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Directional channel model for ultra-wideband indoor applications

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***Abstract*—In this paper a hybrid ray tracing/statistical channel model for the ultra-wideband (UWB) frequency range is proposed. The conventional ray tracing model is complemented with randomly distributed point scatterers placed on the surface of large objects like walls. The wave propagation in such scenario is calculated in a deterministic way. The parameters of the scatterers are derived from the measurements of reflection from typical indoor walls.**

I. Introduction

Ultra wideband (UWB) technology recently became a topic of great interest and attracts a growing number of researchers. UWB systems utilize an extremely large bandwidth (absolute bandwidth $> 500\,\mathrm{MHz}$ or relative bandwidth $> 20\%$), which allows for high data rates and precise imaging. Due to approval of unlicensed operation of UWB systems by the Federal Communications Commission (FCC) in 2002 [1] and by the European Commission in 2007 [2] the way for the commercial applications using UWB has been opened.

To allow the designers of new applications to test their ideas when still in the design stage realistic channel models are necessary. By now some statistical channel models have been established, which are helpful in the early design phase. However, if a system has to be tested in a specific environment deterministic channel models are necessary.

One of the most popular deterministic channel models is ray tracing approach based on geometrical optics and uniform theory of diffraction. For single frequencies ray racing simulations reflect the propagation conditions in outdoor areas very well [3]. Furthermore, recently it has been shown that ray-tracing can be also easily extended to simulate ultra-wideband channels [4]. However, comparisons between measurements and simulation show that the ray tracing predictions are underestimated in terms of received power, mean delay and delay spread. [5], [6]. Up to now only few approaches to improve the ray tracing performance in the UWB frequency band have been presented [7], [8].

In this paper a simple alternative is proposed which combines the ray tracing method with statistically distributed scatterers. This approach is based upon the geometry-based stochastic channel model (GSCM) [9]. The parameters for the stochastic part of the model are derived from the measurements and can be varied for different wall types. Thus a good directive channel impulse response (CIR) prediction can be obtained with almost no additional computational effort.

II. Scattering Model

Comparisons of measurements and ray tracing simulations, which can be found in the literature, show that the measured UWB channel impulse response is much more dense than the simulated one and that the simulated received power and delay spread are underestimated. Characteristical for UWB is that the time resolution is very fine. This means that multipath components, which can not be detected in narrowband measurements, can be resolved. Therefore a model for the UWB frequency range must consider not only the channel statistics but also the shape of the impulse response.

A possible simple modelling approach is shown in [7]. In this model the ray tracing simulated channel impulse response is enhanced with additional empirical field strength term. The prediction of field strength and delay spread is improved, but this model does not allow for evaluation of directional channel characteristics.

Another approach presented in [8] generates additional diffuse scattering paths based on the model proposed in [10]. This model is directional and improves the prediction of channel parameter like delay spread and mean delay but the improvement to the impulse response shape is limited.

The scattering model presented in this work adapts an approach inspired from the geometrically-based stochastic channel model (GSCM), [9] and from the diffuse scattering model for UWB proposed in [8].

In the first step the reflection points are found in the considered scenario using the image theory method. Then N_{scat} scattererrs are placed randomly on the wall surface around the reflection point (cf. Fig. 1) . These scatterers model small structures on the surface not reflected in the scenario data, as well as interactions with inhomogeneities inside the wall and with objects behind the wall.

Each scatterer is characterized by the complex scattering coefficient $\underline{\mathbf{S}}$. The scattered field is described in the frequency domain by:

$$\underline{\mathbf{E}}^{\mathrm{s}} = \frac{e^{-jk_0 d}}{d} \cdot \underline{\mathbf{S}} \cdot \underline{\mathbf{E}}^{\mathrm{i}} \tag{1}$$

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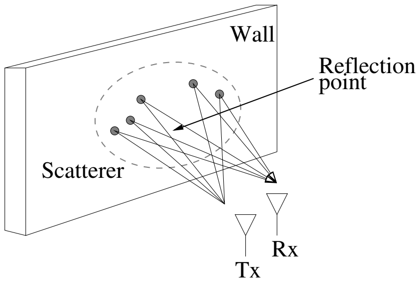


