Massive MIMO Channel Performance Analysis Considering Separation of Simultaneous Users

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Abstract—**One of the key aspects of massive MIMO (mMIMO) is its ability to spatially differentiate between multiple simultaneous users. The spatial separability improves as the number of base station (BS) antenna elements is increased. In real BS deployments, the number of BS array elements will be fixed, and expected to provide the required service to a certain number of simultaneous users in the existing propagation environment. The mMIMO performance is investigated in this paper, in an urban macro-cell scenario, using three kinds of channel models with different complexity levels: the independent and identically distributed Rayleigh fading model, a geometry-based stochastic model, and a physical ray-based software. Two performance indicators are analyzed: the favorable propagation metric and the multi-user eigenvalue distribution. Two frequencies (2 GHz and 28 GHz) and two antenna array shapes (linear and circular) are considered and compared.**

Keywords—*Massive MIMO, channel modelling, ray-based model, favorable propagation, singular value decomposition.*

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 sum capacities, which grow proportionally to the number of users, and are achieved by low-complexity linear transceiver 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 Favorable Propagation (FP) [1] and implies that the mutual interference can be cancelled by low-complexity linear processing techniques, such as zero-forcing, while non-linear successive interference cancelation techniques can only bring minor gains. The mMIMO channel varies from the traditional small-scale MIMO systems by the large number of antennas, which provides more spatial degrees of freedom to serve multiple simultaneous users in the same time-frequency resource and spatially distinguish between their signals. The different antenna elements in the large array receive varying components due to the spatial extent of the array. These variations along the array can be due to the phase variations but also due to the various environmental interactions around the BS. These variations are referred to as non-stationarity along the array. However, in most studies, the channel properties are considered 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 [1]. 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 to have realistic channel models that allow mMIMO studies to be conducted under practical conditions. The ray-based mMIMO model utilized in this work uses efficient deterministic techniques able to predict the channel properties in real environments and has many critical features: incident spherical-wave, possible non-stationarity, and inter-user channel correlation.

The authors have implemented mMIMO H-matrix prediction from the fast ray-based Volcano technology by Siradel [3]. The professional Volcano model has been widely used in the industry for the last twenty years to assess multi-path channel and network performance, either in urban environment or inside buildings. The predicted mMIMO H-matrix is a K x M matrix containing the channel coefficients of all the individual channels between the BS and user antennas, where M is the number of BS antennas and K is the number of single-antenna simultaneous users.

Ray-based predictions are provided by the Volcano software by Siradel. More precisely, the VolcanoUrban model is used [3], which addresses urban or suburban propagation, as well as outdoor-to-indoor penetration. Blockage losses and multi-paths are computed from a precise representation of the environment (high-resolution geographical data) and close approximation of the far-field physical electromagnetic wave propagation (fundamental principles are ray propagation and uniform theory of diffraction). The VolcanoUrban model has been recently integrated into a mMIMO simulation framework, where large antenna arrays (linear, rectangular, and cylindrical) can be created and the MIMO H matrix is automatically computed. In the present study, it was decided to predict the mMIMO channel in the most accurate way: every single channel coefficient of the MIMO H matrix is obtained from a specific ray-based simulation. This approach requires maximum computational effort. It cannot be

ISBN 978-3-8007-4541-8

envisaged for large-scale mMIMO predictions but was chosen here to evaluate the channel non stationarity without any simplification or artefact.

In this paper, a large antenna array consisting of 100 antenna elements separated by half-wavelength is considered in a North American city environment. The antenna array serves multiple simultaneous users located in line-of-sight (LoS), outdoor-to-indoor (O2I) and non-line-of-sight (NLoS) cases.

Section II describes the mMIMO real city environment scenario and setup in the ray-based tool. Section III explains the mMIMO channel characterization and spatial separation evaluation for multiple LoS user channels. The study is further extended to obtain multi-user channel prediction and performance including LoS, O2I and NLoS users in Section IV. Several comparisons are presented: linear antenna array vs circular; ray-based vs stochastic WINNER-II channel predictions. Finally, Section V gives some conclusions and further perspective.

