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Estimation of Reflection Coefficients for the IlmProp Channel Modeling Environment Using Path Loss Models

ABSTRACT

The requirements for current and future mobile radio systems are extremely demanding. Consequently developing realistic channel models is indispensable in designing and testing any system. In this paper an algorithm for the IlmProp channel modeling environment is proposed, yielding more realistic channel impulse responses. The IlmProp is a geometry-based, time-variant, three-dimensional, multi-user channel modeling environment, capable of handling antenna arrays at the transmitter and receiver. The wireless channel is modeled as a sum of paths. When the paths represent reflections, the path-strengths depend on the distances traveled and on the reflection coefficients. In contrast to channel models based on the full-wave or ray-tracing approach, the IlmProp is intended to be used without knowing the physical properties of all objects in the environment, which reduces the environment modeling effort drastically. However, the positions and coefficients of the scatterers, which represent single points of reflections or diffractions, are modeled explicitly. The proposed algorithm estimates the magnitudes of the scattering coefficients of the IlmProp using existing path loss models. In other words, given an IlmProp scenario, the coefficients are chosen so that the resulting path loss matches an arbitrary predefined path loss model. Simulations show the validity of the proposed algorithm.

1 INTRODUCTION

Mobile radio networks beyond 3G require highest bandwidth efficiency and unprecedented flexibility. A common approach to meet these requirements is to exploit the spatial dimension of the wireless channel by using multiple antennas at the transmitter (TX) and receiver (RX). The success of the MIMO principle highly depends on the characteristics of the scattering environment. Therefore, to develop efficient MIMO transmission techniques it is crucial to use channel models which model the characteristics of the scattering environment realistically, consequently providing realistic Channel Impulse Responses (CIRs).

In recent years a vast variety of channel models has been developed. A common approach is to calculate the channel impulse response as a sum of impinging rays at the RX. Given Angle of Arrival (AoA), Angle of Departure (AoD), Delay Time of Arrival (DToA), complex path strength, and possibly a Doppler shift for each path, the CIR can be easily computed. The path strengths depend on the distance traveled and on the reflection or diffraction coefficients. In the following these coefficients are generally referred to as *scattering coefficients*. Full-wave channel models, i.e., models that solve the Maxwell equations directly, such as [1], and ray-tracing models, such as [2], compute the scattering coefficients following the physical lawsof propagation [3, pp. 93-98, 123-142]. The major drawback of this approach is that the physical properties of all objects in the environment have to be known with high precision, so that the biggest time effort is not the computation of the channel but rather the modeling of the environment itself. Directional Channel Models (DCM), e.g., [4, 5], map the path strengths of the impinging rays to a given path loss model while not explicitly modeling the environment between the TX and RX. In channel modeling there is always a trade-off between modeling the environment realistically implying the extensive effort of obtaining a detailed physical description of all objects, and modeling only major channel features at the cost of being less realistic. The IlmProp channel modeling environment [6], developed at the Ilmenau University of Technology, explicitly models the positions and coefficients of the scatterers in the three-dimensional environment and is intended to generate realistic CIRs without defining the physical properties of the objects in the environment.

In this paper we propose an algorithm to estimate the scattering coefficients of given IlmProp scenarios using existing path loss models.

Section 2 introduces the IlmProp channel modeling environment. The developed algorithm for scattering coefficient estimation is discussed in Section 3, while Section 4 evaluates it by showing simulation results for selected IlmProp scenarios. Finally, Section 5 draws the conclusions.

