DEVELOPMENT OF MULTI-LINK GEOMETRY-BASED MIMO CHANNEL MODEL

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### Abstract:

Forthcoming wireless communication systems need larger capacity. MIMO systems are already an answer that enables to achieve large increase to the link capacity. However, a wide and precise knowledge of the radio propagation channel is required in order to exploit the many benefits and capabilities of MIMO systems.

In this master’s thesis a multi-link geometry-based MIMO channel model was developed. This work analyses the effect of common clusters on multi-link MIMO capacity and inter-link correlation based on simulation studies. Furthermore, the basics on radio wave propagation and MIMO systems as well as a review on existing MIMO channel models are also provided.

Finally simulation results revealed that, in general, common clusters increase the inter-link correlation, and so the ML-MIMO capacity decrease. But sometimes cluster geometry together with array geometry fully determines the MIMO system performance independently of the significance of common clusters. In addition, it was shown how often the overall system performance is degraded. Finally, it was also investigated that a common cluster which is really significant for only one link is not in fact a common cluster.

### Keywords: MIMO, common cluster, dual-link capacity, inter-link correlation, geometry-based channel model, Multi-Link channel modeling, propagation channel.
Preface

This master’s thesis study has been carried out in Aalto University School of Science and Technology, Finland. This work is a small contribution of the WILATI+ project which is being performed between three Scandinavian universities together with the NORDITE research program.

First of all, I would like to thank Professor Pertti Vainikainen together with Dr. Tommi Laitinen, the supervisors of this thesis, for their help and attention in several issues.

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Last but not least, warms thanks to my family because without their endless support, I would never have finished my studies. Especially, thanks for giving me love and understanding during these years.

Otaniemi, July 24th, 2010

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<tr>
<td>AoA</td>
<td>Azimuth of Arrival</td>
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<tr>
<td>AoD</td>
<td>Azimuth of Departure</td>
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<tr>
<td>AP</td>
<td>Access Point</td>
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<tr>
<td>BS</td>
<td>Base Station</td>
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<td>BS1</td>
<td>Base Station number 1</td>
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<tr>
<td>BS2</td>
<td>Base Station number 2</td>
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<td>CAS</td>
<td>Cluster Angular Spread</td>
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<td>CDF</td>
<td>Cumulative Distribution Function</td>
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<td>CDS</td>
<td>Cluster Delay Spread</td>
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<tr>
<td>CIR</td>
<td>Channel Impulse Response</td>
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<td>COST</td>
<td>European Cooperation in Science and Technology</td>
</tr>
<tr>
<td>DoA</td>
<td>Direction of Arrival</td>
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<tr>
<td>DoD</td>
<td>Direction of Departure</td>
</tr>
<tr>
<td>EoA</td>
<td>Elevation of Arrival</td>
</tr>
<tr>
<td>EoD</td>
<td>Elevation of Departure</td>
</tr>
<tr>
<td>GSCM</td>
<td>Geometry-based Stochastic Channel Model</td>
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<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>INR</td>
<td>Interference to Noise Ratio</td>
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<tr>
<td>MC</td>
<td>Matrix Collinearity</td>
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<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
</tr>
<tr>
<td>ML-MIMO</td>
<td>Multi-Link Multiple Input Multiple Output</td>
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<tr>
<td>MoM</td>
<td>Method of Moments</td>
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<td>MPC</td>
<td>Multipath Component</td>
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<tr>
<td>MS</td>
<td>Mobile Station</td>
</tr>
<tr>
<td>NLOS</td>
<td>Non-Line-Of-Sight</td>
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<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LOS</td>
<td>Line-Of-Sight</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>---------</td>
<td>--------------------------------------------------</td>
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<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
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<td>PDF</td>
<td>Probability Distribution Function</td>
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<td>PDP</td>
<td>Power Delay Profile</td>
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<tr>
<td>RC</td>
<td>Relative Capacity</td>
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<td>RMS</td>
<td>Root Mean Square</td>
</tr>
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<td>RT</td>
<td>Ray Tracing</td>
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<tr>
<td>RX</td>
<td>Receiver</td>
</tr>
<tr>
<td>SIR</td>
<td>Signal to Interference Ratio</td>
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<tr>
<td>SISO</td>
<td>Single Input Single Output</td>
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<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<tr>
<td>SUI</td>
<td>Stanford University Interim</td>
</tr>
<tr>
<td>TX</td>
<td>Transmitter</td>
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<tr>
<td>VR</td>
<td>Visibility Region</td>
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<tr>
<td>WINNER</td>
<td>Wireless World Initiative New Radio</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
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List of Symbols

\( f \) \quad \text{carrier frequency}
\( \lambda \) \quad \text{wavelength}
\( \rho \) \quad \text{signal to noise ratio}
\( \eta \) \quad \text{interference to noise ratio}
\( \phi_l \) \quad \text{direction of departure of the } l\text{-th MPC}
\( \psi_l \) \quad \text{direction of arrival of the } l\text{-th MPC}
\( \tau_l \) \quad \text{propagation delay of the } l\text{-th MPC}
\( \beta_l \) \quad \text{complex amplitude of the } l\text{-th MPC}
\( \beta_{np} \) \quad \text{complex amplitude of the } p\text{-th MPC in the } n\text{-th cluster}
\( \mu^{(i)}_{\text{common}} \) \quad \text{common cluster power ratio for the } i\text{-th link}
\( \Omega^{\text{BS}}, \Omega^{\text{MS}} \) \quad \text{azimuth and elevation of departure, and azimuth and elevation of arrival}
\( \phi_{l}^{\text{Tx}}, \phi_{l}^{\text{Rx}} \) \quad \text{azimuth angle of departure and arrival for the } l\text{-th MPC}
\( \theta_{l}^{\text{Tx}}, \theta_{l}^{\text{Rx}} \) \quad \text{elevation angle of departure and arrival for the } l\text{-th MPC}
\( C(\mathbf{H}_i) \) \quad \text{single-link MIMO channel capacity}
\( C(\mathbf{H}_i, \mathbf{H}_j) \) \quad \text{dual-link MIMO channel capacity between the } i\text{-th desired link and the } j\text{-th interfering link}
\( d \) \quad \text{distance between cluster centers}
\( d_l \) \quad \text{distance between TX-RX for the } l\text{-th MPC}
\( d_a \) \quad \text{distance between antenna elements in linear arrays}
\( G_T, G_R \) \quad \text{antenna gain in transmission and reception}
\( h(t, \tau) \) \quad \text{impulse response of the channel}
\( h_{i,j} \) \quad \text{impulse response of the channel between the } i\text{-th RX antenna and the } j\text{-th TX antenna}
Development of multi-link geometry-based MIMO channel model

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$h_{i,j}^{VV}, h_{i,j}^{VH}, h_{i,j}^{HV}, h_{i,j}^{HH}$ polarization channel impulse response

$H(t, f)$ MIMO channel transfer function

$H_{i,j}$ sub-matrix of the $H_{ML}$ denoting the MIMO link between the $i$-th BS and the $j$-th user

$H_{ML}$ multi-link MIMO channel matrix

$H_{pol}$ polarimetric MIMO channel matrix

$\hat{H}_i$ normalized MIMO channel matrix for the $i$-th link

$H_i(s)$ channel matrix for the $i$-th link and $s$-th realization

$\hat{H}_i(s)$ normalized channel matrix for the $i$-th link and $s$-th realization

$I_{R_N} \Lambda$ identity matrix of size $N_R$

$L_P$ propagation losses

$L$ number of MPCs

$MC(R^{(i)}, R^{(j)})$ matrix collinearity between the correlation matrices of the $i$-th link and the $j$-th link

$N(t)$ number of MPCs in the instant time $t$

$N_s$ number of channel realizations

$N_T$ number of TX antennas

$N_R$ number of RX antennas

$N_{\text{common}}$ number of active common clusters

$N_{\text{tot}}$ total number of common clusters

$P_R, P_T$ received and transmitted power

$p_{\text{common}}$ probability of common clusters

$p_{\text{common}}^{(i)}$ power of common cluster for the $i$-th link

$p_{\text{common}}^{(i), n}(k)$ power of the $n$-th common cluster for the $i$-th link in the $k$ measurement time

$p_{\text{tot}}^{(i), n}(k)$ total power of the $i$-th link in the $k$ measurement time
Development of multi-link geometry-based MIMO channel model

$P_{\text{tot}}^{(i)}$ total power for the $i$-th link

$PS_i$ phase shift for the $i$-th MPC

$R_i$ instantaneous covariance matrix for the $i$-th link

$R^{(i)}$ TX correlation matrix for the $i$-th link

$RC[\%]$ relative capacity

$r_{\text{life}}^{(i)}$ lifetime of common cluster for the $i$-th link

$r_{\text{dis}}$ disjoint distance

$S_{\text{common},k}(k)$ total significance of common clusters in the $k$ measurement time

$S_{\text{common},n}(k)$ significance for the $n$-th common cluster in the $k$ measurement time

$s_{\text{common},i,n}(k)$ significance of the $n$-th common cluster for the $i$-th link in the $k$ measurement time

$s$ distance between the MS and cluster center
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1 INTRODUCTION

Within last decade, radio communication systems have been constantly demanding higher speed data rates. For developing more efficient systems the radio propagation channel must be widely investigated. To that end, Multiple Input Multiple Output (MIMO) systems are a promising solution to improve the system performance of wireless communication systems.

During the last ten years the MIMO technology has been investigated in detail and theoretically, the use of MIMO in wireless systems involves many benefits that can provide enormous capacity gains. This fact led to consider and include MIMO technology in the recent released IEEE 802.11n standard for WLANs. Since then, MIMO technology has opened its own way towards actual and commercial products for the WLAN market. As the MIMO technology has become more common and popular, it is probable that in the future other wireless access networks will adopt also this technology.

Nevertheless, WLAN is a constantly growing market that during the last few years has become more and more popular as a need of this society. Nowadays, this kind of wireless networks can be found in many places, also known as hotspots, e.g. libraries, hotels, restaurants, cafeterias, airports, universities, schools, and so forth. These hotspots in general require the deployment of several base stations to cover a wide area. Here arises the importance of considering multi-link scenarios for future research. Hence, modeling MIMO propagations channels in multi-link scenarios is absolutely necessary.

Previous research about MIMO channel modeling has been mainly focused on single-link studies. To date, only few studies have been reported in multi-link scenarios. Modeling multi-link scenarios enables to model and study the correlation between different links that in turn affects the performance of wireless communications systems. Firstly, this work aims to develop a simple multi-link geometry-based MIMO channel
model with conceptual modeling of one of the physical phenomena that determine the correlation between different links, that is, common clusters. Secondly, the goal of this thesis relies on investigating the effect of these common clusters on multi-link MIMO (ML-MIMO) system performance.

This thesis is organized in several chapters as follows. In Chapter 2 a quick review of the needed propagation basics and MIMO systems is presented together with a literature review on the existing MIMO channel models. In Chapter 3 motivation in the area of multi-link MIMO channel modeling and recent works in this field are presented together with a description of the multi-link geometry-based MIMO channel model developed in this thesis. In Chapter 4 some simulation results are shown. Finally, conclusions are given in Chapter 5.
2 MIMO CHANNEL MODELING

Only recently, MIMO technology has been taken into practical use. The characteristics of the entire MIMO system are fully determined by the radio propagation channel and it has not been largely tested under realistic propagation conditions. Hence, understanding the propagation phenomena occurring in MIMO channels through easy-to-use methods instead of extensive measurement campaigns has attracted much attention. This fact has led to the development of channel models for wireless MIMO systems in the most accurately manner. Hence, channel modeling has become an important prerequisite in MIMO system development, simulation and deployment. Since then, a variety of MIMO channels models have been performed within the last decade.

This chapter is organized in the following way. In Section 2.1 a quick review of propagation basics together with some information on MIMO systems in Section 2.2 is first presented; after a classification (See Figure 4) and a brief description of MIMO channel and propagation models is provided in Section 2.3 and Section 2.4. Finally, some MIMO channel models that are used within current wireless standardization activities are presented in Section 2.5.

2.1 Propagation principles

Generally, the mechanisms that determine the radio wave propagation and the received signal levels depend on the wavelength, distance and obstacles between the transmitter (TX) and the receiver (RX), interacting objects where the waves bounce, dimension and composition of the objects, and so forth. In the context of this thesis, signal propagation in free space conditions, diffractions in interposed objects and reflections due to objects between antennas are considered. Therefore, in order to get an understanding of radio propagation basics, the following definitions are given:
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Propagation in free space: Under the assumption that a RX is separated by a distance $d$ from the TX antenna and propagation in ideal conditions, i.e. free space conditions, the average level of received power $P$ can be predicted with the Friis transmission equation [1]:

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2$$

(2.1)

where $P_T$ is the transmitted power, $G_T$ and $G_R$ are the antenna gains in TX and RX respectively, $\lambda$ is the wavelength, and $d$ is the TX-RX distance. From the equation described above (2.1), the power attenuation $L_P$ due to the propagation in the medium can be expressed as:

$$L_P = \left(\frac{4\pi d}{\lambda}\right)^2$$

(2.2)

For instance, the free space model can be used in location 1 of Figure 1.

Scattering: Scattering is the physical process where radio waves are forced to deviate from a straight trajectory due to the non-uniformities in the medium through which they travel. These non-uniformities causing scattering are known as scatterers. Otherwise stated, scatterers are physical objects in a real environment that interact with radio waves causing scattering. Scatterers are usually grouped into clusters.

Reflection: This phenomenon occurs when radio waves bounce from large objects compared to the wavelength. One simplifier hypothesis is to consider that reflections occur on smooth and plane surfaces. In such case, reflections can be dealt as a problem of theory of rays by applying the Snell’s law, i.e. the angle of the incident and reflected ray are equivalent. Location 2 of Figure 1 shows also reflections from the Earth’s plane.
**Diffraction**: Diffraction denotes the phenomenon that occurs when a radio wave interact with an obstacle. In the frame of this thesis, buildings, corners, and other obstacles may hide the line-of-sight (LOS) between the TX and RX antenna, and thus cause diffraction. The hidden area to the TX antenna is known as diffraction area [2]. In the diffraction area the electromagnetic fields are not null due to the diffraction caused by the obstacle and, hence, there is still reception even though the attenuations are higher than in free space conditions. Location 3 of Figure 1 shows an example of diffraction.

