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The COST 2100 MIMO Channel Model

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Abstract. The COST 2100 channel model is a geometry-based stochastic channel model (GSCM) that can reproduce the stochastic properties of multi-link Multiple-Input Mulitple-Output (MIMO) channels over time, frequency and space. By contrast to other popular GSCMs, the COST 2100 approach is generic and flexible, making it suitable to model multi-user or distributed MIMO scenarios. In this paper a concise overview of the COST 2100 channel model is presented. Main concepts are described, together with useful implementation guidelines. Recent developments, including dense multipath components, polarization and multi-link aspects are also discussed.

Keywords: channel model, MIMO, cluster, polarization, multi-link, simulation.

I. Introduction

Multiple-Input Multiple-Output (MIMO) is an enabling technology in order to meet the growing demands for faster and more reliable transmissions over harsh wireless channels. Over recent years, researches on MIMO technology have covered the gamut from theory to applications, and the technology is now included as a key component into standards such as LTE/3GPP and WiMAX 802.16e.

In MIMO systems, multiple collocated or distributed antenna arrays replace the traditional single-antenna units, enabling the system to exploit the spatial dimension of radio channels. The technology can be used to increase the channel capacity by spatial multiplexing, to mitigate multipath fading by spatial diversity, and to achieve a better signal-to-noise (SNR) level by directional transmission, i.e. beamforming [1].

As new wireless applications have become more and more sophisticated, the need for more accurate channel models has increased accordingly. For instance, in the planning of conventional GSM networks, simple path loss models were sufficient for sensible coverage prediction, whereas nowadays, the channel models needed in the development of MIMO systems have to represent the signal dispersion in the angular, delay, and Doppler domains simultaneously. The emergence of multi-user MIMO and cooperative communication techniques also calls for realistic multi-link channel models.

Stochastic MIMO channel models rely on a limited number of parameters to efficiently describe the channel statistics in different domains. The computational complexity of the model depends on the scope of the systems. In this respect, there are two major approaches. On the one hand, analytical (non-physical) models characterize the MIMO channel matrix, including the antenna effects, by a mathematical description. Examples include the 802.11n tapped angular-delay line model, the correlation-based Kronecker model, and the eigenspace-based Weichselberger model [2]. On the other hand, physical models characterize the radio waves by their delay, directions-of-departure (DoD), directions-of-arrival (DoA), and complex path weight for different polarizations. Physical models are antenna-independent, hence they can be directly combined with the antenna array responses to synthesize the MIMO channel matrix. Geometry-based stochastic channel models (GSCMs) further constitute a group of advanced stochastic physical MIMO channel models that statistically describe the explicit locations of the scatterers.

The COST 2100 MIMO channel model is a GSCM that was built upon the framework of the earlier COST 259 and 273 models [3]. The COST 259 channel model [4] was the first GSCM considering multi-antenna base stations, while full MIMO systems were later targeted by the COST 273 model. The COST 2100 channel model extends the COST 273 model to cover MIMO systems at large, including multi-user, multi-cellular and cooperative aspects, without requiring a fundamental shift in the original modeling philosophy.

This paper aims to give a concise overview of the COST 2100 channel model, covering the overall structure (see Section III) as well as the individual key elements (see Section IV) constituting the model framework. The most recent achievements, including multi-link aspects, are presented in Section V, while considerations about parameterization, implementation and validation are discussed in Section VI.

II. Review of Geometry-Based Stochastic Channel Models

The principle of GSCMs is to model the stochastic properties of wireless channels, with respect to the delay and double-directional domains, by analyzing the geometric distribution of the interacting objects (or scatterers) in the environment that contribute scattering to the radio channels. In GSCMs, a radio channel results from the superposition of different propagation paths, known as the multipath components (MPCs). Those MPCs are caused by the interaction between the radio waves and the objects in the environment, where each scattered contribution is characterized in both delay and direction domains. These scattering mechanisms may consist of a single interaction, i.e. with one object (single-bounce), or of a number of consecutive interactions with multiple objects (multiple-bounce). The MPCs generated by either of these scattering mechanisms are represented through a geometric description by their properties in three parameter space domains: delay, DoD and DoA.

Experimentally, it was observed that MPCs tend to appear in packets in these domains. Intuitively, this makes sense: if a building acts as an interacting object, it is likely that the building will create several reflected paths, caused by windows, balconies, etc. with similar delays and directions, given the finite size of the building. In addition to being experimentally-based, grouping MPCs with similar delays and directions into packets (or clusters, as they are usually known) enables to significantly reduce the number of modeling parameters. This explains why clusters constitute the basis of all recent GSCMs, from COST 259 to WINNER II.

