2 Channel Modeling

M. Narandžić, A. Hong, W. Kotterman, R. S. Thomä, Ilmenau University of Technology, Germany
L. Reichardt, T. Fügen, T. Zwick, Karlsruhe Institute of Technology (KIT), Germany

In the OFDM signalling concept, the wide-band radio-communication channel is effectively utilized as a collection of narrow-band channels. Basic system parameters like the number of subcarriers N and symbol duration T are selected to mitigate the key channel impairments: Inter-Symbol-Interference (ISI) induced by frequency selectivity and loss of subcarrier orthogonality due to time selectivity [51]. Therefore, a proper channel model is required both for system design and for performance evaluation. Additionally, when Channel-State-Information (CSI) is available during system operation, transmission characteristics, such as the signal constellation or the allocated power, could be adaptively adjusted at transmitter per subcarrier in order to maximize total throughput. Further improvements of the spectral efficiency could be obtained by simultaneous transmission and/or reception from/by multiple antenna elements. Additionally to time and frequency, this concept known as MIMO (*Multiple-Input-Multiple-Output*) exploits the spatial propagation dimension or, more specific, multiplicity of energy propagation paths. Since the reachable spectral efficiency is tightly related to the signal correlation across the antenna array [15], the proper representation of correlation levels becomes essential for the analysis of MIMO systems. In order to obtain an antenna-independent representation of the channel that implicitly comprises correlation properties, *geometry-based* models are generally used.

In this chapter, the necessary concepts for representation of the multidimensional radio-channel are summarized. Data collected during multidimensional channel sounding and post-processed by high-resolution parameter estimation algorithms offer the most detailed insight into radio-propagation mechanisms. In that way, joint space-time-frequency representations being consistent with measurements can be obtained (Section 2.1). On the other hand, when an appropriate description of the EM environment is available (in the form of databases defining geometry and material properties), the EM field could be predicted by use of the Geometrical or Uniform Theory of Diffraction (GTD/UTD), as explained in Section 2.2. Note that for tuning and verification of ray tracing/launching procedures, sounding experiments are still required. For system design and performance evaluation, site-independent modeling with lower complexity is preferred. For this purpose, stochastic characterization of different radio-environment classes could be combined with geometry based propagation aspects. This results in the class of *Geometry-based Stochastic* (GbS) channel models that are described in Section 2.3. In order to properly reproduce space-time channel evolution, this class of empirical models uses stochastic characterization of

H. Rohling (ed.), *OFDM*: *Concepts for Future Communication Systems*,
Signals and Communication Technology, DOI: 10.1007/978-3-642-17496-4_2,

Large-Scale Parameters (LSPs) as explained in Subsection 2.3.1. The radio channels corresponding to specific propagation/deployment scenarios are given as examples of listed general modeling classes. The characteristics of a radio-link that is established between vehicle and stationary or moving objects, analyzed by ray-tracing tools, are presented in Subsection 2.2.2. Subsection 2.3.2 introduces GbS model for relay-links, based on a stochastic representation of channel LSPs. Specific aspects of spatially-distributed transmission corresponding to cooperative downlink are given in Subsection 2.3.3. Due to some inherent weaknesses regarding the representation of spatio-temporal evolution, so called *analytical* models were not considered.

2.1 Joint Space-Time-Frequency Representation

The multidimensional channel transfer function can be equivalently expressed using the system functions [4] in either *faded domains* ($\mathbf{r}$-space, t-time, f-frequency) or *resolved domains* ($\boldsymbol{\Omega}$-directions, ν-Doppler shift, τ-delay) [27]. The physical models being discussed here only use resolved domains for channel analysis and synthesis, equivalent to characterization by constituent Multi-Path-Components (MPCs). Then, the point-to-point propagation channel (i.e. link) is represented as an antenna response to a set of MPCs (usually conveniently grouped into *clusters* [9], [20]):

$$H(\mathbf{r}_{Tx}, \mathbf{r}_{Rx}, t, f) = \sum_i \mathbf{F}_{Tx}^T(\Omega_i^{Tx})\boldsymbol{\alpha}_i \mathbf{F}_{Rx}(\Omega_i^{Rx}) e^{j2\pi(\tau_i f + \nu_i t)}. \tag{2.1}$$