2 THE ILMPROP CHANNEL MODELING ENVIRONMENT

2.1 General description

The IlmProp is a flexible geometry-based multi-user MIMO channel modeling tool, capable of dealing with time-variant frequency selective channels [6]. Its main scope is the generation of CIRs as a sum of propagation rays. Figure 1 illustrates the capabilities of the IlmProp. Three mobiles (M1, M2, and M3) move around the Base Station (BS). Their curvilinear trajectories are shown. The BS and Mobile Stations (MS) can employ any number of antennas arranged in an array with an arbitrary geometry. All parameters defining a scenario are stored in form of Cartesian coordinates and their evolution in time. The multi-path components are obtained by point-like scatterers, which can be placed arbitrarily. The model supports both single- and multiple-reflections. The information about the location of the scatterers and how the paths are linked to them can be obtained either via parameter estimation techniques carried out on channel measurements [7], or be set arbitrarily. Obstacles (such as buildings), which can obstruct the propagation paths, can also be included. Figure 2 shows a simple scenario with an obstructed Line Of Sight (LOS) and three clusters of scatterers which are connected by single and double reflected rays.

After setting up the geometry of the scenario and defining the range and sampling intervals

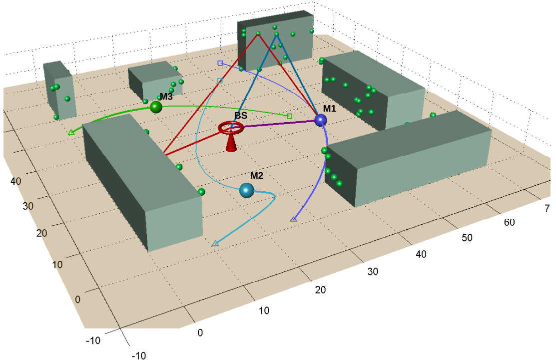


Figure 1: Sample scenario generated with the IlmProp to illustrate its capabilities.

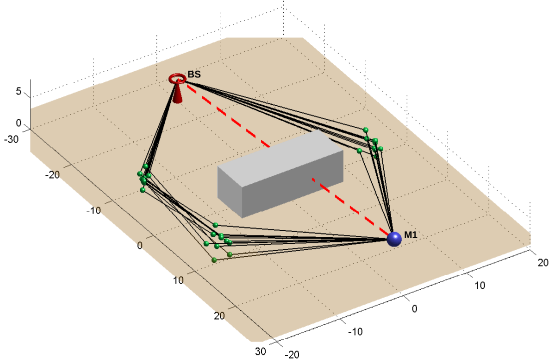


Figure 2: Simple IlmProp scenario showing multiple reflections and an obstructed LOS.

for time and frequency, the IlmProp calculates the CIR as a superposition of the LOS path and M_p Non-LOS (NLOS) paths in the time-frequency domain. For each time snapshot and frequency bin the complex path weight γ_p, path length d_p, AoD $\{\varphi_p^{\mathrm{TX}}, \theta_p^{\mathrm{TX}}\}$, and AoA $\{\varphi_p^{\mathrm{RX}}, \theta_p^{\mathrm{RX}}\}$ is determined for the p-th path. The MIMO channel transfer matrix $\boldsymbol{H} \in \mathbb{C}^{M_{\mathrm{R}} \times M_{\mathrm{TX}}}$, where M_{RX} and M_{TX} are the numbers of RX and TX antennas, respectively, is calculated as

$$\boldsymbol{H} = \sum_{p=0}^{M_p} \gamma_p \, \mathrm{e}^{-jkd_p} \, \boldsymbol{a}_{\mathrm{RX}}(\varphi_p^{\mathrm{RX}}, \theta_p^{\mathrm{RX}}) \cdot \boldsymbol{a}_{\mathrm{TX}}^{\mathrm{H}}(\varphi_p^{\mathrm{TX}}, \theta_p^{\mathrm{TX}}), \qquad (1)$$