**Multipath propagation**: Broadly speaking, this kind of propagation occurs as a consequence of reflections and diffractions in the environment, i.e. radio waves carrying the transmitted information bounce on walls, doors, and other interacting objects, reaching the RX antenna multiples times through different paths and at slightly different time instants.

**Fading**: In wireless communications, fading is a random process that occurs in radio propagation channels and produces significant variations of the attenuation in the received signal amplitude. The fading may vary with time, space and/or frequency. Therefore, a fading channel is a communications channel that experiences fading. In addition, fading may occur due to multipath propagation, referred to as multipath fading, or due to interposed obstacles between TX and RX affecting the radio wave propagation, referred to as shadow fading.

*Figure 1*: Mechanisms involved in the propagation losses according to the TX-RX distance. Location 1 provides LOS between TX and RX. If the RX is moving until location 2, there are also reflections in the Earth plane. Finally, in location 3, diffraction appears as consequence of an obstacle between TX and RX.
2.2 MIMO systems

In wireless communications, a MIMO system contains more than one antenna in both TX and RX and is capable to receive and/or transmit simultaneously through multiple antennas, as shown in Figure 2. MIMO exploits a radio wave phenomenon called multipath propagation. In general, the more antennas a TX or RX uses simultaneously, the higher is its maximum data rate. However, multiple antennas by themselves do not increase data rate. Actually, the real benefit comes from how MIMO systems use its multiple antennas, that is, the advanced signal processing techniques. Therefore, the use of MIMO systems allows using a set of techniques that allow increasing the performance of the transmitted data. These techniques include spatial diversity, spatial multiplexing, and beamforming (array gain).

![Figure 2: Example of radio channel with a rich multipath propagation and MIMO system with 3 antennas at TX and RX.](image)

With spatial multiplexing an outgoing signal stream is divided into multiple parts, called *spatial streams*, which are transmitted through different TX antennas [3]. Each transmission propagates along a different path so that the spatial streams are received by multiple antennas on the RX with different strengths and delays. Hence, this technique
improves performance by dividing data into multiple streams transmitted through multiple antennas.

Spatial diversity combines in reception different signal streams coming from the multipath propagation in order to obtain a signal stream in better conditions. Therefore, diversity exploits the existence of multiple antennas to improve range and reliability [4]. This technique is typically employed to counteract the fast fading of the channel that might affects each signal stream when the number of antennas on the receiving end is higher than the number of streams being transmitted. Moreover, spatial diversity technique can also be used in transmission to send an outgoing signal stream redundantly, each transmitted through different antennas.

Beamforming is a technique for directional signal transmission or reception, i.e. it enables to steer the beam of the array towards the intended direction in order to concentrate the radiated power of the outgoing signal stream in such direction [3]. In reception, beamforming technique is used to improve the received signal strength from the desired direction while other directions are attenuated. Therefore, this technique improves in general range and performance by limiting interference [4].

In general, real WLAN environments with MIMO technology are typically multi-link MIMO systems. ML-MIMO scenarios are the most general scenarios where users and base stations (BSs) use several antennas. The term multi-link means that several MIMO links interact with each other as shown in Figure 3. Next, the signal model for ML-MIMO systems is introduced, which will be used later as operating principle of the MIMO channel model developed in Section 3.3.
Consider a MIMO system for each different link with $N_T$ transmitting antennas and $N_R$ receiving antennas as seen in Figure 3. For $U$ users and $B$ BSs, the signal model would be according to [5] as follows:

$$ y = H_{ML} \cdot x \iff \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_B \end{pmatrix} = H_{ML} \cdot \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_U \end{pmatrix} \quad (2.3) $$

where $H_{ML}$ denotes the multi-link channel matrix that is defined as in [5]:

**Figure 3:** Schematic illustration of a multi-link MIMO system with $U$ users equipped with $N_T$ antennas each one, and $B$ BSs equipped with $N_R$ antennas each one.
Here, $H_{i,j}$ is the channel matrix for each different MIMO link between the $i$-th BS and the $j$-th user defined as in [5], and [6]:

$$H_{i,j} = \begin{pmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N_T} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_T,1} & h_{N_T,2} & \cdots & h_{N_T,N_T} \end{pmatrix}$$

where $h_{i,j}$ is the channel impulse response (CIR) between the $i$-th RX antenna and the $j$-th TX antenna. Indeed, it is the single-input single-output (SISO) channel between each pair of TX and RX antenna. In wireless communications, the mechanisms of radio propagation are contained in the CIR. Hence, the CIR consists of contributions of all individual multipath components (MPCs). Considering a double-directional CIR [7], the temporal and angular dispersions effects of the channel are described in [6] by:

$$h_{i,j}(r_{Tx}, r_{Rx}, \tau, \phi, \psi) = \sum_{l=1}^{L} \beta_l \delta(\tau - \tau_l) \delta(\phi - \phi_l) \delta(\psi - \psi_l)$$

where $\beta_l$, $\tau_l$, $\phi_l$, and $\psi_l$ denote the complex amplitude, delay, direction of departure (DoD), direction of arrival (DoA), respectively, associated with the $l$-th MPC. Furthermore, $r_{tx}$ and $r_{rx}$ denotes the position of the TX and RX, respectively, and $L$ is the total number of MPCs. Note that polarization can be taken into account by extending each CIR to a polarimetric 2 x 2 matrix [5] whose entries contain the coupling between vertical $V$ and horizontal $H$ polarizations [8]:
Development of multi-link geometry-based MIMO channel model

\[
\mathbf{H}_{\text{pol}} = \begin{pmatrix}
    h_{i,j}^{VV} & h_{i,j}^{VH} \\
    h_{i,j}^{HV} & h_{i,j}^{HH}
\end{pmatrix}
\]  

(2.7)

2.3 Physical Models

Physical MIMO channel models use the basis of electromagnetic wave propagation in order to characterize an environment through the double-directional multipath propagation between TX and RX, as described in [7] and [8]. Thereby, they explicitly model wave propagation parameters such as the complex amplitude, phase, DoD, DoA, and delay of MPCs. Physical models can be categorized into three different types: deterministic models, geometry-based stochastic models and non-geometric stochastic models. Physical models are presented briefly below according to [6], and [9] with special emphasis in geometry-based stochastic models.

![Classification of MIMO channel and propagation models](image)

Figure 4: Classification of MIMO channel and propagation models [5], [7].
2.3.1 Deterministic models

In deterministic channel models the physical parameters are determined in a completely deterministic way in order to reproduce the actual physical radio propagation channel for some particular environments. For a given environment or radio link, its geometry and electromagnetic characteristics can be stored so that the propagation process can be reproduced or simulated. Therefore, deterministic models are highly accurate and physically meaningful even though they cannot consider and represent other possible environments. Due to the high accuracy and similitude to the real propagation process, deterministic models may be used instead of measurements campaigns when there is not enough time to set it up or when the case under study is really difficult to measure. For example, electromagnetic models such as the finite element method (FEM), the method of moments (MoM) or the finite-difference in time domain (FDTD) study the near field solving directly the Maxwell’s equations. Other examples of physical-deterministic models are ray tracing (RT) and stored measurements. In stored measurements, data from channel measurements is used as a deterministic channel model. The RT model uses geometric optics theory, or ray optics, to treat reflected and transmitted rays on plane surfaces, and diffraction on rectilinear edges. Therefore, using RT models the multipath propagation can be easily reproduced in the modeled environment. If the model uses beams instead of rays, then the model is called beam launching or ray splitting. This ray approximation is under the assumption that the wavelength is sufficiently small compared with the dimension of the interacting objects in the environment. Nevertheless, this assumption is usually valid in urban environments and consequently the electromagnetic field can be represented in a set of rays.
Figure 5: Simple propagation scenario generated with the RT procedure. There are three different rays representing LOS component, reflection on the walls, and diffraction on the corner.

Figure 5 shows a simple RT illustration. The RT procedure works as follows: initially the TX and RX locations are specified then all possible paths (rays) are determined by the rules of geometrical optics. A maximum number $N_{\text{max}}$ of successive reflections/diffractions (prediction order) are usually fixed. Figure 6 shows a RT strategy with a layered structure called visibility tree which represents the individual propagation paths between the interacting objects in the simulation environment. The root node is the TX antenna and each node of the tree represents the objects (wall, corner, RX antenna, a wedge, etc.) whereas each bracket represents a LOS connection between those objects. The visibility tree is constructed starting from the root of the tree. The nodes in the first layer correspond to those objects for which there is LOS to the TX. In the next layers, two objects will be connected if there is LOS between them. The visibility tree ends when is reached the layer where the RX is contained. Hence, the procedure is repeated till the prediction order. Once the visibility tree is built, the path of each ray is determined going back in the tree structure, i.e. from the last layer to the root node, and applying the rules of geometrical optics.
2.3.2 Geometry-based stochastic models

Geometry-based stochastic channel models (GSCM), sometimes also known as statistical channel models, were originally created for channel simulation in systems with multiple antennas at the BS (diversity antennas, smart antennas). The concept of geometry-based arises from the characterization of modeled radio channels by cluster locations or groups of MPCs. Following the definition given in [10], a cluster is a set of scatterers which have all same long term properties but are not necessarily grouped closely together. With GSCM the cluster locations are chosen stochastically according to a prescribed probability density function (Gaussian, uniform, exponential, etc.). The advantage of GSCM is that they are more suitable for statistical analysis due to its randomness and can reflect much better a set of physical environments than deterministic models. In GSCM the CIR is then characterized by the laws of the propagation applied to specific TX, RX, and cluster geometries and it can be found through a simple RT procedure.
In contrast to deterministic models, stochastic models do not need large databases with channel measurements as input information, and they can even statistically model a large number of scenarios with only one simulation. Deterministic models, on the other hand, require a large number of simulations of different channel representations in order to extract statistical information. Hence, GSCM describe some particular class of environments or scenarios whose characteristics and behavior are modeled statistically.

GSCM can include single-bounce scattering as well as multiple-bounce scattering, i.e. the propagation of radio waves occurs using either one cluster or multiple clusters between the TX and RX. In one hand, single-bounce scattering assumption is often correct for macrocells, but breaks down in micro- and picocells. Under the single-bounce scattering assumption the RT procedure becomes really simple: apart from LOS component, all paths connecting the TX and RX with each cluster consist of two subpaths. These subpaths are typically characterized by the DoD, DoA and delay (propagation time that in turn determines the attenuation according to a power law). However, in many environments the propagation mainly consists in multiple-bounce scattering. In multiple-bounce assumption, the DoD, DoA, and delay are completely decoupled and, in turn, the computational complexity increases significantly in GSCM. For instance, in microcells the propagation mostly consists of waveguiding through street canyons, which involves multiples reflections and diffractions. For picocells, if the TX and RX are in different rooms the propagation is also mainly determined by multiple-bounce scattering. In order to incorporate multiple-bounce scattering into GSCMs, the concept of twin-cluster is a valid approach that was used for example in the COST 273 channel model [11].
The principle of GSCM [10] [12] is shown in Figure 7. One MS is placed within the simulation environment. One BS with several antennas covers the whole area. Local or near clusters are placed around the MS and a velocity vector is assigned to the MS. Each path starts at the TX and is bounced in one or two clusters before reaching the RX. The CIR is calculated using the RT technique for all possible paths. In Figure 7 two kind of clusters can be seen: far clusters, and local clusters which are always centered on the MS. Contribution from far clusters carry less power since they propagate over long distances, and thus they are attenuated more strongly. However, the existence of far clusters (e.g. high-rise buildings, mountains, and so forth) can significantly influence the performance of MIMO systems because they increase the temporal and angular dispersion, i.e. higher delay and angular spreads are achieved. In Section 2.5, some existing GSCM for different purposes are shortly described.

2.3.3 Non-geometric stochastic models

Non-geometric stochastic models, on the contrary, characterize physical parameters stochastically, i.e. describe paths from TX to RX by statistical parameters only, but without consider the geometry of the clusters locations in the environment. Examples
are the extension of the Saleh-Valenzuela model [13] [14] and the model developed by Zwick [15]. The first one deals with clusters of MPCs while the second one considers MPCs individually.

Saleh and Valenzuela observed that for SISO channel models in indoor scenarios the MPCs tend to come in groups called clusters. They developed a stochastic broadband indoor channel model, i.e. the Saleh-Valenzuela model [16], based on the temporal clustering approach with an exponential decay for both power of MPCs within a single cluster as well as for the average cluster power over delay. Furthermore, the cluster and the MPC arrival process within a cluster are modeled as Poisson processes with different arrival dates. Then, this proposed model was extended in [13] [17] to the spatial domain for the MIMO case. From experimental data was also observed that each cluster is a group of MPCs with similar DoDs, DoAs, and delays. Hence, the proposed narrowband channel model is double-directional and the CIR for \( L \) clusters and \( K \) MPCs per cluster can be written as [9]:

\[
\begin{align*}
    h(\varphi_{Rx}, \varphi_{Tx}) &= \frac{1}{\sqrt{LK}} \sum_{l=0}^{L-1} \sum_{k=0}^{K-1} \beta_{kl} \cdot \delta(\varphi_{Tx} - \varphi_{Tx,l} - \Phi_{Tx,kl}) \cdot \delta(\varphi_{Rx} - \varphi_{Rx,l} - \Phi_{Rx,kl}) \\
    &\quad \text{(2.8)}
\end{align*}
\]

where \( \varphi_{Tx} \) and \( \varphi_{Rx} \) are azimuth DoD and DoA. For the \( l \)-th cluster, \( \varphi_{Tx,l} \) and \( \varphi_{Rx,l} \) denote the mean DoD and mean DoA. For the \( l \)-th cluster and its \( k \)-th MPC, \( \Phi_{Tx,kl} \) and \( \Phi_{Rx,kl} \) are the DoD and DoA relative to the respective mean angles, while \( \beta_{kl} \) is the complex amplitude which is modeled by a zero-mean complex Gaussian distribution. For simplicity, those MPCs corresponding to the same cluster have the same power. The model is also based on the assumptions that the directions at both link ends are statistically independent of each other, i.e. DoD and DoA statistics are independent, but have identical distribution. These assumptions allow characterizing the spatial clusters in terms of their mean cluster angle and the cluster angular spread [18]. The clusters centers, i.e. the mean DoDs and mean DoAs of clusters, are uniformly distributed within
[0, 2π) while the angular MPC distribution $p(\phi)$ within each cluster follows a Laplacian distribution with an angular standard deviation of $\sigma$ is given by [9]:

$$p(\phi) = \frac{1}{\sqrt{2\sigma}} \exp\left(\frac{\sqrt{2}}{\sigma} |\phi|\right)$$

(2.9)

Adding the delay domain, the double-directional CIR becomes in, as shown also in [9]:

$$h(\phi_{Rx}, \phi_{Tx}, \tau) = \frac{1}{\sqrt{LK}} \sum_{l=0}^{L-1} \sum_{k=0}^{K-1} \beta_l \cdot \delta(\phi_{Tx} - \phi_{Tx,l} - \Phi_{Tx,l}) \cdot \delta(\phi_{Rx} - \phi_{Rx,k} - \Phi_{Rx,k}) \cdot \delta(\tau - \tau_l - \tau_k)$$

(2.10)

Here, $\tau$ denotes delay, $\tau_l$ is the delay of the $l$-th cluster and $\tau_k$ is the delay of the $k$-th MPC arrival within the $l$-th cluster.

