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Simulation Modelling and Analysis of a Realistic Radio Channel Model for V2V Communications

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Abstract—**Realistic radio channel models are crucial for the success of vehicle-to-vehicle (V2V) system investigations. In this paper, we describe the important parameters for V2V channel modelling and summarize relevant measurement campaigns. Also, we develop and evaluate an ns-3 simulation model of a realistic V2V channel model that is based on measurements in Sweden. The channel model incorporates the effects of obstacles between the transmitter and the receiver. We show that the resulting path loss is very different compared with available models.**

Keywords-vehicular communications; radio channel models; network simulation

I. INTRODUCTION

Vehicular networks are currently a very popular research area and an interesting implementation platform for a variety of applications including those which have the potential to significantly improve road safety. In the medium access control (MAC), network, transport and security layers, new protocols need to be developed, analyzed and compared in order to create reliable applications based on these protocols. Regarding the physical layer, new IEEE and ETSI standards are currently under development.

There are several disruptive properties of the radio channel, such as severe fading and high attenuation, which can cause high bit error rates, large latency, packet errors and frequent retransmissions. Typical consequences are less throughput, deterioration of the applications' performance, and even link outages. In vehicular communication systems, safety applications cannot allow these detrimental outcomes to occur with high probability. Therefore, these systems must incorporate several techniques, including antenna diversity, power control, channel coding and interleaving, equalization, network coding as well as efficient transmission schemes, to handle the influence of the radio channel.

A channel model is a representation of the main characteristics and properties of a propagation medium, i.e., the properties that have an impact on the system performance. As the majority of the protocol tests are done in computer simulations, the selection of the right channel model is vital in order to know the real performance of that protocol. Therefore, it is necessary to study and define a suitable channel model for vehicular communications. Bad channel models lead to inaccurate results but also to a wrong judgment on the comparison between different upper protocols.

In Vehicle-to-Vehicle (V2V) systems, the radio channel has certain characteristics that make it unique: transmitters and receivers are mobile, antennas are placed at low elevations, the Doppler frequency is usually high, the channel is statistically non-stationary, etc. Not all of these characteristics are included in current radio channel models used for cellular communications, where only the receiver is mobile, the base station antenna is placed at a higher location and channel statistics are stationary. Thus, new channel models are needed to characterize these new scenarios.

We need a channel model that reproduces the propagation mechanisms in vehicular communications; and it has to be a model suitable for a computer implementation, where the environmental parameters can easily be changed. In this paper, a geometric stochastic channel model (GSCM) for V2V communications are described and analyzed. Further, we develop and implement a ns-3 simulation channel model for V2V systems, based on the measurements in [1][6][15]. We compare this model with models already available in ns-3.

II. CHANNEL PARAMETERS

For single antenna systems, the influence of the channel can be described by the time-variant impulse response, $h(t,\tau)$, which is the superposition of the contributions of all the multipath components (attenuated, delayed and phase shifted echoes of the signal) that arrive at the receiver because of reflection, diffraction, wave-guiding or another propagation mechanism. This function is time-variant; it shows the response of the channel at a time t is due to an impulse input at a time $t-\tau$. Although the impulse response contains all the information about the channel, there are condensed parameters which describe the channel in a more compact way, e.g. path loss, fading statistics, Doppler spread and delay spread.

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A. *Path Loss*

Path loss is the small-scale attenuation of a radio signal as it propagates through the medium. It includes many effects, such as free-space loss, refraction, diffraction, reflection, coupling loss and absorption; and these propagation mechanisms depend on the terrain contours, the environment (e.g. urban or rural), the medium`s characteristics, the distance between the transmitter and the receiver, and the height and location of antennas. The *average* path loss is calculated in a deterministic way based on the distance *d*. It usually increases as a function of distance like d^n, where *n* is the path loss exponent. It should be noted, however, that the *non-averaged* path loss usually includes large-scale fading and, thus, has a random component.

B. *Fading Statistics*

Fluctuations of the received power can occur on a very short distance, of roughly one wavelength, due to the interference between multipath components, be it constructive or destructive. These fluctuations are called “small-scale fading” and are described statistically. The most common distributions to describe the variations in received signal amplitude are Rayleigh distribution for non-line-of-sight (non-LoS) and Rice distribution for line-of-sight (LoS) scenarios. Sometimes, large objects can obstruct the communication link, generating shadowing or “large-scale fading”. The latter is usually described by a log-normal distribution with a standard deviation given by the scenario .