Whereas clusters are the parameterized quantities, it is important that overall models reflect reality. In particular, the channel large-scale parameters (LSPs), such as the global delay and angular spreads, as synthesized from GSCMs, should be statistically reliable and consistent with experimental observations. This means that clusters should be parameterized individually, yet in such way that the global accuracy is guaranteed. This is where two main approaches can be used: a system-level approach, such as the widely known 3GPP Spatial Channel Model (SCM) [5] and the recent WINNER II model [6], or a cluster-level approach, such as the COST family of channel models. Both approaches rely on essentially different simulation processes. In system-level GSCMs (taking WINNER II as an example), the modeling process is specified for each instance of the channel between a base station (BS) and a mobile station (MS) by:

- defining the LSPs by their stochastic distribution for each channel instance,
- generating the clusters and MPCs according to these LSPs for any given locations of both BS and MS.

By contrast, in the cluster-level COST 2100 model, the modeling process is specified once for the entire environment by:

- defining a large quantity of clusters with consistent stochastic parameters throughout the simulation environment based on the BS location (yet, not all clusters are visible at any time instant),
- defining the MS location and determining the scattering from the so-called visible clusters at each channel instance,
- synthesizing the LSPs based on the cluster scattering.

The advantage of such system-level channel model is that the LSP statistics in a specific scenario are always guaranteed in each series of channel instances. However, forcing the statistical consistency of the LSPs brings two critical limitations:

- the rigid structure of the approach does not spontaneously support continuous channel descriptions over intervals larger than the auto-correlation distance, hence hampering the simulation of larger MS motions,
- as the propagation environment is described from the original LSPs only, adding new LSPs, e.g. the inter-link correlation, requires to re-define the entire initialization of the environment, thereby hindering a straightforward extension of the model.

By contrast, the cluster-level COST 2100 model is not constrained by the LSPs, and the environment is described independently of the MS location. This allows for smoother modeling of time-variant channels. Basically, it is the MS motion through the environment that will cause the channel statistics to vary, even over periods larger than the auto-correlation distance. Furthermore, accounting for new LSPs, such as the correlation properties of multi-link channels, can be carried out in a flexible fashion (i.e. without modifying the model structure) by exploring advanced properties of the clusters. Naturally, in any single realization of the channel, a cluster-level GSCM is expected to exhibit larger deviations of the LSP statistics than the system-level

GSCMs, as these statistics are not expressly forced by the model. Nevertheless, the average LSP statistics remain typically consistent with measurements, as illustrated in Section VI.C.

Regarding complexity, both system- and cluster-level GSCMs are similar as far as simulations are concerned, as they both rely on adding contributions from a number of MPCs. Arguably, the cluster-level COST 2100 model probably relies on a more complex representation of the clusters, making their identification, estimation, and parameterization from measurements a critical task.

III. General Structure of the COST 2100 Channel Model

The COST 2100 channel model was originally proposed for simulating the radio channel between a static multiple-antenna BS and a multiple-antenna MS. In most cases, the MPCs are mapped to the corresponding scatterers and are characterized by their delay, azimuth-of-departure (AoD), elevation-of-departure (EoD), azimuth-of-arrival (AoA), and elevation-of-arrival (EoA). Clusters are formed by grouping scatterers that generate MPCs with similar delays and directions (azimuth and elevation). Figure 1 depicts the scattering mechanisms from the BS to the MS.