On the other hand, Zwick’s model [15] is a stochastic indoor MIMO model that allows a time-variant, polarization-dependent broadband description of the multipath channel. Given the time dependent locations of the TX and RX arrays, the channel transfer function between the center elements of these arrays is shown in [9] as:

$$H(t, f, \Omega_{Tx}, \Omega_{Rx}) = \sum_{l=1}^{N(t)} \Gamma_l(t) \cdot e^{-j2\pi f \tau_l(t)} \cdot \delta(\Omega_{Tx} - \Omega_{Tx,l}(t)) \cdot \delta(\Omega_{Rx} - \Omega_{Rx,l}(t))$$

(2.11)

where $\tau_l(t)$ is the delay, $\Omega_{Tx,l}(t)$ is the DoD, $\Omega_{Rx,l}(t)$ is the DoA, and $\Gamma_l(t)$ is the full polarimetric (2 x 2) transfer matrix for each $l$-th MPC. The elements of $\Gamma_l(t)$ include the pathloss and depolarization of all scattering processes. $N(t)$ is the number of MPCs generated by a birth and death process which is modeled as a Poisson process. Therefore, after the birth of an MPC, its properties are altered until the death of that MPC. Under the planar wave assumption, the previous equation can be extended to MIMO by adding proper phase shifts for each MPC. These phase shifts depend on the relative location of the considered antenna element with respect to the center element of
the array and the direction of the MPC. In [19], and [20] deterministic ray tracing results were used to produce data sets in order to evaluate statistically the parameters in the proposed model. Based on these results, the MPC power decay versus the relative delay is modeled as a combination of two exponential decaying curves, the MPC amplitude around the mean power decay is considered as Rayleigh distributed, DoDs and DoAs are treated as Laplacian distributed for small delays whereas for larger delays are treated as uniformly distributed, and the delays of MPCs are uniformly distributed between the minimum delay given by the distance that connects both arrays and the maximum delay that depends on the simulated dynamic range.

2.4 Analytical Models

In contrast to physical models, analytical models use a mathematical/analytical way to describe the impulse response, or equivalently the transfer function, of the channel between all elements of the antenna arrays at both link ends, i.e. TX and RX locations. Then, these impulse responses are grouped into a MIMO channel matrix obtained by analytical mathematical expression. Analytical models capture implicitly physical wave propagation as well as antenna configuration (antenna pattern, number of antennas, array geometry, and polarization) and system bandwidth simultaneously. Analytical models can be split into two subclasses, propagation-motivated models and correlation-based models which are explained below according to [6], and [9].

2.4.1 Correlation-based models

As the name suggests, correlation-based models characterize the MIMO channel matrix statistically in terms of the correlation between the elements of the matrix. There are some popular correlation-based analytical channel models such as the i.i.d (independent and identical) model, the Kronecker model [21], and the Weichselberger model [22]. Below, some basic principles of correlation-based models will be introduced, followed by a brief description of the channel models aforementioned.
Some narrowband analytical models are based on the multivariate complex Gaussian distribution. The elements of the channel matrix are strictly Rayleigh-fading correlated. It means that the channel matrix elements follow a joint multivariate zero-mean complex Gaussian distribution [13] expressed as:

\[
 f(h) = \frac{1}{\pi^{mn} \det(R_h)} \exp\{-h^H \cdot R_h^{-1} \cdot h\} 
\]  

(2.12)

Here, \( h = \text{vec}(H) \) and vec\{\} is the vector operation that changes the size of a \( m \times n \) matrix into a \( mn \times 1 \) vector. In (2.12), the \( mn \times mn \) full MIMO channel correlation matrix [23], [24] which describes the spatial behavior of the MIMO channel can be modeled by:

\[
 R_h = E\{\text{vec}(H) \cdot \text{vec}(H)^H\} 
\]  

(2.13)

Following the distribution given in (2.12), MIMO channels can be modeled by \( \text{vec}(H) = R_h^{1/2} \cdot \text{vec}(G) \) or equivalently as

\[
 H = \text{unvec}(R_h^{1/2} \cdot \text{vec}(G)) 
\]  

(2.14)

where unvec\{\} is the inverse operation to vec\{\}, and \( G \) is a \( m \times n \) random matrix with zero-mean i.i.d. complex circularly symmetric Gaussian elements. Thereby, all antenna elements have Rayleigh-fading. The operation \((\cdot)^{1/2}\) denotes any matrix square root fulfilling \( R_h^{1/2} \cdot (R_h^{1/2})^H = R_h \).

However, this analytical model has a couple of significant disadvantages. In order to specify completely \( R_h \), \( (mn)^2 \) real valued parameters for the diagonal and \( \frac{1}{2} \cdot (mn \cdot (mn-1)) \) complex valued parameters are needed. Moreover, a direct interpretation between the correlation matrix \( R_h \) and the physical propagation phenomena of the
radio channel is really difficult. Consequently, these disadvantages have lead to introduce some simplifying assumptions in the full MIMO channel correlation matrix on the models that will be explained below.

The \textit{i.i.d model} is the simplest analytical model for MIMO channels. This is an ideal model that considers a random channel matrix with i.i.d zero-mean, complex circularly symmetric Gaussian distribution. Hence, $\mathbf{R}_h = \rho^2 \cdot \mathbf{I}$, i.e. all elements of the MIMO channel matrix are not correlated (that implies statistically independent) and have equal variance $\rho^2$. This situation corresponds to a spatially white MIMO channel which only appears in rich scattering environments with independent MPCs uniformly distributed in all directions. This model is often used in the information theoretic analysis of MIMO systems due to only one real-valued parameter (the channel power $\rho^2$) needs to be specified.

On the other hand, the \textit{Kronecker model} proposed by [24] approximates the full channel correlation by the Kronecker product of the TX correlation matrix and the RX correlation matrix such that it can be expressed as:

$$
\mathbf{R}_h = \frac{1}{\text{tr}[\mathbf{R}_{rx}]} \mathbf{R}_{tx} \otimes \mathbf{R}_{rx}
$$

(2.15)

where $\mathbf{R}_{tx} = E\{ (\mathbf{H}^H \mathbf{H})^T \}$ is the TX correlation matrix and $\mathbf{R}_{rx} = E\{ \mathbf{H} \mathbf{H}^H \}$ is the RX correlation matrix.

Note that $\text{tr}\{\cdot\}$ denotes the trace of a matrix and $\otimes$ the Kronecker product. Using then some identities of the Kronecker product which can be found in [9], (2.14) simplifies to the Kronecker model as follows:

$$
\mathbf{H}_{\text{kron}} = \frac{1}{\sqrt{\text{tr}[\mathbf{R}_{rx}]}} \mathbf{R}_{rx}^{1/2} \cdot \mathbf{G} \cdot (\mathbf{R}_{tx}^{1/2})^T
$$

(2.16)
Here, $G$ is a matrix of i.i.d. zero-mean, complex circularly symmetric Gaussian random variables. Apart from a simple analytical treatment of MIMO systems, this model allows array optimization at both TX and RX independently. Furthermore, the model consists in receive and transmit correlation matrices as parameters. For an $m \times n$ MIMO channel, $m^2 + n^2$ real parameters need to be specified. Because all of this, the Kronecker model has become pretty popular.

However, the Kronecker model has a deficiency due to its separability assumption. It enforces a multipath structure with separable DoD-DoA spectrum, i.e. the joint DoD-DoA spectrum is the product of the DoD spectrum and the DoA spectrum. Hence, the Kronecker model cannot reproduce MIMO channels with single-bounce scattering.

Finally, the Weichselberger model [22] was proposed in order to mitigate the deficiency of the Kronecker model, i.e. it aims to obviate the separable DoD-DoA spectra simplification that neglect the spatial structure of the MIMO channel and describes the MIMO channel by separated link ends. This model introduces the eigenvalue decomposition of the RX and TX correlation matrices, as shown in [6], and [9]:

$$
R_{Rx} = U_{Rx} \cdot \Lambda_{Rx} \cdot U_{Rx}^H \\
R_{Tx} = U_{Tx} \cdot \Lambda_{Tx} \cdot U_{Tx}^H
$$

(2.17)

where $U_{Tx}$ ($U_{Rx}$) is the unitary matrix whose columns denote the eigenvectors at the TX (RX) and $\Lambda_{Tx}$ ($\Lambda_{Rx}$) denote the diagonal matrix of the corresponding eigenvalues. Introducing (2.17) into (2.16), the Kronecker model can also be written as [9]:

$$
H_{Kron} = \frac{1}{\sqrt{\text{tr}\{R_{Rx}\}}} \cdot U_{Rx} \cdot \Lambda_{Rx}^{1/2} \cdot U_{Rx}^H \cdot G \cdot U_{Tx}^\ast \cdot \Lambda_{Tx}^{1/2} \cdot U_{Tx}^T
$$

(2.18)

where the inner part $G' = U_{Rx}^H \cdot G \cdot U_{Tx}^\ast$ describes an i.i.d. random matrix with the same properties as $G$. Therefore, the proposed Weichselberger model is [6], [9]:
\[ H_{\text{weichsel}} = U_{Rx} \cdot (\tilde{\Omega}_{\text{weichsel}} \bullet G) \cdot U_{Tx}^T \]  

(2.19)

Herein, \( G \) is again an i.i.d. complex circularly symmetric Gaussian random fading matrix. The operator \( \bullet \) is the element-wise Schur-Hadamard product, and \( \tilde{\Omega}_{\text{weichsel}} \) is the element-wise square root of the power coupling matrix \( \Omega_{\text{weichsel}} \). An alternative representation for (2.19) can be found in [9]:

\[ H_{\text{weichsel}} = \sum_{l=1}^{m} \sum_{k=1}^{n} g_{lk} \cdot \sqrt{\omega_{\text{weichsel},lk}} \cdot u_{Rx,l} \cdot u_{Tx,k}^T \]  

(2.20)

where \( g_{lk} \) denotes the elements of \( G \), \( \omega_{\text{weichsel},lk} \) are the positive and real-valued elements of the power coupling matrix that determine the average power-coupling between the \( l \)-th and the \( k \)-th receive eigenmode, and \( u_{Tx,k} \) (\( u_{Rx,l} \)) denotes the \( k \)-th (\( l \)-th) column of \( U_{Tx} \) (\( U_{Rx} \)), that is, the \( k \)-th (\( l \)-th) eigenvector of the TX (RX) correlation matrix. Finally, as shown in [9], the full MIMO channel correlation matrix for this model results to

\[ R_{H,\text{weichsel}} = \sum_{l=1}^{m} \sum_{k=1}^{n} \omega_{\text{weichsel},lk} \cdot (u_{Tx,l} \otimes u_{Rx,k}) \cdot (u_{Tx,l} \otimes u_{Rx,k})^H \]  

(2.21)

The parameters in this model are the eigenbases of the TX and RX correlation matrices, \( U_{Tx} \) and \( U_{Rx} \), and the coupling matrix, \( \Omega_{\text{weichsel}} \). Then, for modeling an \( m \times n \) MIMO channel matrix, \( m \cdot n + m \cdot (m - 1) + n \cdot (n - 1) \) real parameters are needed.

### 2.4.2 Propagation-motivated models

Propagation-motivated models characterize the channel matrix by modeling propagation parameters. Some examples are the virtual channel representation [25], the maximum entropy model [26], and the finite scatterer model [27].
The \textit{virtual channel representation} divides the angular range at both link ends into fixed and discrete direction (‘virtual angles’). These directions are determined by the number of antennas of the considered antenna array. Therefore, for \( n \)-element array at one link end, there are \( n \) virtual angles which are chosen such that the steering vectors are orthonormal to each other. The MIMO channel is modeled by specifying the amplitude coupling between those virtual angles at both link ends (See Figure 8). The virtual channel representation \cite{25} can be written as:

\[
H_{\text{virt}} = A_{\text{Rx}} \cdot (\tilde{\Omega}_{\text{virt}} \bullet G) \cdot A_{\text{Tx}}^\dagger \tag{2.22}
\]

where \( A_{\text{Tx}} \) and \( A_{\text{Rx}} \) are orthonormal matrices whose columns contain the steering and response vectors into the directions of the virtual angles. \( \tilde{\Omega}_{\text{virt}} \) is the positive and real-valued coupling matrix whose elements represent the amplitude coupling between the corresponding virtual angles of both link ends. \( G \) is modeled by an i.i.d. matrix so that the fading of the different virtual channel coefficients is independent. An alternative representation \cite{9} with the orthonormal steering vectors \( a_{\text{Tx},l} \) and response vectors \( a_{\text{Rx},k} \) can be used:

\[
H_{\text{virt}} = \sum_{l=1}^{m} \sum_{k=1}^{n} g_{lk} \cdot \sqrt{\omega_{\text{virt},lk}} \cdot a_{\text{Rx},l} \cdot a_{\text{Tx},k}^\dagger \tag{2.23}
\]

Where \( g_{lk} \) denotes the elements of \( G \), and \( \sqrt{\omega_{\text{virt},lk}} \) the elements of the coupling matrix, respectively. Finally, the full channel correlation matrix of the virtual channel representation would be \cite{9}:

\[
R_{H_{\text{virt}}} = \sum_{l=1}^{m} \sum_{k=1}^{n} \omega_{\text{virt},lk} \cdot (a_{\text{Tx},l} \otimes a_{\text{Rx},k}) \cdot (a_{\text{Tx},l} \otimes a_{\text{Rx},k})^H \tag{2.24}
\]
On the other hand, the *maximum entropy model* was intended to determine the distribution of the MIMO channel matrix using a priori information that is available. This a priori information might include properties of the propagation environment and system parameters (e.g. bandwidths, DoAs, DoDs, etc.). Hence, the maximum entropy principle aims to avoid any model assumption not supported by the priori information.