II. SCENARIO AND SETUP

In this paper, the mMIMO channel for multiple simultaneous users is studied using a deterministic ray-tracing tool. The scenario used for the study includes real 3D geographic data from New York city. The BS contains 100 antennas with a single polarization. The antennas on the BS are separated by half-wavelength and are located on the top of a building at a height of 42 m represented by the blue rectangle (in the case of a linear array) in Fig. 1. Different cases with users located in LoS, NLoS and combined locations are considered.

The mMIMO channel performance is also evaluated for a geometry based stochastic channel model (GSCM). The WINNER-II channel model is a bi-directional GSCM that utilizes multipath to model the channel. This channel model has been widely used for the performance evaluation of 4G system level simulations. To achieve MIMO predictions, the channel model provides the channel for a central antenna element and this is then extrapolated using the departure angles for the other antenna elements. The results and a comparison with the deterministic channel model are reported in Section IV.

The FP analysis, that is conducted in Section III, relies on three LoS sites, at different distances from the base station: 72 m, 256 m and 97 m. They are shown in Fig. 1, marked as Site 1, Site 2 and Site 3. Two users are placed at each site.

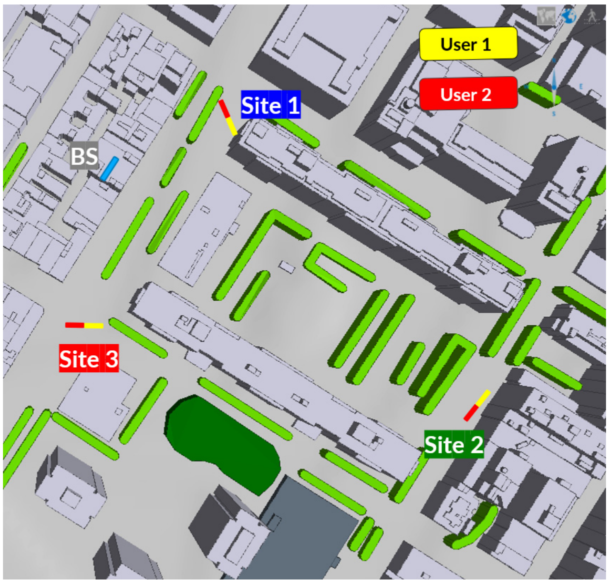

Fig. 1. Multi-user LoS scenario for favorable propagation analysis.

To analyse the FP conditions, the distance between the two LoS users is increased in small steps (in terms of wavelengths), as shown in Fig. 2, to determine at which distance the BS can spatially separate the users. At each position, the mMIMO channel variations between the two users is computed using the ray-based tool, deterministically.

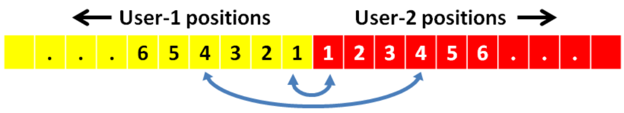

Fig. 2. User positions of two-simultaneous users separated in small steps of a wavelength in each step.

If $\boldsymbol{h}_i$ and $\boldsymbol{h}_k$ denotes the channel vectors of the two users, then the orthogonality of these vectors can be measured as [1]

$$\mathbf{FP} = \frac{\boldsymbol{h}_i^H \boldsymbol{h}_k}{\sqrt{\|\boldsymbol{h}_i\|^2 \|\boldsymbol{h}_k\|^2}}. \tag{1}$$

FP occurs for the given user positions when this metric tends to zero as the number of BS antennas increases. Orthogonality between two users with zero-mean random channels can be studied by computing the variance of (1), because it should also tend to zero asymptotically [1].

In real scenarios, since the number of BS antennas is fixed, we will not obtain ideal FP conditions for the users. When the users are located very close to each other, we can say that FP-like conditions are obtained as the channel directions become orthogonal. For the deterministic channels obtained by our ray-based tool, the equivalence of the variance of (1) is

$$\mathbf{FP\ metric} = \frac{|\boldsymbol{h}_i^H \boldsymbol{h}_k|^2}{\|\boldsymbol{h}_i\|^2 \|\boldsymbol{h}_k\|^2} \tag{2}$$

and it will be analysed in Section III.

Another scenario considered in this paper includes LoS, O2I and NLoS user locations. Here, the user positions are distributed in the streets and inside buildings at a height of 2 m

ISBN 978-3-8007-4541-8

above the ground surrounding the BS. The LoS cases are when the users are located without obstructions in the street facing the BS. The indoor cases constitute users located indoors but with weak obstructions like glass windows. All other users are considered as NLoS.