C. *Power Delay Profile*

The power delay profile (PDP), ($P_h(\tau)$), contains information about how much power arrives at the receiver with a delay between [τ; $\tau+d\tau$] and it can be calculated as the squared magnitude of the impulse response, averaged over the small-scale fading. The PDP provides a description of the frequency selectivity of the channel (how “spread out” the received waveform is, if we transmit a short pulse) and determines the available frequency selectivity and the required length of the cyclic prefix in orthogonal frequency-division multiplexing (OFDM) systems.

D. *Doppler Spectrum*

The Doppler spectrum describes the broadening of the received spectrum due to the different Doppler shifts of the different multipath components. The root mean square Doppler spread (the second moment of the Doppler spectrum, analogy to the moments of the PDP) describes the frequency dispersion and the temporal variability of the channel.

It is important to note that PDP and the Doppler spectrum for vehicular environments are only valid for a short period of time. Otherwise, the conventional assumption of “wide sense stationarity - uncorrelated scatterers” (WSSUS) does not hold.

III. CHANNEL MODELS

There are several approaches when developing a radio channel model. The first of these, namely the ray tracing models, are very powerful and, with an appropriate environment model, the agreement between measured and simulated receive powers can be accurate. The channel model presented in [2] can be included in this deterministic channel model category. The problem with this model is its high computational requirements (i.e. computer time), the difficulty of varying the environment, and the problem of getting a detailed enough description of the environment (i.e. a good 3-dimensional map).

Another group of channel models is the stochastic channel models. These models provide statistics of the power with a certain delay, Doppler shift, etc. The tapped-delay-line channel model presented in [3] belongs to this category. The main drawback with this model is the WSSUS assumption and the supposition of a fixed Doppler spectrum for every delay. Many measurements have demonstrated the erroneous nature of these hypotheses. The non-stationarities of V2V communication channels can be modelled by a birth/death process like in the model presented in [4]. However, these models do not account for the “drift” of scatterers into different delay bins, which can also lead to an unexpected appearance and disappearance of strong multipath components, as explained in [5].

The third major approach to the modeling of V2V channels are the geometry-based stochastic channel models (GSCM), which simulate the channel by using randomly placed scatterers in the simulation environment, performing a simplified ray tracing and, summing up the total signal at the receiver. These kinds of models have a lot of advantages. They take non-stationarities into account automatically. Also, they model inherently the multiple-input multiple-output (MIMO) properties of the channel; and it is easy to change the antenna influence. Furthermore, the environment can be easily changed; and GSCM are much faster than deterministic ray tracing. The drawbacks of these models are that the generation of realizations of channel impulse responses requires more computer time than in tapped-delay-line models and, even if this kind of models try to be valid for all possible scenarios, that the measured data characterize only a certain area, which means that they may not fit in scenarios with different characteristics than those of the measured environments.

IV. RELATED WORK

There are many radio channel models available in the literature. Some of the most relevant ones, those mainly based on measurements, are described here.

In [4], an empirical channel model is proposed based on a V2V measurement campaign in the city of Ohio, collecting data at different times of the day and under different traffic conditions and scenarios. Using their channel measurements, the authors model the channel as a time-varying filter. For testing their V2V channel model, they simulate the standard IEEE 802.16 over it [10]. Their results confirm that the traditional WSSUS assumptions are rather optimistic and not necessarily valid for the V2V environment.

In [3], three V2V radio channel models, (one for each different environment, namely highway, urban, and canyon) are proposed. The models are based on a measurement campaign run at 5.9 GHz in the metropolitan area of Atlanta, USA. They are “tapped delay line” models, where each tap is described as having Rician or Rayleigh fading and by a Doppler power spectral density from a small collection of shapes. Also, the models assume WSSUS conditions.

In [2], a V2V channel model is proposed that is based on ray-tracing as well as the modelling of the road traffic, of the environment adjacent to the road, and of the wave propagation between the vehicles. By assigning appropriate reflection and diffraction properties to the buildings, the authors generate a scenario and simulate the channel behaviour. They also compare the simulation results to wide-band measurements at 5.2 GHz, showing an extremely good agreement.

