An Extended GSCM for Mobile Radio based Positioning in Outdoor-to-Indoor Environment

Wei Wang, Thomas Jost, and Uwe-Carsten Fiebig
German Aerospace Center (DLR)
Institute of Communications and Navigation
Wessling, Germany
Email: {Wei.Wang, Thomas.Jost, Uwe.Fiebig}@DLR.de

Abstract

To develop and validate mobile radio based positioning algorithms under realistic conditions, an accurate description of the propagation channel is of significant importance. However, there is still a lack of outdoor-to-indoor channel models suitable for positioning applications. Two requirements for the channel model to be used for positioning have not been accurately considered yet: the non line-of-sight bias (affecting ranging accuracy) and the evolution of multipath components (MPCs) with time (affecting tracking performance). In this paper an outdoor-to-indoor channel model is proposed based on an extended geometry-based stochastic approach to fulfill the above mentioned requirements. We consider MPCs occurring due to reflection, scattering and combinations of both. Three different types of MPCs are individually defined and modeled according to their characteristics. Each MPC is represented by a virtual scatterer which has a fixed position while the receive antenna is moving.

I. Introduction

In critical scenarios like urban canyons, the position accuracy using global navigation satellite systems (GNSSs) deteriorates due to shadowing, diffraction, and reflection of satellite signals. The situation is even worse if the GNSS receiver is located indoors. Here, severe multipath effects and signal blockage handicap tracking the satellite signals [1]. Enhancing GNSS based positioning by incorporating terrestrial mobile radio signals in critical environments can significantly improve the position accuracy compared to a GNSS-only solution [2].

The performance of positioning algorithms using mobile radio signals strongly depends on the delay estimation of the line-of-sight (LoS) path between the transmitter and the receiver. Multipath propagation significantly influences the performance of the delay estimation for the LoS path. Furthermore, in NLoS scenarios the NLoS bias, defined as the delay offset of the first detectable MPC with respect to the delay of the geometrical line-of-sight (GLoS) path, introduces an additional ranging error [3]. For range estimators which are based on signal tracking, the continuous time evolution of individual MPC affects the performance of estimators like [4]. In order to realistically represent wave propagation for positioning applications, channel models are required to provide a correct representation of the NLoS bias and the evolution of the MPC with time.

Because of its advantages to simulate the time-variant behavior of the channel, the geometry-based stochastic channel model (GSCM) approach is widely used [5], [6]. Channel models developed for mobile radio signals normally consider communication applications. Particularly, there is no outdoor-to-indoor channel model suitable for positioning applications. The well known WINNER II channel model [7] is dedicated to both link and system level evaluations for communication applications. Its usability for outdoor-to-indoor positioning applications is limited as it does not support an accurate representation of the the NLoS bias nor a continuous evolution of all MPC parameters. The recently proposed COST-2100 channel model [8], supports semi-urban and indoor-to-indoor scenarios only.

In the wireless channel, a signal propagates from the transmitter to the receiver along certain geometrical paths. Along each path interactions between the signal and physical objects may occur (e.g., reflection and scattering) [9]. According to distinct interaction phenomena, different models of individual MPCs are needed [10]. In prominent GSCMs, e.g., the COST-259 channel model [11] or the COST-2100 channel model, all MPCs are geometrically represented by the same model (i.e., scatterer points) without considering different propagation phenomena.

To accurately and efficiently simulate the time variant parameters of MPCs, the channel model proposed in this paper considers paths due to reflection, scattering and combinations of both. Three types of MPCs are individually defined and modeled in the channel model. Each MPC is characterized by a so-called fixed scatterer (FS), which is a virtual scatterer whose position does not change during receiver movement. As an essential parameter relevant to positioning applications, the NLoS bias is accurately modeled.

