Ray-based Predictions of the Outdoor-to-Indoor Massive MIMO Channel

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Abstract—Massive MIMO systems serve multiple users in the same time-frequency resource by utilizing large antenna arrays. A uniform linear array (ULA) containing 128 antenna elements is considered in an urban North American city environment with multiple user channels. The simulations are conducted with a ray-based tool with the latest enhancements of outdoor-to-indoor (O2I) channel prediction capabilities. Most massive MIMO research often uses theoretical models which are based on various assumptions which cannot accurately predict the channel performance. In this paper, simulations are conducted to characterize and evaluate massive MIMO channels in O2I scenarios. A comparison is drawn with regard to line-of-sight (LoS) channels using the singular value spread (SVS) analysis for users located in a same building. It is concluded that the channel dispersion caused by the various multi-paths created at the O2I interface contributes to better channel performance in smaller antenna arrays which is only limited by the path-loss. For larger arrays, there is a saturation of the O2I SVS contribution.

Keywords—massive MIMO, channel modelling, ray-based model.

I. INTRODUCTION

Massive multiple-input multiple-output (MIMO) technology serves multiple users in the same time-frequency resource [1]. This is achieved by spatially multiplexing the different users from large antenna arrays at the base station (BS) end. The highly efficient use of the available spectrum provides high channel capacities with simple linear processing [1][2].

An important property of massive MIMO (mMIMO) systems is that the channels to the various users are made nearly orthogonal. This is also known as Favourable Propagation [2] where mutual interference can be cancelled by simple linear processing techniques like zero-forcing and matched filtering. The singular value spread (SVS) of a mMIMO channel matrix H can be used to measure the degree of orthogonality between the different users [2] [3]. This singular value spread is also referred as the condition number [3] and is given by the ratio of the largest singular value to the smallest singular value of the channel matrix. This implies that smaller values for the SVS correspond to better channel orthogonality. The SVS definition given in [3] is used in this paper to characterize the mMIMO channel performance for a scenario composed of several users positioned in the same floor of a building.

The mMIMO channel varies from the traditional MIMO by the large scale of antennas which provide more degrees of freedom to serve multiple users. The different antenna elements along the large array receive varying components due to the spatial extent of the array. However in most studies, the channel properties are considered as stationary, meaning that the channel coefficient variations along the array can be predicted from constant multi-paths (e.g. obtained from geometry-based stochastic approaches) or from independent and identically distributed (i.i.d.) Rayleigh fading [2]. The channel variations due to multi-path non-stationarity, i.e. birth/death of paths or path shadowing, are expected to significantly impact the system performance; therefore it is of great importance having realistic models that allows mMIMO studies to be conducted in such conditions. The ray-based massive MIMO model proposed in this work uses efficient deterministic techniques able to predict the channel properties in complex real environments and supports many critical features: incident spherical-wave, possible non-stationarity, inter-user channel correlation.

The authors have implemented mMIMO H-matrix prediction from the fast ray-based Volcano technology by Siradel [4]. This professional model has been widely used since about twenty years in the industry to assess channel and network performance, either in urban environment or inside buildings. The study that is reported in this paper takes benefit of a recent Volcano extension to address the specific outdoor-to-indoor (O2I) scenario. The new Volcano Flex model handles together the urban vector representation and detailed multi-floor building environment to accurately predict the O2I multi-path channel. The mMIMO channel from a macro base station (BS) to in-building users can thus be finely assessed. Another objective of this study was to demonstrate the ability of the ray-based model to simulate the non-stationarity. The scenario has been chosen accordingly, i.e. major non-stationarity is expected. Therefore the channel properties that result from this study cannot be generalized to any O2I situations. Large-scale application of the massive MIMO model will be carried out in future work.

Section II describes the ray-based channel model and its usage for mMIMO prediction. Section III details the multi-user scenario that was designed to compare the O2I mMIMO channel to the line-of-sight (LoS) one. Non-stationary is characterized in Section III, from analysis of the received power variations along the array. Section IV studies the multi-user
channel performance based on the SVS. Finally, section V draws some conclusions and gives perspective on this still ongoing work.

II. RAY-BASED MASSIVE MIMO CHANNEL MODEL

Volcano Flex is a recent extension of the Volcano ray-based technology [4]. This commercial tool is devoted to multi-paths channel predictions in complex environments such as urban outdoor, multi-floor building, underground stations, tunnels, or any hybrid scenario like a campus. Outdoor clutters like buildings, trees, bridges, etc, are described by their exterior 3D contours. Besides, the façades and interiors of some buildings are represented with more details, i.e. walls, doors, windows, inner partitions and floors are modelled by 3D faces. Multi-paths caused by transmissions, reflections, diffractions and/or diffusions may be generated in any urban scenario, including hybrid outdoor and indoor propagation cases. A key asset is the fine modelling of diffractions at window frames [5][6]. Finally, the model takes advantage of optimised computation processes; rich multi-path propagation links are simulated in either few seconds or few minutes depending on the scenario complexity. The model settings for the current study are as follows: maximum 2 diffractions and 3 reflections along each path; reflections are allowed on the building façades and loadbearing internal walls; and no restriction on the number of internal transmissions.