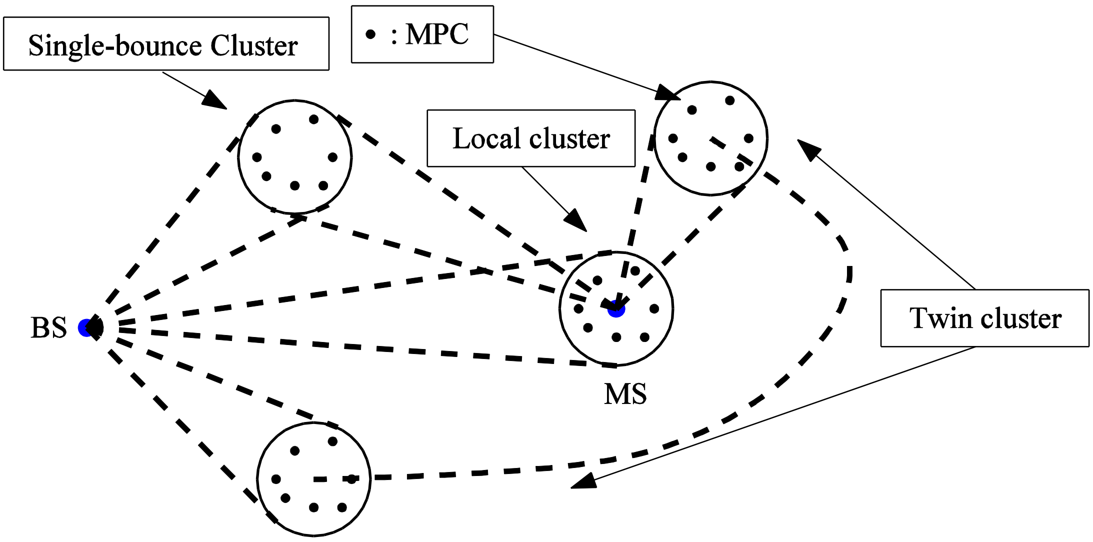

Figure 1: General structure of the COST 2100 channel model

There are three kinds of clusters in the COST 2100 model [3], as illustrated in Figure 1. *Local clusters* are located around the MS or the BS, and those are characterized by single-bounce scatterers only. *Far clusters* are divided into *single-bounce* and *multiple-bounce* clusters. They are distributed throughout the simulation area, with an average density following a Poisson distribution. Given the geometrical cluster distribution, the LSPs of a channel are actually controlled by the average number of clusters that are active, i.e. visible to the MS and thus contributing to the channel. While local clusters are always visible, the visibility of a far cluster is determined by the concept of *visibility region*, which confines the cluster activity within a limited geographical area.

As mentioned, the far clusters include clusters with single-bounce scatterers and clusters with multiple-bounce scatterers. Single-bounce clusters can be explicitly mapped to a certain position by matching their delay and angles through a geometric approach. On the contrary, the multiple-bounce clusters are described by two representations, as viewed from the BS and the MS sides respectively, and called *twin clusters*. Visually, a twin cluster contains therefore two identical images of one cluster, appearing at both sides (see Figure 1). In a specific environment, the ratio of twin to single-bounce clusters is set to be constant [3].

Eventually, the channel impulse response (CIR) is obtained by the superposition of the MPCs from all active clusters determined by the position of the MS. The amplitude of each MPC is jointly determined by the pathloss, the large-scale properties of the cluster to which it belongs, and its own small-scale properties. The CIR can then be combined with antenna steering vectors to form the MIMO channel matrix (see Section VI.B).

IV. Key Modeling Concepts

A. Visibility Regions

A *visibility region* (VR) is a circular region given fixed size in the simulation area. It determines the visibility of only one cluster. When the MS enters inside a VR, the related cluster smoothly increases its visibility as shown in Figure 2. This is accounted for mathematically by a VR gain, which grows from 0 to 1 upon entrance within the VR. Furthermore, when the MS is located in an area where multiple VRs overlap, multiple clusters are visible simultaneously. In the COST 2100 model, the VRs are uniformly distributed in the simulation area, the VR density being related to the average number of visible clusters determined experimentally [3].

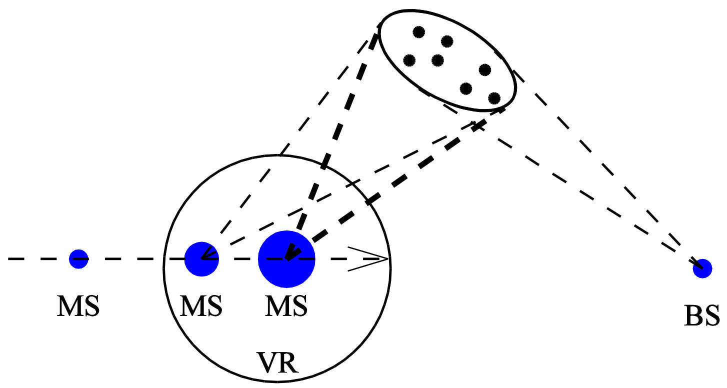

Figure 2: Illustration of the visibility region concept: the size of the circle around the MS represents the visibility level of the cluster to the BS-MS channel; when the MS moves outside the cluster visibility region, the related cluster becomes totally inactive in the transmission.

