A Line-of-Sight Probability Model for VANETs

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***Abstract*—Simulation has become an important method for the evaluation of Vehicular Ad-Hoc Network (VANET) applications and protocols. These simulations often work on the link level with simulation time far off from wall clock time, making them impracticable to be deployed for the performance analysis of real hardware in Hardware-In-The-Loop (HIL) environments or prototype vehicles. Probabilistic communication models can help in this regard, however often suffer from considerably lower accuracy than link-level simulations. It was shown that determining whether a communication link is of Line-of-Sight (LOS) or Non-Line-of-Sight (NLOS) nature greatly increases the quality of probabilistic communication models. This paper presents such an LOS probability model for VANETs in urban and rural environments. We find that typical urban environments such as rural, urban, and industrial areas show similar characteristics across different German and European cities. We utilize this to derive a probabilistic LOS model that reliably predicts LOS constellations and outperforms related work. Our model therefore enables the development of accurate probabilistic packet success or packet arrival rate models to investigate VANET technology in real-time environments.**

I. INTRODUCTION

Vehicular Ad-Hoc Networks (VANETs), that is, vehicles wirelessly communicating with each other or the infrastructure, are believed to be one of the key enabling technologies for the introduction of intelligent transportation systems. This includes not only improved road safety, but also comfort and traffic efficiency applications and eventually support for autonomous driving [1]. The evaluation of novel applications and protocols is often conducted by means of simulation, as real-world field operational tests are demanding in terms of cost and time.

The state of the art for city-scale simulation of these networks is the use of link-level simulation. For each transmitted message, the receive power for all potential receivers is computed, environmental influences such as buildings or other vehicles are considered, and a Signal-to-Interference-plus-Noise Ratio (SINR) is calculated using all other present transmissions and a background noise [2]. Considering high periodic beacon frequencies of up to 10 Hz and hundreds of vehicles within transmission range, this approach requires a large amount of computational power [3], leading to simulation performance far off wall clock time.

One possible solution to this is to trade accuracy versus simulation time, e.g., by deploying an efficient, probabilistic communication model instead of a link-level one. Based on few input parameters, e.g., the sender-receiver distance and current environment, the model allows to probabilistically compute a packet success rate for each message. This considerably lowers the complexity of the simulation and thereby introduces several advantages and use cases.

One important advantage is that these models can then be used for tests in real-time environments [4]. These include Hardware-In-The-Loop (HIL) setups, e.g., for the testing and analysis of IEEE 802.11p on-board units. Real-time simulations can then be used to investigate whether the device under test has enough capability to handle the communication load in certain scenarios. Secondly, probabilistic models can be used to test real deployment scenarios on the streets. The use of just a few vehicles could lead to an overestimation of the performance of different V2X-based functions. A probabilistic model can help by emulating higher network loads or different environments.

Lowering the complexity of V2X simulations also allows the simulation of scenarios where accurate map data (e.g., the position of buildings) is not available or the size of the scenario would require too much computational effort. The overarching challenge is to use a model that does not abstract too much information, as this would oversimplify the complexity of vehicular networks and yield misleading simulation results.

In this paper we address this challenge by presenting an efficient, validated, probabilistic LOS model that represents VANETs in different urban settings. We show, that the type of urban environment, e.g., industrial or residential, leads to considerably different communication characteristics. Most importantly, different types of urban areas show pronounced differences in Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) probabilities, which in turn lead to a difference in achievable communication range and thereby packet success rates.

Our contributions can be summarized as follows:

- We present an efficient, easy-to-use, probabilistic LOS communication model based on sender-receiver distance and the type of urban setting.
- We show how this model can be used to derive packet success rates and thus approximate the number of arriving packets, e.g., in hardware-in-the-loop test setups.
- We identify three different categories of urban environments that are considerably different in terms of LOS and NLOS conditions.
- To show its applicability, we validate our model using the Veins simulation framework.
- We compare it to recent related work and show that it captures LOS/NLOS conditions in vehicular networks more accurately.

II. Related work

There exists an ample body of research addressing the modeling of the communication channel in wireless networks, in particular the effect of obstacles on radio propagation. We differentiate between deterministic and probabilistic models.

