EUROPEAN COOPERATION
IN SCIENCE
AND TECHNOLOGY

EURO-COST

TD(18)08045
Podgorica, Montenegro
Oct 1-3, 2018

SOURCE: SIRADEL, France

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Abstract: *Large-scale massive MIMO network deployments can provide higher spectral efficiency and better coverage for future communication systems like 5G. Due to the large number of antennas at the base station, the system achieves stable channel quality and spatially separable channels to the different users. In this work, linear, planar, circular and cylindrical arrays are used in the evaluation of a large-scale multi-cell massive MIMO network. The system-level performance is predicted using two different kinds of channel models. First, a ray-based deterministic tool is utilized in a real North American city environment. Second, an independent and identically distributed (i.i.d.) Rayleigh fading channel model is considered, as often used in previously published massive MIMO studies. The analysis is conducted in a 16-macro-cell network with outdoor and randomly distributed users. It is shown that the array configuration has a large impact on the throughput statistics. Although the system-level performance with i.i.d. Rayleigh fading can be close to the deterministic prediction in some situations (e.g., with large linear arrays), significant differences are noticed when considering other types of arrays.*

1. Introduction

Massive MIMO (maMIMO) is generally considered as the key technology for improving the spectral efficiency in future cellular networks. As many manufacturers, operators and site providers are today wondering what the potential of this technique is, the accurate assessment of its performance in real-world scenarios is a crucial objective. This permits to properly anticipate the possible applications and gains, refine the systems, and prepare deployment strategies. Most maMIMO studies that consider realistic channel models have so far been run at the scale of a single-cell, see e.g. [1] and [2], with multiple simultaneous users. For future large-scale maMIMO network deployments, it is important to evaluate the multi-cell performance under realistic conditions. In this work, a large-scale macro maMIMO network is analyzed in a real and complex environment, using physical channel realizations and precise system simulations. Base stations installed on rooftops in dense urban areas are considered. We compare various antenna array shapes: linear, planar, circular, and cylindrical. However, it is expected the same approach can be applied to also evaluate other deployments, e.g. different inter-site distances, sectorization, and complementarity with dense small-cells. This work also illustrates the benefit of using a deterministic channel model compared to a purely statistical model, as often done in prior works.

The large number of antennas at the base station (BS) of a maMIMO system can be used to achieve large spatial degrees of freedom to serve multiple users in the same time-frequency resource. These large spatial degrees of freedom contribute towards two key maMIMO properties known as favourable propagation and channel hardening as described in [3] and [4] respectively. Together, these properties should enable a maMIMO system to spatially separate all the simultaneous users [2] (even if closely located) and provide stable stationary channel conditions, even with small user movements. These conditions are satisfied when very large arrays are considered. In reality, the array size of a maMIMO system is limited, although large. Especially when considering 3D arrays like cylindrical arrays, the aperture of the antenna array is limited as compared to a linear array. With these physical limitations, it is important to assess and demonstrate the performance of practical maMIMO systems in real propagation conditions.

The performance of the maMIMO system depends on the cross-correlation between channels, either the multiple channels from all array elements to a single user, or the channels from one base station to the simultaneous users (that may cause mutual interference) [2]. For accurate predictions, this requires the channel models to be spatially consistent, i.e., to be able to reproduce variations and correlations between two antenna positions. Independent and identically distributed (i.i.d.) channel models do not support such spatial correlation and can therefore not accurately predict maMIMO channels. Most stochastic correlated channel models introduce cross-correlation properties based on the distance between the BS and the user. This kind of correlation can often provide misleading results as two users that are not physically close-by may have higher channel correlations as compared to users that are close-by but not at the same distance from the BS. In other words, such stochastic channel models do not consider directionality when considering the channels. Some other models like geometry based stochastic channel models (GSCM) create spatially correlated channels, thus might be appropriate, however, they are not able to manage the specificities of a particular physical environment [2]. This refers to the decorrelation provided by the specific channel environment surrounding the users like buildings that can create different channels even for users that are located close to each other. The ray-based deterministic channels also provide inherent correlation, due to the computation of the physical wave propagation and interactions, but have the additional advantage that they can be run in real environments, using geographical map data. This balance between the channel cross-correlation between two closely spaced users and the decorrelation caused due to the physical environment around the users provides the most realistic channel predictions. A deterministic ray-based tool is chosen in this work to produce the maMIMO channel responses in a real North American city.