Interaction between antennas and MPCs is through the complex, polarimetic antenna response

$$\mathbf{F}_{\mathbf{r}}(\Omega) = [F_\theta(\Omega) F_\varphi(\Omega)]^T \cdot e^{j\mathbf{k}(\Omega)(\mathbf{r}-\mathbf{r_0})}, \tag{2.2}$$

where F_θ and F_φ represent projections onto corresponding unitary vectors of the spherical coordinate system. The exponential term in (2.2) defines the phase shift of MPCs coming from direction Ω w.r.t. the phase center at $\mathbf{r_0}$. The given representation covers all spatial degrees of freedom: transversal movement and antenna rotation, as well as any array geometry for the MIMO case. A single MPC corresponds to a homogeneous plane wave that within narrow frequency bandwidth can be characterized by the following parameters:

$$\mathbf{p} = [\Omega^{Tx}, \Omega^{Rx}, \boldsymbol{\alpha}, \tau, \nu], \tag{2.3}$$

where $\boldsymbol{\Omega}_T$ and $\boldsymbol{\Omega}_R$ describe Directions-of-Departure (DoD) and Arrival (DoA), respectively. Due to the inability (in the general case) to represent the Power-Directional-Spectrum as a product of marginal spectra on departure and arrival, joint characterization of DoD and DoA is to be used - as suggested by the *double-directional* modeling concept [50], [38]. The complex 2-by-2 matrix $\boldsymbol{\alpha} \in \mathcal{C}^{2\times 2}$ is used to jointly describe MPC magnitude, MPC phase, and cross-polarization effects.

The necessary parameters, normally for a large number of MPCs, could be estimated from appropriate multidimensional channel sounding data. These data are gathered during wide-band measurement experiments with specially designed antenna arrays and real-time channel sounding devices [49], [26], [7], [8].

2.1.1 Multidimensional Channel Sounding

In a broader sense, multidimensional sounding comprises investigations into the spatio-temporal structure of a radio channel, aiming to resolve not only the temporal delay of incoming waves (signal components) but also their angular directions at transmission and at reception as well as their polarizations. Especially the combination of angular resolution and polarimetric state is potentially very costly and laborious to record and process at its full extent. Many antenna elements are necessary for high-resolution results, both to fully cover the angular domain and to create the required apertures. Providing coverage in a particular direction demands that antenna elements still have sufficient sensitivity in that direction. Aperture, required for resolution, means that (sensitive) elements are to be spread over space. A popular shortcut like using single-polarized antenna elements leads to biased results [32]. Additionally, for accurate parameter estimation, calibration of every antenna element in the measurement array is mandatory, providing complex radiation pattern $\mathbf{F}_\mathbf{r}(\Omega)$ of (2.2), required to estimate parameters of resolved MPCs in (2.1), in order to relate these to observed faded dimensions. Restricting Ω to the azimuthal cut, another popular saving, also means to risk grossly distorted estimates [32].

Characterization of propagation delay requires nearly instantaneous measurements, meaning the time needed for a measurement over bandwidth or over the full delay span should be considerably shorter than the time it takes the channel to change. Pseudo-random noise sequences, multi-sine tone bursts, or fast frequency-sweeps can be used, each with its own advantages and disadvantages. If the repetition rate is high enough, also the Doppler spectrum or time variability can be determined without aliasing. The temporal and spatial dimension have to be measured jointly, but measuring all antenna elements simultaneously and all transmit-receive combinations in parallel is deemed technically infeasible (exception: the 16×4 parallel sounding in [41]). Therefore, the antenna combinations are multiplexed, making use of one and the same temporal sounding unit. The multiplexing units themselves are still a technical challenge, due to requirements on switching speed, damping losses, feed-through, frequency transfer, delay, and power handling (especially on the transmit side). Seen these imperfections, the multiplexing units should be calibrated too. Synchronization of transmit and receive side, which are often too far apart for synchronization through a cable connection, requires two free-running clocks of very high stability; typically Rubidium or Cesium standards.

So, what is needed? A dedicated channel sounder with calibrated dedicated multiplexing equipment both at transmit and receive side, calibrated dedicated antennas, stable (atomic) clocks, and a high-speed data logger. As an example for the latter, the COST2100 urban reference scenario “Ilmenau” had to be measured at a modest trawling speed of 3 m/s, in order not to exceed the maximum sustained data transfer rate of 1.2 Gbit/s, the product of snapshot rate, number of transmit-receive combinations, impulse response length, and number of bits per time sample [48].