Ray-tracing models were shown to offer great accuracy, however, they not only require very detailed map data but also were shown to be infeasible in terms of required simulation time [5]. Efficient deterministic models to capture the impact of NLOS communication links include the Corner model, proposed by Giordano et al. [6]. Without the need for maps that include positions of buildings, they assume that by looking at the road segments on which sender and receiver are traveling, NLOS and LOS cases can be identified.

Another link-level approach was presented by Sommer et. al [7], where it was argued that the impact of buildings can be quantified by considering the number of walls through which the signal has to travel and the distance inside a building. This model has found wide application and was shown to offer a good approximation, however, it is still too complex to allow for real-time simulation of hundreds of vehicles.

Boban et al. presented an empirical, geometry-based approach for the simulation of VANETs, called GEMV^2 [8]. Their approach contains models for the attenuation of signals caused by buildings, foliage, and vehicles. The above approaches all have in common that received power is computed for any combination of sender and possible receivers within the vicinity each time a message is transmitted. That leads to a detailed but slow simulation.

Apart from the general approaches (such as log-normal shadowing) there exists research that investigates V2X communication on a more abstract level: Oishi et al. examined the influence of the building density within a scenario on channel characteristics [9]. Their work focuses exclusively on the variation of the building density in a constant, artificial road network with only 90 degree corners. Therefore it will not accurately represent cities that evolved historically, as these feature mainly random arrangements of buildings and streets.

Another abstract and less computationally expensive approach is presented by Akhtar et al. [12]. Their method provides a comprehensive representation of VANET channel characteristics in highway scenarios. Their model is limited to highways, hence it cannot be applied to urban scenarios which show completely different communication patterns caused by different mobility and the presence of buildings.

Research closely related to this paper was conducted by Samimi et. al [10] and Sun et. al [11]. In the context of millimeter-wave outdoor communication, [10] presents an LOS probability model. Their model returns an LOS probability based on the sender-receiver distance. Similarly, focusing on 5G mobile communication, Sun et al. also introduced mathematical models to derive LOS/NLOS probabilities [11]. The objective of these works are analogous to the one presented in this paper, therefore we investigate the applicability of their models for vehicular ad-hoc networks and compare it to our own model.

In this paper, we want to find a balance between generality and accuracy by introducing a probabilistic model that takes into account the type of urban or rural environment in which a vehicle is situated.

III. Methodology

In contrast to packet-level channel models, the probabilistic model presented in this paper does not investigate the specific communication link between one sender and one receiver. It allows to derive the probability of a communication link being LOS or NLOS to enable a better representation of the overall communication from a receiver's point of view. This can be used to emulate V2V communication, for example, in HIL test setups or for the evaluation of prototype vehicles with a specific function under test. In these cases, the primary output parameter of the model is the number of decodable messages arriving at one receiver, called packet success rate in the following.

One general probabilistic model will not fit every imaginable scenario, because the environment (e.g. buildings, road layout) around communicating vehicles significantly influences the communication characteristics and quality. Therefore at least some categorization is necessary. Our methodology can be summarized as follows: (a) identify typical urban settings, (b) derive a model to compute the LOS/NLOS probability given sender-receiver distances, and (c) show how this probability can be used as input to determine the packet success rate.

The prerequisite to determine the success rate is to know the success probability of each communication link. Whether a signal is detectable from a receiver heavily depends on the type of link: If there is an LOS between sender and receiver the success probability of a communication link is significantly higher than under NLOS conditions [7].

In the case of communication under LOS conditions, the success probability primarily depends on the distance between sender and receiver. With increasing distance, the arrival rate of messages decreases until the maximum transmission range is reached. The probability of achieving an LOS link depends on the scenario and the distance between sender and receiver. With an increasing distance the likelihood of one or more objects blocking the line of sight between communicating vehicles grows. As a result, the probability of an advantageous LOS constellation is dependent on the environment.