II. Outdoor-to-Indoor Channel Model for Positioning Applications

A. Three Different Types of MPCs

Two kinds of interactions are considered, i.e., reflection and scattering. In this paper we consider a static environment and, thus, the physical objects where scattering occurs do not change their position. According to the number of occurred interactions, each propagation path is defined as single-bounce (SB) or multi-bounce (MB). Based on the interaction, three

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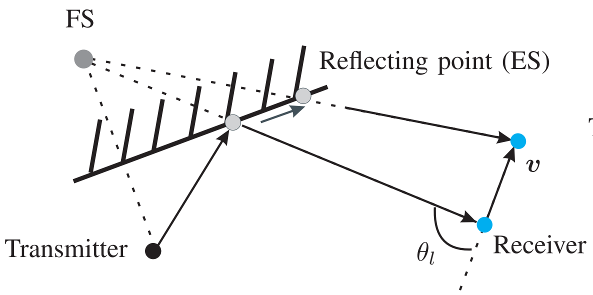
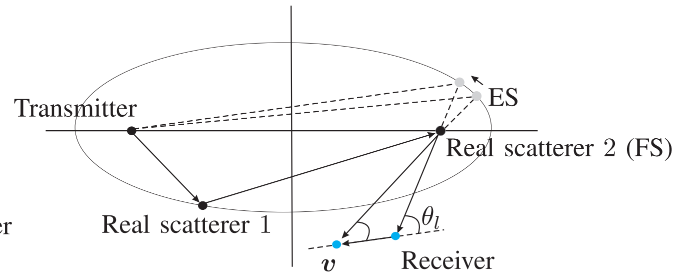


(a) Type M1



(b) Type M2

Fig. 1: (a): Example of a reflected path. The ES is located at the position of the reflecting point. Accordingly, the ES moves along a linear trajectory as the receiver and the FS is fixed in its position. (b): Example of a scattered path with two interactions. The position of the ES changes along an elliptical trajectory while the position of the FS is fixed when the receiver moves. The FS is located at the position of the last real scatterer.

types of MPCs are defined in this paper: (1) reflected MPCs (M1), (2) scattered MPCs with scattering as the last interaction (M2) and (3) scattered MPCs with reflection as the last interaction (M3). A MPC of type M1 contains only reflections as interactions, either SB or MB. MPCs of type M2 and M3 contain at least one scattering interaction [10].

To explain the three different types of MPCs, we use geometrical representations of MPCs involving a fixed scatterer (FS) and by an equivalent scatterer (ES). A FS is a virtual scatterer whose position does not change while the receiver moves. An ES is a virtual SB scatterer resulting from the same geometrical path length and the same angle of arrival (AoA) as the path to be modeled [5], [6], [10]. Please note, that the calculation of the ES position is only needed during the initialization of the path. In the following, the different types of MPCs are described in detail.

1) Reflected MPC $(M1)$: For a SB reflected MPC, the corresponding ES is the interaction point of the propagation wave with the surface, i.e., the reflecting point as shown in Fig. 1(a) [12]. While the receiver changes its position, the ES moves along the reflecting surface, i.e. a wall. For a MB reflected MPC, the corresponding ES is a virtual point in space. It can be easily shown that if the receiver moves on a line the ES of a MB reflected MPC also moves along a linear trajectory. The FS of a reflected MPC is defined as a virtual transmitter whose position does not change. As visualized in Fig. 1(a), the FS locates at the mirror point of the real transmitter. Positions of the FS and of the real transmitter are symmetrical w.r.t. the surface on which the reflection occurs. The FS lies on the line determined by the receiver and the ES positions. It can be seen that the distance between the FS for the l-th MPC and the receiver at traveled distance[1] d, $\|\boldsymbol{l}_r(d) - \boldsymbol{l}_{\mathrm{FS},l}\|$ equals to the geometrical path length $\tau_l(d) \cdot c$, where $\tau_l(d)$ denotes the absolute delay of the path and c the speed of light. The transmitter position $\boldsymbol{l}_t(d)$ and the FS position $\boldsymbol{l}_{\mathrm{FS},l}(d)$ are fixed. Therefore, in this paper the notations $\boldsymbol{l}_t(d)$ and $\boldsymbol{l}_{\mathrm{FS},l}(d)$ are simplified in notation as $\boldsymbol{l}_t$ and $\boldsymbol{l}_{\mathrm{FS},l}$, respectively. Positions of the receiver and the FS are denoted by $\boldsymbol{l}_r(d)$ and $\boldsymbol{l}_{\mathrm{FS},l}$, respectively.