In [11][12], the objective is to show that the channel models available in ns-2 [19][1], the highly acclaimed network simulator, are too optimistic and, by simply introducing some buildings to the simulation, the results are far from the reality. They compare the existing models with three models of their own. For testing their models, the authors create a simulation environment, using: standard 802.11p, a MAC layer with priorities, streets with two lanes and buildings at the sides, road intersections and a mobility model called the “downtown model”. They compare their models with the “two ray ground” model available in ns-2. In the two ray ground model, the received energy is the sum of the direct LoS and the reflected component from the ground. It does not consider obstacles; and transmitter and receiver have to be at the same height. The results underline the necessity of taking into consideration the position of the cars against each other; e.g. it is necessary to model the interruption of LoS when there is an obstacle between the transmitter and the receiver.

In [13], the impact of realistic radio propagation models on the design of vehicular communication systems is investigated. Using the data from a measurement campaign in urban and suburban environments in Chicago (at 2.412 GHz), the authors find that the signal propagation varies especially between LoS (down the block) and non-LoS (around the corner) conditions. For example, the effective communication window for two vehicles in an urban environment can be nearly 35% shorter than in an open field (45 s vs. 70 s), and the total throughput can be twice as much in the open field case.

In [14], a new geometry-based channel model is proposed, in which vehicles move towards a junction with a side road and corner buildings. The authors conclude that the distance from the receiver as well as from the transmitter to the corner has a big impact on the temporal and frequency correlation properties.

V. A GSCM FOR V2V COMMUNICATIONS

In [6][15], a parameterized GSCM for V2V is proposed; and in [1], a corresponding path loss model is introduced. The models are based on the measurements from a highway near the city of Lund, Sweden. The highway measurements are performed on a two-lane highway, with a low separating wall between travel directions, low-rise commercial buildings as well as fields on the roadside, and low to medium traffic density. The authors performed the measurements with the transmitter and the receiver driving in the same direction as well as in the opposite.

First, the V2V channel characteristics are analyzed. Regarding the time-delay domain, the measurements show that:

- The LoS path is always strong.
- Significant energy is available in discrete components, represented by a single tap.
- Important discrete multipath components typically move through many delay bins during a measurement, i.e., the WSSUS assumption is not valid.
- Discrete components can be mobile or static scattering objects.
- The LoS tap is usually followed by a tail of weak components that can be described by a Rayleigh distribution.

Looking at the delay-Doppler domain, the following conclusions are made:

- The Doppler spectrum can change significantly during a measurement because of the movement of the receiver, the transmitter and the scatterers.
- The Doppler spread of discrete scatters is typically small.
- There is a part of the channel denoted as “diffuse”, which is composed of a tail of weak components with large delay as well as Doppler spread.

The channel characterization is concluded by an analysis of the time-varying signal contribution of the discrete scatterers, finding out that the standard GSCM way to model the complex path amplitudes as non-fading is not suitable in this case. After this analysis, the authors present their geometry-based stochastic MIMO model:

The model in [15] distinguishes between three types of scatterers: mobile-discrete (MD), static-discrete (SD) and diffuse (DI); and they model the double-directional, time-variant, complex impulse response of the channel, $h(t,\tau)$. The impulse response is divided into four parts: (i) the LoS component; (ii) discrete components stemming from reflections off mobile scatterers; (iii) discrete components stemming from reflections off static scatterers; and (iv) diffuse components. The model requires some signal model parameters that the authors have extracted from the measurement data.

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[1] The same channel models are also available in ns-3.

In [1], a path loss model is proposed for four different types of V2V environments: Highway, rural, suburban and urban. From the 62 million time-samples of the channel transfer-function that they obtain during the measurements, the authors determine the small-scale averaged channel gain, $G_{ssa}(t_k)$. The path loss (PL) is calculated from $G_{ssa}(t_k)$ as:

$$PL(t_k) = -10\log_{10} G_{ssa}(t_k) - 2G_a, \qquad (1)$$

where G_a is the gain of the transmitter and receiver antennas.