B. Clusters

A cluster is depicted as an ellipsoid in space as viewed from the BS and from the MS, as illustrated in Figure 3. The local cluster and the far clusters are characterized with specific positions and orientations toward the BS and MS respectively, so that their spatial spreads match their corresponding delay and angular spreads. The geometric correspondence between the cluster spatial spread and the cluster delay and angular spreads is simple. For instance, the length a_C, width b_C, and height h_C, of the single-bounce cluster in Figure 3 correspond to the cluster delay, azimuth, and elevation spreads respectively.

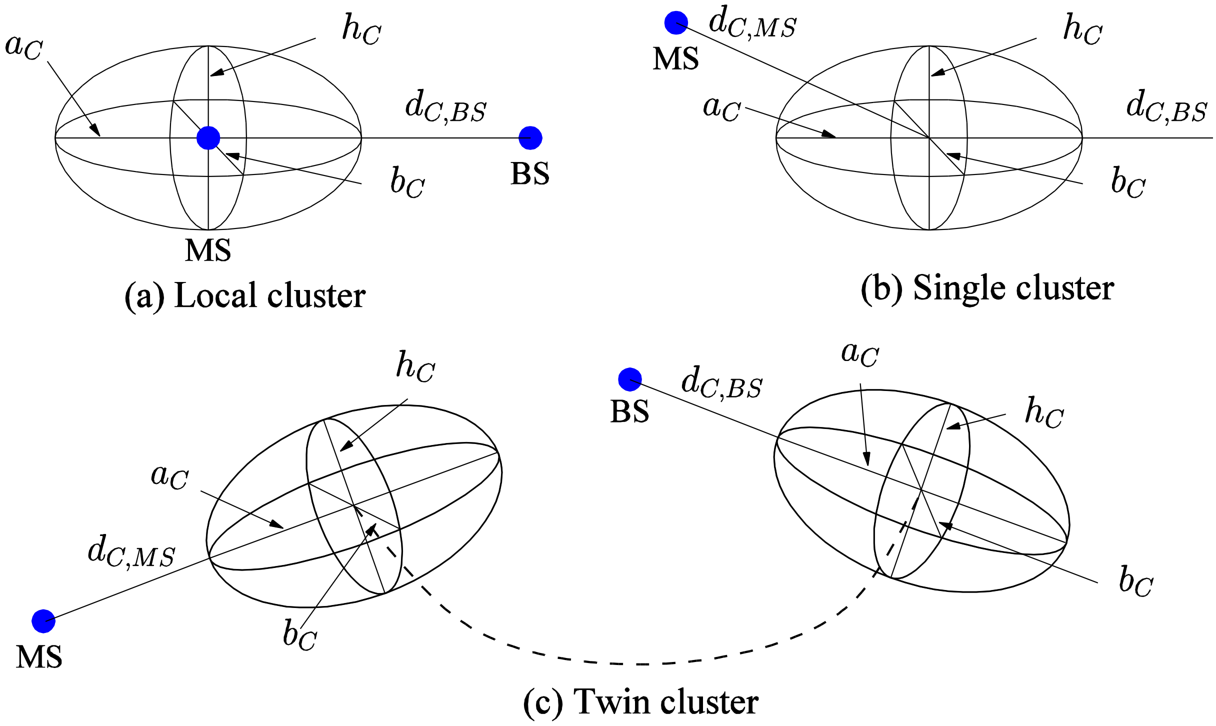

Figure 3: Spatial description of the local, single-bounce and twin clusters: a_C, b_C and h_C represent the length, width, and height of the cluster; $d_{C,MS}$ and $d_{C,BS}$ are the distances from the cluster to the MS and BS respectively.

1) **Local cluster(s):** A local cluster has an omnidirectional spread in the azimuth plane. Its spatial spread is only determined by its delay and elevation spread.

2) **Single-bounce clusters:** Single-bounce clusters have independent delay and azimuth spreads. Each single-bounce cluster is rotated toward the BS so that its spatial spreads along its different axes adequately fit the delay and angular spreads as viewed from the BS. The position of a single-bounce cluster is determined by a random vector originating from the BS and rotated with a Gaussian distributed angle relative to the imaginary line between the BS and the center of its corresponding VR. The length of the vector follows a lower-bounded non-negative distribution, e.g. an exponential distribution in macro-cellular scenarios.