The Volcano Flex model has been integrated into a mMIMO simulation framework, where large antenna arrays (linear, rectangular, cylindrical) can be created and the MIMO channel is automatically computed. In the present study, it was decided to predict the mMIMO channel in a rudimentary but most accurate way: every single prediction between a couple of transmit and receive antennas is obtained by a specific ray-based simulation. This approach requires maximum computation effort. It cannot be envisaged for large-scale mMIMO predictions, but was chosen here to evaluate the channel non-stationarity without any simplification or artefact.

III. SCENARIO AND SETUP

The study aims at characterizing mMIMO channels performance and demonstrate some specific non-stationary situations, using a deterministic ray-tracing approach. The considered scenario uses 3D geographical data from New York city with the inclusion of detailed 3D buildings. A BS consisting of a uniform linear array (ULA) of 128 antenna elements with half-wavelength separation is located on top of a building, 42 m above ground. It serves users located either inside (in same floor of a building) or outside in its surrounding, as shown in Fig. 1. The user equipment (UEs) consists of a single antenna. The frequency considered for simulations is 2 GHz.

Three particular simulation results are investigated: 1) the single-user channel non-stationarity due to the large antenna array; 2) the multi-user channel non-stationarity; and 3) the user’s separation. According to author’s knowledge, such investigation in O2I scenario has not been deeply considered earlier.

The complex O2I environment creates rich multi-path components, which is beneficial to the mMIMO system. Particularly in scenarios in which the users are located close to each other, the angle-of-arrivals (AoA) of the different users are usually similar, making the separation difficult. The presence of strong fading with small distance correlation, e.g. due to the rapid succession of windows and walls in the user vicinity can strongly help in the separation. Fig. 1 illustrates how the propagation paths towards two users in the same floor of a building can differ, especially due to the interactions at the O2I interface as shown in Fig. 2.

Fig. 1. O2I scenario with 3D building.

Orthogonal channels are often assumed for users located in rich scattering environments with non line-of-sight (NLoS). However, there is a degree of correlation that may be assessed by the deterministic model. This is evaluated from two scenarios:

1) Co-located users: In this case, four users are located close to each other, on a circle with radius 4 m. For the O2I sub-scenario, the co-located users are indoors, in a same room situated in the 8th floor of a building (22 m above the ground). They are positioned near a window as shown in Fig. 3. The O2I sub-scenario is compared to a LoS sub-scenario, where users have same 2D positions, but are moved at a height of 25 m, i.e. on the rooftop.

Fig. 2. Various interactions at the edge of window in O2I scenarios.
2) Distributed users: Four users are now considered to be distributed at much different locations as shown in Fig. 3. In the O2I sub-scenario, the users are still in the same floor but distributed inside different rooms. The main O2I penetration paths can significantly vary from one user to another, leading to variations in both the angle-of-departures (AoD) at the BS and angle-of-arrivals (AoA) at the UE. The LoS sub-scenario considers same user 2D positions, but 3 meters above, i.e. on the rooftop.

The co-located scenario is used in section IV, while both the co-located and distributed scenarios are compared in section V.

![Co-located and distributed O2I scenarios.](image)

**IV. MASSIVE MIMO CHANNEL CHARACTERIZATION AND SPATIAL SEPARATION**

A. Non stationarity along the antenna array

It is often assumed that the propagation channel experienced by each couple of transmit and receive antennas is stationary, meaning that the properties of the main channel propagation paths (field strength in particular) are constant; the only major variation along the antenna array comes from the field phases that generate local fading. This stationarity assumption is made when using i.i.d. Rayleigh fading channels, or even when extrapolating the MIMO properties from a single bi-directional channel prediction (ray-based or stochastic-based) at the center of the array. However, the stationarity is not true in all real situations as significant variations along the array may be caused by some scatterers or obstructions which are visible to only certain parts of the array. These variations are the least in LoS cases and can vary significantly as we move towards NLoS cases.

We validated and decided to illustrate the capability of our model to predict the non-stationarity by considering an extreme scenario. The transmit antenna array is separated from the receive user antenna by simply a building façade; and the users are positioned in the vicinity of a window (co-located scenario defined in the previous section).

The received power along the array for each user varies due to the spatial separation between the different antenna elements. In the LoS case, the (small) variations are caused only due to the phase recombination effects. In the O2I case, higher variations are due to the various multi-paths but also from the path non-stationarity, in particular when a dominant ray path penetrating through a window appears or disappears. This is shown in Fig. 4, where the received power has been computed in a non-coherent way, i.e. from the sum of the individual ray powers. The non-coherent summation is independent of the phase recombination, and thus allows observing the fluctuations due to scattering or obstructions. Finally, the main O2I variations (as high as 20 dB) result from direct path penetration that occurs either at a wall or glass window. Similar impact, however not always that obvious and strong, is expected in real environments with multiple interactions at urban furniture, rooftop structures, or O2I interface.

