Satellite-to-Indoor Channel Model for Mobile Receivers

Thomas Jost*, Wei Wang*, Uwe-Carsten Fiebig* and Fernando Pérez-Fontán†
*German Aerospace Center (DLR), Institute of Communications and Navigation, Wessling, Germany
Email: {Thomas.Jost, Wei.Wang, Uwe.Fiebig}@DLR.de
†University of Vigo, Signal Theory and Communications, Vigo, Spain
Email: fpfontan@tsc.uvigo.es

Abstract

Realistic channel models are prerequisites to develop advanced receiver positioning algorithms able to cope with the effects of signal propagation such as shadowing and multipath. In this contribution, we propose a novel and accurate wideband satellite-to-indoor channel model applicable to testing and validating range estimation algorithms for positioning applications. The advantage of the channel model compared to the state of the art is the ability to reproduce the spatial characteristics of multipath propagation seen by a moving receiver. To model satellite-to-indoor propagation, a combination of physical-deterministic mechanisms and stochastic methods is used. In this context, components occurring due to diffraction and transmission by walls, windows and doors are treated using physical-deterministic near field methods. For paths occurring due to indoor multipath propagation, a hybrid approach is used combining physical-deterministic and stochastic methods.

I. Introduction

Since many years location based services and, in turn, location awareness has gained in importance. The fundamental technology for location determination for mass market applications is based on Global Positioning System (GPS). However, in indoor environments the accuracy of GPS is not adequate [1]. Therefore, significant effort is spent in order to improve the performance of satellite navigation receivers in indoor environments. To test and validate range estimation algorithms in computer simulations accurate channel models are important.

In this contribution, we propose a wideband satellite-to-indoor channel model. The new channel model includes physical-deterministic and stochastic components. It is able to reproduce propagation phenomena such as reflection, diffraction, and scattering including their spatial characteristics. Compared to the state of the art [2], our approach allows to simulate the propagation conditions which are experienced by a moving receiver. The concept is as follows: we simulate physical deterministic propagation effects for the room where the moving receiver is located, whereas channel contributions from outside the room but inside the building and from interior objects like furniture are treated in a stochastic manner. Within this contribution, we present only an overview of the channel model without giving deeper insights and parametrization due to page limitation.

II. Measurement Campaign and Data Processing

A. Measurement Campaign

In the measurement campaign a Medav RUSK channel sounder operating at center frequency $1.51\,\mathrm{GHz}$ was used. While the receiving antenna was located indoors, the transmitter was mounted on a mobile crane, as shown on the left side of Fig. 1. We focused on the propagation path segment into and inside the building. Therefore, a directional transmit antenna was used. To assess the propagation conditions for a receiver in motion, the receive antenna was mounted on an experimental mobile platform using a model train as depicted on the right side of Fig. 1. More details on the measurement campaign itself can be found in [3].

B. Estimation of Time-Variant Channel Parameters

A feature of the measurement campaign is that the position of the receive antenna for each measured channel impulse response (CIR) snapshot is precisely known. Therefore, it is possible to form a linear antenna array from the time-variant measurement as described in [4]. For the estimation process an array consisting of 7 elements with an aperture size of $30\,\mathrm{cm}$ along the track was used. To track the time-variant channel characteristics a Kalman filter smoothing estimates obtained by a space-alternating generalized expectation-maximization (SAGE) algorithm was used as described in [5]. The algorithm estimates and tracks the delay, the complex amplitude and the 1-d angle of arrival (AoA) for each path. To reduce the complexity of the data processing, we evaluated the measurement data every $1\,\mathrm{mm}$ along the track.

Fig. 1. The left picture shows the basic measurement setup with the building and the mobile crane as transmitter platform while the right hand side visualizes the model train including the receiving antenna which has a hemispheric beam-width and right hand circular polarization.

Combining the building layout, the known transmitter and receiver positions and the estimated parameters' of paths, propagation effects like reflection and scattering can be identified and characterized independently for modeling.

III. Channel Model Description

Using physical-deterministic methods requires a layout of the environment. As a complete building layout including its interior is cumbersome to be used within simulations, the proposed satellite-to-indoor channel model applies physical-deterministic methods only for the room where the receiver is located. The layout of the room will be denoted as scenery in the following. Other channel contributions from outside the room but inside the building or interior objects, like furniture, are simulated stochastically.

