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A Geometry-Based Stochastic MIMO Channel Model for 4G Indoor Broadband Packet Access

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ABSTRACT

We present a MIMO channel modelling approach that combines the advantages of geometry-based and stochastic elements. The channel is characterised by a time- and delay-dependent MIMO channel matrix that contains the impulse responses from each transmit to each receive antenna (for both polarisations), calculated from dual-polarised double-directional wave propagation. Based on 5GHz indoor measurements it captures all essential channel parameters of a broadband MIMO system for packet access, while providing reasonable simulation times for the development of MIMO transceiver algorithms with arbitrary antenna array configurations in three-dimensional environments with interference.

INTRODUCTION

Multiple-input multiple output (MIMO) systems will be *the* enabling technology for very high-speed data over the radio interface. To design algorithms that can actually reach the ambitious goal of up to 1000Mbit/s (see e.g. [1]), set by ITU, it is essential to have MIMO channel models that (i) describe the radio channel precisely (in order to fully exploit its spatio-temporal characteristics), and that (ii) are also computationally efficient. In this paper we present an indoor MIMO channel model that is able to model frequency-selective, time-varying MIMO channels with interference. The combined geometry-based stochastic modelling structure allows for the synthesis of realistic channels for algorithmic development for common indoor scenarios. The purely stochastic approach as proposed by 3GPP for outdoor MIMO scenarios with independent modelling of DoAs and DoDs appears to be not adequate for an indoor scenario since this independence does not hold there [2, 3].

MODEL

The model we describe uses a geometry-based stochastic approach for modelling the dual-polarised, double-directional and frequency-selective radio channel (see overview in [4]). A well proven approach is to assume clustering of mult-ipath components (MPCs) in the modeled dimensions [5]. Clustering was shown to have an important influence on channel properties [6].

We consider LOS, wall-reflections, reflections/scattering at interacting objects, up to 2nd order, and diffuse scattering. Scattering objects are modelled as clusters of MPCs in space and delay, and are described by the location of their centres and their size. Because elevation can play an important role in indoor channels, the model incorporates all three spatial dimensions. The coupling between directions-of-departure (DoDs), directions-of-arrival (DoAs), and delay of the cluster centres is given implicitly by the geometry of the room and the scattering clusters. In contrast, the MPCs *within* a cluster are modelled stochastically.

Propagation Model

Geometry-Based Part

The delay, DoA and DoD (both in azimuth and elevation) of the *LOS* component and *wall reflections* are modelled deterministically by simple three-dimensional ray tracing. The power of these components diminishes with distance squared (d^{-2}). For wall-reflections a real-valued reflection coefficient is incorporated. We allow for different reflection coefficients for horizontal and vertical polarisations, but not for a depolarisation of the wave.

The centre positions and sizes, $\sigma^{(space)}$, of the *scatterers or 'interacting objects'* can be chosen either randomly or deterministic if they are known beforehand. Local scattering clusters may be modelled around the link ends. In case of a moving terminal, the *local* scattering cluster will simultaneously move along the same route. The rms angular spread, $\sigma^{(angle)}$, of MPCs within a cluster (*cluster angular spread* [7]) is determined from their spatial extension by simple geometric considerations as $\sigma^{(angle)} = \arctan(\sigma^{(space)}/d)$.

Each interacting object introduces polarisation dependent attenuation of the scattered signal and a depolarisation. The reflection and depolarisation coefficients of the ℓ-th cluster form the elements of the reflection matrix $\boldsymbol{B}_\ell$, being on the

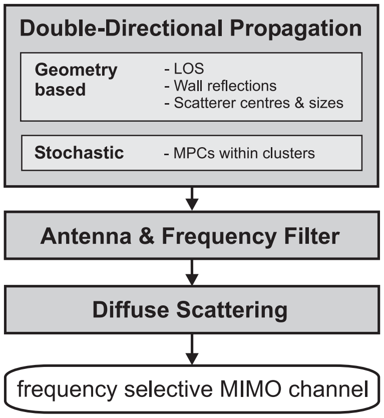

Figure 1: Model structure.

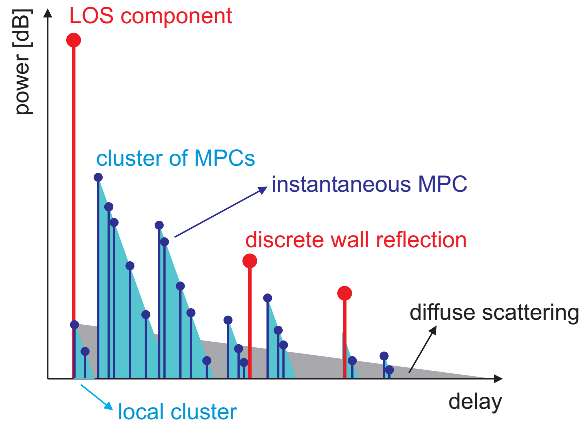

Figure 2: Illustration of model components in the delay domain: LOS, discrete reflections, clusters, MPCs, and diffuse scattering.

main diagonal and anti-diagonal, respectively. In order to keep the model simple, we define the reflection mechanism to be independent of the angle of the impinging wave.