For network simulations, the interesting value is PL as a function of the position of the transmitter and the receiver, not of the time sample t_k. Thus, using the recorded geographical location data, the authors model the distance-dependent path loss as:

$$PL\left(\frac{d}{d_0}\right) = PL_0 + 10n\log_{10}\left(\frac{d}{d_0}\right) + X, \qquad (2)$$

where d is the transmitter-receiver distance, n is the path loss exponent, PL_0 is the path loss at a reference distance $d_0 = 10$ m, and X is a zero-mean, normally distributed random variable with standard deviation σ_x. It should be noted that this model is valid only for $d > 10$ m. This limitation came from the absence of valid measurements for transmitter-receiver separations smaller than 10 m.

The parameters of the model, extracted from data for different environments, can be found in Table I.

TABLE I. PARAMETERS OF LUND CHANNEL MODEL [1].

Scenario	**PL_0**	***n***	**σ_x (dB)**
Highway	31.9	1.83	4.98
Rural	35.9	1.51	4.44
Suburban	36.9	1.54	1.99
Urban	39.8	0.76	5.33

VI. IMPLEMENTATION IN NS-3

In order to design and tune all the layers that compose a system, we need to perform tests and simulations. In vehicular communications, the simulations are especially important due to the difficulty of performing real tests in the roads involving hundreds of cars. Thus, we develop a simulation model using the implementation “recipe” in [6].

We prefer ns-3 [7] for our simulations because of its large number of models and functionalities. In addition, ns-3`s behavior is highly trusted within the networking community. Ns-3 is a discrete-event network simulator, specialized on Internet systems, created for research and educational use; and it allows us to study large-scale systems in a controlled environment. Ns-3 is free software, licensed under the GNU GPLv2 license, and it is proposed as a replacement for the popular ns-2 simulator.

A. Model Description

Because of its advantages mentioned above and its ability to create realistic temporal variations of the channel, we pick the model developed in [6] for implementation in ns-3. We call the model simply “Lund Model”. It is in the GSCM category. As mentioned previously, the basic idea of a GSCM model is to place a group of scatterers between the transmitter and the receiver, according to a statistical distribution, assign them different channel properties, determine their signal contribution and finally sum up the total contribution at the receiver.

Our implementation consists of two versions, which we call Lund Model 1 and Lund Model 2. Lund Model 1 implements the complete GSCM model presented in [6], which allows us to calculate the impulse response of the channel depending on the positions of the scatterers, the transmitter and the receiver. Lund Model 2, on the other hand, implements the path loss model described in [1], which allows us to calculate the path loss of the channel for different environments depending on the distance between the receiver and the transmitter.

Note that the latter model is based on the specific conditions during the measurements; so the number and positions of the scatterers is modelled in the random variable X and its standard deviation σ_x. This means that the second method is more general and might be unrealistic in scenarios very different from the measurement environment described at the beginning of the previous section. If we try to simulate the channel in a highway with different conditions, e.g. high traffic density, a 4-lane highway, high-rise buildings, etc, the parameters may change considerably and the results might be quite different.

The results from the first model, on the other hand, are based on the number and position of the scatterers and, even if the parameters are calculated for conditions different from those of the measurements, these results are more general.

B. Channel Modelling in ns-3

As we simulate the characteristics of a wireless channel in ns-3, we utilize the following classes: *YansWifiPhy* (the physical layer), *YansWifiChannel* (the wireless channel) and *PropagationLossModel* (the different path loss models).

YansWifiPhy is a reimplementation of the ns-3 class called *WifiPhy* [8]. It manages the different properties of the channel and allows the user to know the number of devices connected to the wireless channel and “get” one of them in order to work with it.

The class also sets the propagation loss model and the propagation delay model to be used; and it contains a method to send packets. The method needs to receive the following as arguments: (i) the device that wants to transmit; (ii) the packet to send; (iii) the transmit power; (iv) the transmit mode; and (v) a preamble for the packet. The propagation delay model calculates the propagation delay between a specified source and the destination of the transmission. The propagation loss model uses different propagation channel models in order to calculate the received power depending on the transmitted power and the mobility model for the transmitter and the receiver.

C. *Lund Propagation Loss Model*

Lund Model is a propagation loss model, i.e. it returns the received power, based on the transmitted power and the environment. This last point makes this model especially suitable for V2V communications, because it takes into consideration the position of all the possible scatterers surrounding the transmitter and the receiver, in order to calculate the real received power. This means that the received power is not only a function of the distance between transmitter and receiver, but also, it considers the distance to the other cars in the road, to the road signals and other discrete scatterers and to the diffuse scatterers on the side of the road.