Our underlying hypothesis is that there is a strong relation between the LOS probability, the sender-receiver distance, and the type of urban environment. This would allow the estimation of the amount of LOS and NLOS connections for a certain distribution of vehicles in a specific scenario, and in turn, serve as the input parameter for the computation of the packet success rate. In conclusion, the LOS probability is the parameter that allows the abstraction of a certain scenario regarding the success rate of a VANET in it.

To derive such an LOS probability, we select four typical European (in particular, German) urban scenarios:

(a) rural residential area
(b) urban residential area
(c) industrial area

(a) Rural residential area: Gerolfing

(b) Urban residential area: Ingolstadt, Richard-Wagner-Straße

(c) Industrial area: Ingolstadt, Manchinger Straße

(d) Historical city center: Ingolstadt, inner city

Figure 1. One representative area of 800m x 800m per scenario, buildings are drawn in red

(d) historical center

For each category, typical example settings in and around the German city of Ingolstadt were chosen. Figure 1 shows one representative area per category: The scenarios (a)-(d) are characterized by typical settings of buildings and streets: Urban residential (a) and industrial areas (c) normally have a low building density compared to rural residential areas (b) or historical city centers (d), with the latter one having the highest building density. These four categories differ also by the average building floor area. Industrial areas (c) consist of large halls, rural residential areas (a) mainly consist of one- to three-family homes with a smaller building floor area, whereas urban residential areas (b) mainly consist of apartment blocks with a building floor area somewhere between the ones of industrial and rural areas. Historical centers (d) of German (and many European) cities have evolved over centuries, therefore we did not find a typical size of the building floor area for these scenarios. They usually contain a mixture of large and small buildings with a very high building density.

The time of origin of an urban area has a decisive influence on its setting. Like in other European countries in Germany the arrangement of buildings is regulated by law. For reasons of neighbor and fire protection the distance between buildings has to increase with their height. Areas like historical city centers, that originate before that regulation existed, do not have to fulfill the law retroactively.

IV. Simulative Investigation

To understand the impact of different urban settings, we conducted an extensive simulation study using the Veins framework [13]. We used the obstacle model presented in [7] combined with Nakagami-m fading [14] to account for fast-fading effects. Based on models for communication using IEEE WAVE/802.11p [15], we recorded statistics for every packet sent and received in the network. The beacon frequency was set to 10 Hz, transmission power to 20 mW and sensitivity of the receivers antennas to -89 dBm.

We use the LOS probability depending on the sender-receiver distance as the primary indicator for the communication characteristic. Consequently, the probability of being able to successfully decode arrived messages under LOS and NLOS conditions (also depending on sender-receiver distance) allows us to determine an expected packet success rate. Hence, from a receiver's point of view, these simulations allow us to quantify the impact of the environmental scenario on the communication quality of a VANET.

Table I
Overall LOS rate

Scenario	Location	LOS rate
Rural1	Gerolfing, Germany	4.4%
Rural2	Etting, Germany	5.1%
HistCtr	Ingolstadt, Germany, inner city	4.9%
Urban1	Ingolstadt, Germany, Feselenstr.	12.1%
Urban2	Ingolstadt, Germany, Richard-Wagner Str.	12.6%
Indust1	Ingolstadt, Germany, Manchinger Str.	25.4%
Indust2	Ingolstadt, Germany, GVZ	30.0%

A. *Categorization of environmental scenarios*

In a first step, we investigated the overall LOS rate, that is, the percentage of transmissions in a given scenario that had a direct LOS connection within the maximum transmission range computed by the free-space path loss model, including failed transmission. This will be used as the first indicator whether a categorization based on the type of urban environment is feasible. To this end, we manually selected seven representative areas in and around the city of Ingolstadt, Germany, which can be seen as a typical German or European city.

Table I shows the overall LOS rate values for the simulated areas. The results for the rural residential areas (a) and the historical city center (d) were found to be the lowest and also to be similar. Only approx. 4% - 5% of all communication links were found to be LOS. The high building density and the number of side-streets consequently lead to a large portion of communications to be of NLOS nature. The urban residential areas (b) show a noticeably higher value, averaging at about 12%. Industrial areas (c) provide even higher LOS probability than every other simulated type of scenario, with LOS rates as high as 30%. This is caused by a rather straight street layout with only a small number of side streets.

