On the Impact of Street Width on 5.9 GHz Radio Signal Propagation in Vehicular Networks

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***Abstract*—Given the broad acceptance of the DSRC/WAVE protocol stack in the vehicular networking community, both the automotive industry and the scientific community are working towards so-called "day one" applications. Currently, large scale field operational tests are going on to assess the performance of developed protocols and applications. Still, the key technique for performance evaluation is simulation. Accurate microscopic simulation of Inter-Vehicle Communication (IVC) is needed, especially for safety critical applications. This is reflected in many recent publications trying to push this in terms of radio shadowing models, signal propagation, etc. Still, it is not fully understood how to characterize some effects given the constraints in terms of simulation time and performance. We concentrate on the fading model. Simulating freeway scenarios, the Two-Ray Interference model is considered the base line, but what about suburban and city scenarios? This paper looks into this, investigating, for the first time, the impact of the street width, i.e., distance between buildings, and its relation to the correct use of propagation models. We conducted different measurement campaigns on streets with different widths and compare the results to theoretic models that are frequently used for IVC studies. The most prominent result is that we discovered a clear difference when assessing safety applications in wide streets compared to narrow streets.**

I. INTRODUCTION

In Vehicular Ad Hoc Networks (VANETs), street traffic participants (e.g., cars and motorcycles) are nodes in a highly mobile network. There are many use cases that benefit from Inter-Vehicle Communication (IVC) ranging from safety applications like emergency braking or cooperative awareness to non-safety applications like road traffic efficiency or entertainment applications [1], [2]. The scientific community together with the automotive industry agreed to rely on the Dedicated Short-Range Communication / Wireless Access in Vehicular Environments (DSRC/WAVE) protocol stack that is based on IEEE 802.11p [3], which is an adaption of the IEEE 802.11a physical layer. It operates on the 5.9 GHz band, which is reserved exclusively for IVC.

Currently, field operational tests are ongoing to validate a subset of the developed concepts. They will inarguably produce valuable results, but the vast majority of developers have to test and analyze their software and application scenarios using simulation techniques. Of course, it is crucial that these simulation-based performance evaluations are as realistic as possible [4]. One of the challenges in this field is the precise modeling of the physical radio wave propagation.

This is most important for safety critical applications, which need accurate microscopic simulations. This is reflected in many recent publications providing more accurate radio signal fading and shadowing models [5]–[8]. Thus, it is desirable to have accurate models for as many different scenarios as possible. In the scope of IVC, the trend is to either use stochastic models such as Rice or Nakagami-m, or to rely on simple free space or Two-Ray ground models [8], [9]. Both can be combined with signal shadowing models covering buildings and even moving vehicles [4], [5], [10], [11].

It has been shown that the Two-Ray Interference model is highly accurate in freeway scenarios [8]. It is, however, unclear, whether this also holds for suburban and downtown scenarios where the signal is also reflected by the buildings covering the street.

In this paper we look into this problem, investigating, for the first time, the impact of the street width, i.e., distance between buildings, on the radio wave propagation. We started several measurement campaigns to investigate the correct use of models. We see this work as a first step to an improved set of models for microscopic simulation of safety critical communication between vehicles, which is especially important for applications such as intersection assistance and emergency braking.

Our contributions are twofold:

- We performed an experimental assessment of the signal propagation characteristics considering different street widths.
- Using curve fitting techniques, we carefully compare the typically used models with the experiment results. The measurement results of the below described streets are publicly available.[1]

II. FUNDAMENTALS

A. Related Work

A study on path-loss, power-delay profiles and delay-Doppler spectra at 5.2 GHz has been performed by Paier et al. [12]. As opposed to this work they did their measurements with vehicles traveling in opposite directions.

Sommer et al. examined the simplified *Two-Ray Ground model*, which is used widely in simulations and demonstrate that a more exact *Two-Ray Interference model* shows more

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[1] http://data.car2x.org/p/wons2014impact

accurate results [8]. They verify their results with a comprehensive measurement campaign. We use this Two-Ray Interference model as a baseline in this work (we describe it in detail later in this section).

An investigation of 5.9 GHz radio propagation in Non Line of Sight (NLOS) environments like intersections has been performed by Mangel et al. [5]. Based on their findings, they came up with a new set of validated simulation models. Similar work has been done by Sommer at el. [10], who developed a model for building shadowing based on data available in OpenStreetMap.