Figure 1 depicts the relation between the different classes in ns-3 and the changes implemented in the simulator. Each level has access to all the methods and information of the objects below it, i.e., *YansWifiPhy* can use the methods of its *YansWifiChannel* and *PropagationLossModel*, but *YansWifiChannel* has only access to the methods of its *PropagationLossModel* and *PropagationDelayModel*. Also, classes cannot access any method or variable of their upper classes. In other words, ns-3 was not designed to allow access from the propagation loss models to any method of the channel or physical layer. The problem is that our new class, *LundPropagationLossModel*, needs the position of all the nodes in each instant. In order to have access to that information and, thus, to successfully integrate our model as a new class into ns-3, there are two changes we need to make in the simulator's source code:

- Set the channel: In order to have access to all the nodes and their information, *LundPropagationLossModel* needs to know the current channel where all the nodes will be added. Hence, in all the classes that call *LundPropagationLossModel*, we have to use the method *SetChannel ()* before defining the propagation loss model for the channel. The method is included in *LundPropagationLossModel* and is different from the one available in *YansWifiPhy*, although they have the same purpose: send to the respective class the object that represents the current channel.
- Get the nodes connected to the channel: Once we have sent the current channel to our class, we can access all the methods of the class called *Channel* in ns-3. As of ns-3.6, the latest ns-3 release at the time of this study, there is not any method that can return the list of all the devices connected to the channel. In order to add this functionality, we need to include a method called *GetPhy ()* in *YansWifiChannel*.

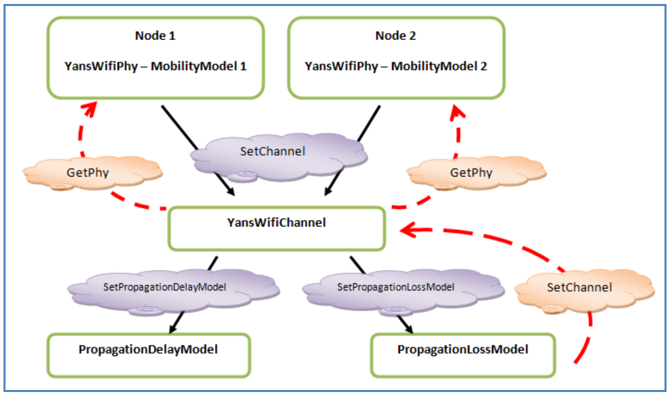

Figure 1. Relations between the WiFi methods and classes in ns-3.

Regarding the mobility model, there is not any suitable ns-3 mobility model for V2V communications; but there is a separate module that can be developed in the same way as the propagation loss models are developed. For our simulations, we have used (i) a constant position mobility model with static nodes, performing the movement of the cars manually for each simulated instant; and (ii) a constant speed mobility model, where cars move on a straight line.

VII. SIMULATION SCENARIOS

We use two different simulation scenarios. The validation test is about transmitting a defined number of packets to all the nodes in a scenario, and then calculating the path loss for each path, using different propagation loss models.

A. *Scenario 1*

In the first scenario, we have a common highway snapshot, with 7 cars travelling in both directions. The cars represent a transmitter (TX), a receiver (RX) and 5 mobile scatterers. Also, there are 4 static scatterers (road signs) and 6 diffuse scatterers (buildings) on the side of the road. Although these numbers are too small for realistic simulations, we think this small-scale scenario is sufficient as proof of concept. In this scenario, there is no difference between being a receiver and a mobile scatterer. All the nodes receive packets. Figure 2 illustrates the scenario in a simplified way, depicting as stars all the nodes taking part in the simulation.

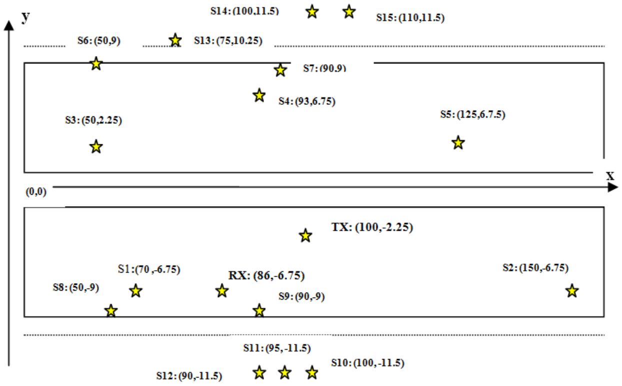

Figure 2. Scenario 1 – a highway with 7 vehicles travelling in both directions, 4 road signs and 6 buildings.