The indoor received narrowband power $P_{\rm nb}$ is the sum of two components $P_{\rm nb} = P_{\rm e} + P_{\rm mp}$. While $P_{\rm mp}$ describes the received power due to indoor multipath propagation, $P_{\rm e}$ denotes the received power of a band-limited impulse at the geometrical line-of-sight (LoS) path[1] delay. For the satellite-to-indoor channel model, we use the physical-deterministic model described in [6] to calculate $P_{\rm e}$ which equals to the power delay profile (PDP) at the delay of the geometrical LoS path. Assuming an exponential decay, the PDP can be characterized by $P_{\rm e}$ and the delay spread σ_τ [6].

Because of the importance of the LoS path in the positioning application, the direct path is calculated using physical-deterministic mechanisms applied on the scenery. Additional diffracted paths occur with small additional path lengths compared to the geometrical LoS path. Therefore, we denote in the following a group of paths as *direct components* which are received by diffraction and transmission on the the walls aperture of the LoS path to the building. These components will be described in more detail in Section III-A.
A second group described in Section III-B denoted as *reflected components* simulate paths which are reflected by the walls of the scenery. Paths occurring due to indoor located objects are seen as a third group and are simulated using stochastic methods as described in Section III-C. These paths are denoted as *scattered components*.

A. Direct Components

Based upon the entry loss model [6], the direct components are calculated. Within the satellite-to-indoor channel model, each wall i will contribute to the CIR if the vector product between the wall normal $\mathbf{n}_i$ and the direction vector to the satellite $\tilde{\mathbf{x}}_{\rm t} = {}^{\mathbf{x}_{\rm t}}/_{\|\mathbf{x}_{\rm t}\|}$ is positive. Each element $\{i, k, g\}$ of a wall i with k the element number of type $g \in \{\mathrm{wall}, \mathrm{window}, \mathrm{door}\}$ is considered to be the source of an individual propagation path.

Like in [6], the diffraction factor $D_{i,k,g}(\mathbf{x}_{\rm r}, \mathbf{x}_{\rm t})$ and the angular dependent transmission factor $T_{i,g}(\tilde{\mathbf{x}}_{\rm t})$ of the element $\{i, k, g\}$ is calculated deterministically. The complex amplitude of the path associated to the element $\{i, k, g\}$ for $g \in \{\mathrm{window}, \mathrm{door}\}$ is calculated straightforward as

$$\alpha_{i,k,g}(\mathbf{x}_{\rm r}, \mathbf{x}_{\rm t}) = T_{i,g}(\tilde{\mathbf{x}}_{\rm t}) \cdot D_{i,k,g}(\mathbf{x}_{\rm r}, \mathbf{x}_{\rm t}) \ , \quad (1)$$

[1] We refer to the term "geometrical LoS path" for a path which is only affected by free space propagation between the transmitter and the receiver.

for all i where $\mathbf{n}_i^T \cdot \tilde{\mathbf{x}}_\mathrm{t} > 0$. For the path which is directly received through the wall i, the complex amplitude is calculated as

$$\alpha_{i,1,\mathrm{wall}}(\mathbf{x}_\mathrm{r}, \mathbf{x}_\mathrm{t}) = T_{i,\mathrm{wall}}\left(\tilde{\mathbf{x}}_\mathrm{t}\right) \left(D_{i,1,\mathrm{wall}}\left(\mathbf{x}_\mathrm{r}, \mathbf{x}_\mathrm{t}\right) - \sum_{l=0}^{L_{i,\mathrm{window}}-1} D_{i,l,\mathrm{window}}\left(\mathbf{x}_\mathrm{r}, \mathbf{x}_\mathrm{t}\right) - \sum_{k=0}^{L_{i,\mathrm{door}}-1} D_{i,k,\mathrm{door}}\left(\mathbf{x}_\mathrm{r}, \mathbf{x}_\mathrm{t}\right) \right), \quad (2)$$

where $L_{i,\mathrm{window}}$ and $L_{i,\mathrm{door}}$ stand for the number of windows and doors which belong to the aperture of wall i, respectively.

B. Reflected Components

Reflected components are calculated by a combination of physical-deterministic and stochastic methods based on the scenery. Taking the scenery, the receiver and transmitter positions into account, we can deterministically calculate the reflection point located on the wall and, therefore, the delay and the AoA of the multipath component (MPC).