2.1.2 Extraction of Parameters for Dominant MPCs

The estimation procedure of MPC parameters from channel sounding data requires the use of so called *high-resolution algorithms* , like, e.g., Maximum Likelihood

Estimation [60], ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques) [44], [52], SAGE (Space-Alternating Generalized Expectation-maximization) [14], or RIMAX [53], [46], [32]. An alternative to measurements is the extraction of model parameters by means of ray tracing (Section 2.2).

Both methods could provide reliable (reality matching) parameters for only a limited number of MPCs: the measurement-based estimation due to the limited number of space-time-frequency observations [46] and the limited precision of antenna calibration [32], and ray-tracing due to the limited precision of the radio-environment model. The remaining part, usually associated with diffuse scattering, is typically characterized by stochastic means both during parameter estimation [46], [32] and ray generation [10].

2.2 Deterministic Modeling

Deterministic models are used for site-specific channel modeling; they consist of an environment model and a wave propagation model. The environment model describes position, geometry, material composition and surface properties of the wave propagation relevant objects and obstacles (e.g. trees, houses, vehicles, walls, etc.). The well-known Maxwell equations [3] always form the basis for all investigations of electromagnetic fields. In practical applications an analytic solution of the Maxwell equations, due to the computation time, is not possible. Also numeric approximation methods, like, e.g., the Parabolic Equation Method (PEM) or the Finite Difference Time Domain Method (FDTD) [21], [57], [59] fail for efficiency reasons with problems, which are larger than some wavelengths in the examined frequency range. Substantially less complexity and computing time is achievable with geometric-optical models [30], [5], [56], [2], [25], [35], [17], [16]. These models are based on iterated approaches, which use the border behavior of electromagnetic fields for high frequencies [37]. The use of these procedures makes substantial simplifications of the description of the wave propagation possible. This allows to compute electrically very large problems very efficient and exactly.

2.2.1 Relevant GTD/UTD Aspects

The modern geometrical optics (GO) is an important representative of these iterated procedures, and it forms the basis for the uniform geometrical theory of diffraction (UTD). The validity of the GO does not alone depend on the frequency. A further condition is, that the scattering objects contained in the propagation vicinity are large in relation to the wavelength. Additionally the surface texture is not allowed to change over a wavelength. Further the material properties of the propagation medium must be constant within the range of a wavelength [37]. This is fulfilled in good approximation for frequencies above 1 GHz.

Due to its flexibility and accuracy geometric-optical models are already today in use. They are able to calculate, a place-dependent prognosis of the full-polarimetric field strength and/or receiving power in the regarded propagation area. Besides this a complete narrow- and wide-band description of the mobile channel is possible, why they find increased use in system simulations [12], [36].

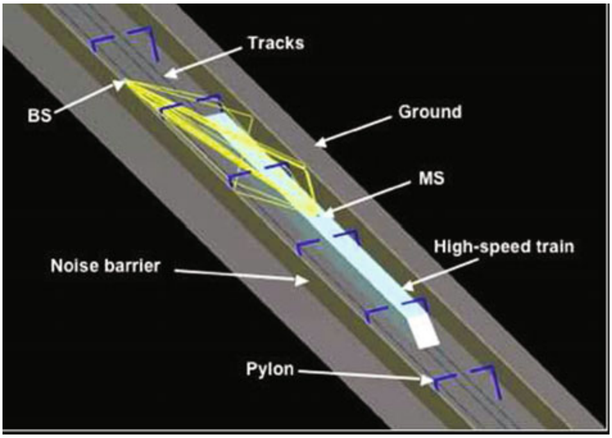


Figure 2.1: With Ray-tracing calculated wave propagation in a high-speed train scenario [29].