Considering available the prior information that follows: the number of scatterers $s_{tx}$ and $s_{rx}$ at the TX and RX, the steering vectors for all TX and RX scatterers contained in the matrices $\Phi$ and $\Psi$, the corresponding scatterer powers $P_{tx}$ and $P_{rx}$, and the path gains between TX and RX scatterers, characterized by the coupling matrix $\Omega$. Then, the maximum entropy channel [26] model is expressed as:

$$H = \Psi \cdot P_{rx}^{1/2} \cdot (\Omega \cdot G) \cdot P_{tx}^{1/2} \cdot \Phi^{T}$$

(2.25)

where $G$ is an $s_{tx} \times s_{rx}$ Gaussian matrix with i.i.d. elements; $P_{rx}$ and $P_{tx}$ are the corresponding scatterer powers; $\Phi$ and $\Psi$ are $m \times s_{tx}$ and $n \times s_{rx}$ matrices containing the steering vectors for all TX and RX scatterers, respectively. More details about this MIMO channel representation can be found in [6].
The finite scatterer model [27] treats with the double-directional channel by modeling the propagation of the signal between the TX and RX in terms of a finite number of MPCs. Figure 9 illustrates the different propagation mechanisms included in the model such as single-bounce scattering, multiple-bounce scattering and even both together, i.e. a “split” component which have a single DoD which is divided into two or more paths with different DoAs (or vice versa). Hence, each multipath is determined by its DoD, DoA, complex amplitude, and delay. The finite scatterer model can be modeled as follows according to [9]:

\[
H = \tilde{A}_{Rx} \cdot (S \cdot G) \cdot \tilde{A}_{Tx}^T = \sum_{j=1}^{m} \sum_{k=1}^{n} g_{jk} \cdot s_{ik} \cdot \tilde{a}_{Rx} \cdot (\Phi_{Rx,k}) \cdot \tilde{a}_{Tx} \cdot (\Phi_{Rx,k})^T
\]  

(2.26)

where \( \tilde{A}_{Rx} \) denotes a matrix whose columns are the response vectors \( \tilde{a}_{Rx} (\Phi_{Rx,k}) \) and \( \tilde{A}_{Tx} \) the matrix whose columns contain the steering vectors, \( \tilde{a}_{Tx} (\Phi_{Tx,k}) \). \( S \) is the matrix of the path amplitudes \( s_{ik} \), while \( G \) is a random fading matrix with \( g_{jk} \) as its elements. The number of DoDs determines the number of columns of \( S \), while the number of DoAs determines the number of rows of \( S \).

**Figure 9:** Example of finite scatterer model with single-, multiple- and split-scattering.
2.5 Existing Standardized Channel Models

Standardized models are an important tool for the design, development and deployment of new radio systems. They allow evaluate the functionality of different techniques in order to enhance the capacity and improve the system performance. Some of them were widely used, e.g. the COST 207 wideband power delay profile (PDP) model [28] was used in the development of GSM, and as a basis for the decision on modulation and multiple-access methods. Next, an overview of five standardized directional MIMO channels models will be provided.

2.5.1 COST 273 MIMO Channel Model

The COST 273 MIMO channel model [29] is a physical model that follows a geometry-based stochastic approach. It was intentionally designed for macro-, micro-, and picocells and intended for single-link scenarios, i.e. one MS and one BS. Therefore, the COST 273 model is not capable to simulate multi-link scenarios. The COST 273 model was built with a generic cluster-based structure, i.e. it describes the propagation channel in the delay and the direction domains in both TX and RX sides by clusters or groups of MPCs. In other words, the COST 273 model generates a multipath radio channel that is based on clusters that emulate physical scatterers in the environment and visibility regions (VR).

Clusters are placed in different locations so that it is generated a channel is dispersive in both domains angular and delay. A general COST 273 channel model implementation is presented in [30]. In the COST 273 approach, clusters are intended to emulate local scattering, far scattering or reflections by single bounces and multiple bounces. In such implementation there are three different kinds of clusters [31]: Local clusters, single-bounce clusters and twin clusters. Local clusters are located closely around the BS or MS while the others clusters are defined as far o remote clusters. Single-bounce clusters are those viewed from both the BS and MS sides which follow a strict geometrical relationship. Otherwise, those clusters which can not follow this geometrical
relationship are defined as twin clusters. Furthermore, in this implementation clusters are defined as ellipsoids in space and the lengths of its axes are related to the maximum cluster delay spread (CDS) and the cluster angular spread (CAS).

Furthermore, the COST 273 model defines and implements the concept of VRs in order to emulate the appearance of clusters while the MS is moving in the environment. Therefore, the dynamic behavior can be emulated with VRs by associating each cluster with exactly one VR. In a given environment with a certain number of clusters, it is obvious to notice that all clusters are not capable to contribute to the propagation channel at the same time. Indeed, clusters that contribute with enough power to the propagation channel are defined as visible or active. The VRs can be seen as circular region on the horizontal plane which determines the activity of clusters. Each cluster has only one VR and it is visible from the MS only when the MS is located inside its VR, i.e. a cluster becomes active whenever the MS is located inside its VR.

Figure 10 shows a general structure of the COST 273 channel model where the three types of clusters are represented with several MPCs. In Figure 10, the radio waves travel from the BS to the MS through MPCs as a result of a reflection in the environment. Each MPC is characterized by its delay ($\tau$), azimuth and elevation of departure (AoD/EoD) and azimuth and elevation of arrival (AoA/EoA). Here, AoD and AoA are referred to DoD and DoA, respectively. Therefore, those MPCs with similar parameters, i.e. similar delay and directions at both BS and MS sides, are considered as part of the same cluster.
The COST 273 channel model is a double-directional [7] since the time-varying CIR can be calculated in delay and direction domain as:

$$h(t, \tau, \Omega_{\text{BS}}, \Omega_{\text{MS}}) = \sum_{n \in \wp} \sum_p \beta_{np} \delta(\tau - \tau_{np}) \delta(\Omega_{\text{BS}} - \Omega_{np}^{\text{BS}}) \delta(\Omega_{\text{MS}} - \Omega_{np}^{\text{MS}})$$  \hspace{1cm} (2.27)

Here, $\wp$ specifies the set of active clusters, and $\beta_{np}$, $\Omega_{np}^{\text{BS}}$, $\Omega_{np}^{\text{MS}}$ are the complex amplitude, the direction of departure (azimuth and elevation), and the direction of arrival (azimuth and elevation) of the $p$-th MPC in the $n$-th cluster, respectively.

Considering a MIMO system using $V$ and $U$ multiple antennas at the BS and MS respectively, the MIMO channel transfer function is given by [30]:

$$\mathbf{H}(t, f) = \sum_{n \in \wp} \sum_p \beta_{np} e^{-j2\pi f \tau_{np}} \mathbf{s}_{\text{MS}}(\Omega_{np}^{\text{MS}}) \mathbf{s}_{\text{BS}}^{T}(\Omega_{np}^{\text{BS}})$$  \hspace{1cm} (2.28)
where \( (\cdot)^T \) designates transposition, \( \beta_{np} \) denotes the complex amplitude, \( \tau_{np} \) denotes the delay of the \( p \)-th MPC in the \( n \)-th cluster, and \( s_{MS} (s_{BS}) \) is the steering vector of the MS (BS) array in the direction \( \Omega_{np}^{MS} (\Omega_{np}^{BS}) \) of the \( p \)-th MPC in the \( n \)-th cluster.

### 2.5.2 WINNER

The WINNER channel model was developed in [32] for wireless communication systems in radio frequencies between 2 and 6 GHz and channel bandwidth of up to 100 MHz. The WINNER models are related to the COST 259 model and the 3GPP SCM model so that they adopted the GSCM principle, the “drop” concept, and the same generic structure for model all scenarios. WINNER channel models consider seven indoor, urban micro- and macro-cellular, suburban macro-cellular, and rural scenarios for both LOS and NLOS conditions. Thanks to five partners with different devices in different European countries, various measurement campaigns were carried out in order to provide the parameters (e.g. path-loss, shadow fading characteristics, power delay profiles, delay spreads, angular spreads, and cross-polarization ratio) for characterize the scenarios of interest. There are two types of channel models for each scenario: clustered delay line (CDL) models and generic channel models. CDL models are used for calibration and comparison simulations. The parameters for the CDL models are delay, power, AoD, AoA, Ricean K-factor, MS speed, number of rays per cluster, ray powers, and cluster and composite cluster azimuth-spread at both BS and MS. On the other hand, the generic models were created for both link- and system-level simulations. The generic model, also called stochastic multi-segment model, is a ray-based multi-link model that is antenna independent, scalable, and can generate channels for MIMO links.

The WINNER modeling work was divided into two parts. Firstly, the channel modeling effort was focused in create channel models with limited number of parameters for immediate simulation needs in prioritized propagation scenarios. Hence, the 3GPP SCM model was selected for cover this need. Secondly, the channel models were upgraded...
due to the narrow bandwidth and the limited frequency applicability range of the 3GPP SCM. Hence, the SCM model was extended to the SCM-Extended (SCME) model. More parameters were included, for example, the bandwidth was extended to 100 MHz by introducing a new concept called intra-cluster delay spread and center frequencies of 5 GHz by defining corresponding path-loss functions. It was also added two more scenarios: indoor large hall and suburban. Further upgrades to the original model include the LOS option for all three SCM scenarios. In [32] is available a MATLAB implementation of the SCME model. The 3GPP adopted a simplified version if this model for standardization of the long term evolution (LTE).

2.5.3 IEEE 802.11 n

The IEEE 802.11 standard for WLANs developed the TGn channel model [33] which is focused on MIMO WLANs for indoor environments in the 2 GHz and 5 GHz bands. The TGn channel model specifies up to six environments (A to F) and the corresponding parameter sets for each one. Moreover, it considers LOS and NLOS for environments such as small and large offices, residential homes, and open spaces. An implementation of the TGn channel model is available at [34]. The 802.11 TGn model is a physical model with a nongeometric stochastic approach. The directional impulse response is characterized by a sum of clusters. Based on measurement data, the number of clusters ranges from 2 to 6 and each cluster contains up to 18 delay taps separated by at least 10 ns. Then, for each tap is assigned a DoA, DoD and a truncated Laplacian power azimuth spectrums with angular spread between 20° and 40° for both, the DoA and the DoD. The overall RMS (root mean square) delay spread for the simulation environment varies between 0 (flat fading) and 150 ns. Each MIMO channel tap is modeled as is described in [35], whereas the Kronecker model was chosen for describe the Rayleigh-fading part of the model. The TX and RX correlation matrix are determined by the power azimuth spectrum and the antenna array geometry. The model considers time variations in order to emulate those scatterers in the environment which are in movement. Polarization can also be included as an additional feature.


2.5.4 IEEE 802.16 e / SUI

Initially, the Stanford University Interim (SUI) developed the SUI channel models for macrocellular fixed wireless access networks at 2.5 GHz. Subsequently, these models were enhanced and used in the IEEE 802.16a standard [36]. These models were selected for scenarios with the following characteristics:

1. Cell radius is less than 10 km.
2. The antenna in the user side is fixed and has to be installed under-the-eave or on rooftop because NLOS conditions are required.
3. The height of the BS is from 15 to 40 meters, above rooftop level.
4. System bandwidth is flexible from 2 to 20 MHz.

Although these models do not include the MIMO or directional component within the standard, there are extensions of the standard where it is described. In the original SUI models, antennas were assumed to be omnidirectional at both sides. Afterwards, a modified version (for both omnidirectional and directional antennas) of the SUI channel models were adopted for the IEEE 802.16a models. Furthermore, a spatial channel model based on 802.16a standard was developed in [37].

2.5.5 3GPP SCM

The 3GPP spatial channel model (SCM) [38] was developed by 3GPP/3GPP2 (3rd Generation Partnership Project) in order to become in a common reference for evaluating different MIMO parameters and methods in outdoor environments at a center frequency of 2 GHz and a system bandwidth of 5 MHz. The 3GPP SCM has two different parts: calibration model and system-simulation model.

The calibration model allows checking whether the simulation implementation is correct with respect to the specifications. This simplified channel model is necessary during the standardization process in order to compare the different implementations of the same
algorithm developed by different companies. Hence, the calibration model was intended with the purpose of assess whether two implementations are equivalent instead of evaluate its performance. It can be implemented either as a physical or analytical model. The physical model is a non-geometrical stochastic model that is a spatial extension of the ITU-R channel models [39] and describes the wideband characteristics of the channel as a tapped delay line. Those taps with different delays have independent fading, and each tap is characterized by fixed parameters such as its power azimuth spectrum, angular spread, and means direction, at both BS and MS side. Thus, it allows representing stationary conditions of the channel. The Doppler spectrum is also introduced by defining the speed and direction of travel of the MS. The model also defines a number of antenna configurations.

On the other hand, the simulation model aims to assess the performance. This model is physical model and distinguishes three different kinds of environments: urban macrocell, suburban macrocell, and urban microcell. Each environment has different values for its parameters (angular spread, delay spread, and so forth) but the structure and the methodology are identical for all of these. It can be both geometrical and stochastic. For example, considering a single link between one MS and one BS, the geometrical component is such that the MSs locations, the antenna array orientation as well as the direction of movement within the cell are chosen randomly. Then, from the MS position can be determined the pathloss, Okumura-Hata model for macrocells and Walfish-Ikegami model for microcells. The number of taps with different delays is 6 but their delay and average power are chosen randomly from a probability density function as well. The angular dispersion (at the BS and the MS) of each tap is implemented by representing a set of subpaths which all have the same delay but different DoAs and DoDs. This means that each path is a cluster with 20 scatterers which have different directions but equal time of propagation. The mean DoA (or DoD) of one tap is randomly distributed with a Gaussian distribution whose center is around the mean (the variance is one of the model parameters). Furthermore, each subpath has different offset $\Delta \phi_i$ from the tap mean so that all subpaths have deterministic amplitudes but different phases. These offsets, $\Delta \phi_i$, are fixed and defined previously in the 3GPP standard.
Therefore, this angular dispersion principle results in Rayleigh and Rice fading. Furthermore, temporal variation in the impulse response comes from the movement of the MS, which in turn leads to different phase shifts of the subpaths.