Signal propagation in Line of Sight (LOS) paths has also been assessed by Boban et al. [13]. The authors performed a measurement series with two cars in different environments (urban, suburban and highway) and argue, seconding the findings in [8], that using a more sophisticated Two-Ray Interference model with appropriately chosen input values better fits their measurement results compared to the simple Two-Ray Ground or Free-Space propagation models.

B. Radio Signal Propagation

To analytically model radio signal propagation, the received power P_r is calculated as a function of all path loss processes L_x, the transmit and receive antenna gains $G_{(t,r)}$, as well as the sending power P_t:

$$P_r[dBm] = P_t[dBm] + G_t[dB] + G_r[dB] - \sum L_x[dB]. \quad (1)$$

In free space, a wireless signal only has one path to the receiver, and therefore it is limited by the attenuation of distance fading according to the classical Friis *Free-Space model* [14]. The more obstacles interfering with the signal, the more the radio waves can be reflected, diffracted, and scattered along their path to the receiver [15]. The intensity of these phenomena depends on the frequency and power of the signal, the material of the obstacles, the angle of incidence, and several other nondeterministic minor influences.

1) Free-Space Model: The simplest model for radio wave propagation is the so called *Free-Space model* [14], [15]. It considers only one path of signal propagation that fades with distance, where λ is the wavelength of the carrier band, and d is the distance between the receiver and the sender. The path loss can be described as

$$L_{\text{freespace}}[\text{dB}] = 20\log_{10}\left(4\pi\frac{d}{\lambda}\right). \quad (2)$$

Due to its simplicity and computationally inexpensive calculation, this model is very often used. But as the communication in VANETs often has to deal with lots of obstacles within the signal propagation path, this model should be used with great care [10].

2) Two-Ray Interference Model: The Two-Ray Interference model is a more realistic scenario than the Free-Space model because it considers an additional path a ray can take besides the LOS path that directly goes to the receiver [7], [8]. This additional path is the one that is reflected by the ground (cf. Figure 1). The amount of reflected energy depends highly on the relative permittivity of the reflecting material. Depending on the distance of the receiver these two paths have a positive or a negative interference resulting in the typical waveform seen in Figure 2.

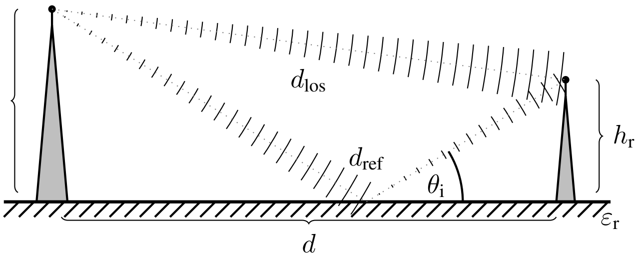

Figure 1. Sketch of a typical Two-Ray Interference scenario.

The loss processes in this model include the attenuation of the LOS path by distance and the attenuation of the electromagnetic wave reflected by the ground. These processes are calculated according to

$$L_{\text{tworay-interf.}}[\text{dB}] = 20\log_{10}\left(4\pi\frac{d}{\lambda}\left|1+\Gamma_\perp e^{i\varphi}\right|^{-1}\right). \quad (3)$$

Here d is the distance between sender and receiver, λ again is the effective wavelength of the used carrier band. The influence of the reflected ray is modeled using the reflection coefficient Γ which is calculated using ϵ as the relative permittivity of the ground as well as the incidence angle θ and the phase difference φ of the interfering rays calculated using the distance between the antennas and their heights h_t and h_r respectively. See [8] for details.

III. EXPERIMENT SETUP

In the following, we describe our measurement campaign in detail, including the used equipment, the selected streets for the experiments, as well as the measurement application.

A. Measurement Equipment

As measurement devices, we used two *PC Engines Alix* system boards, each equipped with a *Unex DCMA-86P2* IEEE 802.11p compliant wireless NIC. We used two omnidirectional *Mobile Mark ECOM9-5500* antennas. According to the data sheet, these antennas have a gain of 9 dBi and a height of 36 cm. To measure the distance between the involved cars, we used *u-blox NEO-7N* based GPS receivers connected to *Taoglas AA.161* antennas.

In order to obtain comparable and realistic results, we placed the antennas (5.9 GHz and GPS) on the rear end of the car roof, just in front of the FM radio antenna mount. The height of the car roofs was about 150 cm, which is close to the common height used in typical studies [16].