For a reflected MPC with either SB or MB propagation, the time variant absolute delay is calculated as

$$\tau_l(d) = \frac{\|\boldsymbol{l}_r(d) - \boldsymbol{l}_{\mathrm{FS},l}\|}{c}. \tag{1}$$

The time variant AoAs of individual MPCs can be calculated straightforwardly according to the positions of the FS and the mobile station (MS).

2) Scattered MPC, scattering as the last interaction $(M2)$: For this kind of MPC the last interaction is scattering. It can be found that the ES of a SB scattered MPC is the physical object where scattering occurs. While the receiver moves, the ES of a SB scattered MPC does not change its position. For a MB MPC of type M2, the ES is not a physical object but a virtual point in space as visualized in Fig. 1(b). Since the last interaction point (i.e., the physical object or "Real scatterer 2" in Fig. 1(b)) does not change its position, the propagation time from the transmitter to the last interaction point is fixed. As a result, while the receiver changes its position, the ES moves along an elliptical trajectory [10]. As visualized in Fig. 1(b), the FS for a MPC of type M2 is equivalent to the last real scatterer of the propagation path. It lies on the line through the receiver and the ES.

For a MPC of type M2 with either SB or MB propagation, the time variant absolute delay is calculated as

$$\tau_l(d) = \frac{d_{e,l} + \|\boldsymbol{l}_r(d) - \boldsymbol{l}_{\mathrm{FS},l}\|}{c} = \frac{\|\boldsymbol{l}_t - \boldsymbol{l}_{\mathrm{ES},l}(d)\| + \|\boldsymbol{l}_{\mathrm{ES},l}(d) - \boldsymbol{l}_{\mathrm{FS},l}\| + \|\boldsymbol{l}_r(d) - \boldsymbol{l}_{\mathrm{FS},l}\|}{c}, \tag{2}$$

where $d_{e,l}$ is the excess distance and $\boldsymbol{l}_{\mathrm{ES},l}(d)$ is the position of the ES for a receiver traveled distance d. According to the visualization in Fig. 1(b), the excess distance $d_{e,l}$ is constant while the receiver moves. Therefore, $d_{e,l}$ is determined initialization

[1]Within the channel model, we assume the receiver to be traveling on a linear trajectory with constant speed $\boldsymbol{v}$. Therefore, the time instant t is linearly related to the traveled distance d.

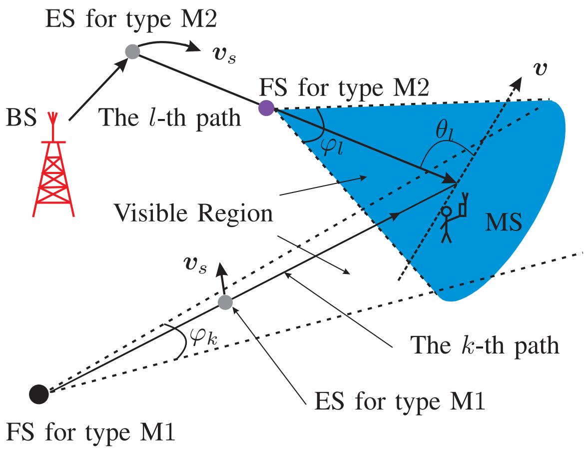


Fig. 2: Visualization of the proposed channel model. For representation convenience, only the MPCs of type M1 and M2 are visualized. $\boldsymbol{v}_s$ represents the velocity of the ES and $\boldsymbol{v}$ the velocity of the receiver.