2.2.2 Vechicle2X Channel Modeling

The realistic channel representation at *very high participant velocities* in combination with high data rate transmission and MIMO-OFDM techniques can be obtained by a ray-optical description of the multi-path propagation. In the context of the key program *TakeOFDM* of the Deutsche Forschungsgesellschaft (DFG) such a channel model for high-speed train communication was developed (Fig. 2.1) [29]. A detailed description of the vehicle's vicinity is essential for a proper modeling of the wave propagation. This includes the track, on which the vehicles are driving, and the environment adjacent to the track. E.g. in the surrounding of train tracks possible objects are noise barriers, trees, signs, bridges, and pylons, whereas in urban or suburban areas buildings are more probable. A new map generator has been developed for this ray-tracing simulator. With this, it is possible to import standard CAD (Computer Aided Design) data with the STL (Standard Triangulation Language) format. In the map generator the electrical parameters like the permittivity ϵ_r, permeability μ_r and the standard deviation of the surface roughness σ are assigned to the objects and it is possible to shift, scale or rotate them. Furthermore it is possible to define velocities for the objects to create a time series of snapshots of the scenario to simulate the time-variant behavior of the channel. For the channel simulations each object can be equipped with a receiver and a transmitter. The position of the corresponding antennas as well as the antenna pattern and orientation can be chosen arbitrarily. An accurate description of the multi-path wave propagation in the aforementioned scenarios is required to produce realistic time series of Channel Impulse Responses (CIRs).

At the Institut für Hochfrequenztechnik und Elektronik a three-dimensional ray-tracing algorithm has been developed and implemented [36]. The results of the applied ray tracing algorithms have been verified by measurements in different sce-

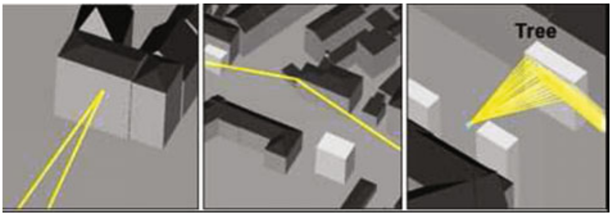


Figure 2.2: Considered multi-path effects: reflection (left), diffraction (middle), and scattering (right).

narios and have shown to reach a very high accuracy [18], [29]. Ray-optics are based on the assumption, that the wavelength is small compared to the dimensions of the modeled objects in the simulation scenario. If this is the case, different multi-path components, characterized by different types of propagation phenomena (e.g. reflection, diffraction, scattering (Fig. 2.2)), can be considered. Each multi-path is represented by a ray, which may consecutively experience several different propagation phenomena. As propagation phenomena multiple reflections, multiple diffractions and single scattering are taken into account. Mixed propagation paths containing reflections and diffractions are possible as well. The modified Fresnel reflection coefficients, which account for slightly rough surfaces, are used to model the reflections. Diffractions are described by the Uniform Theory of Diffraction (UTD) and the corresponding coefficients for wedge diffraction. To describe scattering, e.g., from trees, the surface of scattering objects is subdivided into small squared tiles. Depending on the energy, which is incident on the surface of the objects, each tile gives rise to a Lambertian scattering source. The adjustment of ray-optical models to the reality takes place via the exact modeling of the environment and the physical wave propagation. This means that measurements are not needed for the alignment of model parameters but only for the verification of the model. Investigations for the accuracy of deterministic channel models are subject of numerous publications [30], [28], [24], [11], [33], [2], [45], [47], [36], [29].

A realistic evaluation of the behavior of a communication system is however only possible if a multiplicity of spatial scanning points are used in the system simulation. Due to the complexity of geometric-optical models a substantial computing and expenditure time must be taken into account. The main advantage in contrast to other channel models is that spatially-colored multi-user interference, one of the most limiting factors for the achievable performance in multi-user MIMO-systems, is inherently considered [19].

2.3 Stochastic Driving of Multi-Path Model

When designing a wireless transmission system, it is useful to evaluate its performance over at least a minimum number of channel realizations. These could be generated by deterministic propagation models described in the previous section, however, their high computational complexity prohibits the intensive link or system level simulations required during system design. Thus, procedures with a lower computational complexity that could emulate a whole class of radio-propagation environments (i.e. *propagation scenario*) are preferred. These requirements have led to the *Geometry-based Stochastic* (GbS) channel models where generated multi-path components are not directly related to any particular (or very detailed) radio-environment. Instead, the channel realizations are determined as realizations of a multidimensional random process that characterizes all aspect of physical plane-wave propagation.