3) **Twin clusters:** In this case, the cluster ellipsoids at the BS and MS sides are rotated toward the BS and MS respectively, similarly to the single-bounce clusters. To determine the position of a twin cluster, the method applied for a single-bounce cluster is performed twice: first from the BS side, then from the VR side. This approach is used to control the delay and angles of the twin cluster once the MS is located inside the related VR. A cluster-link delay was introduced in the COST 273 model to compensate for the extra delay caused by the multiple-bounce propagation via a twin-cluster. The cluster-link delay is a non-negative random variable. Its minimum value is defined when the single-bounce propagation between the two centers of the twin cluster occurs. Local and single-bounce clusters can be treated as special twin clusters with a cluster-link delay always equal to zero. Since the cluster-link delay is a large-scale property, it should be applied to all MPCs belonging to the corresponding cluster.

4) **Cluster parameterization:** The clustering of paths enables to characterize the large-scale properties of the channel, i.e. the delay and angular spreads of the MPCs within each cluster, the cluster-link delay, the random shadowing level S_n, and the cluster attenuation L_n. The cluster attenuation exponentially increases when the cluster excess delay increases, i.e. the difference between the total delay of the cluster and the delay of line-of-sight (LOS) component. Note that uncorrelated-clustering is normally assumed, meaning that LSPs of different clusters are statistically independent. The values of these LSPs are tabulated in [3] for macro-, micro- and pico-cellular scenarios.

C. Line-of-Sight and Multi-Path Components

The Line-of-Sight (LOS) component is the direct propagation path from the BS to the MS. The COST 2100 model considers the LOS component as a special cluster containing only one MPC, whose power is randomly scaled with respect to the active cluster power. The visibility of the LOS component is also associated with a VR, which is characterized by its own size and distribution.

The scatterers constituting a far cluster have a Gaussian-distribution in space (angle) within the cluster, whereas the local scatterers are uniformly distributed within the local cluster. Scatterers defining a twin cluster are identically distributed in space within the clusters at both BS and VR sides to maintain a consistent spatial spread. Each scatterer results in one MPC, whose delay and angles are calculated geometrically. The total delay of a MPC is the sum of three delays: the delay from the BS to the scatterer at the BS side, from the MS to the scatterer at the MS side, and the cluster-link delay.

D. Time Evolution

The COST 2100 framework enables a time-varying channel description using a single realization of the clusters as long as the environment remains static. Indeed, the environment (i.e. the clusters and the VRs) is generated independently of the MS position. This is actually very similar to the generation of virtual environments. While virtual environments reproduce the exact location and shape of scatterers (buildings, obstacles, etc.), clusters and their visibility regions stochastically represent a typical environment. As mentioned, a whole different approach is followed from WINNER II, where small (stationary) pieces of MS motion are connected by correlating the LSPs between these pieces, thereby enabling to simulate *explicitly* non-stationary channels. In the COST family of models, the whole environment is first generated, and the movement of the MS in this simulation area causes the visibility of different clusters to change as the MS enters and leaves different VRs[1], resulting *implicitly* in non-stationary channel simulations. This also implies that the COST 2100 model structure and parameterization are independent of the MS speed: the higher the speed, the faster the MS moves in and out of visibility regions, decreasing the stationarity length of the channel. Thereby, scenarios involving high-speed MSs can readily be simulated using the COST 2100 approach.

[1] Note however that the local cluster moves with the MS, resulting in necessary updates of the local MPCs to maintain the spread of this local cluster.

V. COST 2100 Novel Developments

A. Polarization

The polarization behavior of the channel is described on the cluster level. As proposed by [7], a MPC contains 4 polarization components: vertical to vertical (VV) polarization, horizontal to horizontal (HH) polarization, vertical to horizontal (VH) polarization, and horizontal to vertical (HV). The polarization components can be then projected accordingly onto the MIMO antenna array to form multi-polarized sub-channels.

The power ratios between the 4 polarization components of each MPC is characterized by a polarization matrix [7]. These ratios follow different lognormal distributions with a mean and standard deviation generated per MPC. Each polarization component also contains a uniformly distributed random phase.

B. Dense Multi-Path Components

So far, the model relies on specular scattering. This simplification assumes that the interaction between a scatterer and the electromagnetic wave only produces one propagation path. In reality, scattering mechanisms are more complex and cannot be fully described by a few specular paths with corresponding explicit geometry as described in the previous sections. Rough surface reflections, corner diffractions, and reflections from different layers of a scatterer can all contribute to a large amount of diffuse scattering. Hence, diffuse scattering can form a significant component in both delay and angular domains, which a few specular MPCs fail to capture. There are two approaches to include diffuse scattering: 1) by extending the propagation paths with a continuous dispersion over delay and angular domains to include diffuse scattering characteristics, as studied in [8]; and 2) by the superposition of a large number of specular paths with modified delays, angles, and amplitudes, called the dense multi-path components (DMCs) [9]. Whereas the first method relies on the quality of the path dispersion modeling, namely the model mismatch might create a significant amount of artifacts, the second method increases the total number of parameters but provides the best capture of the residual channel spectrum as long as the number of the DMCs is sufficiently large. The COST 2100 model considers the second approach as a direct extension of the MPC concept.