The study aims to characterize the mMIMO channel performance by comparing different types of array structures (linear and circular) at two different frequencies of 2 GHz (conventional cellular band) and 28 GHz (mm-wave band) using a deterministic ray-based approach. It is interesting to note that in reality the BS deployment strategies at 2 GHz and 28 GHz frequencies are expected to be rather different. This means that the user distributions would also be very different. In this paper, two different user distributions are used, with one user distribution (UD1) being considered only for the 2 GHz macro-cell scenario as the path loss and fading for the users located in deep NLOS can be very high for the 28 GHz case.

From the user distributions shown in Fig. 3, 10 users are considered to be connected to the BS simultaneously in the same time-frequency slot. 10 such snapshots of 10 random user positions result in a total of 100 user locations per distribution, as shown in Fig. 3. Two different user distributions (UD1 and UD2) are considered. UD1 has users distributed all over a larger area with LoS, NLoS and indoor users. This scenario is more suitable for the 2 GHz macro-cell case. UD2 mostly considers only LoS users and is suitable for the 28 GHz case. UD2 has also been used with the 2 GHz frequency to facilitate a comparison between the frequencies. These user distributions are considered for the eigenvalue spread analysis in Section IV.

Fig. 3. Two user distributions, UD1 and UD2, each obtained from 10-snapshots of 10 random users connected to the BS.

III. MASSIVE MIMO CHANNEL CHARACTERIZATION AND SPATIAL SEPARATION

The FP condition is the ability of the BS to observe mMIMO channels of two users that are nearly orthogonal. Under such conditions, the interference between the simultaneous users can be easily mitigated and the spectral efficiency per user is high, as if the two users are alone in the system. To study these conditions in real scenarios, LoS simulations were conducted between the BS and the closely located users. The users are separated in small steps (in terms of wavelengths) to analyze the FP conditions.

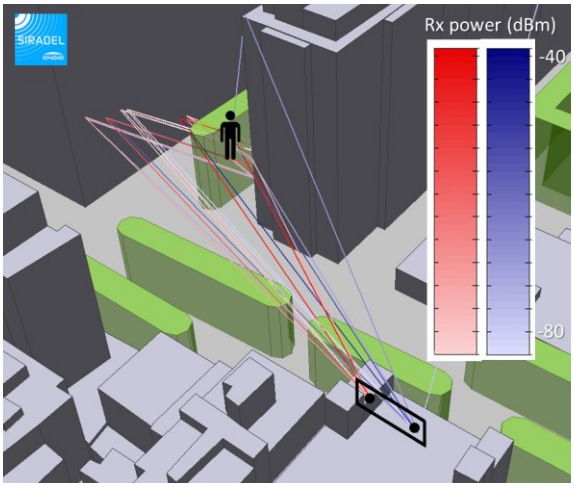

Fig. 4. Example of in-street user as seen from the BS array for the FP analysis.

Channel orthogonality can be observed when considering i.i.d. Rayleigh fading channels even for a small number of antennas. However, there is a degree of correlation that may be assessed by the deterministic model. This is evaluated by considering the first scenario introduced in Section II, in which two LoS users are considered and are separated in small steps (in terms of wavelengths) as shown in Fig. 2 using the ray-tracing tool shown in Fig. 4.

In Fig. 5, the FP metric in (2) is used to analyze the FP-like conditions obtained when the distance between two users is small. For all the three LoS sites, the FP metric oscillates as the distance increases, but tends towards zero at a distance of about 20 wavelengths. This is equivalent to 3 m distance at 2 GHz frequency. Therefore, for the given user locations, it can be said that the FP-like conditions are achieved when the minimum distance between the users is at least 3 m in LoS conditions.

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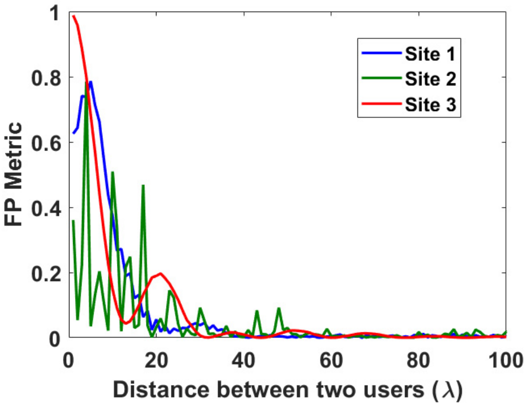

Fig. 5. Minimum distance required between the two users to obtain FP-like conditions.