We consider reflections of up to second order. Contributions of higher order reflections are considered by the spatially white i.i.d. part described later. As a result, a cluster of MPCs in the joint angular-temporal domain can be generated by (i) a first-order reflection via a single scatterer, (ii) a second-order reflection via two scatterers, or (iii) a second-order reflection via a wall and a scatterer. The first and the last cluster of a specific propagation path define the actual angular spread at transmit and receive side, respectively. This means each propagation path between transmitter and receiver is finally governed by the resulting angular means and spreads at transmit and receive sides, the mean delay, and the reflection matrix $\boldsymbol{A} = \boldsymbol{B}_{\ell_1}\boldsymbol{B}_{\ell_2}$ covering the cascaded coupling between the different polarisations. All clusters are described in the same way, independent of the underlying physical mechanism. *This significantly reduces the computational complexity compared to fully geometric approaches.*

In addition to the reflection matrix, the mean cluster power is proportional to the inverse of the squared distance, i.e. d^{-2}, between Tx and Rx via all scatterers/reflections. The rms delay spread $\sigma^{(delay)}$ is defined to be equal for all clusters, c.f. [8]. It has to be specified as an input parameter to the model.

Stochastic Part

For the discrete components, i.e. LOS and wall reflections, all spread values are zero by definition. Thus, only a single MPC is used to model these propagation mechanisms. In the case of clusters that are due to scatterers, the MPCs are randomly distributed within the cluster. This distribution is performed in the angular domains of both link ends and in the delay domain, *independently*. Each MPC is described by two polarisations, vertical and horizontal.

In the delay domain, the MPCs within a cluster are distributed according to a Poisson process [8]. Its only parameter is the MPC arrival rate. We stop generating more MPCs when the intra-cluster delay of the last MPC is larger than $4\sigma^{(delay)}$ because of low power. Thus, the total number of MPCs is given implicitly by the Poisson process. The relative strength of a single MPC w.r.t. its cluster power is deterministically defined by the exponential power delay profile (PDP) of the cluster.

The intra-cluster DoDs, $\varphi_{\ell,k}^{(Tx)}$, and DoAs, $\varphi_{\ell,k}^{(Rx)}$, of the k-th MPC relative to the ℓ-th cluster centre (both in azimuth and elevation) are randomly generated according to a von Mises distribution [9] with zero mean. While the power of the MPCs is given by the exponential cluster PDP, the *initial phases* of all MPCs are independent random variables, which are evenly distributed over $[0, 2\pi)$. Each MPC carries four random phases and four complex amplitudes, because each MPC couples vertical and horizontal Tx polarisations to vertical and horizontal Rx polarisations.

All multipath components of a cluster are superposed *coherently*. So are the contributions from each wall reflection and the LOS component. Thus, the small scale fading is not modelled explicitly but results from the coherent superposition of all MPCs.

Antennas and Frequency Filtering

The result so far is a double-directional *propagation model* with infinite spatial and temporal resolution. In order to get system-dependent antenna signals (i.e. delay dependent *MIMO channel matrices*), we need to filter both in spatial and temporal domains.

The spatial filtering part contains, first, the different delays each MPC faces for each Tx/Rx antenna and, second, the complex antenna pattern of each antenna element. Since our model is designed for a bandwidth of up to 100MHz, delay differences between antenna elements cannot be replaced by phase shifts but have to be modelled explicitly. Additionally, the complex antenna pattern of each antenna element is applied to the MPCs to allow for *heterogeneous* antenna elements and *arbitrary* array configurations. To keep the computational effort as low as possible, we assume the DoAs (DoDs) of a MPC to be the same for all Rx (Tx) antenna elements (local clusters excepted), i.e. array dimensions are small compared to scatterer distance.

In the temporal domain all MPCs are filtered with the frequency transfer function of the considered system. This transfer function is specified by the pulse shaping at the Tx, and the band-pass filters at Rx and Tx. In addition to the filtering the channel impulse is *discretised in time and delay*, by sampling the continuous physical channel. As a result we get a set of discrete channel coefficents, which describe the frequency-selective MIMO channel in the *base band* for each time instance, delay, Tx and Rx antenna element.

Diffuse Scattering

In addition to discrete, identifiable MPCs, there exist typically a large number of MPCs that cannot be modelled discretely. We model this experimental observation by superimposing an exponentially decaying, random spatially white i.i.d. channel matrix to the channel matrix resulting from clusters and discrete components [10]. The relative power of this i.i.d. component has to be specified beforehand (between 10% in LOS and 70% in NLOS [10]). The time constant of the decay is either estimated via the room geometry and reflection coefficients or given as an input parameter that has to be fitted from measurements.

Temporal Evolution

We incorporate four effects to realise temporal evolution of the MIMO channel matrix in a given scenario.

Stationary scenario for packet access: In order to create independent channel realisations, the phases of each MPC and polarisation are randomly varied within $[0, 2\pi)$ for each realisation [11]. Also the diffuse component is created anew for each MIMO channel realisation.