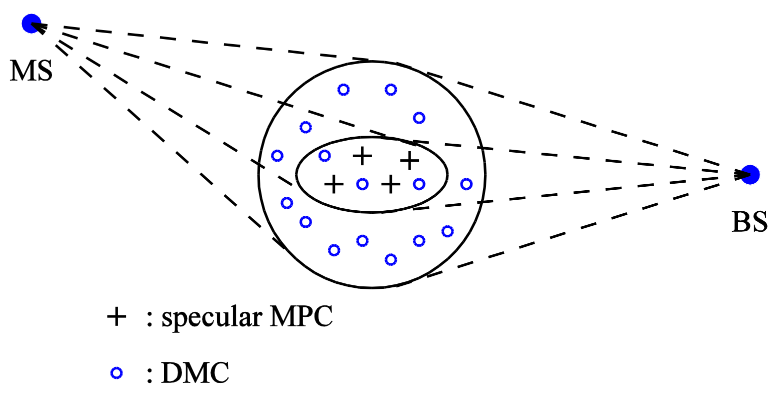

Figure 4: Cluster-based DMC description: the clustering of DMC is superimposed to the MPC clustering at the same centroid.

In principle, a DMC is a modified MPC that is described by its own delay, angles, fading, and power attenuation. The modeling complexity is kept at a reasonable level by characterizing the DMC at a cluster level. As depicted in Figure 4, the delay and angular spectra from each MPC inside the cluster are expanded by a sub-group of DMCs, whose powers are decaying relatively to the MPC power in both delay and angular domains. Naturally, the DMCs share the large-scale properties of the cluster, such as the shadowing and cluster power attenuation.

C. Multi-Link Aspects

Multi-link communications refer to concurrent communications between multiple BSs and multiple MSs that are spatially separated. This structure is usually interesting for cooperative schemes and for multi-user signal processing to exploit the spatial variety of different radio links. The single-link COST 2100 model support multi-user scenarios by definition, as it characterizes the propagation environment with respect to one BS irrespective of the MS location, so that channels between one BS and multiple MSs at different locations can be characterized simultaneously. A similar principle could be further applied to model channels in multiple-BS multiple-MS scenarios, simply by adding up multiple single-link channel realizations. However, since clusters and the corresponding visibility regions have been conventionally generated separately and independently for each BS, there is no guarantee that the multiple links reflect the important features of the multi-link scenarios realistically, in particular large-scale correlations.

Measurements have shown that different links might be correlated even if the BSs or MSs are well separated [10]. To describe this behavior, large-scale correlations are introduced referring to correlations between two links separated at the BS side or the MS side by a distance larger than the coherence distance. One possible explanation for such correlation is the existence of correlated clustering, i.e. clusters in different links show correlated fading or LSPs, as investigated in [11]. Using correlated clusters would contradict the uncorrelated-clustering assumption adopted in the COST 2100 model, hence requiring substantial modifications of the modeling approach. Another possibility is to consider that clusters are simultaneously visible in different links, in other words that some clusters are common between multiple links. This solution requires characterizing the visibility of the clusters in different links, without altering the other physical properties of the clusters. Consequently, this approach would guarantee a compatible extension of the COST 2100 model upon the existing structure in single-link scenarios.

As discussed in Section IV, in the single-link COST 2100 model the visibility of a cluster to one BS is determined by means of a single VR. This can be viewed as a special case of the general multi-link communication as the VRs in a single-link scenario actually determines the cluster visibility to only one BS. In multi-link scenarios, the VRs define the cluster visibility to multiple BSs, i.e. the VR associated to a given cluster determines to which BSs the cluster will be connected. More generally, a link-common cluster will be associated to multiple VRs, and each VR determines connection of a cluster to the BSs, as shown in Figure 5.