where c is the speed of light and $\boldsymbol{a}_{\mathrm{TX}}$ and $\boldsymbol{a}_{\mathrm{RX}}$ are the TX and RX array response vectors for the plane wave impinging from azimuth angle φ and elevation angle θ, respectively. The wave number k is $2\pi f/c$. The superscript $(.)^{\mathrm{H}}$ denotes the Hermitian transpose operator, which is the complex conjugate of the transposed vector. It should be noted that γ_p, d_p, the AoDs, and AoAs are time-variant due to the time-variant environment. We omit the dependency on time in the formulas for simplicity. Time and frequency are sampled in the IlmProp with M_t and M_f samples, respectively. Therefore, the calculation above has to be repeated for every time and frequency sample in order to obtain the four-dimensional tensor $\mathcal{H} \in \mathbb{C}^{M_{\mathrm{RX}} \times M_{\mathrm{TX}} \times M_t \times M_f}$ containing the channel coefficients.

The complex path weights γ_p can be expressed as

$$\gamma_p = \omega_p \, \rho_p \, \frac{c}{4\pi f d_p}, \qquad (2)$$

where ρ_p is the product of the scattering coefficients along the p-th path and ω_p is a boolean variable which is zero if an obstacle is obstructing the path and one if not. For the LOS component (i.e., for $p = 0$), ρ_0 is one and d_0 is the distance between the BS and MS antenna arrays. Note that the terms ω_p, ρ_p, and d_p are time-variant.

In the multi-user case the MIMO channel matrix is computed for each user separately, using the same environment information. The resulting dimensions of the channel coefficient tensor $\mathcal{H}$ are $M_{\mathrm{RX}} \times M_{\mathrm{TX}} \cdot M_{\mathrm{U}} \times M_t \times M_f$, where M_{U} is the number of users which all have M_{TX} antennas.

More information on the IlmProp, as well as the source code and some exemplary scenarios can be found at `http://tu-ilmenau.de/ilmprop`.

2.2 Modeling of the scatterers

Each scatterer represents a single point of either a reflection or a diffraction and is characterized by a complex scattering coefficient having magnitude less or equal than one. This coefficient might be time-variant. The amplitude of the coefficients influences greatly the channel features, such as the Rician K-factor and the spatial richness of the MIMO channel. In order to obtain realistic channels it is crucial to set these coefficients carefully.

The IlmProp does not require detailed physical information and therefore does not rely on physical laws to compute the scattering coefficients. However, the positions and coefficient of the scatterers are modeled explicitly. The next section explains how path loss models can be used to estimate the magnitudes of the reflection coefficients of the IlmProp without providing detailed physical information.

3 THE COEFFICIENT ESTIMATION ALGORITHM

Path loss models describe the mean received power for given distances [8]. The basic principle of the proposed algorithm is to adjust the IlmProp scattering coefficients in order to obtain the same mean received power as given by the path loss model. Hence, after selecting an appropriate path loss model for a given IlmProp scenario, a multidimensional optimization has to be carried out in order to obtain the scattering coefficients.

3.1 Assumptions

In reality scattering coefficients are generally time-variant, due to object movement or changes of temperature and sunlight, and depend on the angle of incidence [3, pp. 93-98, 123-142]. However, we assume constant scattering coefficients independent of the angle of incidence to reduce the degrees of freedom and computational complexity of the estimation algorithm.

Since no physical information about the objects is given, the phases of the scattering coefficients are assumed to be independent random variables which do not influence the mean received power. Only the magnitudes are estimated, the phases are assumed random variables uniformly distributed between 0 and 2π.

3.2 Optimization problem

The scattering coefficient vector $\boldsymbol{\rho}_{\mathrm{s}}$ is defined as

$$\boldsymbol{\rho}_{\mathrm{s}} = \begin{bmatrix} \rho_{\mathrm{s},0} & \rho_{\mathrm{s},1} & \dots & \rho_{\mathrm{s},i} & \dots & \rho_{\mathrm{s},N-1} \end{bmatrix}^{\mathrm{T}} , \tag{3}$$

where i is the scatterer index and N is the total number of scatterers. For convenience we define a time index set $\mathscr{T}$ as

$$\mathscr{T} = \{\nu : \nu \in \mathbb{N}_0, 0 \leq \nu \leq M_{\mathrm{t}} - 1\} , \tag{4}$$

where M_t is the number of time snapshots of the IlmProp model. To achieve the optimization goal, it is necessary to find an expression for the logarithmic IlmProp path loss, so that the error with respect to the path loss model can be expressed.