The operating principle of the simulation model works as follows: the entire system behavior arises from a sequence of simulations, also called “drops”. Each drop is a one simulation run over a certain time period. That period is usually assumed to be short so that large-scale channel parameters, such as angle spread, mean DoA, delay spread, mean DoD, and shadowing stay constant during the drop. Then, these channel parameters are drawn according to distribution functions. The MS positions are chosen randomly at the beginning of each drop; however, the BS locations and the cell layout remain fixed for a certain number of successive drops. The model is antenna independent, i.e. antenna radiation patterns, antenna geometries, and orientations can be chosen arbitrary. Once defined all parameters and antenna effects, the analytical results can be extracted from the physical model. These results consist in a different correlation matrix for each drop that will be used for the analytical model. Moreover, the simulation model has several optional features such as a polarization model, far scatterers clusters, LOS component for microcells, and a modified distribution of the angular dispersion at the MS, which allows to emulate an urban street canyon propagation environment.
3 MULTI-LINK MIMO CHANNEL MODELING

So far, all background provided in Chapter 2 describes existing MIMO channel models that were developed for single-link scenarios. In multi-link scenarios multiple BSs and/or MSs coexist in the same environment. Although single-link MIMO channel models can be extended to multi-link scenarios by a simple dropping concept, i.e. using the same models with several BSs and MSs, the validity of such models is not yet known due to the lack of investigation.

In this chapter the multi-link concept for channel modeling activities is introduced. In Section 3.1 the importance to model multi-link scenarios is discussed. After that, earlier works on multi-link channel models are presented in Section 3.2. Finally, the multi-link geometry-based MIMO channel model developed in this thesis is described in detail in Section 3.3.

3.1 Motivation on multi-link scenarios

In general, any realistic wireless network has multiple BSs and/or MSs. It means that all users have to share the networks resources and interference might appear between them. Hence, multi-link scenarios are present nowadays in several radio communication systems. However, investigations on multi-link scenarios are lacking and it has led to concentrate the research effort on channel modeling for multi-link scenarios. Accurate and realistic multi-link channel models are important for future radio communication systems, especially those based on MIMO technology, because in multi-link scenarios the correlation between different links can be investigated. MIMO systems are suitable for multi-link scenarios as long as there is capability of interference cancellation.

Indeed, correlation between propagation channels of different links, also referred as inter-link correlation, must be investigated since it is a crucial property in multi-link scenarios that determines the overall system performance. Consequently, the physical
propagation phenomena affecting the inter-link correlation must be modeled somehow in multi-link scenarios. Common clusters are one the physical propagation phenomena which increases the inter-link correlation and they can be seen as clusters that are simultaneously active in different links. Nevertheless, in a real environment there are also clusters which are active individually for each different link, i.e. clusters which are not shared for different links, also known as uncommon clusters. As was observed in [40], if multiple links share the same clusters then the inter-link correlation increases and the spatial filtering of the links become difficult. Note that systems depending on the spatial characteristics of the channel such as MIMO systems, can be especially deteriorated, i.e. the channel capacity decreases. Therefore, the significance of common clusters should not be underestimated since it can lead to overestimation of the system performance in simulations. Because of this common clusters are one crucial aspect to take into account in multi-link scenarios and a key concept in this thesis. Figure 11 illustrate this key concept that will be further explained in Section 3.2.1. In Figure 11, the equivalence between a modeled and real environment can also be observed.

To summarize, in multi-link scenarios the correlation between links that depends partly on common clusters can be modeled, and so the ML-MIMO channel capacity can be thoroughly investigated. That is why the modeling of ML-MIMO radio channels has attracted special attention within future research activities.

Figure 11: Modeling a common cluster in a simulated and real environment.
3.2 Earlier works on multi-link modeling

To date, there are not too many contributions on multi-link channel modeling. However, one of the ongoing implementations on multi-link MIMO channel modeling is under the framework of the COST activities. In Section 3.2.1 the COST 2100 MIMO channel model is described, that is, the multi-link extension for the channel model introduced by the COST 273 action [41]. Therefore, following the reported work in [42], the basic principles and concepts to consider in multi-link geometry-based MIMO channel modeling are described.

3.2.1 Multi-link extension to COST 273 MIMO Channel Model

The COST 273 MIMO channel model was intended initially for single-link scenarios, hence, it is not able to simulate multi-link scenarios successfully. This shortage led to implement a new channel model based on the previous COST 273 model but with the capability to simulate multi-link scenarios. This multi-link extension is referred as COST 2100 MIMO channel model and it is still under development. Hence, COST 2100 model is a continuation of the COST 273 model and it operates with the same modeling concepts developed under that framework. However, it has many updated features compared to the COST 273 model. The main update of COST 2100 model is its capability to simulate multi-link scenarios, i.e. the model supports simulations with multiple BSs and/or MSs in the simulation environment.

In COST 2100 model, clusters and VRs are generated in the same way as in COST 273 model as described in Section 2.5.1. As multiple BSs can exist in the simulation environment, clusters are possibly associated with more than one VR. Therefore, clusters and its corresponding VRs are generated individually for each BS. It should be kept in mind that VRs in multi-link scenario are important because the quality of a multi-link channel model depends on how VRs are assigned to different BSs. Simulating a multi-MS scenario can be easily done by dropping multiples MSs into the simulation environment and using the same clusters and VRs for each MSs as is shown
in Figure 12a). However, the real difficulty of simulating multi-link scenarios relies on multi-BS scenarios as is shown in Figure 12b). In this class of scenarios, one of the essential properties to take into account is how to realistically model those clusters that are seen by multiple BSs simultaneously. In principle, the distribution of the clusters seen by different BSs is more similar as the distance between them decreases. However, in other scenarios such as corridor scenarios, the clusters seen by different BSs might be the same even if the BSs are separated by a long distance [40]. Therefore, it is not relevant to study scenarios where the distance between the BSs is very small, besides it does not make sense in real wireless networks.

**Figure 12:** Simulation of a) Multi-MS and b) Multi-BS scenario with one common cluster.
The COST 2100 MIMO channel model is then a cluster-based multi-link channel model that includes the crucial concept of *common cluster*. Common cluster is defined as a cluster which is active simultaneously in different links. In other words, common cluster means a cluster that is used at the same time by different links as propagation mechanism of the radio waves. In real environments, this kind of clusters is typically found in corridor environments with NLOS conditions in indoors, and cities with skyscrapers or high buildings emulating a canyon in outdoors. As mentioned in Section 3.1, common clusters increase the correlation between different links and make the spatial filtering of the links difficult. Therefore, common clusters must be taken into account in simulations since the system performance can be totally influenced by its effect.

In [40] there are the criteria that any cluster must follow in order to be considered as common cluster. These criteria are based on the limitations of practical radio communication systems. Following this criteria, common clusters have to satisfy:

1. The physical scattering object is the same for the different links.
2. The distance between the cluster centers of different links \( d \) is less than 10 meters.
3. The angular separation of the cluster centers \( \varphi \) seen from the terminal is less than 90°.
Figure 13: Definition of geometry-dependent conditions in order to consider common clusters as such.

In Figure 13, the small colored circles correspond to individual MPCs whereas the bigger circles are the cluster centers. As shown in [40], the angular separation of the cluster centers $\varphi$ can be easily related with the distance between the cluster centers $d$ and the distance between the MS and cluster center $s$:

$$\tan^{-1}\left(\frac{d}{2s}\right) = \frac{\varphi}{2}$$  \hspace{1cm} (3.1)

In addition, common cluster can be classified into three types, as shown in Figure 14:

1. Common clusters visible only on the BS side.
2. Common clusters visible only on the MS side.
3. Common clusters visible on both the BS and the MS side.
Figure 14: Classification of common cluster according with if they are visible a) only on the BS side, b) only on the MS side, and c) on both the BS and MS sides.
In [42] several additional cluster parameters as inputs for the COST 2100 multi-link channel model are introduced. These parameters describe how similar are the clusters seen by different BSs:

1. Probability of common clusters
2. Common cluster power ratio
3. Lifetime of common clusters
4. The disjoint distance of common clusters

The probability of common clusters \( p_{\text{common}} ^{[42]} \) is the number of clusters simultaneously used by different BSs with respect to the total number of clusters. \( p_{\text{common}} \) can be simply obtained as:

\[
p_{\text{common}} = \frac{N_{\text{common}}}{N_{\text{tot}}} \tag{3.2}
\]

On the other hand, the common cluster power ratio \( \mu_{\text{common}} ^{(i)} ^{[42]} \) is the power conveyed by the common cluster with respect to the total power in the \( i \)-th link:

\[
\mu_{\text{common}} ^{(i)} = \frac{P_{\text{common}} ^{(i)}}{P_{\text{tot}} ^{(i)}} \tag{3.3}
\]

where \( P_{\text{common}} ^{(i)} \) and \( P_{\text{tot}} ^{(i)} \) are the power of common cluster and the total power for the \( i \)-th link, respectively. In fact, this is the measure that was used as significance of common clusters (\( S_{\text{common}} \)) in the channel model developed in this thesis (See Section 3.3.2).

The lifetime of common cluster \( r_{\text{life}} ^{(i)} \) denotes the time that the common cluster is active for the \( i \)-th link (See Figure 15). This lifetime is determined according to the VRs of each link since in general common clusters are not active during exactly the same time in the different links. Note that the common cluster VRs for the different links may have
different radii and even the center points may be in different locations. Therefore, the disjoint distance $r_{dis}$ denotes the distance between the center points of the common cluster VRs in the different links, as seen in Figure 15.

![Clusters](image)

**Figure 15:** Modeling common clusters in the COST 2100 MIMO channel model.

As far as the common cluster power is concerned, a measure called *significance of common scatterers* was also introduced in [40] in order to quantify the amount of the total power that is originating from clusters that are common for the different links. In a dual-link case, the significance of the $n$-th common cluster is expressed in the $k$ measurement time instant as:

$$S_{common}^n(k) = \sqrt{s_{common}^{(1),n}(k) \cdot s_{common}^{(2),n}(k)}$$

(3.4)

where $s_{common}^{(i),n}(k)$ is the significance of the $n$-th common cluster with respect to the $i$-th link defined in [40] as:
Development of multi-link geometry-based MIMO channel model

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\[ S_{\text{common}}^{(i),n}(k) = \frac{P_{\text{common}}^{(i),n}(k)}{P_{\text{tot}}^{(i)}(k)} \] (3.5)

where \( P_{\text{common}}^{(i),n}(k) \) is the amount of power originating from \( n \)-th common cluster for the \( i \)-th link and \( P_{\text{tot}}^{(i)}(k) \) is the total power of the \( i \)-th link. Therefore, the total significance of common clusters was proposed in [40] as the sum of the significance for each individual common clusters \( S_{\text{common}}^{n}(k) \):

\[ S_{\text{common, tot}}(k) = \sum_{n=1}^{N(k)} S_{\text{common}}^{n}(k) \] (3.6)

where \( N(k) \) denotes the total number of clusters that are common for the different links. The total significance of common clusters \( S_{\text{common, tot}}(k) \) gets values between 0 and 1, where 0 means that there are not common cluster for the different links and 1 means that all clusters are common for the different links.

The so-called significance of common scatterers was investigated in [40] based on the previous definitions and experimental results obtained through measurements in two indoor scenarios. These measurements were conducted first in an indoor hall with LOS conditions and second in an office corridor environment with NLOS conditions. In addition, several indoor channel measurements in these scenarios were used in order to define and extract model parameters needed in the COST 2100 model implementation [43].

3.3 Development of simple Multi-link MIMO Channel Model

One of the goals of this thesis is to develop a simple multi-link geometry-based MIMO channel model capable to simulate dual-link scenarios. As mentioned in Section 3.1,
simulating dual-link scenarios allows modeling the correlation between different links in order to investigate its effect on ML-MIMO channel capacity.

### 3.3.1 Approach and key features

According to the classification of MIMO channel and propagation models given in Figure 4, the channel model developed in this thesis is a physical model that adopts the GSCM principle, and the generic approach to model all scenarios with the same generic structure. In principle, the channel model was designed for indoor environments at 5.3 GHz band with a focus on MIMO WLANs. However, it can also be used for outdoor environment by changing the boundaries of the simulation environment and the working frequency. One of the main features adopted from the COST 273 MIMO channel model [30] is the concept of clusters. The channel model developed in this thesis generates clusters that emulate far scattering or single-bounce reflections. The modeling structure of the whole channel model relies on the concept of distinguish among two different kinds of clusters: uncommon and common. Another important feature of this channel model is its capability to simulate multi-link scenarios just by dropping multiple BSs and/or MSs to the simulation environment. As was already mentioned in Section 3.1, common clusters are a key feature in this channel model since they allow modeling the correlation between different links, and thus investigate the ML-MIMO channel capacity. Finally, an implementation code of this simple multi-link geometry-based MIMO channel model was developed with MATLAB.

### 3.3.2 Operating principles

Before going deep into the operating principles, it should be mentioned that any general implementation of this multi-link geometry-based MIMO channel model consists in several steps which are listed below. A dual-link case with one MS and two BSs is considered here.
1. MS, BS1 and BS2 are dropped in the simulation environment.
2. Common cluster centers and corresponding MPCs are generated.
3. Centers and MPCs for uncommon clusters in link 1 are generated.
4. Propagation parameters for all paths determined by the common and uncommon clusters in link 1 are calculated.
5. The power of uncommon clusters in link 1 is tuned in order to match with desired significance of common clusters (0 – 100%).
6. The MIMO channel matrix in link 1 is reconstructed using the propagation parameters calculated previously in step 4, i.e. DoD, DoA, delay, and power of clusters.
7. The sequence is repeated from step 3 for the link 2.
8. The MIMO channel matrix is normalized for link 1 and 2.

Next, let us present the basic operating principles of this multi-link geometry-based MIMO channel model:

First of all, the basic settings configuration allows changing various model parameters Table 1, which will define the desired simulation environment.