Fig. 1. Modelling approach

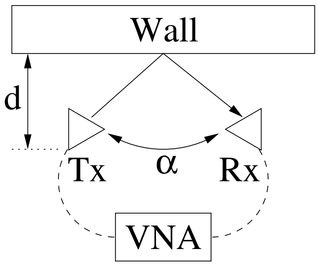


Fig. 2. Measurement setup

where $\underline{\mathbf{E}}^{\mathrm{s}}$ is the scattered field, $\underline{\mathbf{E}}^{\mathrm{i}}$ is the incident field, k_0 is the wavenumber and d is the distance to the scatterer.

By adding a $e^{-jk_0\delta}$ term to the scattering coefficient an additional delay can be assigned to the scatterer. This is done because in most measurements some multipath components have been observed with delays larger than the delay of a scatterer placed at the furthermost edge of the wall. In the following, δ is chosen randomly using uniform distribution in the range $[0, \delta_{\max}]$, where $\delta_{\max}$ is the maximal delay with respect to the reflected path observed in the measurements.

The magnitude of the scattering coefficient is set to $a \cdot \Gamma$, where Γ is the reflection coefficient for the corresponding surface and the scaling factor a is chosen to get the best fit with the measurements. The resulting scattering coefficient has a following form:

$$\underline{S}_{\mathrm{hh}} = \underline{S}_{\mathrm{vv}} = a \cdot \Gamma \cdot e^{-jk_0\delta} \tag{2}$$

Once the scatterers are generated the wave propagation calculation is done in a deterministical way. Thus the direction information is preserved in the prediction. An image theory based ray tracing tool described in [4] and [5] is used for the simulations. This model considers multiple reflections, diffractions and scattering at point scatterers. The characteristics of the antennas used for the measurements are measured in an anechoic chamber and inserted into the simulations.

III. Measurement Setup and Scenarios

Measurements are done with a vector network analyzer (VNA). The transmit (Tx) and receive (Rx) antennas are put in the front of the wall at a defined angle α (cf. Fig. 2) at the height of 1 m above the floor. A dual polarized Vivaldi antenna [11] is used on the transmitter and receiver side. The measurements presented in this work are done using the horizontal polarization.

For each measurement a frequency sweep between 2.5 and 12.5 GHz with 1601 frequency points is done. This corresponds to the resolution of 6.25 MHz. To remove the transfer coefficients for frequencies out of FCC band a blackman filter is applied in the band between 3.1 GHz and 10.6 GHz. Eventually the transfer function is transformed into time domain with the Fourier transform.

Four different wall types are considered: For the first measurement an artificial wall has been prepared by applying a thin plaster layer on a Styrofoam block of dimensions $2 \times 1.5 \times 0.1\,\mathrm{m}^3$. This wall is placed in an anechoic chamber and measured with angle α is 20 degree. The distance of the antennas to the wall is 1 m. This type of wall is expected to cause almost no scattering in non-specular directions and no significant cross-polarization coupling and is therefore used as reference.

The three additional walls comprising a 20 cm thick brick wall, a thin wooden compartment wall and a 10 cm thick concrete wall are measured in typical indoor environments like corridors and office rooms. To reduce the influence of the scenario details other than the considered walls (e.g. reflections floor, ceiling or the other walls in the corridor) each measurement is done in two steps. In the first step the wall is covered with an absorbing screen, then the absorber is removed. Subtracting the channel transfer function of the measurement with absorber from the measurement without the absorber delivers the channel impulse response for the considered wall. The attenuation of the used absorber in the considered frequency range is approximately 35 dB. The transmitter and receiver are placed 20 cm apart and are moved along the wall in the distance of 1.5 m to the wall surface. This configuration results in angle α = 7.2 deg. For each wall type 41 measurement points with spacing of 2.5 cm are collected.

IV. Assignment of model parameters

The model parameters N_{scat}, a and $\delta_{\max}$ are estimated from the measurements. The criteria used for this estimation are delay spread and the power contained in the channel impulse response.