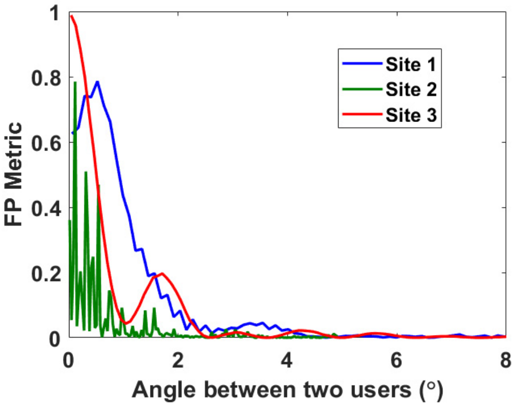

Fig. 6. Minimum angle required between the two users to obtain FP-like conditions.

The geometric distance between the two users, as considered in Fig. 5, may not accurately predict the FP-like conditions when the distance of the users from the BS are different. In such cases, a more appropriate metric is the angle between the two users as seen from the BS, since the spatial resolution of an antenna array is specified by its ability to resolve signals with small differences in angle-of-arrival [1]. In Fig. 6, the angular separation between the users is considered to evaluate the channels of the users to predict the FP-like conditions. The FP metric for Site 2 tends towards zero at smaller angles as compared to the other two sites. This can be explained by the fact that the angle between the two users as seen from the BS decreases with an increase in linear distance between the BS and the users. Since Site 2 is located the furthest at 256 m from the BS, the corresponding angles between the two users at the different positions are smaller. As the distance between the BS and the user positions decreases the angular values increase. From Fig. 6, it can be said that for the given user positions FP-like conditions are achieved when the angular separation between the two users in all three cases is at least 2.5 degrees.

IV. MULTI-USER CHANNEL PREDICTION AND PERFORMANCE

The FP metric, considered in Section III, demonstrates how separable a pair of users is. In this section, the singular value spread (SVS) is analysed to evaluate the joint spatial separability of all the users in the combined LoS, NLoS and O2I scenarios. Singular values are obtained from the MIMO channel matrix $\boldsymbol{H} = [\boldsymbol{h}_1 \ldots \boldsymbol{h}_K]^T$ that is composed of all user channels. This single-cell multi-user MIMO channel matrix is of size $K \times M$, where K is the number of users and M is the number of BS antennas. The rows of the mMIMO channel matrix $\boldsymbol{H}$ representing each user are then normalized by dividing each row by its norm.This is done such that the channel attenuations between the users is removed while the variations over the antenna elements and the frequencies remain. This normalized matrix is used for the calculation of the SVS. Then the singular value decomposition of the channel matrix is given as [4]

$$\boldsymbol{H} = \boldsymbol{U}\Sigma\boldsymbol{V}^H,$$

where$\Sigma = \mathrm{diag}\{\sigma_1, \sigma_2, \ldots, \sigma_K\}$ is a diagonal matrix with the singular values. The SVS is the ratio between the largest and the smallest singular values, given as [4]

$$SVS = \frac{\sigma_{max}}{\sigma_{min}}.$$

The smaller the SVS, the greater the orthogonality between the considered users, since a small singular value implies that some of the channel vectors are spatially similar. The channels obtained from 10 simultaneously served users in the same time-frequency resource are used to calculate the singular values and analyze the mMIMO channel performance. To obtain the spread, 2000 random selections of 10 simultaneous users from a total of 100 random user positions shown in Fig. 3 are made. The 10 simultaneously connected user distributions vary with each selection.