Table 1: Channel model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>5.3 GHz</td>
</tr>
<tr>
<td>Number of BSs</td>
<td>2</td>
</tr>
<tr>
<td>Number of MSs</td>
<td>1</td>
</tr>
<tr>
<td>Number of common clusters</td>
<td>1</td>
</tr>
<tr>
<td>Number of uncommon clusters</td>
<td>1</td>
</tr>
<tr>
<td>Number of MPCs within each cluster</td>
<td>1</td>
</tr>
<tr>
<td>Number of TX antennas</td>
<td>4</td>
</tr>
<tr>
<td>Number of RX antennas</td>
<td>4</td>
</tr>
<tr>
<td>Array orientation</td>
<td>( x )</td>
</tr>
<tr>
<td>Distance between antenna elements</td>
<td>$\lambda/2$</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Number of channel realizations</td>
<td>100</td>
</tr>
<tr>
<td>Significance of common clusters</td>
<td>[0,1]</td>
</tr>
<tr>
<td>SNR ($\rho$)</td>
<td>15 dB</td>
</tr>
<tr>
<td>INR ($\eta$)</td>
<td>15 dB</td>
</tr>
</tbody>
</table>

After that, the simulation environment is created based on BSs, MS, and cluster locations that can be generated in either stochastic (random) or deterministic (manually) way. In Figure 17, it can be seen that the boundaries of the simulation environment range tens of meters in both dimensions since the simulation studies carried out in this thesis are focused generally on indoor scenarios. Figure 16 illustrates a general overview of the developed channel model. In Figure 16, the radio waves travel between the TX and the RX through the clusters corresponding to a group of MPCs. Each MPC is characterized by several propagation parameters such as delay ($\tau$), DoD, DoA, phase shift ($\theta$) and power of clusters. From the different parameters calculated before, the CIR or channel transfer function, equivalently, can be exactly reconstructed.

*Figure 16: General overview of channel model developed in this thesis. Here, the generated channel contains two links (MS-BS 1 and MS-BS 2) with 1 uncommon cluster each one and 1 cluster that is active simultaneously for both links (common cluster).*
Figure 17 illustrates an example of simulation environment after run the channel model code created with MATLAB. In the figure, two BSs, one MS, two uncommon clusters (one for each BS) and one common cluster are generated and dropped in the simulation environment. Firstly, BS1 and BS2 are dropped in the simulation environment. Secondly, uncommon cluster locations are generated individually for each BS, i.e. red circles for BS1 and blue circles for BS2. Thirdly, the model generates common cluster locations (black circles in Figure 17). As the number of MPCs within clusters is four, cluster centers were initially calculated to generate after the MPC locations. The MPC locations are uniformly (randomly) distributed at most one meter away around its cluster center. Note that the distance between the cluster center and its MPCs can be also changed in the model. Finally, signals are plotted as rays in order to visualize roughly the length of each path.

![Simulation environment](image)

**Figure 17:** Example of dual-link scenario with 2 uncommon clusters each link and 1 common cluster.
Having fully determined the channel geometry by specific TX, RX, and cluster locations, the following wave propagation parameters are calculated in order to characterize each MPC:

1. **Delay**: The propagation delay $\tau_i$ measures the travelling time of radio waves between the TX and the RX for the $l$-th propagation path. This time can be calculated as:

$$\tau_i = \frac{d_i}{c} \quad (3.7)$$

where $d_i$ is the length of the signal path and $c$ is the speed of light, $3 \cdot 10^8$ m/s.

2. **Phase shift**: It is known that in radio communications, the received signal arises from the sum of different propagation paths caused by the reflection of radio waves with the interacting objects in the environment. Each bounce arrives to the RX antenna with different amplitudes and phases, depending on the reflectivity coefficient, and different delay. Considering the transmission of a carrier-modulated signal, the effect of different delays implies that the signal is received in the antenna with totally different phases. This change in the phase for the $l$-th propagation path is calculated in [1] as:

$$PS_i = 2\pi \cdot f \cdot \tau_i \quad (3.8)$$

where $f$ is the working frequency at 5.3 GHz, and $\tau_i$ is the $l$-th propagation path delay.

3. **Direction of departure and arrival**: They are calculated as the angle between a reference direction and the direction of each MPC seen from the MS (DoD) and BS (DoA) sides. Figure 18 shows the criterion that is used to calculate these
angles, i.e. what reference direction is considered to calculate the DoD and the DoA. In Figure 18, DoD and DoA always range between $-180^\circ$ and $180^\circ$.

![Diagram](image)

**Figure 18:** Method used to calculate DoD and DoA parameters according to the established reference direction. In this example, the DoD is equal to $45^\circ$ while the DoA is $-125^\circ$.

4. *Path loss and received power*: The path loss $L_p$ of each MPC is calculated as in the equation (2.2). From equation (2.19), the received power of each individual MPC considering unity gain antennas is calculated as:

$$P_R = \frac{P_T}{L_p \cdot L_R} \quad (3.9)$$

where $P_T$ is the transmitted power whose value is set to 1 Watt, and $L_R$ is defined as reflection losses and its value is set to 6 dB in the model.
Once all propagation parameters for each MPC are calculated, the model generates three graphics (Power of clusters, DoD vs DoA, and PDP) in order to visualize the differences between links in terms of delay, direction, and power of its clusters. The following example results correspond to Figure 17 where there are two uncommon clusters per BS and one common cluster.

Figure 19 presents a comparison of the amount of the total power that is carried by each cluster in each propagation channel. In counterclockwise direction, the percentages correspond first to the uncommon clusters (blue and green color) and second to the common clusters (brown color).

![Figure 19: Percentage of power conveyed by each different cluster. In this particular example, the significance of common clusters is 60% whereas the uncommon clusters convey the rest of power, 40%.](image)

**Figure 19:** Percentage of power conveyed by each different cluster. In this particular example, the significance of common clusters is 60% whereas the uncommon clusters convey the rest of power, 40%.

¡Error! No se encuentra el origen de la referencia. illustrates a comparison of the geometry between each propagation channel by plotting the DoD and DoA of each individual MPC. The blue circles correspond to uncommon clusters whereas green circles correspond to the common cluster. Note that the axes are defined between -180 and 180 degrees according to the criterion chosen above. ¡Error! No se encuentra el origen de la referencia., on the other hand, shows a comparison of the PDP between links. Theoretically, in radio communications the PDP is defined as the average of CIRs due to temporal evolution of the channel (time-variant). Here, the PDP is just used to
characterize the channel with respect the received power and the propagation delay. Circles correspond to the common cluster and triangles to uncommon clusters.
Figure 20: a) DoD vs DoA, and b) Power Delay Profile for each individual MPC. Green circles correspond to MPCs within common clusters whereas blue circles correspond to MPCs within uncommon clusters. Note that MPCs within a cluster have close values.
The significance of common clusters (S_common in the labeling of figures) is a model parameter that is chosen in a deterministic way in the beginning. Therefore, it is required to tune the power of uncommon clusters in order to match with the wanted significance of common clusters for each link. The significance of common clusters [40] in the i-th link is calculated in the own channel model as already defined in equation (3.5):

\[
S^{(i)}_{\text{common}} = \frac{P^{(i)}_{\text{common}}}{P^{(i)}_{\text{tot}}} = \frac{P^{(i)}_{\text{common}}}{P^{(i)}_{\text{common}} + P^{(i)}_{\text{uncommon}}} \quad \text{(3.10)}
\]

where \( P^{(i)}_{\text{common}} \) is the total power of common clusters of the i-th link, \( P^{(i)}_{\text{uncommon}} \) is the total power of uncommon clusters of the i-th link, and \( P^{(i)}_{\text{tot}} \) is the total power of the i-th link. Furthermore, the significance of common clusters can be considered equal or different for the different links, as seen in Figure 21.

From the definition given above (3.10), the total power of uncommon clusters has to be modified applying an extra attenuation which is calculated as:

\[
S^{(i)}_{\text{common}} = \frac{P^{(i)}_{\text{common}}}{P^{(i)}_{\text{tot}}} + L \cdot P^{(i)}_{\text{uncommon}} \quad \Leftrightarrow \quad L = \frac{P^{(i)}_{\text{common}} \cdot (1 - S^{(i)}_{\text{common}})}{P^{(i)}_{\text{uncommon}} \cdot S^{(i)}_{\text{common}}} \quad \text{(3.11)}
\]

It should be paid special attention to extreme cases where the significance of common clusters is 0 or 1. For \( S^{(i)}_{\text{common}} = 0 \) the extra attenuation is infinite, it means that all power is conveyed by the uncommon clusters since the common clusters are not contributing to the propagation mechanism of radio waves. On the other hand, for \( S^{(i)}_{\text{common}} = 1 \) the extra attenuation is 0 because common clusters convey the entire power and then \( P^{(i)}_{\text{uncommon}} \) has not to be modified.
Figure 21: Modeling a common cluster with a) the same significance and b) different significance for the different links.
All in all, the channel transfer function is then calculated for each different link. As already mentioned in Section 2.3.2, any GSCM is determined by the cluster locations. The CIR is then characterized by the laws of wave propagation applied to specific TX, RX and cluster geometries, and hence it will consist of contributions of all individual MPCs. Disregarding polarization in the model and considering a static channel (time-invariant), the propagation channel can be described by the double-directional CIR, as in equation (2.27). In other words, this model describes the propagation channel in the delay and the direction domains at both TX and RX sides using clusters. Therefore, the MIMO channel transfer function or channel matrix is reconstructed using the propagation parameters calculated in the previous steps, i.e. DoD, DoA, delay, and power of each MPC. The MIMO channel matrix [44] for the $i$-th link is given by:

$$
\mathbf{H}^{(i)}(f) = \sum_{l} \beta_{l} \cdot e^{-j(2\pi f \tau_{l} + \xi_{l}^{(i)})} \cdot \mathbf{a}_{l,\text{Tx}}(\phi_{l}^{\text{Tx}}) \cdot \mathbf{a}_{l,\text{Rx}}^{T}(\phi_{l}^{\text{Rx}}) 
$$

(3.12)

Here, $L$ is the total number of propagation paths, $\beta_{l}$ is the complex amplitude calculated as the square root of the received power of the $l$-th propagation path, $\tau_{l}$ is the propagation time of the $l$-th propagation path, and $e^{-j2\pi f \tau_{l}}$ is the complex exponential resulting from the delay domain. Further, $\mathbf{a}_{l,\text{Tx}}$ ($\mathbf{a}_{l,\text{Rx}}$) is the steering vector of the TX (RX) array in the direction $\phi_{l}^{\text{Tx}}$ ($\phi_{l}^{\text{Rx}}$), and $(\cdot)^{T}$ denotes transpose operation. For instance, considering a broadside TX array (same amplitude and phase) with four elements [44]:

$$
\mathbf{a}_{l,\text{Tx}}(\phi_{l}^{\text{Tx}}) = \begin{bmatrix} 1 & \exp\left(j(\mathbf{d}_{a}, \mathbf{k})\right) & \exp\left(j(2 \cdot \mathbf{d}_{a}, \mathbf{k})\right) & \exp\left(j(3 \cdot \mathbf{d}_{a}, \mathbf{k})\right) \end{bmatrix}^{T} 
$$

(3.13)

$$
\mathbf{k} = \frac{2\pi}{\lambda} \begin{bmatrix} \sin \theta_{l}^{\text{Tx}} \cos \phi_{l}^{\text{Tx}} & \sin \theta_{l}^{\text{Tx}} \sin \phi_{l}^{\text{Tx}} \cos \theta_{l}^{\text{Tx}} \end{bmatrix}^{T} 
$$

(3.14)

Note that each MPC is spatially characterized only by its azimuth of departure and arrival, i.e. DoD and DoA. As elevation is not considered in this channel model, $\theta$ is $90^\circ$ for all propagation paths so that $\mathbf{k}$ is calculated as:
\[ k = \frac{2\pi}{\lambda} \begin{bmatrix} \cos \phi_{T}^{x} & \sin \phi_{R}^{x} & 0 \end{bmatrix} \]  

(3.15)

For \( x \)-oriented arrays, the distance between antenna elements is:

\[ \mathbf{d}_a = \frac{\lambda}{2} \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \]  

(3.16)

For \( y \)-oriented arrays, the distance between antenna elements is:

\[ \mathbf{d}_a = \frac{\lambda}{2} \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \]  

(3.17)

Finally, uniformly distributed random phases \( \xi(l) \) are applied to the MPCs in order to create independent channel matrix realizations. This technique that was introduced in [45] relies on the fact that different realizations of the transfer function can be generated by changing the phases of the MPCs. This is a well-established fact in radio communications that these phases are uniformly distributed random variables, whose different realizations occur as either TX, RX or clusters move [46]. Therefore, this technique only requires a single calculation of the propagation parameters of the channel to get several realizations.

Having calculated all realizations of the channel matrix for each link, the received power for the \( i \)-th link can be expressed as reported in [44], and [47]:

\[ P_i = \frac{1}{N_S \cdot N_T \cdot N_R} \sum_{s=1}^{N_s} \| \mathbf{H}_i(s) \|_F^2 \]  

(3.18)

where \( N_S \), \( N_T \), and \( N_R \) denote the number of channel realizations, TX antennas, and RX antennas, respectively. Further, \( \mathbf{H}_i(s) \) is the \( s \)-th realization of the channel matrix for the \( i \)-th link.
Finally, the MIMO channel matrix for the $i$-th link and $s$-th realization is normalized in the same way as described in [44], and [47]:

$$
\hat{H}_i(s) = \frac{H_i(s)}{\sqrt{P_i}}
$$

(3.19)

Hereafter, these channel matrices will be used in the analysis of the inter-link correlation and consequently in the capacity analysis, as in Section 4.1.

### 3.3.3 Verification of the channel model

In this section, a simple verification of the multi-link geometry-based MIMO channel model developed in this work is performed. It must be somehow checked out that the channel model works properly. To that end, a very simple channel where it is know how the results should be is used in order to verify that channel matrices, capacities and correlations are calculated correctly. Figure 22 illustrates the simple dual-link simulation environment that was chosen for that purpose. In the figure, the simulation environment contains one common cluster with only one MPC, one MS, two BSs, and $x$-oriented arrays in TX and RX with four antenna elements. Link 1 is defined between MS and BS1 and link 2 between MS and BS2. As the propagation mechanism is only based on one cluster that is common for BS1 and BS2, the normalized $4 \times 4$ MIMO channel matrix for both links should be like:

$$
\hat{H} = \begin{pmatrix}
a & a & a & a \\
b & b & b & b \\
c & c & c & c \\
d & d & d & d \\
\end{pmatrix}
$$

(3.20)

where it can be observed that the columns of the channel matrix are equal. This indicates that the propagation channel seen by the MS side has the same spatial and
delay properties. Note that the DoD is totally horizontal to the array geometry (90°), and thus the transmitted signal from each different TX antenna has to be the same. However, the propagation channel seen by the BS side is different for each different RX antenna.