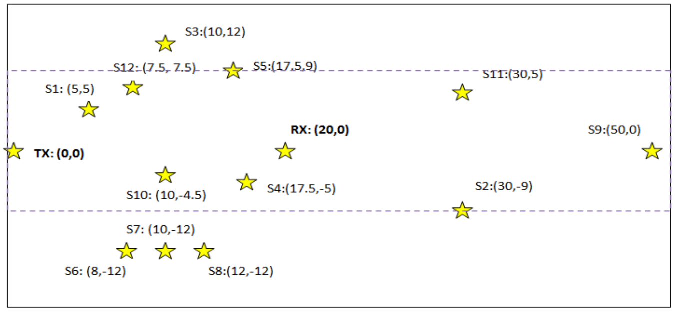

Figure 3. Scenario 2 – a highway with 8 vehicles, 2 road signs and 4 buildings. S12 is obstructed by S1, and S9 by RX, as TX transmits.

B. *Scenario 2*

An extra capability of Lund Model is the detection of an obstruction in LoS between the receiver and the transmitter. This is a result of the fact that all position information is used in the calculations. Therefore, the second scenario, illustrated in Figure 3, introduces some obstructions of LoS to test this capability. In this scenario, there are 6 mobile, 2 static, and 4 diffuse scatterers, in addition to TX and RX. The mobile scatterers S12 and S9 want to receive the transmitted signal. They suffer the obstruction from S1 and RX, respectively; and that is especially important for S9, which, in addition to being obstructed, is also located far away from the transmitter. The obstruction constraint is impossible to detect using the other models available in ns-3; and Lund Model allows us to model the large scale fading effects with its special capability.

C. *Compared Propagation Loss Models*

The class *PropagationLossModel* can use different propagation channel models in order to calculate the received power as a function of the transmitted power as well as the mobility model of the transmitter and the receiver. So, we compare our model to the available propagation loss models in ns-3. Friis propagation loss model calculates the propagation loss according to the Friis formula [16]. Log-distance propagation loss model calculates the propagation loss with a so-called log-distance formula [17]. Finally, Nakagami propagation loss model applies the Nakagami-m fast fading propagation loss model [18].

VIII. RESULTS

In this section, we evaluate the Lund Model implementation in ns-3 and compare it with the available propagation loss models mentioned above.

A. *Scenario 1*

Table II shows the results for the first simulation scenario. As can be seen, the data from Lund Model (both 1 and 2) differ significantly from the results of the other models. However, this table alone is not sufficient for validation. Therefore, the results of our model are also compared to the data from the measurement campaigns in Lund. The measurement results are shown in Figure 4, where the dashed blue line represents the mathematical model obtained from the measurements and formulated by Equation 2 with a measured path loss exponent of 1.83. The details can be found in [1][9].

TABLE II. PATH LOSS (DB) RESULTS FOR SCENARIO 1.

Node	Dist (m)	Lund1	Lund2	Friis	LogDist	Naka
RX	14.70	35.8	37.7	70.0	81.7	20.2
S1	30.33	42.0	41.6	76.3	91.1	16.3
S2	50.20	46.0	44.5	80.7	97.7	15.7
S3	50.20	46.1	39.4	80.7	97.7	14.9
S4	11.40	35.0	31.8	67.8	78.4	15.5
S5	26.57	41.1	42.3	75.2	89.4	18.9
S6	51.25	46.3	42.9	80.9	98.0	20.8
S7	15.05	37.1	35.6	70.2	82.0	20.5
S8	50.45	46.0	46.1	80.7	97.8	14.4
S9	12.06	36.4	33.7	68.3	79.1	13.3
S10	9.25	33.1	31.9	66.0	75.7	19.9
S11	10.51	30.3	35.2	67.1	77.3	17.6
S12	13.62	33.5	34.9	69.4	80.7	19.9
S13	27.55	41.6	39.0	75.6	90.1	15.3
S14	13.75	36.0	36.0	69.4	80.8	21.3
S15	17.00	37.5	35.0	71.3	83.6	19.1