The stochastic generation of multipath can be done in several different forms. We would distinguish two classes according to the use of the scattering (or interacting) objects during the physical model synthesis. E.g. it is possible to place *interacting objects* in a 2D/3D coordinating system, and to perform their abstraction in the form of multipath clusters as in the COST 273 model [8]. By assigning *visibility regions* [1] to each of the clusters, a simplified ray-tracing engine is obtained. The randomness in this approach is attained by random selection of visibility regions and the intra-cluster structure. An alternative would be to fully remove scatterers from the model synthesis. In this case multipath components are no longer related to particular scatterers, but are generated in the so called *parametric domain* instead. This term relates to the parameters of multipath components as given by (2.3). Typical representatives are the 3GPP Spatial-Channel-Model [54], the channel model developed in the WINNER project [31], and the reference model for evaluation of IMT-Advanced radio interface technologies [34].

2.3.1 Usage of the Large-Scale Parameters for Channel Characterization

The consequence of the environment abstraction introduced by parametric domain synthesis is that the evolution of a space-time model can not be implicitly given by relative distances of scattering objects. Instead, the channel dynamic is represented by correlated realizations (over space-time) of so called *Large-Scale Parameters* (LSPs). The term LSPs is used to denote a group of channel parameters that typically experience notable change only over distances exceeding several wavelengths. The relative MPC positions in parametric space (2.3) define the *MPC structure* , that can be described by the power distribution over resolved channel dimensions. Since (dis)appearance of a small portion of MPCs have minor effect on the marginal (e.g. delay and directional) spread parameters, they could be exploited for abstraction of large-scale channel behavior. The main role of the LSPs is, therefore, to describe the joint distribution of the MPC power over different domains (direction, polarization, delay, Doppler, etc.) as observed at the same instant and additionally to describe space-time channel evolution. The set of relevant LSPs established within the SCM/WINNER models is listed in Table 2.1[1].

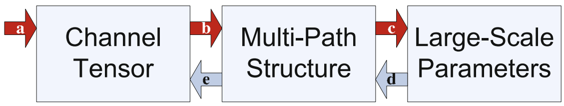
Using the concept of correlated random LSPs it is easy to repeat stochastic properties of parameters being observed during channel sounding and therefore this enables the straightforward scenario-based representation. By performing the measurement

[1]Please, note that the Doppler shift is not explicitly parametrized, but for a given velocity vector it will be implicitly determined by the directions of departure and arrival

Table 2.1: Large-Scale Parameters of SCM/WINNER model.

LSP Name	Acronym	Power distribution...
Shadow Fading	SF	around mean transmission loss
Delay Spread	DS	over delay domain
Directional (Angular) Spread	AS	over angular domain: - at departure and arrival - over azimuth and elevation
Narrowband K-factor	K	btw. LoS and NLoS clusters
Cross polarization Ratio	XPR	btw. co- and cross-polar MPCs

experiment with particular antenna deployment in a given scenario it is possible to define empirical multipath model. This process is illustrated in Fig. 2.3.



a Multidimensional channel sounding,

b High-resolution estimation of joint MPC parameters,

c Statistic characterization of LSPs and their space-time dependencies,

d Guided random positioning of MPC in parameter space, according to random realization of multivariate LSP process,

e Determination of antenna array response to given multi-path structure.

Figure 2.3: Generation of empirical, scenario-based multipath channel model

LSPs Viewed as Correlated Multivariate Random Process

General methods for generation of random variables (RVs) with targeted first-order (i.e. probability distribution) and second-order (auto-correlation over time) statistics have been suggested in literature [6], [13]. These methods reproduce statistical behavior of a random process w.r.t. its realization over time, by using a transformation of the Gaussian autoregressive process. In order to avoid complex matching of correlations between original and transformed domain the LSPs are first mapped into new variables (*transformed LSPs*) having Gaussian distributions and the subsequent analysis of LSP inter-dependence is performed in transformed domain [54], [31]. For LSP P_i with cumulative distribution function (cdf) F_i, the necessary mapping[2] could be determined in the form of $P_i = F_i^{-1}(\Phi(Q_i))$, where Q_i designates the transformed

[2]The solution of an inverse problem, [43]

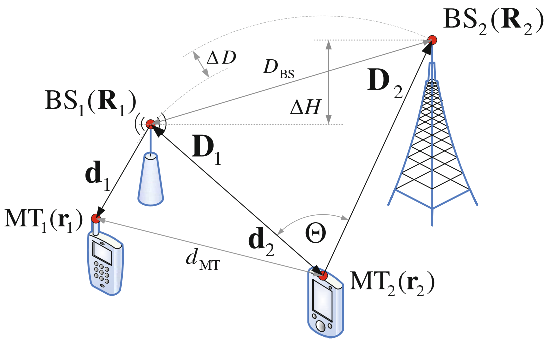


Figure 2.4: System layout defined by positions of communication terminals.