Within the channel model, the complex amplitude $\alpha_{l,\mathrm{re}}(\tau_{l,\mathrm{re}}, \mathbf{x}_{l,\mathrm{re}})$ of the reflection l from wall i is calculated by

$$\alpha_{l,\mathrm{re}}(\tau_{l,\mathrm{re}}, \mathbf{x}_{l,\mathrm{re}}) = \sigma(\tau_{l,\mathrm{re}}) \cdot a_{i,p} \cdot w_{i,\mathrm{re}}(\mathbf{x}_{l,\mathrm{re}}) \left(s_{i,\mathrm{re}}(\mathbf{x}_{l,\mathrm{re}}) + \sqrt{K_{i,\mathrm{re}}}\, e^{j\varphi_{i,\mathrm{re}}} \right) \cdot \frac{e^{-j\,2\pi f_c \tau_{l,\mathrm{re}}}}{\sqrt{1+K_{i,\mathrm{re}}}}, \quad (3)$$

where $\mathbf{x}_{l,\mathrm{re}} = [x_{l,\mathrm{re}},\, y_{l,\mathrm{re}}]^T$ is the two dimensional reflection point on the wall surface, $\sigma(\tau_{l,\mathrm{re}})$ is a power adaptation to the PDP dependent on the delay $\tau_{l,\mathrm{re}}$ of the path, $w_{i,\mathrm{re}}(\mathbf{x}_{l,\mathrm{re}})$ is a windowing function for the amplitude, $s_{i,\mathrm{re}}(\mathbf{x}_{l,\mathrm{re}})$ is the stochastic process modeled by a first order autoregressive process (AR) of unit mean power, $K_{i,\mathrm{re}}$ is the Rice factor [7] and $\varphi_{i,\mathrm{re}}$ is a random phase uniformly distributed over $[0, 2\pi]$. The factor $a_{i,p}$ denotes the delay independent amplitude of the MPC which is a reflected path from the wall i where $p \in \{1, 2\}$ stands for the number of reflections.

C. Scattered Components

The scattered components model a specific type of propagation paths, where at least one physical scatterer is present in the geometrical pathway. In order to model such paths, the geometry-based stochastic channel model (GSCM) approach [8], [9] is used.

In an initialization step of a simulation, N_sc point scatterers at positions $\mathbf{x}_{l,\mathrm{sc}}$, $l = 1, \ldots, N_\mathrm{sc}$ are distributed in space around the center of the scenery. Using the geometrical relation, the delay $\tau_{l,\mathrm{sc}}$ of the l-th path is calculated by

$$\tau_{l,\mathrm{sc}} = \left(\|\mathbf{x}_\mathrm{t} - \mathbf{x}_{l,\mathrm{sc}}\| + \|\mathbf{x}_\mathrm{r} - \mathbf{x}_{l,\mathrm{sc}}\| \right) \frac{1}{c_0} + \tau_{l,\mathrm{add}}, \quad (4)$$

where c_0 denotes the speed of light and $\tau_{l,\mathrm{add}}$ models an additional delay in order to simulate paths resulting from multiple interactions [10], [11]. In the proposed channel model, the model for the complex amplitude $\alpha_{l,\mathrm{sc}}(\tau_{l,\mathrm{sc}}, \nu_{l,\mathrm{sc}})$ follows the model used for the reflected components as