Delay spread characterizes the widening of the impulse response due to multipath propagation:

$$\tau_{\mathrm{DS}} = \sqrt{\frac{\int\limits_{-\infty}^{+\infty} \tau^2 P_\tau}{\int\limits_{-\infty}^{+\infty} P_\tau} - \left(\frac{\int\limits_{-\infty}^{+\infty} \tau P_\tau}{\int\limits_{-\infty}^{+\infty} P_\tau}\right)^2} \tag{3}$$

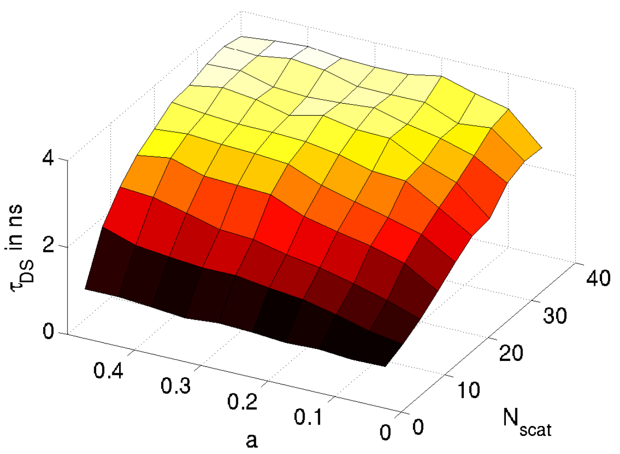
where P_τ is normalized power delay profile (PDP) and τ is the delay of multipath components. In the following the delay spread threshold of 30 dB is used.

The power contained in each channel realization is calculated as:

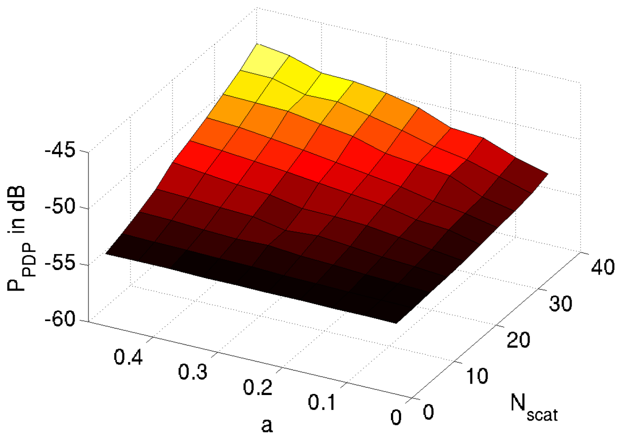
$$P_{\mathrm{CIR}} = \int_{0}^{+\infty} |h(\tau)|^2 \, d\tau \qquad (4)$$

In the simulation both channel characteristics depend on the model parameters. In the following it is assumed that δ_{max} is the delay at which the magnitude of the multipath contributions falls under -25 dB with respect to the reflected path. The other parameters are chosen so that the best match of the channel characteristics between the measurements and simulations is given.

In Fig. 3 the delay spread and the impulse response power are plotted against the number of scatterers N_{scat} and the scaling factor a of the scattering coefficient. For each parameters set 20 channel realizations are generated. The plots show values averaged over these realizations. Comparison with channel characteristics derived from the measurement delivers two possible parameters sets, one set with large N_{scat} and low a and other with small N_{scat} and larger a. The latter set causes less computational effort and is thus chosen for further considerations.



(a) delay spread



(b) IR power

Fig. 3. Dependency of delay spread and power contained in the impulse response on parameters N_{scat} and a for $\delta_{\mathrm{max}} = 10$ ns and the 1.5 m distance to the wall

The resulting parameters for different walls are summarized in Tab. I.

	N_{scat}	a	δ_{max} in ns
plaster	-	-	-
brick	10	0.2	6.67
wood	10	0.25	10
concrete	8	0.2	3.33

TABLE I
PARAMETERS USED FOR SIMULATION

V. COMPARISON OF MEASUREMENTS AND SIMULATIONS

In the case of the plaster layer a strong reflection path and some weak additional propagation paths are present in the measured data (cf. Fig. 4). As their amplitudes are 30 dB below the reflection their contribution to the delay spread and total power is negligible. This kind of surface can be simulated with conventional ray tracing model very well. The simulated and measured delay spread is 0.43 ns and 0.58 ns and the power contained in the channel impulse response is -53.91 dB and -52.68 dB respectively.

