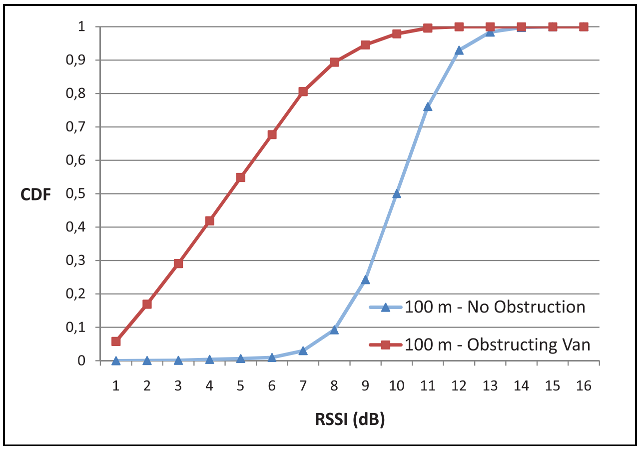


Fig. 9. Distribution of the RSSI for 100 m in case of LOS (no obstruction) and non-LOS (obstructing van) at 2.4 GHz.

other communicating vehicles. Next, we designed a mechanism for calculating additional attenuation due to vehicles as obstacles, and we showed that the obstructing vehicles significantly decrease the received signal power and the packet success rate. We also performed experimental measurements in order to confirm the significance of the impact of obstructing vehicles on the received signal strength. The results clearly indicate that vehicles as obstacles have a significant impact on signal propagation (see Fig. 5 and 8); therefore, in order to properly model V2V communication, it is imperative to account for vehicles as obstacles. Furthermore, the effect of vehicles as obstacles can not be neglected even in the case of relatively sparse vehicular networks, as the analyzed A3 highway dataset showed. Another important conclusion is that the stochastic models, such as shadow fading [32], that aim at averaging the additional attenuation due to vehicles, would fail to adequately describe the complex and significant impact of vehicles on the received signal power (depicted in Fig. 5).

Furthermore, neglecting vehicles as obstacles in VANET simulation and modeling has profound effects on the performance evaluation of upper layers of the communication stack. The expected effects on the data link layer are twofold: a) the medium contention is overestimated in models that do not include vehicles as obstacles in the calculation, thus potentially representing a more pessimistic situation than the real-world with regards to contention and collision; and b) the network reachability is bound to be overestimated, due to the fact that the signal is considered to reach more neighbors and at a higher power than in the real world. These results have important implications for vehicular Medium Access Control (MAC) protocol design; MAC protocols will have to cope with an increased number of hidden vehicles due to other vehicles obstructing them.

The algorithm behind the proposed model, even though microscopically evaluating the attenuation due to vehicles (i.e., calculating additional attenuation due to vehicles for each communicating pair separately), remains computationally efficient, location independent, and compatible with models that evaluate the effect of other types of obstacles. By implementing the proposed model in VANET simulators, significant benefits can be obtained with respect to increased credibility of simulation results, at the expense of a relatively small computational overhead.

As part of our ongoing research efforts, we are performing extensive experimental measurements to quantify the impact of obstructing vehicles on V2V communication in various mobile environments (e.g., urban, suburban, highway) with different vehicular densities (low, medium, high) in both 2.4 GHz and 5.9 GHz bands. The measurements are aimed at isolating and characterizing the effects of the obstructing vehicles on V2V communication in order to thoroughly test and optimize our proposed model.

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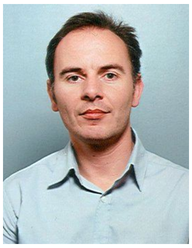

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