Correlated phase variations according to movement/*Doppler*-shift: The mobile is assumed to be moving with a constant speed but only within a small area, such that the spatial structure of the channel does not change (virtual movement). Channel realisations are created by varying the phase of each MPC according to the Doppler-shift it faces, considering its DoD and DoA. The diffuse component of the MIMO channel is filtered with a Doppler spectrum corresponding to the velocity of the mobile.

Large-Scale Fading: To create large-scale variations, we specify a route of movement through the scenario to obtain the resulting changes in geometry, i.e. DoAs, DoDs, delays, and path loss for each MPC.

Shadowing due to moving people is implemented as additional random (or previously determined) attenuation of specific clusters.

NUMERICAL SIMULATION RESULTS

The exemplary setup is a rectangular room with reflecting walls and three scattering clusters (Fig. 3, left). The ceiling and the floor where not included in the simulation. The mobile transmitter, Tx, is positioned one meter above ground and surrounded by a local scattering cluster. It performs a virtual movement along the y-axis. The receiver, Rx, is fixed and positioned at the ceiling in the middle of the room. A centre frequency of 5GHz, a bandwith of 100MHz and an oversampling factor of 4 were simulated.

The LOS component and reflections up to second order are simulated, resulting in a total of 59 possible propagation paths: LOS (direct and via local Tx cluster), 12 specular wall reflections (direct and via local Tx cluster), 3 single cluster reflections, 6 double cluster reflections, and 24 cluster-wall reflections. Assuming a blocking probability of 40%, 31 effective clusters within a dynamic range of 50dB were randomly chosen by the simulator. These 31 effective clusters used in the simulation are also shown on the right hand side of Fig. 3. The red line depicts the LOS component, the blue lines depict the specular reflections, and the cluster reflections are shown in green. The propagation paths between the clusters are shown in purple, and the local scattering cluster is visualised by a blue circle. The combination of intra-cluster time constant (16ns) and average intra-cluster path arrival time (4ns) resulted in an average of 6 modelled multi-path components per cluster. In total, 147 MPCs were simulated.

Fig. 4 shows an exemplary instantaneous PDP. The markers visualise the delay and power of the single MPCs of all clusters. Markers of the same type (shape and color) belong to the same cluster. It can be clearly seen that the intra-cluster MPC power decays according to the exponential intra-cluster PDP. More interestingly, the PDP of the overall

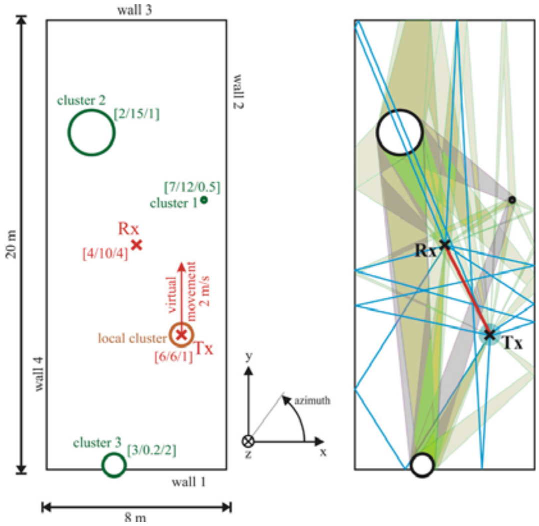

Figure 3: Room layout with physical clusters and link ends, and considered propagation paths.

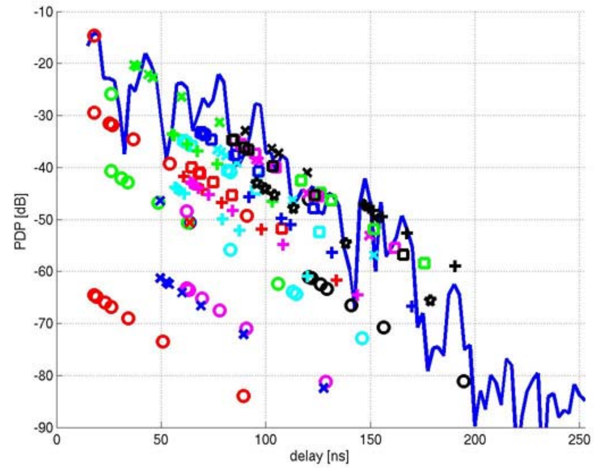

Figure 4: Exemplary instantaneous impulse response (blue line), and delay and power of all MPCs (colored markers).

channel impulse response (blue line) also shows a nearly perfect exponential shape. *This exponential shape is not a model assumption but a result of the free space loss and the reflection coefficients of the walls and scattering clusters.*

CONCLUSIONS

The proposed model is capable of modelling arbitrary three-dimensional environments, arbitrary array geometries and arbitrarily polarised antenna patterns. It describes the MIMO channel as a function of azimuth and elevation at both link ends as well as delay, and is therefore suited for modelling space-selective and frequency-selective radio channels. Furthermore, it also allows for the modelling of time-variant channels due to moving link ends. The geometry-based core of the model allows for the authentic modelling of interference situations.

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