These first results indicate that rural residential areas (a) and the historical city center (d) have a similar impact on VANET communication and can therefore be combined into one category. Urban residential areas (b) and industrial areas

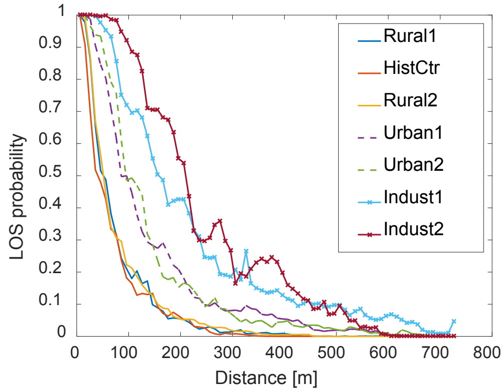


Figure 2. Probability of LOS over distance between sender and receiver evaluated in steps of 10m

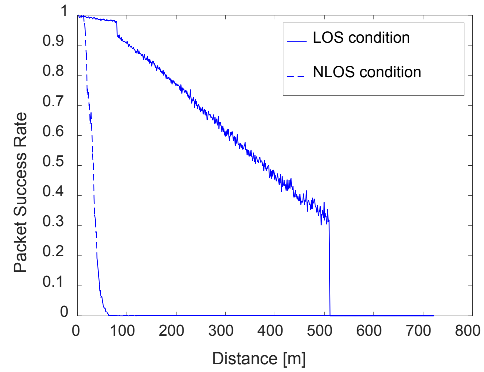


Figure 3. Packet success rate under LOS and NLOS conditions over the sender-receiver distance for all simulation scenarios (see Table I)

(c) are assigned to separate categories. The three resulting categories therefore are:

- rural residential area or historical city center
- urban residential area
- industrial area

The overall LOS rate can be a good indicator to describe the influence of certain urban settings, but is certainly not sufficient to derive a probabilistic model. To further understand the impact of the building and street layout, and also to justify our categorization, we investigated how the probability for an advantageous LOS constellation depends on the distance between sender and receiver. These two parameters, i.e., environment and distance, will then serve as input for the probabilistic model.

Figure 2 shows the simulation results for the seven selected representative areas. Again, the LOS probability is derived by the number of LOS links with regard to all links at a certain distance value. The results agree with our categorization as can be seen by the similar behavior for both residential areas and the historical city center. In these scenarios the LOS probability rapidly falls at low distance values. Similarly, the urban scenarios show only little difference. Lastly, the industrial areas are shown to provide better LOS conditions for VANETs, with a slightly larger intra-category difference. The LOS probability here starts to fall at larger distance values and decreases slower than it does for the other two categories.

B. Packet success rate

Having identified the type of urban environment as the primary factor to derive the LOS probability based on the sender-receiver distance, the next step is to derive a packet success rate to introduce an additional abstraction layer to quantify that influence. Therefore, we investigated the packet success probability of received messages depending on the distance between communicating partners under LOS and NLOS conditions. Please note that this merely serves as a demonstration on how the LOS probability model can be used to derive packet success rates. The curves shown in Figure 3 are highly dependent on the simulation parameters such as transmission power, radio sensitivity, fading parameters, traffic density, and so on.

All scenarios showed similar behavior for LOS communication. In our simulation environment, the packet success rate here is influenced by free-space path loss and the Nakagami-m fading to account for multi-path propagation. Other phenomena like the hidden terminal problem were shown to have only marginal impact in VANETs and can therefore be neglected for probabilistic communication models [16]. The sudden drop at about 80 meters is caused by the Nakagami fading model, which was configured to use different values of m for distances smaller and larger than 80 meters [17].

Interestingly, we also found that the chance of successfully decoding a packet under NLOS conditions is not dependent on the scenario. For distances larger than approx. 70 meters, packets could no longer be successfully received when buildings blocked the line of sight. This is inline with real-word results [7].

From this we follow that only to determine the probability of LOS/NLOS constellations do we have to take the type of environment into account. To actually compute the packet success rate, this LOS probability can be used without further distinguishing between the categories. This finding emphasizes the importance and usefulness of accurate LOS probability models.