The ray-based predictions are compared to those given by the bi-directional WINNER-II GSCM (Geometry-based stochastic channel model) [5]. This latter model creates clustered multi-paths characterized by their angles, delays and powers. The so-called large-scale parameters as Ricean K-factor, mean angles and angle spreads are cross-correlated. And variations of each large-scale parameter are spatially correlated, driven by a correlation distance that depends on the scenario (macro, micro, indoor, etc). The C2 and C4 sub-models are respectively employed for predicting the macro outdoor links and O2I links, with respective correlation distances 40 and 10 meters. As for the Volcano ray-based predictions, the mMIMO channel matrix is deduced from extrapolation of multi-paths computed at the central array location. Contrary to the widely-used i.i.d. Rayleigh method, the WINNER-II model is able to simulate cross-correlation between the channel coefficients along the antenna array and between closed-by users; however this cross-correlation is governed by statistical laws, and thus are independent of the site-specific environment.

Fig. 7 and Fig. 8 show the SVS distributions for respectively the UD1 and UD2 users, calculated from the i.i.d. Rayleigh, stochastic WINNER-II and deterministic Volcano

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models. The i.i.d. Rayleigh results in Fig. 7 have been derived for the original 100-element linear array, but also for a smaller 32-element array; the reason for involving this smaller array will be given later.

At the lowest percentiles, the SVS is relatively small (lower or equal to 5 dB). This corresponds to good user separability, which is achieved when all 10 simultaneous users have very different channel properties. This corresponds to favourable propagation like conditions. Remark even two users located close-by could have different channels; this is a systematic predicted behavior with the i.i.d. Rayleigh model (no spatial correlation), but is also possible with both other approaches due to the multi-paths diversity.

At the higher percentiles, i.e. poorest propagation conditions, the simultaneous users in each selected group have multi-antenna channels that are correlated. These higher percentiles are of great interest to analyze the mMIMO channel as it represents its performance in the most critical situations. One important result is the strong difference between the linear and circular antenna arrays. Another observation is that the chosen propagation model significantly impacts the predicted mMIMO limit performance. The way the channel correlations are computed must obviously be carefully considered.

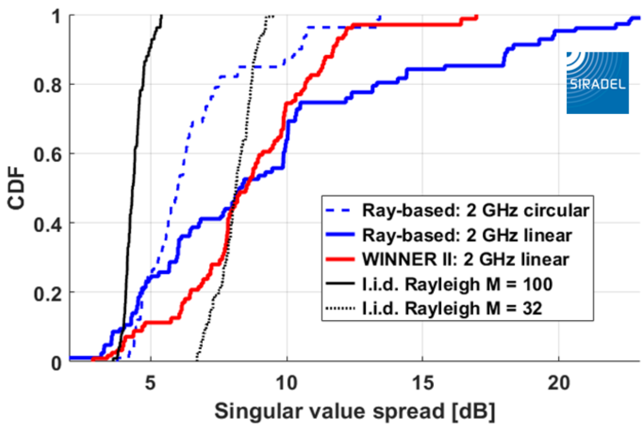

Fig.7. SVS at 2 GHz for the user distribution, UD1.

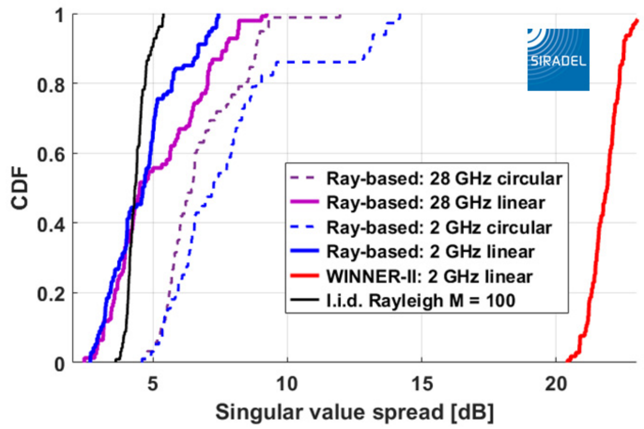

Fig.8. SVS at 2 GHz and 28 GHz for the user distribution, UD2.