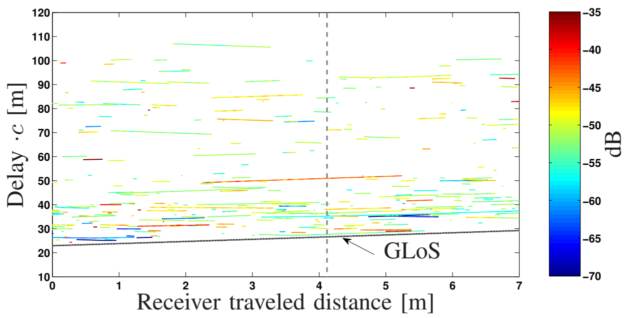


Fig. 3: Example of generated time variant CIR.

of the path l. It is worth to note that a similar concept is used in the COST-2100 channel model denoted as twin-clusters. The time variant AoAs of individual MPCs can be calculated straightforwardly according to the positions of the FS and the MS.

3) Scattered MPC, reflection as the last interaction ($M3$)*:* For this kind of MPC, the last interaction is reflection. It has been discussed in [10], that the ES may move along a hyperbolical trajectory according to the geometry. As described in [12], the FS is defined as the mirror point of the last scatterer w.r.t. to the reflecting surface. We denote the distance between the transmitter and the FS as d_{TM}, and the propagation length between the transmitter and the last scatterer as d_{TS}. The ES moves along different types of trajectories according to the relation between d_{TM} and d_{TS}: (1) If d_{TM} is smaller than d_{TS}, the ES moves along an elliptical trajectory while the receiver moves. Thus, this kind of MPC is categorized as type M2. (2) If d_{TM} equals to d_{TS}, the ES and the FS are located at the same position. (3) If d_{TM} is larger than d_{TS}, the ES moves along a hyperbolic trajectory. For simplicity, we will only consider the case (3) for the type M3. Therefore, the position of the ES $\boldsymbol{l}_{\mathrm{ES},l}(d)$ lies on a line bounded by $\boldsymbol{l}_{\mathrm{FS},l}$ and $\boldsymbol{l}_r(d)$. More descriptions can be found in [12].

For a MPC of type M3, the time variant absolute delay of the MPC is calculated according to (2) with the excess distance

$$d_{e,l} = d_{TS} - d_{TM} \,. \tag{3}$$

It can be seen that the excess distance $d_{e,l}$ is constant while the receiver moves. Therefore, $d_{e,l}$ is determined at the initialization of the path. The time variant AoAs of individual MPCs can be calculated straightforwardly according to the position of the FS and the MS.

B. Proposed Outdoor-to-Indoor Channel Model

The construct of the proposed outdoor-to-indoor channel model is visualized in Fig. 2. The transmitter and the receiver are denoted by BS and MS, respectively. In the model the environment is assumed to be static and only the MS moves. Three types of MPCs are individually modeled as described in Section II-A. In physical-deterministic channel models like [13], parameters of reflected paths are calculated based on a given environment layout. However, this approach is computational complex, particularly, considering outdoor reflections occurring in outdoor-to-indoor wave propagations for mobile radio transmissions. Thus, reflected MPCs are modeled using a statistical approach in the proposed channel model.

The time variant delay $\tau_l(d)$ and the AoA $\theta_l(d)$ of the MPC l are calculated based on the geometrical relation of the positions for the MS and the FS. As described in Section II-A, the calculation of the absolute delay for all types of MPCs can be generically represented by (2). The FS for the MPC of type M1 acts as a virtual transmitter and, therefore, $d_{e,l}$ is zero. For all types of MPCs $d_{e,l}$ is constant during the movement of the MS. As a result, the excess distance $d_{e,l}$ for the l-th MPC does not depend on the position of the MS and is determined while the MPC is initialized.