Since path loss models are generally defined for single isotropic antennas, the array response vectors in equation (1) simplify to one. Only the carrier frequency f_c is relevant for path loss analysis. Thus, the logarithmic path loss of the IlmProp channel can be written as

$$L_\mathrm{IlmProp}(\nu) = -10\log_{10} \mathrm{E}\left\{ \left| \sum_{p=0}^{M_p} \omega_p(\nu)\,\rho_p(\nu)\,\frac{c}{4\pi f_\mathrm{c} d_p(\nu)}\,\mathrm{e}^{-j\,k\,d_p(\nu)} \right|^2 \right\} , \tag{5}$$

where the notation $\mathrm{E}\{\cdot\}$ denotes the expected value over all realizations at one time snapshot ν. The path coefficients ρ_p are complex in general, modeled with random phases according to the assumptions. Furthermore, due to the different lengths d_p and the high number of paths, the path phases can be assumed to be uncorrelated random variables. Therefore, the total power can be calculated as sum of the powers of each path. These powers are deterministic, thus, the IlmProp path loss formula simplifies to

$$L_\mathrm{IlmProp}(\boldsymbol{\rho}_\mathbf{s},\nu) = -10\log_{10}\left(\sum_{p=0}^{M_p} \left| \omega_p(\nu)\,\rho_p(\boldsymbol{\rho}_\mathbf{s},p,\nu)\,\frac{c}{4\pi f_\mathrm{c} d_p(\nu)} \right|^2 \right) , \tag{6}$$

where the coefficient of the p-th path ρ_p can be written in terms of the scattering coefficient vector $\boldsymbol{\rho}_\mathrm{s}$ as

$$\rho_p = \rho_p(\boldsymbol{\rho}_\mathrm{s},p,\nu) = \prod_{i\,\in\,\mathscr{I}} \rho_{s,i} \; . \tag{7}$$

The index set $\mathscr{I}$ is defined as $\mathscr{I} = \{$indices of scatterers on path p at time index $\nu\}$.

Generally, path loss models from the literature can be written as

$$L_\mathrm{model} = L_\mathrm{model}\left(d_0, \boldsymbol{\delta}\right) \; , \tag{8}$$

where $\boldsymbol{\delta}$ is a vector containing all other parameters on which the chosen model depends. Note that d_0 and $\boldsymbol{\delta}$ are time-variant, thus, they are functions of the time-snapshot ν.

The mismatch $e(\boldsymbol{\rho}_\mathrm{s},\nu)$ between the IlmProp path loss and a given measurement-based path loss model at time index ν is

$$e(\boldsymbol{\rho}_\mathrm{s},\nu) = L_\mathrm{IlmProp}(\boldsymbol{\rho}_\mathrm{s},\nu) - L_\mathrm{model}\left(d_0(\nu), \boldsymbol{\delta}(\nu)\right) \; . \tag{9}$$

Since the path loss is the mean received signal power, it is straightforward to choose the mean error as a cost function for the optimization. However, simulations showed that in this case the IlmProp path loss might show variations about the mean exceeding 30 dB. Therefore, the variance of the error is also considered. Simulations showed that weighting the variance 10 % and the squared mean 90 % yields best results and numerical convergency. Thus, the cost function $J(\boldsymbol{\rho}_\mathrm{s})$ is

$$J(\boldsymbol{\rho}_\mathrm{s}) = 0.9\,\overline{e}^{\,2}(\boldsymbol{\rho}_\mathrm{s}) + 0.1\; s_e^2(\boldsymbol{\rho}_\mathrm{s}) \; , \tag{10}$$

where $\overline{e}$ and s_e^2 are the mean and the variance of the error $e(\boldsymbol{\rho}_\mathrm{s}, \nu)$ in equation (9), respectively, calculated over the time index set $\mathscr{T}$. In the multi user case, the values for L_IlmProp and L_model are obtained for each user. Then $\overline{e}^{\,2}$ and s_e^2 are calculated jointly for all time snapshots and users.