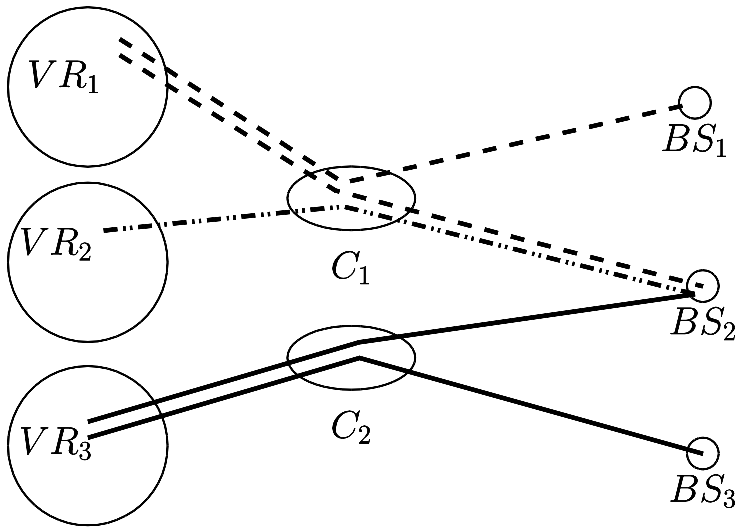

Figure 5: Link-commonness of two clusters, C_1 and C_2, which are associated to three VRs and three BSs: dash lines indicate the link-visibility of the clusters to the BSs defined in each VR.

The cluster link-commonness is an auxiliary characteristic of the clusters in multi-link scenarios. It will not affect the description of the clusters, such as their spatial spread and power attenuation. However, the stochastic properties of the cluster link commonness have to be properly modeled to guarantee the consistency between the channels of individual link in the multi-link scenarios and the conventional single-link model.

VI. Parameterization, Implementation and Validation

A. Parameterization

The parameterization of the COST 2100 model in various scenarios represents a huge effort, which has been performed by several research groups with COST 2100 Action. The model defines the stochastic parameters for 1) VR and cluster link-connections, 2) VR, cluster, LOS, and MPC locations, 3) VR, LOS, and cluster powers, 4) cluster shadowing and MPC fading, 5) field polarization, and finally, 6) DMC locations, powers, and fading. In addition to previous parameterizations carried out for macro-, micro-, and pico-cellular [3], outdoor rural environments at 400 MHz band and indoor pico-cellular scenarios at 3.6 [7] and 5.3 GHz [9] bands have been covered, respectively for polarized and multi-link aspects. A complete list of parameters and recommended distributions is presented in [13]. The overall availability of the parameters is broad, though it must be noted that advanced parameters for DMC and multi-link aspects are still not sufficiently supported by measurements.

B. Implementation

The implementation of the COST 2100 model consists of a full description of the environment and the synthesis of the MIMO channel matrix by combining the double-directional channel with the transmit and receive antenna steering vectors $\mathbf{s}_t$ and $\mathbf{s}_r$:

$$\mathbf{H}(t,\tau)=\frac{1}{L}\sum_{n\in C}V_n\sqrt{\frac{S_n}{L_n}}\left[\sum_{p=1}^{P}a_{n,p}\,\mathbf{s}_t\left(\Omega_{n,p}\right)\mathbf{s}_r\left(\Psi_{n,p}\right)\delta\left(\tau-\tau_n^{(l)}-\tau_{n,p}^{(M)}\right)\right] \tag{1}$$

where

- L is the overall pathloss, which provides the dependence towards the BS-MS distance,
- C is the set of visible clusters determined by the MS location,
- $\tau_n^{(l)}$ is the cluster-link delay,
- V_n, S_n and L_n are respectively the cluster visibility gain accounting for the transition in/out of the VR, the cluster shadow fading, and the cluster attenuation, the latter growing exponentially with the cluster excess delay,
- $a_{n,p}$ is the complex Gaussian fading of the p^{th} MPC in cluster n,
- $\tau_{n,p}^{(M)}$ is the geometric delay, corresponding to the BS-to-scatterer-to-MS path,
- $\Omega_{n,p}$ and $\Psi_{n,p}$ are respectively the DoD and DoA of the p^{th} MPC in cluster n,
- $\delta(.)$ is the Dirac function.

Finally, the DMCs are implemented analogous to MPCs, while the multi-polarized sub-channels are obtained by projecting each MPC in (1) onto its polarization matrix.

A complete implementation has been developed and can be freely downloaded from [12].

C. Model Validation

The validity of the model has been widely discussed in various metrics such as angular and delay spread, parameter distributions, and inter-link correlation. In general, the comparison between the measured LSPs and synthesized LSPs from the model depends on the qualities of channel estimation and model parameterization. The COST 2100 model validation is extensively covered in [14]. In the following, we focus on one metric representative of multi-link scenarios.