![Received power variations along the array.](image)

**B. O2I massive MIMO power delay profiles**

Apart from the non-coherent received power variations, other channel properties as departure/arrival angles and delays do vary along the array. This effect is captured by the single-user power delay profiles (PDPs) plotted in Fig. 5 and Fig. 6 for respectively LoS and NLoS users having same 2D coordinates. In LoS case, the number of delay components is limited. The first delay component is the direct path with maximum power. Its power is almost constant along the whole antenna array. The other components arise from interactions with surrounding building façades or rooftop details. Power variations may be observed, as well as a delay shift. The delay changes linearly along the array, and is directly linked to the AoD at the BS. Its rapidity is at a maximum when the propagation path leaves the antenna array in grazing direction.

Power delay dispersion is higher in the O2I case, with strong dispersion just after the direct path arrival time, and some major echoes between 280 ns and 330 ns. Attenuation of the direct path varies when either penetrating through the window or the wall. Same effect is visible for other indirect propagation path. Besides, death and birth of some paths is clearly observed, not necessarily happening the wall-window penetration transition; this phenomenon is obviously more frequent in O2I than LoS case.
C. Multi user spatial separation/fingerprints

The mMIMO system will have multiple users being allocated the same time-frequency resources. This means that the channel must also be evaluated for multi-user cases. The observation of non-stationarity in the multi-user channel can be observed from the multi-user channel fingerprint. It does aggregate each-user PDP in a same graph, as shown in Fig. 7 and Fig. 8 for respectively the distributed LoS and O2I cases.

The four users are represented by different colours and the shade represents the power level variation. For clarity, only the components with relative power greater than -70 dB are displayed. The components in the O2I case arrive with varying delays and can therefore be separated with different simultaneous channels more easily.

The spatial separation in the LoS scenario is more difficult as the components are fewer although stronger. The different antenna elements receive components equally from most of the users. The delays here depend on the distance between the antenna elements and the users. The spatial fingerprints however do not capture the impact of phase variations along the array and the SVS analysis better represents this.

V. MULTI-USER CHANNEL PREDICTION

Singular value spread (SVS) analysis is performed to characterize and evaluate the impact of the spatial separation of the users in the O2I and LoS scenarios. Singular values are obtained from the MIMO H-matrix that is composed of all users channel coefficients. In a single cell, the MIMO H-matrix is of size $K \times M$, where $K$ is the number of users and $M$ is the number of BS antennas. Then the singular value decomposition of the H-matrix can be given as

$$H = U \Sigma V^H,$$

$U$ and $V^H$ are unitary matrices and $\Sigma = \text{diag}\{\sigma_1, \sigma_2, ..., \sigma_K\}$ gives the singular values. The SVS is the ratio between the largest and the smallest singular values, given as

$$SVS = \frac{\sigma_{\text{max}}}{\sigma_{\text{min}}},$$

The smaller the SVS the greater the orthogonality between the considered users. An antenna array with 128 elements is simulated from the four-user scenarios described here above, as well as all possible subsets of 16, 32, 64, 100 and 120 antennas. The cumulative distribution functions (CDFs) of the singular value spreads in both the O2I and LoS scenarios for respectively the co-located and distributed scenarios are plotted in Fig. 9 and Fig. 10.

As expected, the SVS decreases when the number of antennas increases. The 50th percentile is maximum in the 120-antennas situations and very similar in both scenarios: respectively 5.4 and 4.9 dB for LoS co-located and distributed. In the distributed scenario, as the number of antennas decreases from 120 to 16 antennas, the LoS SVS 50th percentile increases from 4.9 dB to 9.0 dB. For same situation, but in the co-located case, the 50th percentile rises by 13.6 dB. The impact of the antenna array size is more critical in the case of co-located users, as the user separation capability is highly sensible to the offered angular resolution. It can be concluded that increasing
the number of antennas at the BS will increase the spatial separation capability and capacity of the system, however this effect is not linear and depends on the scenarios.

VI. CONCLUSIONS AND PERSPECTIVES

The channel characterization and evaluation of a mMIMO system in an urban O2I scenario using a realistic ray-based model has been presented and analysed. A 128-element ULA is considered in an urban North American city environment. The predictions are carried out using the latest enhancements of Siradel’s Volcano tool which is capable of predicting multi-paths in complex environments including O2I scenarios. Two multi-user distribution cases are considered namely, co-located and distributed in an O2I scenario where the BS is located on a rooftop and the users are indoors. Capability to assess non-stationarity in the mMIMO channel matrix is demonstrated. And the singular spread distribution (SVS) for both LoS and O2I scenarios is discussed.

Higher number of antennas leads to smaller singular value spread and thus higher capacities. However, the relationship between the SVS and the antenna array size significantly varies depending on the scenario. In the distributed case, the increase in the number of antennas does not have a large impact as compared to the co-located case. This implies that increasing the number of antennas helps much more in cases where the users are difficult to separate. It is also observed that, as the array size increases, the decrease of the O2I co-located SVS saturates due to common interaction points in the propagation channel. The O2I scenario also increases the variations along the large array which contributes to the saturation of the SVS, while the LoS SVS decreases in the mMIMO channel.

Same approach as presented in this article can be applied at a larger scale, i.e. with users distributed all over a macro cell. This will be the next step of this work.

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