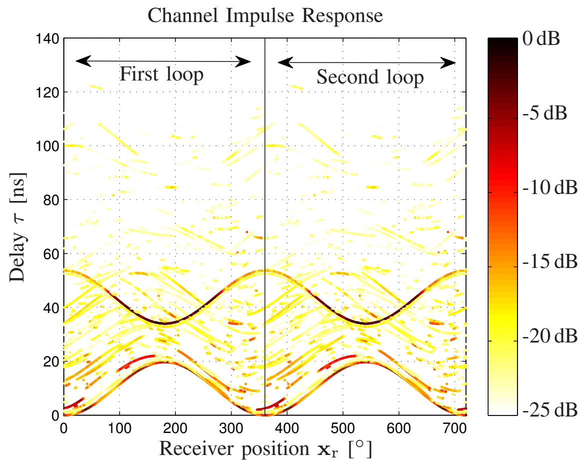
$$\alpha_{l,\mathrm{sc}}(\tau_{l,\mathrm{sc}}, \nu_{l,\mathrm{sc}}) = \sigma(\tau_{l,\mathrm{sc}}) \cdot a_l \cdot w\left(\frac{\nu_{l,\mathrm{sc}} - \bar{\nu}_{l,\mathrm{sc}}}{\nu_{l,\mathrm{op}}} \right) \times \left(s_{l,\mathrm{sc}}(\nu_{l,\mathrm{sc}}) + \sqrt{K_{l,\mathrm{sc}}}\, e^{j\varphi_{l,\mathrm{sc}}} \right) \frac{e^{-j\,2\pi f_c \tau_{l,\mathrm{sc}}}}{\sqrt{1+K_{l,\mathrm{sc}}}}. \quad (5)$$

The main difference between (5) and (3) is the dependence of $\alpha_{l,\mathrm{sc}}(\tau_{l,\mathrm{sc}}, \nu_{l,\mathrm{sc}})$ on $\nu_{l,\mathrm{sc}}$, where $\nu_{l,\mathrm{sc}}$ is the angle between $\mathbf{x}_{l,\mathrm{sc}}$ and $\mathbf{x}_\mathrm{r}$ on the horizontal plane. Therefore, (5) can be interpreted as an angular pattern for the l-th scattered component directed towards $\bar{\nu}_{l,\mathrm{sc}}$ with a 6 dB beam-width $\nu_{l,\mathrm{op}}$. A stochastic variation of the complex amplitude $\alpha_{l,\mathrm{sc}}(\tau_{l,\mathrm{sc}}, \nu_{l,\mathrm{sc}})$ is simulated using a Rice process [7] with Rice factor $K_{l,\mathrm{sc}}$. The zero-mean correlated process of unit power $s_{l,\mathrm{sc}}(\nu_{l,\mathrm{sc}})$ is modeled by a first order AR having a pole located on the positive real axis inside the unit circle.

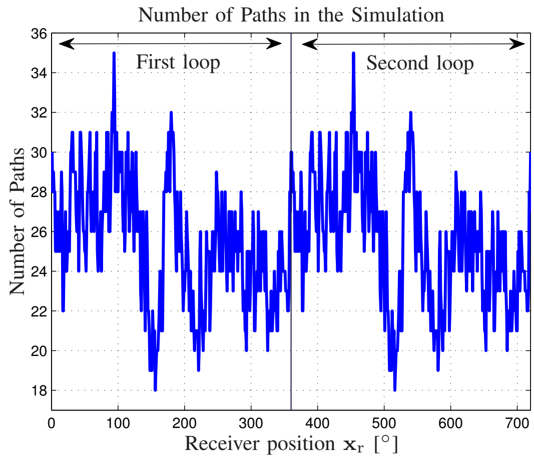
D. Simulation Example

To visually inspect the output of the satellite-to-indoor channel model, we present a simulation example. In the underlying scenario the receiver moves along a circle with a $3\,\mathrm{m}$ radius around the center of the room. CIRs are calculated for every degree on the circle for two loops of the receiver movement, i.e. for the angles $0\,^\circ$ to $719\,^\circ$.

Fig. 2(a) visualizes the CIRs calculated for each receiver position. The delays of the paths are subtracted by the propagation delay of the geometrical LoS path at the first receiver position which is the closest point on the circular trajectory to the transmitter. Fig. 2(a) shows a repetition of CIRs for the first and the second loop of the receiver movement. The channel model assumes static or quasi-static transmitter and environment. Therefore, the CIR changes only with the receiver position and repeats for the same transmitter-receiver geometry. Naturally, MPCs of the class of direct components have the smallest delays among all paths. Because the receiver is moving on a circular trajectory, the delays of the direct components follow a



(a) The figure shows the CIRs generated by channel model for the circular trajectory of the receiver. As the receiver performs two loops, a repetition of the CIRs occurs.



(b) The figure visualizes the number of MPCs which have a minimum amplitude of -25 dB with respect to the geometrical LoS path amplitude. As the receiver performs two identical loops, the curve repeats itself.