Finally, the optimization problem to estimate the scattering coefficients can be expressed as follows

$$\boldsymbol{\rho}_\mathrm{s} = \arg\min_{\boldsymbol{\rho}_\mathrm{s}} J(\boldsymbol{\rho}_\mathrm{s}) \; . \tag{11}$$

Due to the fact that only the amplitudes of the coefficients are to be estimated, they have to be real positive numbers. Additionally, they must be less than one since scatterers cannot amplify the power of the impinging rays. Therefore, the constraints for the optimization are

$$\boldsymbol{\rho}_\mathrm{s} \in \mathbb{R}^{N\times 1}, \qquad 0 \le \rho_{s,i} \le 1 \quad \text{for} \;\; 0 \le i \le N-1 \; . \tag{12}$$

Note that the optimization problem (11) is non-linear. Finding a general analytical solution is extremely complex due to the products of scattering coefficients involved (equation (7)) and due to the fact that the term $\omega_p(\nu)$ is obtained by a ray tracing engine. Therefore, we use a numerical approach for the estimator.

3.3 Extension to clusters

In geometry-based channel modeling, scatterers are usually arranged in clusters [9]. These are responsible for approximately one multi-path component in the CIR and have similar characteristics. Therefore, to reduce the computational complexity, it is convenient to define a single virtual scatterer for each cluster, which we call *centroid*. It represents the overall behavior of the cluster with respect to the path loss. The centroid is characterized by a scattering coefficient which we refer to as the *effective cluster coefficient*. Once every cluster has been replaced by the corresponding centroid, the coefficient optimization algorithm is performed in the same way as explained above on the effective cluster coefficients. This accelerates the algorithm drastically since the number of parameters is much smaller. The optimized effective cluster coefficients $\boldsymbol{\rho}_\mathrm{c}$ can then be used to calculate the coefficients of the individual scatterers. Assuming the same coefficient for all scatterers within one cluster, these can be calculated as

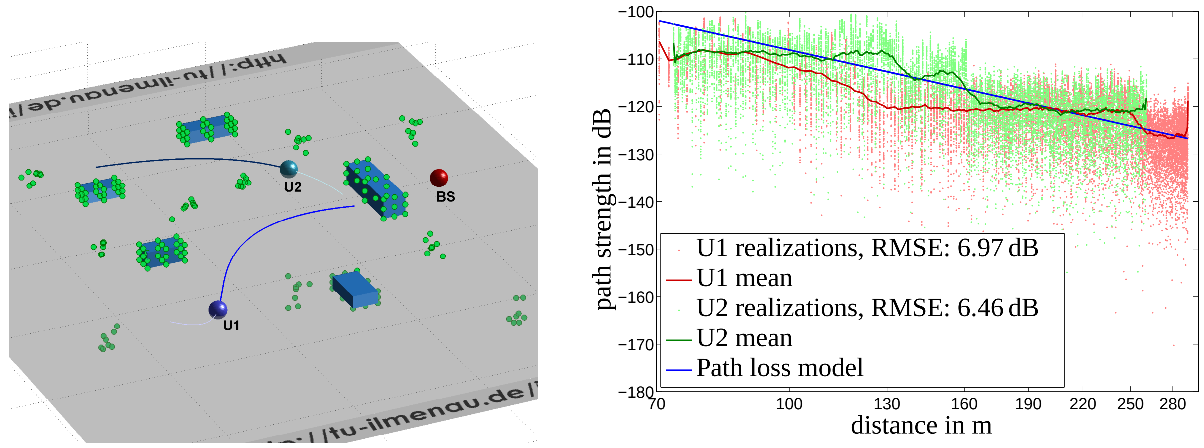
$$\rho_{\mathrm{s},j}^2 = \frac{\rho_{\mathrm{c},j}^2}{N_j} \; , \tag{13}$$

where the j-th cluster contains N_j scatterers and is characterized by the coefficient $\rho_{\mathrm{c},j}$.