In Fig. 7, which gives the SVS for the UD1 case, the performance of the mMIMO channel is similar utilizing both the stochastic and deterministic models. At the median value, the SVS has a value of 8.5 dB for the WINNER-II model whereas it is 8.2 dB for the deterministic Volcano model considering ULA. These similar values indicate that when considering several groups of users in mixed LOS, NLOS and indoor cases, the WINNER-II and ray-based models have the same average mMIMO channel representation. However, in particular scenarios when the user channels are similar like at the 90th percentile, the WINNER-II SVS is 10.5 dB as compared to the 18.1 dB given by Volcano. It seems the ray-based cross-user correlation at this percentile is much stronger than predicted with the stochastic approach. The difference is even greater with the uncorrelated i.i.d. Rayleigh prediction, which gives 5.0 dB SVS. Actually, if considering WINNER-II and Volcano results as relevant references, it appears the i.i.d Rayleigh assumption leads to strong overestimate of the antenna array size benefit. Indeed, the reference median mMIMO performance is reached by an i.i.d. Rayleigh channel having only 32 antennas instead of 100 (about one third).

The linear and circular antenna arrays, as assessed by Volcano, show very similar performance up to the 25th percentile. However above this 25th percentile, the SVS by the linear array degrades far more rapidly. The correlation between the antenna elements is not as strong in the circular array; this is surely caused by the change in the azimuth of the directive per-element radiation patterns. Finally, the SVS difference at the 90th percentile is 7.5 dB.

The study continues with a comparison between sub-6GHz and mmWave mMIMO. To get an understanding of the mMIMO channel performance at higher frequencies the same SVS analysis as performed at 2 GHz has been repeated for 28 GHz utilizing UD2 that contains only optical LoS users. It has to be noted that although the number of antennas at both frequencies is the same (100); the physical sizes of the arrays are different due to the smaller wavelengths at 28 GHz which corresponds to a 14 times smaller size in both linear and circular cases. In Fig. 8, both the linear arrays at 2 GHz and 28 GHz (predicted with Volcano) have similar performance. This good result is caused by two complementary phenomena: 1) the angular separation capability of the antenna array, which strongly benefit to users located at a short range; and 2) the multi-path environment that leads to channel decorrelation. This can also be seen by comparing the linear arrays at 2 GHz using the Volcano model in the different user distributions UD1 and UD2 in Fig. 7 and Fig. 8 respectively. Whatever the percentile is, the short-range LoS channels (UD2) are leading to better conditions than the UD1 channels.

Besides, the WINNER-II model does predict high SVS values, i.e. above 20 dB even at low percentile. The reason is that the LoS component from the WINNER-II model is far dominant compared to the multi-paths (large Ricean K-factor). Therefore the multi-paths do insignificantly contribute to UD2 decorrelation.

The circular arrays in this UD2 user distribution perform slightly worse than the linear arrays as all the LoS users are physically located on the same side of the BS; this means that

ISBN 978-3-8007-4541-8

a part of the antenna array is not capturing any significant multi-path components, and thus is almost useless.

This analysis motivates the need for accurate channel models, which are able to predict the channel properties in different scenarios. Deterministic ray-based models are expected to be an appropriate solution. Advanced geometry based stochastic models with correlation like the WINNER-II which consider bidirectional multi-path propagation environments perform well in global scenarios but are unable to accurately predict all specific scenarios.

V. CONCLUSIONS AND PERSPECTIVES

The BSs in mMIMO systems will serve multiple simultaneously connected users in the same time-frequency resource. The distance between these users is crucial in determining if the BS can resolve the channels, so that the users do not interfere with each other. FP-like conditions are achieved when the simultaneously connected users have almost orthogonal channels. In this paper, the distance and angle between the simultaneously connected users is analysed for a given BS antenna setup in an urban macro-cell environment with a ray-based deterministic approach. Further, the map-based environment is utilized to study the similarities between the user channels in a macro-cell environment. The impact of antenna structures like linear and circular arrays with different frequencies is evaluated when considering the multiple simultaneously connected users.

The performance of the mMIMO channel with multiple simultaneous users has been evaluated as well from the stochastic WINNER-II channel model, which has been widely used in 4G system level simulations. It is shown that although the stochastic and deterministic channel models lead to comparable results in a macro-cell scenario that mix LoS, NLoS and indoor users, they can strongly differ in specific use cases, e.g. when considering a short-range LoS cell.

This work will continue via the integration of the channel data in multi-cell multi-user system simulations. The authors will also investigate the possibility to predict deterministic mMIMO performance maps, as this will be required in 5G radio-planning.

ACKNOWLEDGMENT

This work is supported by the European Commission through the H2020-ETN-5Gwireless project under grant 641985.

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