Fig. 2. Results for a simulation example.

sinusoidal curve. Between $\tau = 32\,\mathrm{ns}$ and $\tau = 54\,\mathrm{ns}$ a path is visible in Fig. 2(a) showing a converse delay behavior compared to the direct components. This paths is a reflection at the rear-wall of the room seen from the transmitter. Other paths visualized in Fig. 2(a) show a random-like delay behavior. The amplitude variation of individual paths follows a correlated process with a rising and a falling slope in cases of appearance and disappearance, respectively.

The number of MPCs with amplitudes larger than $-25\,\mathrm{dB}$ compared to the geometrical LoS path amplitude is visualized in Fig. 2(b). Like in Fig. 2(a), the curve repeats for the first and the second loop of the circular receiver movement. For this specific simulation, the number of paths changes between a minimum of 18 and a maximum of 35 for the simulated receiver trajectory.

IV. Conclusion

The paper describes a novel wideband satellite-to-indoor channel model applicable for positioning applications. Especially a moving receiver is taken into account. This includes the spatial dependencies of the propagation channel for slow receiver movements, i.e. receiver positions which are close such that the CIRs are correlated. Within the model multipath propagation is described by using a combination of physical-deterministic and stochastic components. We model occuring propagation paths by three different types denoted as direct, reflected and scattered components. While the direct components represent paths diffracted and transmitted through the aperture of the building walls, the reflected and scattered components correspond to indoor originated multipath. The parameters needed for the channel model are extracted from a channel sounder measurement. A simulation example of the channel model shows the modeled spatial characteristics of satellite-to-indoor multipath propagation for a moving receiver.

References

[1] G. Seco-Granados, J. López-Salcedo, D. Jiménez-Baños, and G. López-Risueño, “Challenges in Indoor Global Navigation Satellite Systems,” *IEEE Signal Process. Mag.*, vol. 29, no. 2, pp. 108–131, Mar. 2012.

[2] F. Pérez-Fontán, V. Hovinen, M. Schönhuber, R. Prieto-Cerdeira, F. Teschl, J. Kyrolainen, and P. Valtr, “A wideband, directional model for the satellite-to-indoor propagation channel at S-band,” *Int. Journal of Satellite Communications and Networking*, vol. 29, no. 1, pp. 23–45, 2011.

[3] T. Jost, W. Wang, U.-C. Fiebig, and F. Pérez-Fontán, “Comparison of L- and C-Band Satellite-to-Indoor Broadband Wave Propagation for Navigation Applications,” *IEEE Trans. Antennas Propag.*, vol. 59, no. 10, pp. 3899–3909, Oct. 2011.

[4] W. Wang and T. Jost, “A Low-Cost Platform for Time-Variant Wireless Channel Measurements with Application to Positioning,” *IEEE Trans. Instrum. Meas.*, vol. 61, no. 6, pp. 1597–1604, June 2012.

[5] T. Jost, W. Wang, U.-C. Fiebig, and F. Pérez-Fontán, “Detection and Tracking of Mobile Propagation Channel Paths,” *IEEE Trans. Antennas Propag.*, vol. 60, no. 10, pp. 4875–4883, Oct. 2012.

[6] T. Jost, G. Carrié, F. Pérez-Fontán, W. Wang, and U.-C. Fiebig, “A Deterministic Satellite-to-Indoor Entry Loss Model,” *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 2223–2230, Apr. 2013.

[7] M. Pätzold, *Mobile Fading Channels*. John Wiley & Sons, 2002.

[8] A. F. Molisch, A. Kuchar, J. Laurila, K. Hugl, and R. Schmalenberger, “Geometry-based directional model for mobile radio channels – principles and implementation,” *European Transactions on Telecommunications (ETT)*, vol. 14, pp. 351–359, 2003.

[9] J. J. Blanz and P. Jung, “A Flexibly Configurable Spatial Model for Mobile Radio Channels,” *IEEE Trans. Commun.*, vol. 46, no. 3, Mar. 1998.

[10] T. Jost, W. Wang, U.-C. Fiebig, and F. Pérez-Fontán, “Movement of equivalent scatterers in geometry-based stochastic channel models,” *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 555–558, 2012.

[11] N. Czink and C. Oestges, “The COST 273 MIMO Channel Model: Three Kinds of Clusters,” in *ISSSTA*, Bologna, Italy, Aug. 2008, pp. 282–286.