Figure 6 presents a comparison between measurements and corresponding model simulations on the inter-link correlation in a dual-BS single-MS communication scenario [14]. The measurements were performed in an indoor corridor environment at 5.3 GHz [9]. Vertically-polarized planar dipole antenna arrays were considered at the BSs and MS. Detailed settings of the measurements and the simulations can be found in [14]. Because of the dominant waveguiding propagation in the corridor, the measurements show significant inter-link correlation between two BSs located at different wings of the same building. Such inter-link correlation is measured by the correlation matrix co-linearity (CMC) between the correlation matrices of the two BS-MS links [14].

The CMC is a distance between the correlation matrices, giving 1 when the matrices are linearly dependent and yielding 0 if they are orthogonal. In Figure 6, three CMC curves, representing 5, 50, and 95 % percentile values, are derived from the model simulations. The measured curve, as shown in the figure, remains below the range of simulations, demonstrating that the model is capable to predict the inter-link correlation as observed in the measurements.

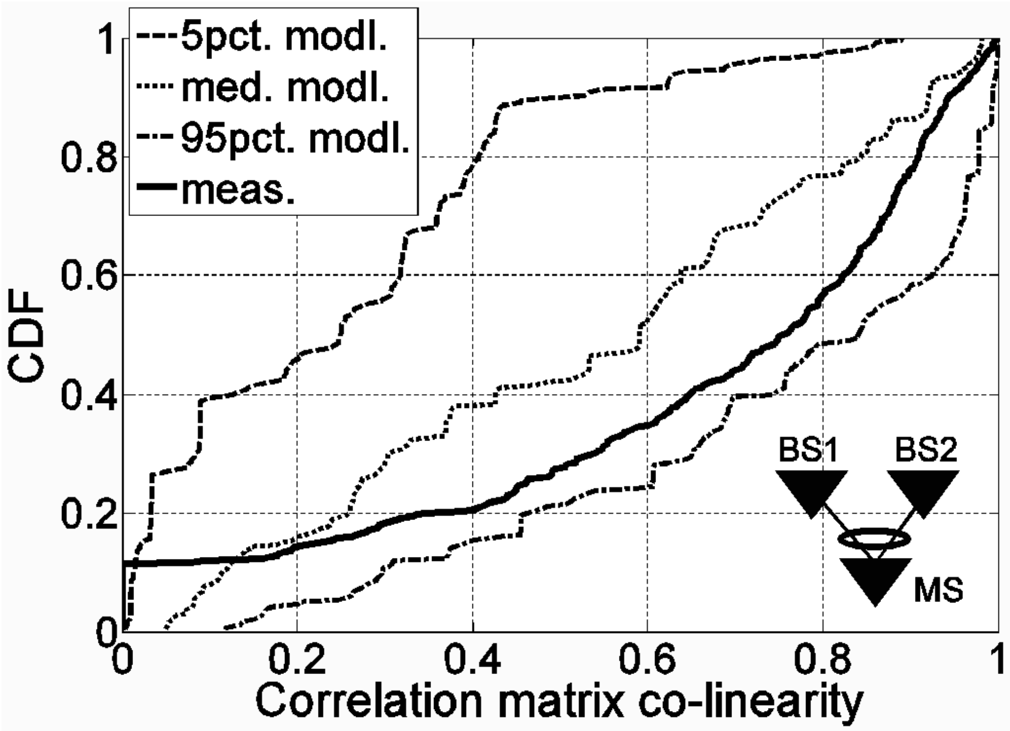

Figure 6: Comparison of a correlation matrix co-linearity from measurements and channel model outputs. The curve from measurements falls within the range of 5 and 95 percentile curves of the channel model outputs, revealing the validity of the channel model to re-create measured channel characteristics.

D. Conclusions

Relying on a limited number of parameters, the COST 2100 MIMO channel model is able to fully characterize the stochastic radio channel behavior in multi-link MIMO scenarios. As wireless communication systems become more and more complex, the cluster-level structure of the COST 2100 model provides an efficient and realistic solution to incorporate various channel properties into the channel description. Extensions of the model provide a promising solution to model multi-link and cooperative aspects in the design of future communication systems.

However, the extension of the model also challenges the parameterization and validation effort. Therefore, it makes no doubt that the successful development and the sustainable use of the COST 2100 model requires more advanced channel estimation methods as well as sufficient number of measurement campaigns for parameterization and validation of the model.

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