To use this cluster-wise optimization, the information of which scatterer belongs to which cluster is required. This can be specified manually or obtained automatically using a cluster estimation algorithm, such as the one in [10].

3.4 Interpretation of the results

In general, the resulting scattering coefficients do not behave like realistic reflection or diffraction coefficients, since only the total received power is fitted to a physical model; not the power



(a) NLOS Suburban microcell scenario: BS (red), 2 MS (blue, cyan) moving along different trajectories, buildings (blue), and scatterers (green).

(b) Coefficient estimation result: IlmProp path loss for users one (U1) and two (U2) compared to the path loss model $L(d) = 40.2 \log_{10} d + 27.2$ (blue).

Figure 3: NLOS suburban microcell with the WINNER C1 NLOS path loss model [11].

of the individual paths. Moreover, the estimation algorithm fits the path loss to the given model only for the user trajectories present in the IlmProp scenario, i.e., other trajectories might result in higher errors with respect to the path loss model.

4 SIMULATION RESULTS

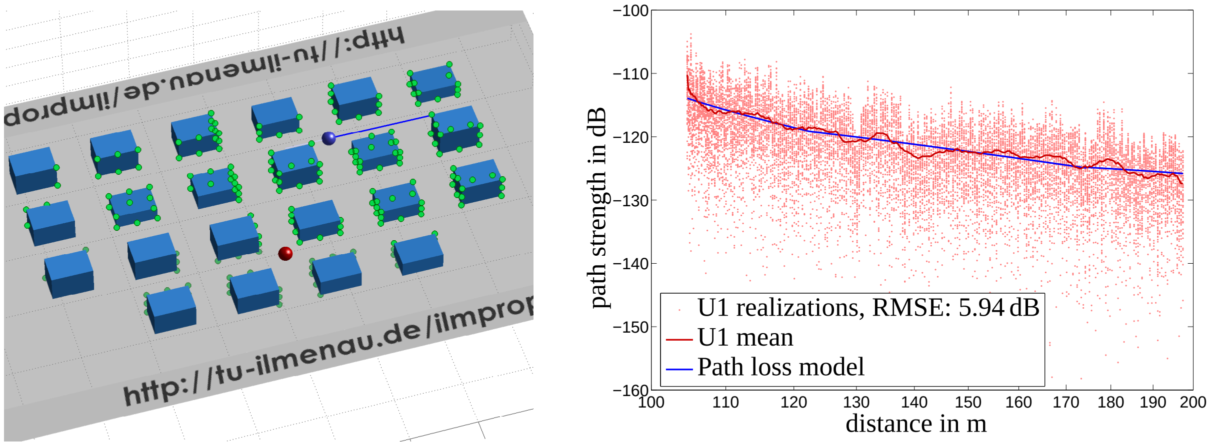
This section shows simulation results for a selection of three different scenarios. In all cases the IlmProp geometry was initialized first, the coefficient estimation algorithm was applied, and uniformly distributed random phases were added to the obtained scattering coefficients afterwards. Then, the full MIMO time-variant channel impulse response was computed using the IlmProp tools ($M_{\mathrm{RX}} = 12$, $M_{\mathrm{TX}} = 5$). For graphical comparison of the IlmProp path loss with the model, the mean of the channels between the different antennas was plotted. Furthermore, the Root Mean Square Error (RMSE) with respect to the path loss model was calculated.