In reception, the wave fronts impinging each different RX antenna will arrive at different temporal instants. The DoA is -26.5° and -153.4° for BS1 and BS2 respectively, and thus the propagated signals will be received in the corresponding RX antenna with a different phase. Indeed, the channel matrices obtained for one particular channel realization fulfill the equation (3.20):

**Figure 22:** Modeling a simple propagation channel with 2 links and only one common cluster as propagation mechanism.
As the propagation mechanism is the same for link 1 and link 2, the correlation between links or inter-link correlation (See Section 4.1 for more details) should be close to one for all values of significance of common clusters different to 0. Indeed, Figure 23b) illustrates the expected results for the inter-link correlation. Therefore, the TX correlation matrices for links 1 and 2 should be the same and all its entries equal to one. Exactly, the normalized correlation matrices look as expected for both links:

\[
\begin{pmatrix}
1.0000 & 1.0000 + j0.0000 & 1.0000 + j0.0000 & 1.0000 + j0.0000 \\
1.0000 + j0.0000 & 1.0000 & 1.0000 + j0.0000 & 1.0000 + j0.0000 \\
1.0000 + j0.0000 & 1.0000 + j0.0000 & 1.0000 & 1.0000 + j0.0000 \\
1.0000 + j0.0000 & 1.0000 + j0.0000 & 1.0000 + j0.0000 & 1.0000
\end{pmatrix}
\]

As the inter-link correlation determines the system performance, it might be expected that the dual-link to single-link capacity ratio (a further explanation can be found in Section 4.1) will be always close to the theoretical minimum for all significance of common clusters different to zero. Indeed, Figure 23a) shows the expected results for the capacity over the significance of common clusters. Figure 23 was obtained under the assumption that the significance of common clusters is the same for the different links, as shown in Figure 21a).
Figure 23: Simulation results on a) channel capacity and b) inter-link correlation. As the main propagation mechanism consist in only one common cluster, the inter-link correlation is always close to one and, in turn, the dual-link to single-link capacity ratio reaches always the lowest possible value.
3.3.4 Relation to COST 2100 MIMO channel model

As mentioned in Section 3.2.1, the COST 2100 model is a geometry-based MIMO channel model capable to simulate multi-link scenarios. However, there are some relevant differences between the COST 2100 model and the own multi-link geometry-based MIMO channel model developed in this thesis. Note that COST 2100 model is the successor of COST 273 model and therefore, there is also an implicit relation with the COST 273 model in the following comparison. The comparison between the ongoing COST 2100 model and the channel model developed in this thesis is explained below:

To begin with, both models follow the same approach since they are a geometry-based stochastic physical MIMO channel model. They have also a cluster-based structure and are capable to simulate multi-link scenarios. In both models, clusters are implemented and treated as a group of MPCs and involves the use two kinds of clusters: common and uncommon clusters. Both models calculate the power of common clusters as described in equation (3.3), that is, the significance of common clusters for one specific link. Both models are double-directional, i.e. they calculate the CIR in delay and direction as in (2.25) because the generated radio channels are dispersive in the angular and delay domain. Therefore, the MIMO channel matrices will be derived in both models from the double-directional channel impulse response.

Although they share this features, the COST 2100 model provides more detailed and realistic characterization of clusters and MPCs than in the channel model developed in this thesis (e.g. the COST 2100 cluster-based structure allows to simulate local and far clusters or reflections by single bounces and multiple bounces). In addition, the COST 2100 model goes further than the own model and includes the concept of VRs in order to simulate the dynamic behavior of the channel, as explained in Section 3.2.1. It should be also mentioned that LOS component is not calculated in the own channel model, and
COST 2100 cluster parameters such as probability of common clusters, lifetime of common clusters, and disjoint distance of common clusters either.

To sum up, the developed multi-link geometry-based MIMO channel model generates a static multipath radio channel by single bounce clusters that emulate far scattering and since there are not VRs, clusters are always active for its corresponding BS. Clusters are implemented as a conceptual term because they have a simple characterization in comparison to COST 2100 model. It has been included the option to distinguish between two types of clusters: common and uncommon, as in the COST 2100 model. Finally, the MIMO channel calculation is carried out in the same way as in COST models, i.e. as described in Section 2.5.1.


4 EFFECT OF COMMON CLUSTERS ON MULTI-LINK MIMO CAPACITY AND INTER-LINK CORRELATION

The greatest motivation in this thesis is to investigate how the common clusters affect the ML-MIMO system performance depending on its significance or geometry. As already mentioned, common clusters for two or more different links are one of the physical phenomena affecting significantly the correlation between different links in multi-link scenarios. Hence, radio communication systems depending on the spatial characteristics of the channel such as MIMO system can be especially deteriorated, e.g. if multiple links share the same clusters then the inter-link correlation increases and the spatial filtering of the links becomes difficult. Therefore, it is important to have an understanding of common clusters because underestimate the significance of common clusters is not appropriate since it can lead to overestimate the system performance in system-level simulations.

This chapter is organized in the following way. In Section 4.1, some definitions are given in order to perform the data analysis that will enable to study the ML-MIMO channel capacity and the correlation between links. In Section 4.2, previous works where the dual-link capacity and inter-link correlation are analyzed with measured channel data from indoor ML-MIMO channels are briefly presented. In Section 4.3, the capacity and correlation results obtained in this thesis are provided.

4.1 Data analysis

The analysis and processing of the obtained channel matrices are explained in this section following the same methodology that was conducted in [44] and [47].

4.1.1 Single-link MIMO Capacity

For the single-link case, the vector of received signal can be written as [47]
\[ y = \sqrt{\rho} \cdot \hat{H} \cdot x + n \]  

where \( \hat{H} \) is the normalized channel matrix calculated in (3.19), \( \rho \) is the signal to noise ratio (SNR), and \( n \) is a noise vector. Hence, the single-link capacity can be calculated as [44]:

\[
C(\hat{H}) = \log_2 \left[ \det \left( I_{N_s} + \frac{\rho}{N_T} \hat{H} \cdot \hat{H}^H \right) \right]
\]  (4.2)

where \( I_{N_s} \) is the identity matrix of size \( N_s \), and \((\cdot)^H\) denotes the conjugate transpose.

Finally, considering a dual-link MIMO channel the single-link sum rate capacity would be \( C(\hat{H}_1) + C(\hat{H}_2) \).

### 4.1.2 MIMO Capacity with Interference

For the dual-link case, the received signal can be written as in [48]:

\[ y = \sqrt{\rho} \hat{H}_1 x_1 + \sqrt{\eta} \hat{H}_2 x_2 + n \]  (4.3)

where \( \hat{H}_1 \) and \( \hat{H}_2 \) represent the normalized channels matrices of the desired and interfering link. In addition, \( \rho \) and \( \eta \) are the SNR and the interference to noise ratio (INR), respectively, and \( n \) is a noise vector. Hence, the dual-link capacity with interference [44], [47] is expressed as

\[
C(\hat{H}_1, \hat{H}_2) = \log_2 \left[ \det \left( I_{N_s} + \frac{\rho}{N_T} \hat{H}_1 \hat{H}_1^H R_2^{-1} \right) \right]
\]  (4.4)

where the instantaneous covariance matrix is calculated as
\[
R_2 = \eta \hat{H}_2 \hat{H}_2^H + I_{N_s} \quad (4.5)
\]

Here, \(\hat{H}_1\) and \(\hat{H}_2\) are the channel matrices of the desired and the interfering user, respectively. \(I_{N_s}\) is the identity matrix of size \(N_R\) and \((\cdot)^H\) denotes the conjugate transpose. Here, the dual-link sum rate capacity is defined as \(C(\hat{H}_1, \hat{H}_2) + C(\hat{H}_2, \hat{H}_1)\).

As far as the results are concerned, the sum rate dual-link channel capacity is compared with the sum rate single-link channel capacity [47], i.e. the sum-rate channel capacity with interference cancellation is compared with the sum rate channel capacity with perfect interference cancellation. Hence, the following relative capacity (RC), i.e. the dual-link to single-link capacity ratio, measures the percentage of the single-link capacity and ranges between 0\% and 100\%:

\[
RC[\%] = \frac{\text{Dual - link sum rate capacity}}{\text{Single - link sum rate capacity}} = \frac{C(\hat{H}_1, \hat{H}_2) + C(\hat{H}_2, \hat{H}_1)}{C(\hat{H}_1) + C(\hat{H}_2)} \quad (4.6)
\]

### 4.1.3 Correlation and Matrix Collinearity

Once channel matrices are obtained, a TX correlation matrix is calculated individually for each link [44]:

\[
R^{(i)} = \frac{\sum_{s=1}^{N_s} (\hat{H}_i(s))^H \cdot \hat{H}_i(s)}{\left(\frac{1}{N_T} \sum_{s=1}^{N_s} \|\hat{H}_i(s)\|_F^2\right)} \quad (4.7)
\]

where \(\hat{H}_i(s)\) is an \(s\)-th realization of channel matrix for the link \(i\) \((i = 1, 2)\), \(N_s\) the number of channel realizations, \(N_T\) the number of transmitter antennas, and \((\cdot)^H\) is the
complex conjugate. Furthermore, the correlation matrix is normalized in order to remove path losses.

Having calculated the full correlation matrix, the inter-link correlation is investigated as the collinearity [49] between the correlation matrices $\mathbf{R}^{(1)}$ and $\mathbf{R}^{(2)}$. The collinearity quantifies the channel similarity in the following way:

$$MC(\mathbf{R}^{(1)}, \mathbf{R}^{(2)}) = \frac{|tr\left(\mathbf{R}^{(1)}\left(\mathbf{R}^{(2)}\right)^H\right)|}{\|\mathbf{R}^{(1)}\|_F \|\mathbf{R}^{(2)}\|_F}$$  \hspace{1cm} (4.8)

where $\mathbf{R}^{(1)}$ and $\mathbf{R}^{(2)}$ are the complex-valued matrices to be compared, $tr\left(\cdot\right)$ denote the trace of a matrix, $\|\cdot\|_F$ denotes the Frobenius norm of a matrix, and $(\cdot)^H$ is the matrix conjugate transpose operation. In general, this measure describes how similar the subspaces of the compared matrices are. The collinearity ranges between zero (no collinearity, i.e. matrices are orthogonal to each other) and one (full collinearity, matrices are similar).

### 4.2 Earlier works

To date, only few contributions have targeted capacity and correlation analysis in multi-link scenarios. First capacity studies measuring simultaneously multi-user MIMO data were performed in [50] and [51]. But recently, novel works using measured channel data have been also performed by Aalto University in the Department of Radio Science and Engineering in order to analyze the inter-link correlation [44] and dual-link MIMO channel capacity [47].

In [44] a measurement campaign in a real environment with one TX and two RX was conducted in order to analyze the inter-link correlation properties between two 4 x 4 MIMO links. In this analysis, after the dual-link channel measurements and data
processing, the correlation matrices of the links are reconstructed and used to investigate the inter-link correlation and how the physical propagation mechanisms produce the inter-link correlation. Conclusions given in this work reveal that the inter-link correlation arises as a result of the similarity of dominant propagation mechanisms such as LOS and reflections due to proximity objects, and antenna array geometry.

In [47] the dual-link MIMO channel capacity was analyzed based on simulations and a channel measurement campaign in an indoor office environment with two 4 x 4 MIMO links. The measurements were conducted using recently developed measurement system [52], i.e. using a 5.3 GHz dynamic dual-link dual-polarized wideband MIMO channel sounder. In order to provide results, the dual-link channel capacity was compared to the single-link channel capacity. The analysis of the results concluded that the dual-link channel capacity is more affected by the signal to interference ratio (SIR) than the spatial separation of the RXs, and the human shadowing produces variations of SIR up to ±10 dB that cause large fluctuations in the dual-link channel capacity.

### 4.3 Results

In order to provide results, simulation studies were done using the multi-link geometry-based MIMO channel model developed in Section 3.3. Each simulation environment is analyzed based on the previous definitions of Section 4.1. A dual-link case working at 5.3 GHz with NLOS conditions is considered for all conducted simulations.

The results on the dual-link to single capacity ratio and inter-link correlation are presented for different values of significance ranging between 0 % and 100%. Unless otherwise noted, the following simulation results consider the same significance of common clusters for each different link, as shown in Figure 21a).

Initially, a simple simulation environment was created with one common cluster located between both BSs at [0, 20] and two uncommon clusters around the MS, as seen in
Figure 24. In the figure, the number of MPCs for each cluster was set to four and the x-oriented array in TX and RX has four antenna elements. In Table 2 other model parameters are presented.

Figure 24: First simulation environment studied. MS and BSs are equipped with arrays of 4 antenna elements. MS-BS1 defines link 1 which contain one uncommon cluster (red circles). Equivalently, MS-BS2 defines link 2 with its uncommon cluster (blue circles). Finally, black circles denote the common cluster for link 1 and link 2. As can be observed, the number of MPCs was set to 4 according to [43].
Table 2: Model parameters for implementation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS position</td>
<td>[0, 0] / [m]</td>
</tr>
<tr>
<td>BS1 position</td>
<td>[-20, 20] / [m]</td>
</tr>
<tr>
<td>BS2 position</td>
<td>[20, 20] / [m]</td>
</tr>
<tr>
<td>Number of uncommon clusters</td>
<td>1</td>
</tr>
<tr>
<td>Number of common clusters</td>
<td>1</td>
</tr>
<tr>
<td>Number of MPCs</td>
<td>4</td>
</tr>
<tr>
<td>Number of channel realizations</td>
<td>100</td>
</tr>
<tr>
<td>SNR</td>
<td>15 dB</td>
</tr>
<tr>
<td>INR</td>
<td>15 dB</td>
</tr>
<tr>
<td>Number of TX antennas</td>
<td>4</td>
</tr>
<tr>
<td>Number of RX antennas</td>
<td>4</td>
</tr>
<tr>
<td>Array orientation</td>
<td>X</td>
</tr>
<tr>
<td>Distance between antenna elements</td>
<td>$\lambda / 2$</td>
</tr>
<tr>
<td>Number of channel realizations</td>
<td>100</td>
</tr>
<tr>
<td>SNR</td>
<td>15 dB</td>
</tr>
<tr>
<td>INR</td>
<td>15 dB</td>
</tr>
</tbody>
</table>

Figure 25 illustrates the expected results where, in general, the inter-link correlation increases and the dual-link to single-link capacity ratio decreases with increasing significance of common clusters. When the significance of common clusters is 0% the propagation mechanism is only based on the uncommon clusters and the system performance depends on the cluster geometries. In this case, it can be observed that different links are not correlated and the dual-link capacity is roughly equal to the single-link capacity. On the other hand, for 100% of significance of common clusters the propagation mechanism consists only in the common cluster and then the inter-link correlation is one whereas the dual-link channel capacity reaches a minimum value (30% of the single-link channel capacity).
Figure 25: Results on a) dual-link channel capacity and b) inter-link correlation for the first simulation environment. It can be observed how a) the dual-link to single-link capacity ratio and b) the inter-link correlation decreases and increases with increasing significance of common clusters, respectively.
Secondly, the simulation environment under consideration has the same configuration (Table 2) than in Figure 24 but different geometry. Here, the uncommon cluster centers for different links are overlaid in the same location, and so the MPCs could be partially or totally overlapped. As uncommon clusters behave as common clusters, it is equal to have a scenario with two common clusters placed in [0, 20] and [10, 0]. Figure 26 shows the simulation environment with this particular geometry.