In the proposed channel model, the time variant complex amplitude of the MPC is a stochastic process parameterized by the Rice factor and the Doppler spread. Furthermore, the time variant number of MPCs is simulated by a two-step approach: First, the number of disappeared MPCs is determined according to the path life. The statistically generated path life can be interpreted as the opening angle φ_l of an angular pattern which determines the visible region (VR) of the l-th MPC as shown in Fig. 2. Second, the number of newly appearing MPCs is statistically generated.

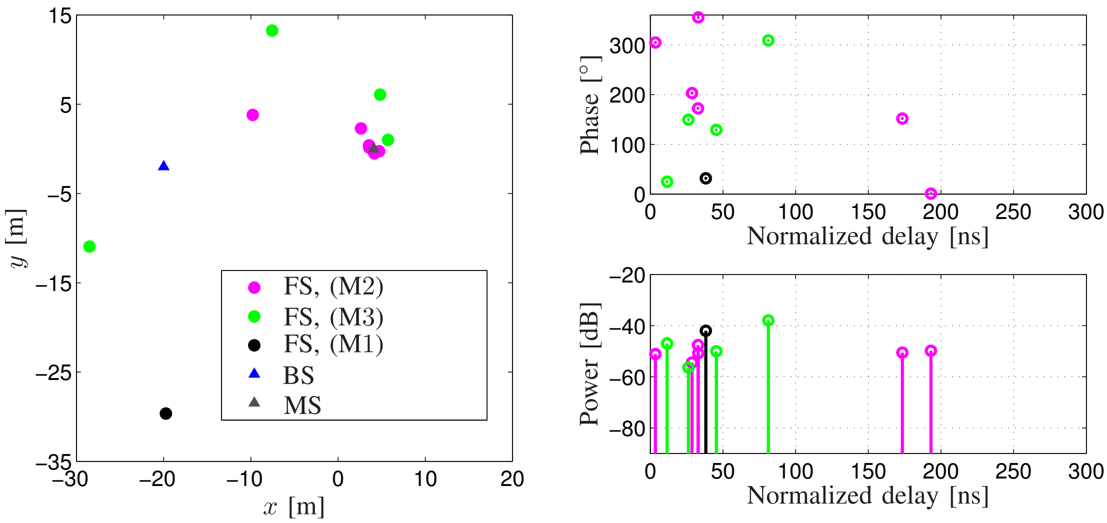


Fig. 4: Details of the MPCs for the snapshot at a MS traveled distance of 4.11 m. The left plot visualizes the spatial locations of the FSs for all MPCs, the MS and the BS. The right plots show the phase and power in dependence of the delay for the different MPCs.

C. Example of Simulated channel impulse response (CIR)

To demonstrate the proposed time variant channel model, an example of generated CIRs in a NLoS scenario is visualized in Fig. 3. The parameters of the channel model are obtained based on the channel measurement campaign described in [3]. The MS moves over a total distance of $7\,\mathrm{m}$. The power levels of MPCs are depicted in colors and are ranging between $-70\,\mathrm{dB}$ and $-35\,\mathrm{dB}$. To visualize the NLoS bias, the time variant delay of the GLoS path is shown by the grey line. Variations of the delay and the amplitude can be clearly seen from the figure. Fig. 4 visualizes a detailed CIR snapshot at $d = 4.11\,\mathrm{m}$, where all three types of MPCs are present. The left figure shows the spatial positions of the FSs for all MPCs, the MS and the base station (BS). On the right hand side the phase-delay plot and the power-delay plot are presented where different types of MPCs are visualized by distinct colors.

III. Conclusion

The contribution of this paper is an outdoor-to-indoor channel model fulfilling the requirements for the simulation of mobile radio based positioning algorithms. The channel model is based on an extended geometry-stochastic modeling approach. We consider MPCs occurring due to reflection, scattering and combinations of both. Three different types of multipath components are individually defined and modeled according to their characteristics. Each multipath component is represented by a virtual scatterer which has a fixed position while the receiver moves.

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