Table II and Figure 4 show us together that, at least for distances between 10 m and 50 m, the data from Lund Model (*Lund1* and *Lund2*) match very well the measured results. If we compare the reference values (lower and upper bounds) from Figure 4 to the results given in Table II, we see that Nakagami Model (*Naka*) is too optimistic, whereas Friis Model (*Friis*) and log-distance model (*LogDist*) are overly pessimistic. Another interesting result from Table II is that S2 and S3, being located at the same distance from the transmitter, get the same path loss values from *Friis* and *LogDist*. *Lund1*, *Lund2* and *Naka*, however, produce different values since their methods

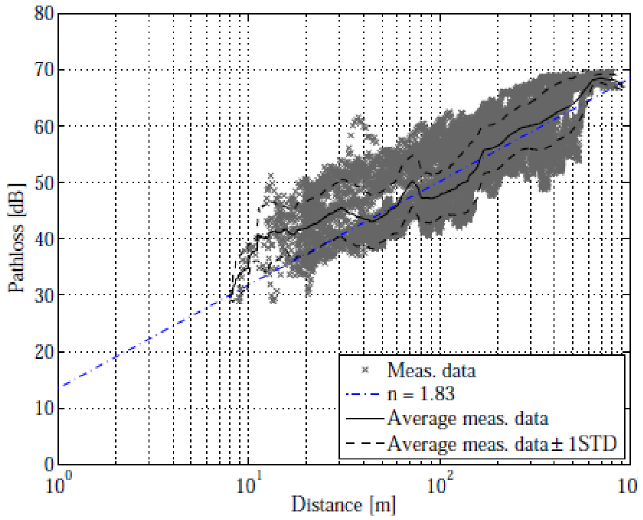

Figure 4. Path loss measured on the Lund highway [1].

do not depend on the distance only.

In order to validate our Lund Model implementation, we perform a more extensive simulation with 20 receivers. Changing the cars' locations, we first create 200 different snapshots. We then derive a trend line from the resulting 4000 path loss calculations (i.e. data points) for the models Lund, Friis, and log-distance. Figure 5 shows the result of this simulation. We can see how the trend line of the simulated path loss, using Lund Model (black; with a path loss exponent of $n = 1.81$), is similar to the trend line of the measured data (red; with a path loss exponent of $n = 1.83$). The trend lines we obtained using Friis (green) and log-distance (blue) propagation loss models do not match the reference line from the measurement campaign as closely as our model does.

B. Scenario 2

TABLE III. PATH LOSS (DB) RESULTS FOR SCENARIO 2 – THE SCATTERERS S9 AND S12 SHOW A HIGHER LOSS DUE TO THE OBSTRUCTIONS IN THEIR LINE OF SIGHT (LOS COMPONENT).

Node	**Dist (m)**	**Lund1**	**Lund2**	**Friis**	**LogDist**	**Naka**
RX	20.00	38.7	40.1	72.7	85.7	20.2
S1	7.07	30.9	32.0	63.7	72.2	16.3
S2	31.32	42.1	41.9	76.6	91.6	15.7
S3	15.62	37.2	35.2	70.6	82.5	14.9
S4	18.20	38.4	31.3	71.9	84.5	15.5
S5	19.67	39.1	36.2	72.6	85.5	18.9
S6	14.22	29.3	38.1	70.6	82.5	20.8
S7	15.62	38.8	34.1	71.3	83.5	20.5
S8	16.97	34.6	35.2	69.9	81.4	14.4
S9	50.00	96.6	46.0	80.7	97.9	13.3
S10	10.97	34.0	33.0	67.5	77. 9	19.9
S11	30.41	42.2	43.6	76.3	91.2	17.6
S12	10.61	55.0	32.9	67.2	77.4	19. 9

Table III shows the path loss measured at various nodes when the transmitter sends a packet in the second scenario. Here, our attention is particularly drawn to S9 and S12; the mobile scatterers suffering from obstruction; and we compare their path loss values to those of S11 and S10, respectively, which are at a comparable distance from TX, only not obstructed. From the table we can see that only Lund Model 1 satisfactorily distinguishes between obstructed and unobstructed nodes (i.e. S9 vs. S11 and S12 vs. S10), assigning them quite different path loss values. The other models do not take the impact of obstructed LoS into account as effectively as Lund Model 1, and assign the nodes in question path loss values which fail to reflect the situation more realistically.