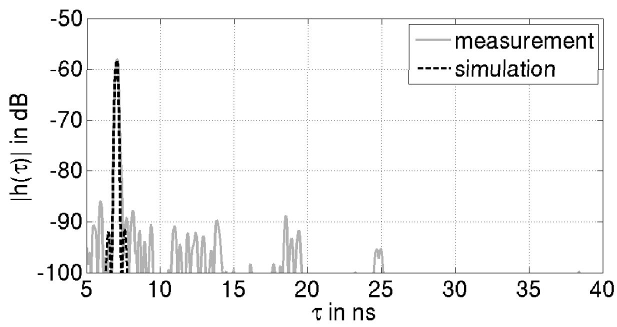


Fig. 4. Measured and simulated (conventional ray tracing) impulse response of a plaster layer at angle α = 20 deg.

However, the comparison of the measured channel impulse responses of different walls with the ray tracing simulations shows missing multipath contributions. In Fig. 5 the channel impulse response measured at the brick wall and a simulation with the conventional ray tracing are compared. The delay spread of the measured channel is 2.69 ns and of the simulated one 0.54 ns and the power is -53.95 dB and -56.32 dB respectively. To get the same conditions as in the measurement a CIR simulated in a scenario containing only the floor and ceiling is subtracted from the result of the simulation considering the wall as well as floor and ceilings. Thus all single and multiple interactions with the considered wall are taken into account and other effects like direct coupling between the antennas or reflections from ceiling and floor are removed from the data set.

If the proposed model is used the shape of the channel impulse response is improved, as shown in Fig. 6. The delay spread of the simulated channel is 1.78 ns and the power contained in the simulated impulse answer is -53.90 dB.

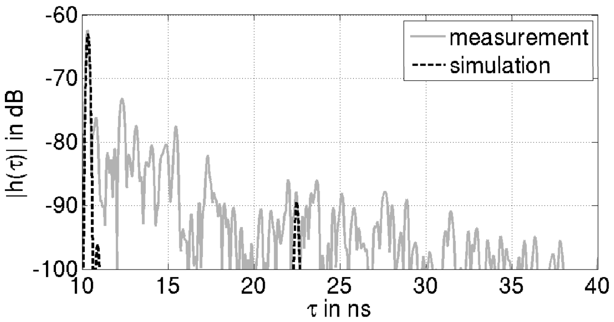


Fig. 5. Measured and simulated (conventional ray tracing) impulse response of a brick wall at angle α = 7.2 deg.

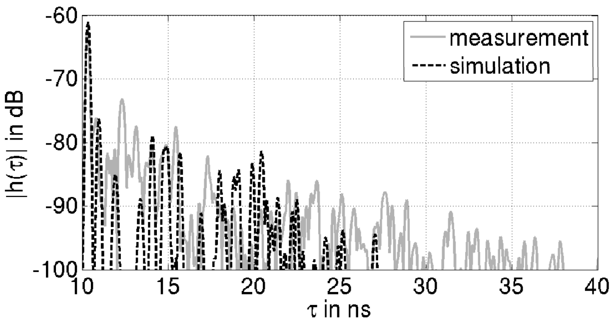


Fig. 6. Measured and simulated (proposed model) impulse response of a brick wall at angle α = 7.2 deg.

Since the model is partially stochastic each simulation will yield a different impulse response. Therefore the simulated contributions can not perfectly match the measured impulse response. The main peaks, however, do not change since they are represented by the deterministic part of the model.

In the next step the simulations are done for a set of points along the wall corresponding to the measurement setup positions. In Fig. 7 the measured and simulated channel impulse responses for three considered wall types are depicted. For each scenario the scatterers have been generated only once in the middle of the wall, thus the wavefronts from single scatterers are curved. However, this effect can be neglected in the considered scenario.