LSP with normal cdf Φ. Using a linear transformation

$$\boldsymbol{Q} = \boldsymbol{C}\boldsymbol{\xi} + \boldsymbol{b} \tag{2.4}$$

of the standard multivariate normal process $\boldsymbol{\xi}$ with distribution $\mathcal{N}_{\xi}(\mathbf{0}_{M\times 1}, \mathbf{I}_{M\times M})$ a process $\mathbf{Q} = [Q_1, Q_2, \ldots, Q_M]^T$ with the targeted covariance matrix $\mathbf{CC^T}$ could be easily reproduced.

Dependence of Covariance Matrix on System Layout

The channel model of a system with K coexisting links should generate $K \cdot M$ correlated LSPs, where M is the number of LSP's per each link. The corresponding full covariance matrix $\mathbf{CC^T}$ would have, for each time instant, size $M \cdot K \times M \cdot K$. This matrix characterizes the correlations between all LSPs describing all coexisting links, however its proper synthesis is not trivial due to strong dependence upon the system layout. The problem can be addressed by proper decomposition of the transformation matrix, $\mathbf{C}$, according to *link-level*[3] and *layout-level* correlations . The link-level correlations correspond to cross-correlations of the LSPs characterizing the same link, and according to the proposed simplification they will not change over space-time. On the other hand, the layout-level correlations explicitly depend on the relative position of the terminals at both link ends. Depending on at which link's end a terminal displacement occurs, it is possible to distinguish *intra-site* and *inter-site* correlations (Fig. 2.4). Since two different links with single common end could not simultaneously exhibit both correlation types, the intra-site ($\mathbf{R}_i = \mathbf{R}_j$) and inter-site ($\mathbf{r}_i = \mathbf{r}_j$) correlations could be conveniently combined for given system layout. These correlations are typically expressed in the form of layout-dependent correlation coefficient $\rho_{XY}(\mathbf{L}) = \frac{\sigma_{XY}}{\sqrt{\sigma_{XX}\sigma_{YY}}}$, where $\sigma_{XY} = E[(X - E[X])(Y - E[Y])]$ denotes covariance between LSPs X and Y. The geometry parameters $\mathbf{L}$ are determined from the vectors defining the relative position of mobile terminals $(\mathbf{d}_i, \mathbf{d}_j) = (\mathbf{r}_i -$

[3] A single link realization, when compared to itself, could be considered as a special case in system layout, where there is neither displacement of the mobile terminal nor of the base station.

$\mathbf{R}, \mathbf{r}_j - \mathbf{R}$) or base stations $(\mathbf{D}_i, \mathbf{D}_j) = (\mathbf{R}_i - \mathbf{r}, \mathbf{R}_j - \mathbf{r})$ w.r.t. to single common position (Fig. 2.4). The set of relevant parameters $\mathbf{L}$ for intra-site correlations could be reduced to Euclidean distance between mobile terminals $d_{\mathrm{MT}} = ||\mathbf{r}_i - \mathbf{r}_j||$ [31]. The characterization of inter-site correlations , however, requires a more complex parameter space $\mathbf{L} = [\Theta, \Delta D, D_{\mathrm{BS}}, \Delta H]^T$ [40] being defined at Fig. 2.4.

2.3.2 Relaying

In wireless communication systems, the nodes with a relaying capability are integrated into conventional networks in order to provide a ubiquitous coverage with high data rates, especially in the areas with a high shadowing [42]. In relay networks, intermediate Relay-Stations (RSs) are introduced into the communication between a base station and a mobile terminal. If station labeled as BS_1 has relay functionality, than the Fig. 2.4 can be interpreted as an example of the basic three-station structured relay network [55]. The purpose of intermediate RS (BS_1) would be to forward received signals from BS_2 toward mobile terminal MT_1, and vice versa [58]. The introduction of intermediate RSs results in a meshed topology of relay networks, and brings new challenges in channel modeling. Moreover, characterizing and modeling of the relationship between meshed links, is one of the most crucial points in the channel modeling of relay networks . The correlation properties between meshed links can be captured in the form of the intra- and inter-site correlations of large scale parameters [22], as discussed in previous subsection. The observed correlation properties for relay measurements in Ilmenau inner city, could be summarized as follows [23]:

1. The de-correlation distance (used to characterize intra-site correlations) of SF, DS as well as XPR decrease with a reduced BS height. This confirms that even the intra-site correlation could exhibit more complex layout dependence.