![Simulation environment](image)

**Figure 26:** Second simulation environment studied where the uncommon clusters are overlaid.

Indeed, the main propagation mechanism in this scenario consists in two common clusters. In Figure 27 it can be seen that the correlation between links is always very close to one, and so the dual-link capacity decrease. Low values of the dual-link channel capacity are then observed (20% of the single link capacity) with all significance of common clusters. Note that the dual-link to single-link capacity ratio remains almost constant along the significance of common clusters; only small fluctuations are observed due to the fading of the different propagation paths.
Development of multi-link geometry-based MIMO channel model

Alvaro Palacios

Figure 27: Results on a) dual-link channel capacity and b) inter-link correlation for the second simulation environment. As there are only common clusters as propagation mechanism in the channel, the inter-link correlation was always close to one, and thus the dual-link capacity reached low values compared to the single-link case for any value of significance.
Thirdly, the following simulation environment holds the same parameters (See Table 2) but different geometry of uncommon clusters, as shown in Figure 28. In the figure it can be seen that the geometry of uncommon clusters is symmetrical respect to the array orientation.

![Simulation environment](image)

**Figure 28:** Third simulation environment studied. Interestingly, here, the uncommon clusters have symmetric geometry respect to the array. The common cluster still remains in the same position than in the simulation studies conducted before.

In principle, here, it might be expected the same results than in the first simulation scenario. Interestingly, Figure 29 shows that the inter-link correlation is always very high and consequently the dual-link capacity takes low values compared to the single-link case even if uncommon clusters are not overlaid in the same location. Therefore, here, the geometry of uncommon clusters and antenna array play an important role in the ML-MIMO system performance.
Figure 29: Results on a) dual-link channel capacity and b) inter-link correlation for the third simulated environment. As consequence of the ambiguity of linear arrays [53], the channel geometry shown in Figure 28 is especially harmful for the system performance as can be seen here.
Figure 29 revealed that these results are due to the ambiguity of linear arrays [53] to distinguish signals impinging on the array from symmetric directions respect its orientation. For instance, in any linear array using beamforming, if the search is performed from 0° to 360°, then the mirror image of each signal impinging the array with respect to 180° is considered as a signal coming from the same direction. In Figure 28 the x-oriented antenna array in the MS is not able to resolve in the spatial domain those signals travelling through the uncommon clusters. The uncommon cluster for BS1 is seen at angle 135° and its mirror at -135° corresponds to the uncommon cluster for BS2. These angles cannot be seen as different directions (DoD) due to the ambiguity of the x-oriented linear array. In such case the simulation environment shown in Figure 28 could be seen as an equivalent scenario with two common cluster locations, as shown in Figure 30. As a result, the ML-MIMO channel capacity and inter-link correlation are quite similar to the previous simulation environment (Figure 26) where uncommon clusters are intentionally overlaid.

Figure 30: Equivalent scenario to the simulation environment shown in Figure 28.
Even if both directions are parallel to the array, as shown in Figure 31, those directions cannot be resolved by the array due to the lack of resolution. Interestingly, it was noticed again a degradation in the ML-MIMO system performance as a consequence of the clusters and array geometry, as seen in Figure 32.

Figure 31: Simulation environments with directions of departure parallel to the MS array.
Figure 32: a) and c) illustrate the dual-link to single-link capacity ratio and inter-link correlation respectively for the simulation environment shown in Figure 31a), whereas b) and d) are for the simulation environment shown in Figure 31b). From these results, it can be concluded that the channel geometries shown in Figure 31 cannot be resolved for linear array either.

Hence, it can be concluded that the overall system performance might depend on either common clusters or channel geometry (clusters and arrays). In order to thoroughly investigate how often each case restrict the ML-MIMO system performance, a set of 1000 samples were taken from simulations that were performed for individual values of significance of common clusters such as 0%, 1%, 10%, 50%, 99%, 100%. Here, a
sample can be understood as the obtained value of RC, or MC according to specific channel geometry after conduct a simulation. For that purpose, it was considered a random placement of all clusters (common and uncommon). In addition, some model parameters that were extracted from measurement data in a typical indoor scenario [43] are used. For instance, it was noticed that the average number of active clusters is 3.69 and the number of MPCs within a cluster is rarely more than five. Table 3 presents the model parameters configuration that was utilized in order to model an indoor scenario in a more realistic manner than before.

Table 3: Channel model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS position</td>
<td>[0, 0] / [m]</td>
</tr>
<tr>
<td>BS1 position</td>
<td>[-20, 20] / [m]</td>
</tr>
<tr>
<td>BS2 position</td>
<td>[20, 20] / [m]</td>
</tr>
<tr>
<td>Number of uncommon clusters</td>
<td>3 (random)</td>
</tr>
<tr>
<td>Number of common clusters</td>
<td>1 (random)</td>
</tr>
<tr>
<td>Number of MPCs</td>
<td>4</td>
</tr>
<tr>
<td>Number of channel realizations</td>
<td>100</td>
</tr>
<tr>
<td>SNR</td>
<td>15 dB</td>
</tr>
<tr>
<td>INR</td>
<td>15 dB</td>
</tr>
<tr>
<td>Number of TX antennas</td>
<td>4</td>
</tr>
<tr>
<td>Number of RX antennas</td>
<td>4</td>
</tr>
<tr>
<td>Array orientation</td>
<td>X</td>
</tr>
<tr>
<td>Distance between antenna elements</td>
<td>$\lambda / 2$</td>
</tr>
<tr>
<td>Number of channel realizations</td>
<td>100</td>
</tr>
<tr>
<td>SNR</td>
<td>15 dB</td>
</tr>
<tr>
<td>INR</td>
<td>15 dB</td>
</tr>
</tbody>
</table>
Figure 33 shows one possible example of simulation environment. The BSs and MS were fixed again in the same locations whereas all clusters were uniformly distributed within simulation environment. The total number of clusters for each link is four and the number of MPCs within a cluster is also four.

Figure 33: Example of dual-link scenario with 3 uncommon clusters per link and 1 common cluster. The number of MPCs within a cluster was set to 4. The cluster locations were generated randomly.
In Figure 34a) it can be observed that for 99% and 100% of significance of common clusters the ratio between the dual-link and single-link capacity is ranging between 10% and 25% with 50% of probability. However, for values of significance below 50% the dual-link to single-link capacity ratio is ranging between 25% and 65% with also 50% of probability. Moreover, values above 65% are rarely observed for 99% and 100% of significance; values above 75% are not very common for 50% of significance. In the extreme cases with low values of significance (below 10%), it can be even reached theoretical values of 95% but not more. To sum up, lower values of dual-link to single-link capacity ratio can be reached more probably with increasing significance of common clusters.

As far as the inter-link correlation is concerned, Figure 34b) shows that curves for 0%, 1% and 10% of significance of common clusters behave similarly. These curves are almost linear with the inter-link correlation and this situation corresponds to the uniform distribution of the inter-link correlation between 0 and 1. However, values below 0.6 are rarely observed for 50% of significance and typically more than 0.95 in the extreme case, i.e. 99% and 100% of significance of common clusters. In brief, the inter-link correlation could adopt any value between 0 and 1 with low values of significance of common clusters, whereas for high significance of common clusters, the inter-link correlation is always very close to 1 with high probability.
Figure 34: CDF over 1000 samples of a) dual-link to single-link capacity ratio and b) inter-link correlation, for each different value of S_common (significance of common clusters)
Further, it would be also interesting to study a simple scenario where the significance of common clusters is different for the different links, as shown in Figure 21b). The following analysis was intended to investigate whether it is meaningful to treat a cluster as common cluster for the different links when it is very significant only for one of the links. The analysis is also restricted to a dual-link case with 4 x 4 MIMO links. For simplicity, one common cluster and two uncommon clusters are again considered, as seen in Figure 35. The analysis is carried out in four different dual-link scenarios where the significance of the common cluster for the different links is:

a) $s^{(1)}_{\text{common}} = 10\%$ and $s^{(2)}_{\text{common}} = 90\%$

b) $s^{(1)}_{\text{common}} = 90\%$ and $s^{(2)}_{\text{common}} = 10\%$

c) $s^{(1)}_{\text{common}} = 10\%$ and $s^{(2)}_{\text{common}} = 10\%$

d) $s^{(1)}_{\text{common}} = 90\%$ and $s^{(2)}_{\text{common}} = 90\%$

First of all, considering the equation (3.4) given in Section 3.2.1, the total significance of the common cluster for each case is:

a) $S_{\text{common}} = \sqrt{s^{(1)}_{\text{common}} \cdot s^{(2)}_{\text{common}}} = \sqrt{0.1 \cdot 0.9} = 0.3$

b) $S_{\text{common}} = \sqrt{0.9 \cdot 0.1} = 0.3$

c) $S_{\text{common}} = \sqrt{0.1 \cdot 0.1} = 0.1$

d) $S_{\text{common}} = \sqrt{0.9 \cdot 0.9} = 0.9$

From these results, it can be concluded that the common cluster in a) and b) as propagation mechanism should have similar relevance as in c). In order to make sure of this behavior, an analysis based on simulations is conducted for the different cases.
Figure 35: Dual-link scenario with one common cluster fixed in (0, 20), and one uncommon cluster per link whose location is generated randomly.

Figure 35 shows one possible simulation environment with random placement of uncommon clusters. The rest of model parameters were established as in Table 2. However, the significance of common clusters was changed for the different links according to cases a), b), c), and d). Considering this, the CDF was extracted by taking 1000 samples of dual-link to single-link capacity ratio and inter-link correlation. Here, a single sample is the value taken from the generated environment after simulate.

Figure 36a) illustrates the CDF of the dual-link to single-link capacity ratio. Interestingly, it can be appreciated that curves corresponding to different significance for different links have similar evolution than the curve corresponding to 10% of significance of common clusters for both links. In Figure 36b) the CDF of inter-link correlation is shown. Therefore, as expected, Figure 36 indicates clearly that cases a) and b) behave much like c) than d).
Figure 36: CDF over 1000 samples of a) dual-link to single-link capacity ratio, and b) inter-link correlation. The simulated curves are shown for the cases mentioned above.
Intuitively, under the assumption that common clusters have a noticeable difference between its significance for the different links, e.g. case a) or b), the link with higher significance will use mainly the common cluster as propagation mechanism. In contrast, the other link has low significance of common clusters, and thus the main propagation mechanism consists of its uncommon clusters. Indeed, each link uses different propagation mechanism as in a dual-link scenario where common clusters have low significance for both links, e.g. case c), that is, each link using its uncommon clusters.

However, in case d) the common cluster is the main propagation mechanism for link 1 and 2 due to its high significance for both links. As a consequence, the inter-link correlation is always close to one, as shown in Figure 36b), and values above 65% are rarely observed for the ratio between the dual-link and single-link capacity, as shown in Figure 36a).
5 CONCLUSIONS

As an initial goal of this master’s thesis, a simple multi-link geometry-based MIMO channel model was successfully developed. The greatest motivation of this thesis was to investigate the overall ML-MIMO system performance when two links share the same clusters. For this reason, it was especially interesting to develop a channel model based on two kinds of clusters: common and uncommon clusters. Based on earlier studies, it was observed that common clusters are one of the physical phenomena causing the correlation between different links. As the developed channel model is then based on common clusters, it is also capable of controlling the inter-link correlation.

This thesis was started by introducing basic principles and concepts of radio propagation and MIMO systems. After this, a literature review on MIMO channel modeling was also given. In this review, physical models and analytical models were briefly described together with some popular examples from both model types.

The work continued by discussing the motivation on multi-link scenarios as well as a reviewing briefly earlier works on multi-link scenarios. The channel model developed in this thesis was presented next, emphasizing in its approach, key features, operating principles, verification, and relation to other multi-link channel models.

Before starting with the simulation studies, the conducted data analysis was discussed based on earlier studies related to the issue. Also earlier works investigating the correlation between links and the dual-link capacity were introduced. After this, the simulation studies started by analyzing the ML-MIMO channel capacity and inter-link correlation in different channel representations where the cluster locations were manually modified to different positions. Results so far showed that, in general, correlation between links increases whereas dual-link capacity decreases with increasing significance of common clusters. However, a high correlation between links and low dual-capacity compared to the single-link capacity was sometimes observed with all significance of common clusters. In the latter case, it was concluded that
common clusters are not the main cause limiting the ML-MIMO system performance, but however, the imposed geometry of clusters and antenna array is what fully determines the overall system performance. It was found that the reason of this arises from symmetric or parallel cluster directions to the array which cannot be resolved by linear arrays due to the lack of resolution.

Next, a set of simulations with random cluster geometries were made in order to statistically study how often the ML-MIMO system performance might be degraded by either the common clusters or channel geometry. The reported results revealed that the inter-link correlation can take any value with low values of significance of common clusters depending on the channel geometry (clusters and array). As the inter-link correlation can adopt a wide range of values, the dual-link to single-link channel capacity can also take any value. However, the inter-link correlation indicated moderate to very high values whether the significance of common clusters is equal or higher than 50%, respectively.

To conclude the work, it was also considered especially interesting to investigate a dual-link scenario with one common cluster which has different significance for the different links and apparently pretty unequal. To that end, a comparison based on simulations was done in two scenarios with same significance for the different links in order to investigate which of them had similar behavior. From the observed results, it was found out that clusters which are common for two links but with large difference between the significance for each different link cannot be considered as common cluster. As expected, the ML-MIMO system performance matched more with the scenario where the cluster that is supposed to be common for the two links has low significance in both links.
References


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Development of multi-link geometry-based MIMO channel model

Alvaro Palacios


MIMO channel sounder for 5.3 GHz”, accepted for publication in IEEE Transactions on Instrumentation and Measurement.