B. Streets Considered for the Measurement Campaign

Our objective was to assess the impact of the street width on the signal propagation, and thus, on the models to be used to accurately reflect this behavior in network simulation. Thus, the first and most important question was to choose appropriate streets. Please note that we define the street width as the distance between the two rows of buildings that cover the street on each side. The goal was to find streets without additional obstacles to verify our measurement equipment and, further, to select streets with different widths and similar, uniform buildings on both sides.

We performed the measurements in the city of Innsbruck, Austria, relying on the following streets:

- *Kranebitter Landesstrasse* is a street between hayfields in the outskirts of Innsbruck, which has no obstacles on either side. This is referred to as the *wide* street in our campaign. There are no buildings in the vicinity.
- *Museumstrasse* is located in the center of Innsbruck, representing a *medium* street width. It supports four lanes and is partly closed for public traffic. Its width is 28 m.
- *Goethestrasse*, which we refer to as a *narrow* street, is located in a residential area of the city. It has a street width of only 18 m.

The latter two streets share a surrounding building height of approximately 18 m. They all are perfectly straight, allowing LOS between the antennas all the time. All streets have a pavement made of asphalt, which is important for the reflection coefficient when calculating the Two-Ray Interference model.

C. Measurement Setup

Following the approach used in other studies, our basic idea was to send packets of constant size with a fixed packet rate from one car to another and continuously measure the Received Signal Strength (RSS) over a certain distance. For this, we placed one car stationary at one end of the measurement area and drove the other car at a constant speed towards or away from the stationary car. The speed of the moving car was very low (10 km/h), so effects like Doppler Shift should not be an issue. Both cars were always in LOS and facing in the same direction.

The application we used for sending packets and measuring the RSS is working as follows. One radio was configured to send with a transmission power of 20 dBm and a packet sending rate of 20 Hz. Each packet includes, among other data, the GPS coordinates of the sender. At the receiver, all packets where logged to a persistent memory including the RSS value of the packet and the GPS position of the receiver. For better accuracy, a new GPS fix was requested only every 200 ms.

The measurement devices gave us only discrete values for the RSS, for a realistic comparison we distributed them uniformly by ± 0.5 dBm. We repeated every experiment several times to see if the results are reproducible. Apart for some minor differences because of shadowing by moving obstacles all repetitions show very similar results.

D. Model Fitting

As can be seen in Section II the models have many parameters that influence their results. To come up with the most accurate parameters for the models we determined Nonlinear Least-Squares (NLS) estimates via model fitting. We employed the statistical program R, more specifically the `nls` function from its statistics library. This function iteratively determines the set of parameter values that minimizes the difference between the measurement results and the fitted theoretical model. The error is expressed as the sum-of-squares of the residual errors of the model and the measurement results. The outcome should be the best fitting parameters of the model to the measured data.

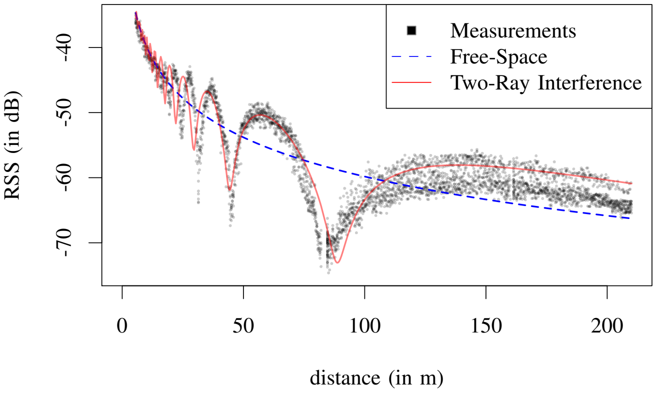

Figure 2. Measurements and modeling for the wide street.

The Two-Ray Interference model takes, among others, as input parameter the emitted power at the sender antenna. This can be calculated by taking the transmitting power of the chip, adding the antenna gain, and subtracting the loss of the cable and the cable connectors. This parameter should stay static over all measurements as we never changed the setup, and it should not be prone to environmental influences. We therefore left this parameter fixed during the estimation process.