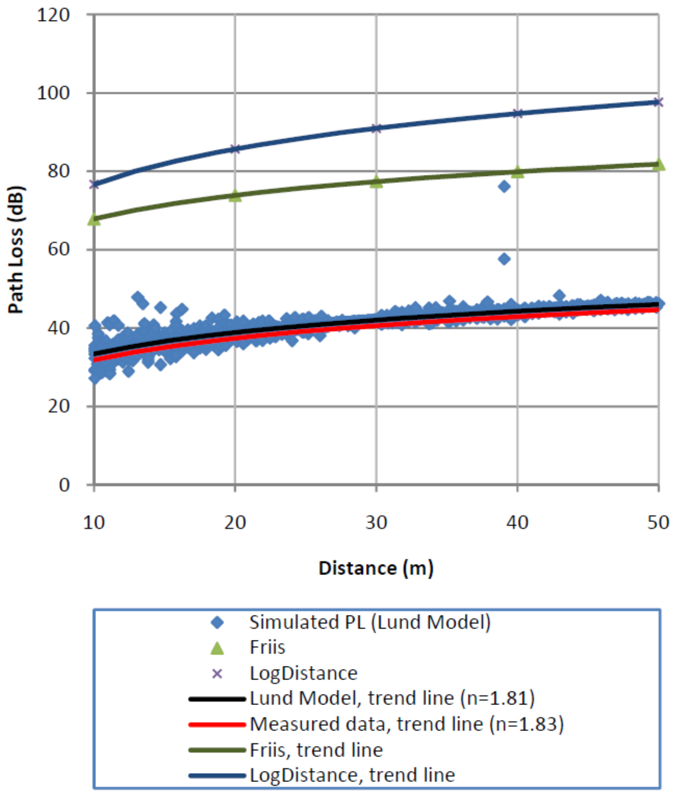

Figure 5. Scenario 1 – comparison between two of the propagation loss models available in ns-3, Lund Model and measured data.

If we focus on the receiver and perform a simulation moving the nodes in the scenario with different speeds, we can compare the average path loss values calculated by the different ns-3 propagation loss models as a function of the distance. The results are illustrated in Figure 6. We can see that Lund Model 1 and Lund Model 2 return almost the same values and match the measurement results better, whereas the other two channel models give much higher values for this particular simulation.

IX. CONCLUSIONS

Accurate radio channel models are crucial for the realistic evaluation of a vehicular communication system's performance, considering that most of these systems are investigated with large-scale simulations only. In this paper, we

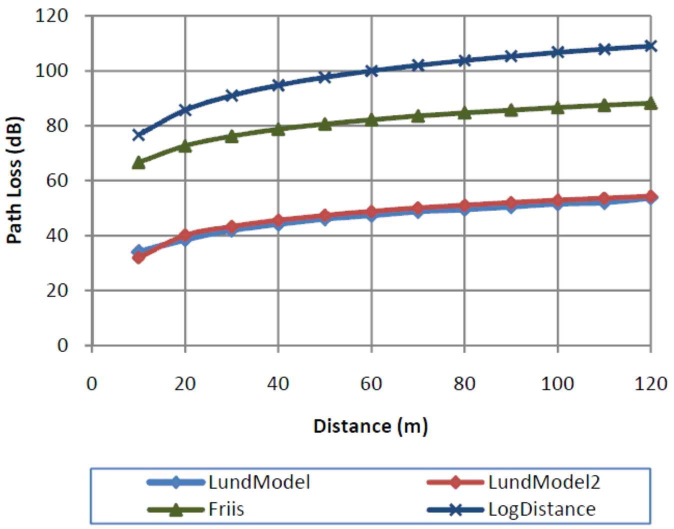

Figure 6. Scenario 2 – average path loss at the receiver.

analyze a realistic radio channel model, which uses data from previous measurement campaigns in Sweden, developed for V2V communications. With the help of this channel model, we also develop a new propagation loss model to be used in computer simulations. We compare the new model to three other available models under two simulation scenarios in ns-3 and show that, depending on the model used, there can be significant differences in the systems' performance.

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