2. The inter-site correlation of LSPs is high when two BSs/RSs are near to each other but a MT is far away from both.

3. The larger the difference in the height of two BSs/RSs, the lower the inter-site correlation.

4. The inter-site correlation decreases for larger angular separation of BSs, Θ. Figure 2.5 shows the experimental results for inter-site correlation coefficient of XPR. Note, that measured correlation does not decrease monotonically neither with angular nor distance separation ΔD.

2.3.3 Cooperative Downlink

One of the main goals behind the physical modeling is to make the channel representation as independent from the system aspects as possible. However, when characterizing the cooperative downlink (e.g. $(-\mathbf{D}_1, -\mathbf{D}_2)$ from Fig. 2.4) it is not possible to disregard the influence of the receiver's limited dynamic range on *perceived* LSPs of the cooperative links [39]. Namely, the perception of power spreading expressed

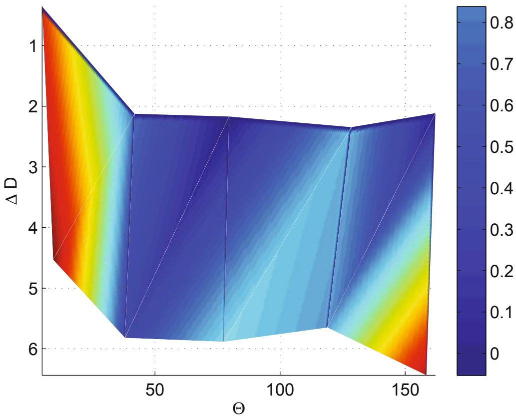


Figure 2.5: Dependence of XPR correlation coefficient from network layout parameters, $\rho(\varTheta, \varDelta D)$.

by DS or AS depends on the effective dynamic range of the particular radio-link, as shown in Fig. 2.6. Consequently, the characterization of inter-site correlations between cooperative links requires previous adjustment of effective dynamic ranges[4]. These will depend on the total power received from all cooperative links, and in general they will be lower for the weaker links. If *peak power level differences*, $\varDelta P$ are statistically characterized for particular multi-link configurations and targeted scenario, they can be included into model as an additional LSP [39]. During model synthesis the randomly generated values of $\varDelta P$ will define the effective dynamic ranges, and the parameters of spread-related LSP distributions should be modified accordingly.

One of the implications of *receiver perceived* channel representation is that reciprocity (normally assumed in channel modeling) will not be preserved. In a mesh network, the link between two communication sinks, each having other spatially distributed links too, will be experienced differently by the two sinks because of the unequal influence of the additional (distributed) links at both sides.

[4]When measured separately each link will be characterized according to the dynamic range of the measurement equipment, what is not relevant for reception of simultaneous signals.

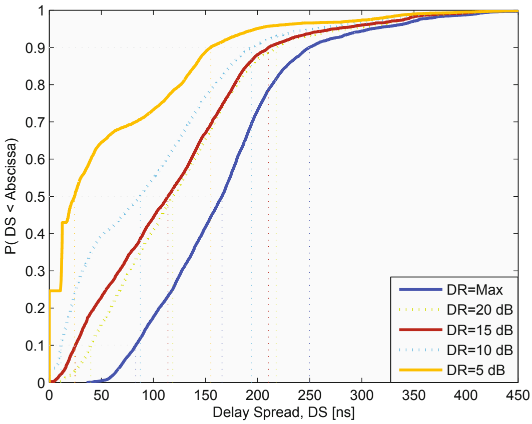


Figure 2.6: Dependence of DS empirical distribution from effective Dynamic-Range (DR).

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OFDM
Concepts for Future Communication Systems
Rohling, H. (Ed.)
2011, XIV, 254 p., Hardcover
ISBN: 978-3-642-17495-7