4.1 NLOS suburban microcell

This scenario is a typical suburban microcell with five buildings of different heights and ten clusters of scatterers, which might be trees or cars. Each cluster contains eight scatterers within a sphere of 15 m radius. Two users (U1, U2) moving on different curvilinear trajectories are involved, each within 70 m to 300 m distance from the base station (BS). The scenario is located in an area of approximately 400 m × 400 m. One building is situated in front of the BS to block the LOS path. The MSs, at 1.5 m height, are connected with the BS, at 10 m height, via many single and double reflected rays. Figure 3(a) depicts the IlmProp scenario.

An appropriate NLOS path loss model is the WINNER suburban macrocell model (WINNER C1 scenario [11]) since the applicability range matches this IlmProp geometry. They use the simplified empirical path loss model for a carrier frequency of 5 GHz,

$$L(d) = 40.2 \log_{10} d + 27.2 \,. \tag{14}$$



(a) NLOS urban microcell scenario: BS (red), MS (blue) moving along a transversal street, buildings (blue), and scatterers (green).

(b) Coefficient estimation result: IlmProp path loss (red) compared to the COST231-WI NLOS path loss model (blue).

Figure 4: NLOS urban microcell with the COST 231 Walfisch-Ikegami path loss model [12, pp. 135-140].

The scattering coefficients were estimated cluster-wise. Figure 3(b) shows the results. The path loss model (blue line) and the mean IlmProp path losses (red and green lines) match sufficiently. It should be noted that the coefficient estimation is performed jointly for both users since they are connected to the same paths and scatterers. Since the model is matched well, the RMSE with respect to the model can be interpreted as the standard deviation of the shadow fading, which approaches the experienced 8 dB during the WINNER measurements.

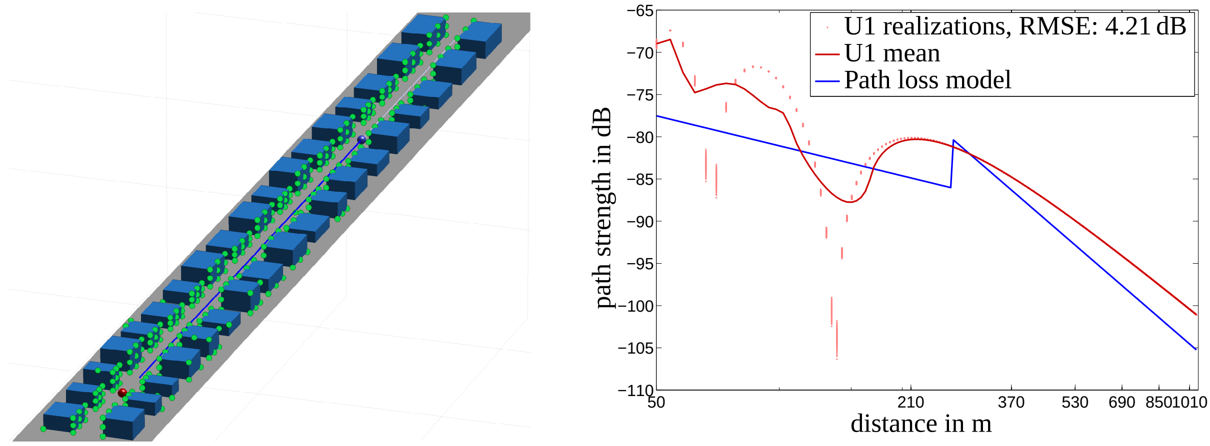
As a conclusion, it can be said that the cluster-wise multiple user coefficient estimation algorithm performs well for this scenario.