The other parameters are the transceiver and receiver antenna height and the relative permittivity of the ground material. As the Two-Ray Interference model only considers two rays, these parameters might not always be perfectly in line. This is because the measured signal strength is also influenced by environmental noise or very weak radio waves from the sender that are reflected by, for example, a building on the side. NLS model fitting changes parameters to better fit the model to the measured results despite these effects; however, the parameters do not change very much which means that their impact is minimal.

IV. RESULTS AND DISCUSSION

We started with baseline measurements in the wide street. We measured the RSS over a distance of more than 200 m. The results are plotted in Figure 2, which also shows the fitted Two-Ray Interference as well as the Free-Space models. The Two-Ray Interference model (using an antenna height of 1.5 m and a relative permittivity coefficient of 1.1; the received power at 0 m from the antenna $P_r\,(0\,\mathrm{m})$ was 28 dBm) fits almost perfectly the measured data. The sum of squared residuals of the Free-Space model is more than twice that of the Two-Ray Interference model. This confirms once more that the Two-Ray Interference model is the best candidate for wide streets with no obstacles on either side.

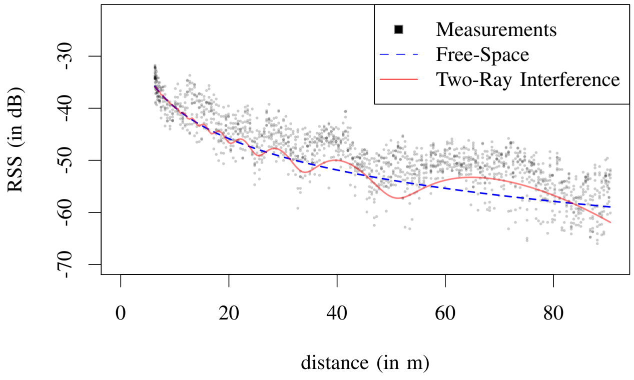

Figure 3. Measurements and modeling for the medium street (28 m).

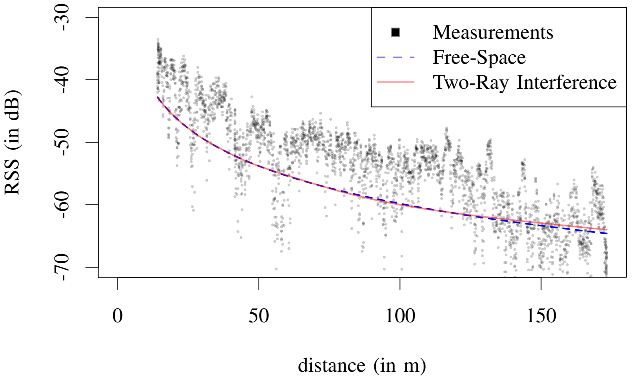

Figure 4. Measurements and modeling for the narrow street (18 m).

Our second set of measurements was for the medium street width. We were restricted to a 100 m strip of the street. To avoid other traffic, we did the measurements late at night. Again we used NLS model fitting to estimate the model parameters for the Two-Ray Interference model. All results including the fitted models are depicted in Figure 3. As we can see, the Two-Ray Interference model still fits better than the Free-Space model results. This suggests to conclude that at 28 m of street width the rays that are reflected by the side walls do not influence the received signal considerably. However, the difference in squared residuals is not that high anymore.

The final measurements have been done for the narrow street. This time the environment allowed a measurement distance of 160 m. For a street width of only 18 m, we were expecting different results than above. The results confirm this hypothesis: the difference between the two models is negligible. NLS model fitting estimates a relative permittivity of the ground material of nearly one. That is, if the relative permittivity reaches one, the Two-Ray Interference model basically converges to the Free-Space model. This leads to the conclusion that at a street width of 18 m the Two-Ray Interference model does not produce reliable results.

V. CONCLUSION

In conclusion, it can be said that the Two-Ray Interference model is only suited for freeway scenarios and suburban or downtown environments that are rather wide. For a street width below 28 m it should be used with great care as, according to the shown results, it does not produce realistic results anymore. This is due to the influence of the electromagnetic waves that are reflected by the walls becoming more dominant the narrower the street gets. Thus, the overall conclusion is that the street width has a strong influence on the radio signal modeling in simulation.

Next possible steps include the addition of stochastic effects to the models, e.g., assuming a Nakagami-m fading with different parameters, and to evaluate the model fitting for even more measurements. We also suggest to investigate the impact of the height of the buildings and its influence on the radio signal propagation.

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