V. Deriving a Probabilistic Model

Our simulation study showed a strong correlation between typical scenario categories and the occurring LOS probability and packet success rates. The prerequisite to use that relation in a probabilistic communication model is a formal mathematical description.

To this end, we compare our model to the ones presented by Samimi et al. [10] and Sun et al. [11] (see Section II). These models take as input the sender-receiver distance d and output the probability of the communication link being LOS. It has to be noted that these models were presented in the context of 5G mobile communication and milli-meter wave communication, however, can be parametrized to fit 5.9GHz IEEE 802.11p communication.

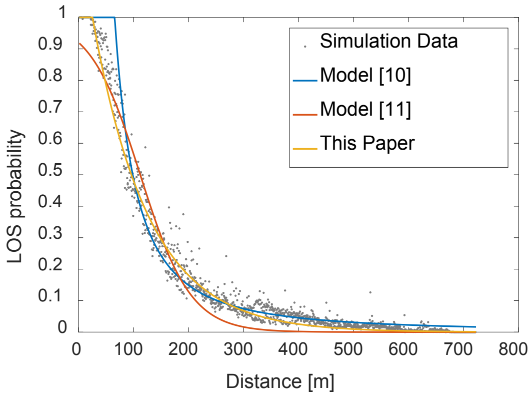


Figure 4. Comparison of three different fitting models applied to the simulation data of the urban residential category

The model presented by Samimi et al. uses four parameters (in the original publication c was set to 2, but is treated as variable here to better fit the urban setting).

$$P_{[10]}(d) = \left(min\left(\frac{a}{d}, 1\right) \times \left(1 - e^{-\frac{d}{b}}\right) + e^{-\frac{d}{b}}\right)^{c} \quad (1)$$

The final model by Sun et al. uses two parameters a and b:

$$P_{[11]}(d) = \frac{1}{1 + e^{a(d-b)}} \quad (2)$$

We define our model as a step function that always yields 1 for distances shorter than a category-specific threshold tp to account for the fact that we could not observe any NLOS communication links for smaller distances. The parameter tp is empirically set to a value of 9m for rural residential areas/historical centers, 25.5m for urban residential areas and 52.5m for industrial areas. This is due to the fact, that it was not possible to place two vehicles in a way so that a building blocked their line of sight for distances smaller than tp.

Our final model is:

$$P_{\text{LOS}}(d) = \begin{cases} 1 & , d \leq tp \\ ae^{bd} & , d > tp \end{cases} \quad (3)$$

We fitted all three models (non-linear least squares) using the simulation data, combining the data for scenarios in the same category. Figure 4 shows the results for all three models in comparison using the urban residential category as an example. The behavior of the LOS probability over the sender-receiver distance is determined by three key features: The transition point tp for small distances, the gradient of the decrease, and the convergence towards zero for large distances. We observe that while the model from [10] fits our data quite well, it overestimates both, the 100% and the 0% LOS probability sectors. This kind of overestimation of LOS conditions makes it unsuitable for the test of safety critical vehicle functions, as it would model a false amount of information available to the function. The model from [11] underestimates the LOS probability for distances up to 80m and larger than 200m. Although that model provides an holistic underestimation of the LOS probability, for safety critical tests it should be preferred over the model from [10]. Our model was able to capture all key features of the LOS probability accurately, outperforming the other models.

Table II
Average percentage deviation of the simulation data from the mathematical model per scenario category and fitting model

Scenario category	[10]	[11]	**This Paper**
rural res. area / hist. center	2.8%	2.3%	**1.3%**
urban residential area	3.0%	4.0%	**2.3%**
industrial area	5.6%	6.2%	**4.6%**

Table II shows the average percentage deviation, that is, the average distance between the simulation data and the fitted model. The smaller the value, the better the prediction by the fitted model. Our model outperformed the other models in all three categories, showing its applicability to reliably predict LOS probabilities for vehicular network communication. The fitted parameters for our model were:

Scenario	**a**	**b**	**tp**
rural	1.154	-0.01617	9m
urban	1.283	-0.009808	25.5m
industrial	1.366	-0.005948	52.5m