4.2 NLOS urban microcell

In this scenario a typical urban microcell with a rectangular grid of streets and buildings was modeled. The buildings are at different heights, between 12 m and 21 m, the scatterers are attached to the building surfaces. The user moves along a transversal street having no LOS connection to the base station within a distance of 100 m to 200 m. Numerous paths, single, double, and triple reflections, connect the MS (2 m above ground) with the BS (10 m above ground). The scenario spans an area of approximately 350 m × 200 m. The carrier frequency was chosen to be 2 GHz. Figure 4(a) depicts the IlmProp geometry; the scatterers which are always on obstructed paths are not shown.

The path loss model applied here was the COST 231 Walfish-Ikegami NLOS path loss model [12, pp. 135-140], which is well suited for this kind of urban scenarios. The scattering coefficients were estimated individually. The result can be seen in Figure 4(b). The algorithm performs very well for this scenario, since the blue path loss model curve matches almost exactly the red smoothed IlmProp path loss curve. The RMSE of 5.94 dB can be interpreted as the standard deviation of the shadow fading and is a typical value for urban microcells.

The coefficient estimation algorithm shows very good results when used with the COST 231 Walfish-Ikegami model in this urban microcell scenario.



(a) LOS urban microcell scenario: BS (red), MS (blue) moving along a long LOS street, buildings (blue), and scatterers (green).

(b) Coefficient estimation result: IlmProp path loss (red) compared to the Har et al. LOS dual slope path loss model (blue).

Figure 5: LOS urban microcell with the Har et al. LOS dual slope path loss model [13].

4.3 LOS urban microcell

To demonstrate the dual slope behavior of the path loss in urban LOS microcells, this scenario has been modeled. The MS (2 m above ground) moves 1 km along a street with buildings on both sides. The BS is located on this street at a height of 5 m, connected to the MS by single, double, and triple reflected rays. The carrier frequency is 2 GHz. Figure 5(a) depicts the IlmProp scenario; the scatterers which are always on obstructed paths are not shown.

In LOS environments the ground reflection has a significant impact on the path loss, hence, its position and coefficient has been calculated before the estimation was carried out applying the physical laws [14, pp. 65-67]. Due to the reflection angle being close to $90°$, the reflection coefficient approaches -1. Thus, the power of the ground reflected path gets subtracted from the LOS path. This coefficient has been kept fixed by the estimation algorithm, only adjusting the other ones to match the path loss model.

The Har et al. LOS dual slope path loss model [13] had been chosen for this scenario since its assumptions are fulfilled. As can be seen in Figure 5(b), the path loss model is far away from the IlmProp path loss. The estimated coefficients were mostly below -60 dB, hence, they have nearly no contribution to the total path loss. That is why the realizations in the figure show very little spread, i.e., the resulting path loss approximates that of the two-ray model (LOS and ground reflection only).

A possible explanation of this result is that in this kind of scenario the buildings on the left and right of the street in reality generate a reflection that is similar to the ground reflection. The corresponding reflection coefficients would also be close to -1, yielding a further reduction of the received power. Thus, in reality, a higher path loss than in the two-path model would be experienced. These building reflections were not modeled in the IlmProp scenario, therefore, the IlmProp path loss cannot exceed the two-ray path loss. That is why, even with very low scattering coefficients in the IlmProp scenario, the realistic path loss cannot be reached. The best possible solution is that the coefficients are set close to zero, which was indeed found by the estimator.

The modeled urban LOS IlmProp scenario was not suitable for the used path loss model. However, the estimated coefficients are still the best possible solution of the optimization problem.

5 CONCLUSIONS

The proposed scattering coefficient estimator for the IlmProp channel modeling environment has been successfully applied to different kinds of scenarios. It can be used with arbitrary path loss models. The algorithm has sufficiently attained its goal to improve the IlmProp channel model in order to make the synthetic channels more realistic. This was achieved without modeling the physical properties of the objects in the environment. However, the estimator can only operate successfully when the provided path loss model is suitable for the IlmProp scenario. If this is not the case, it still finds those coefficients that best fit the model.

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