The proposed model delivers denser channel impulse responses, which correspond well to the measured ones. In the table II the mean values of delay spread, and total received power obtained from the measurement and from the simulations are summarized for the proposed method. In all cases a quite good match is achieved.

	τ_{DS} in ns		P_{CIR} in dB	
	meas.	sim.	meas.	sim
brick	1.76	1.60	-55.80	-54.03
wood	2.08	2.01	-53.99	-56.40
concrete	1.14	1.57	-58.16	-58.29

TABLE II
MEASURED AND SIMULATED CHANNEL PARAMETERS

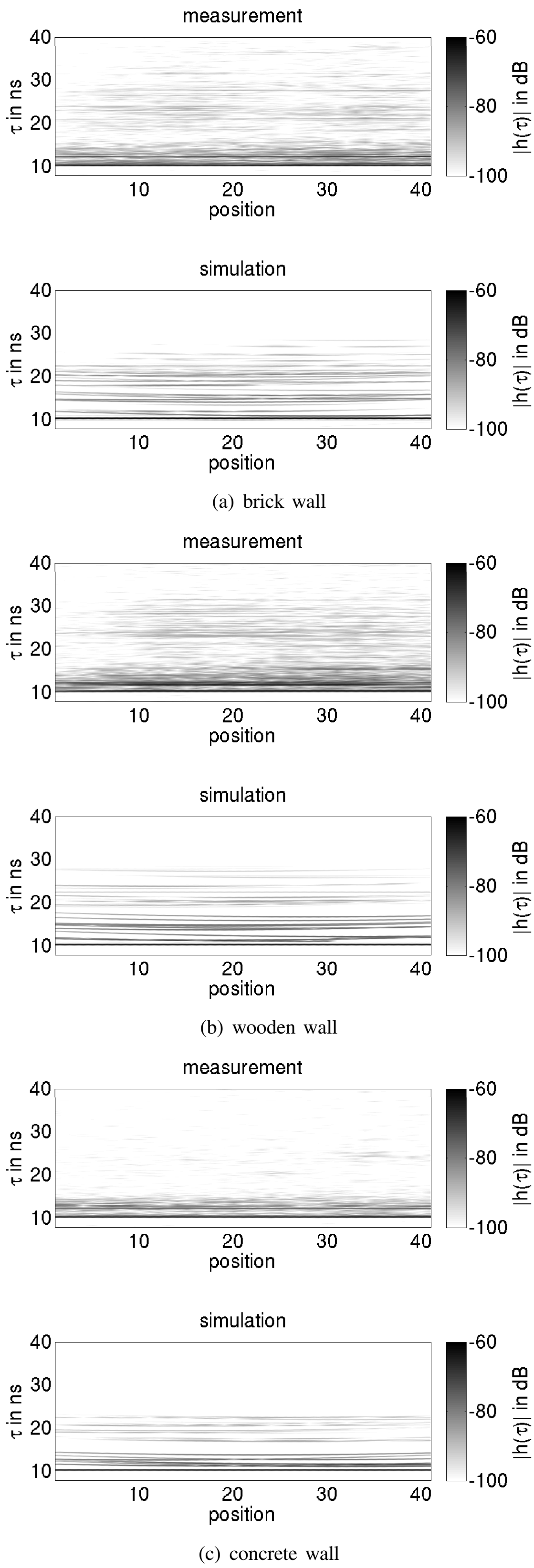


Fig. 7. Measured and simulated (proposed model) impulse responses of different wall types at angle α = 7.2 deg.

VI. Conclusions

The presented approach is capable of improving the match between the ray tracing simulations and measurements in indoor scenarios. It delivers realistic delay spread and received power. Also the shape of the channel impulse response is enhanced. Since a deterministical model is used for the propagation calculation the directional properties of the channel can be estimated form the simulations. However up to now the placement of the scatterers on the surface is arbitrary. Further work is dedicated to proper characterization of directive channel properties. Also a larger number of measurements of is needed to make the model more general. Nevertheless for indoor channels with known wall types a more accurate propagation prediction is now possible.

VII. Acknowledgment

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