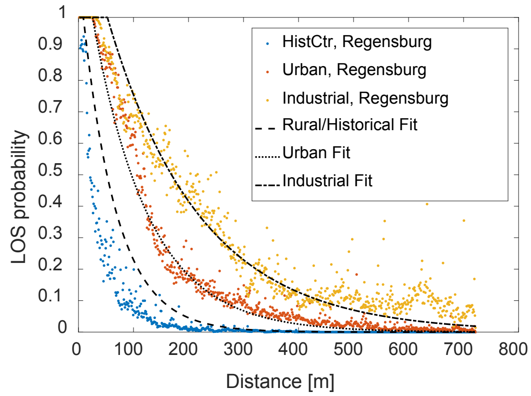
VI. Validation

For cross-validation, we manually selected areas from other German cities as the testing dataset, conducted extensive simulations and evaluated the models' accuracy. We chose the city of Regensburg, Germany which is similar to the validation data in terms of population, and the city of Munich, Germany with a population ten times as high. The purpose of this validation is to show the applicability of our model to general German/European cities and to further illustrate the higher accuracy of our model compared to related work.

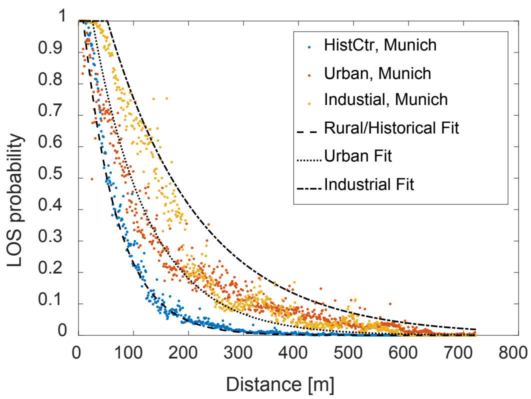
Figure 5 shows our results. We observe that the LOS conditions for the historical city center of Regensburg (Figure 5a) are worse than in Ingolstadt, whereas our model matches the urban residential and industrial areas. For Munich (Fig 5b), our model accurately represents the characteristics of the inner city and the urban residential area, however, slightly overestimates LOS probability for the industrial area. This suggests the need

Table III
Comparison of models w.r.t the average percentage deviation for the testing dataset. Highlighted in bold are the best results per city and scenario

Category	**Regensburg**			**Munich**		
	[10]	[11]	This Paper	[10]	[11]	This Paper
Rural	5.7%	**3.4%**	4.3%	2.3%	2.5%	**1.3%**
Urban	**2.3%**	4.2%	2.6%	5.5%	6.5%	**4.4%**
Industrial	6.3%	7.4%	**4.8%**	9.1%	7.6%	**7.2%**



(a) Validation with simulation data of areas in Regensburg



(b) Validation with simulation data of areas in Munich

Figure 5. Validation of the LOS probability model using Regensburg, Germany and Munich, Germany.

for an automated finding of the model parameters to account for untypical area layouts and will be the focus of future work.

Lastly, we compare the accuracy of all models. Results are given in the form of the average deviation and are shown in Table III. All but one scenario (Indutrial, Munich) have an accuracy similar to the training dataset. This is further indication that scenarios within a category show similar characteristics caused by typical building and road layout. For the city of Regensburg, all models performed well, our model being the one with the highest overall accuracy. For the city of Munich, our model outperformed the other models across all categories, serving as a reliable predictor for the LOS probability with an average percentage deviation for the urban areas as low as 1.3%.

VII. Conclusion and Future Work

We presented an LOS probability model for VANETs and showed that the type of environment (rural, urban, industrial) can be utilized to derive accurate LOS probability predictions. We showed that, using typical German areas as training data, we were able to predict the LOS probabilities for other areas. Our model shows higher prediction quality than models from recent literature and can therefore be used as an efficient alternative to packet-level simulation models when accurate map data is unavailable or requirements in terms of performance are high.

Future work focuses on the automated determination of area type based on the building and road layout to further increase prediction quality. Secondly, even though the distance could be shown as the decisive input, we will investigate additional properties of communication links to derive LOS probabilities.

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