The achievable performance of a maMIMO network is evaluated from the system-level simulator described in [5], which can take channel inputs from any kind of model and generate data rate statistics using state-of-the-art signal processing schemes. This simulator implements the transmit precoding and power allocation schemes, among other system-level calculations.

Section II describes briefly the system-level maMIMO simulator and its usage to obtain the rates that are achievable by the maMIMO system. Section III details the multi-cell multi-user scenario and setup. Section IV presents the system-level maMIMO performance for different antenna array configurations and channel models. Finally, Section V provides some conclusions, perspectives and future work to be conducted on maMIMO system-level studies, with 5G radio-planning as an objective.

2. Massive MIMO System-level Simulator

The first open-source system-level simulator for maMIMO systems was delivered as supplementary material to the book [5]. This Matlab simulator supports state-of-the-art methods for channel estimation, receive combining, transmit precoding, and power allocation, as well as quantifying the corresponding achievable rates. While some of these methods are tailored for statistical channel models, with known first- and second-order moments, in this work, we use methods that support any channel model. More precisely, we consider least-square channel estimation (under the presence of pilot contamination) and regularized zero-forcing (RZF) precoding. The power allocation is selected to maximize the product of the users' effective SINRs, which is essentially the same as maximizing the sum rate, except that there is a "bias" towards giving higher rates to the most unfortunate users than they would get with pure sum-rate maximization (which could lead to zero rate for the weakest users). The rates presented in this work are obtained for full-buffer transmission. We have modified the original simulator from [5] to support our setup, for example, by including BS-user association.

In a maMIMO system, the number of simultaneous users is typically much smaller than the number of BS antennas, because there is a limited number of pilot sequences available for channel estimation. In this work, we have considered a maximum of 20 simultaneously active users that can be connected to any single BS simultaneously. If there are more users, then the system has the possibility to select and allocate some of them on different time slots or frequency sub-bands. Once a set of users is selected for simultaneous allocation, i.e. at the same time and frequency, the BS allocates one of the 20 pilots uniformly at random to the users. Each pilot is only used once per cell, but will be reused across cells, which leads to pilot contamination. The different propagation and interference conditions experienced by the users are partly mitigated by carefully attributing the powers.

3. Scenario and Setup

The objective of this study is to utilize the ray-based deterministic multi-path channel model [7] along with the previoulsy described simulator in order to evaluate the impact of different maMIMO antenna configurations. Results in [1] and [6] suggest that the rate performance in many real propagation environments is comparable to i.i.d. Rayleigh fading. Some explanation of the reason for this is given in [3]. This is due to the favourable propagation and channel hardening properties of maMIMO, which appear as the number of antennas at the BS increase. In reality, the number of BS antennas are limited (far from infinity) and deployed in a limited amount of space, depending on the antenna configuration. This actually restricts the ability of large antenna arrays to observe various channel components and can have a significant impact on the performance.

The selected scenario utilizes 3D geographic map data from New York City which includes buildings of very different heights. The selected map area contains various different geographic features like narrow and wide streets, open squares, and cross-sections. This map data makes it possible to obtain realistic and highly variable channel predictions for the given study. The network is composed of 16 maMIMO BSs located on top of dominant (or quasi dominant) buildings such that the area of interest shown in Fig. 1 is fully covered. Each BS array is formed of 192 antennas. The average inter-site distance (ISD) is 320 m over an area of 1.6 km^2. The furthest BSs (diagonally opposite) are located 1.365 km apart. The carrier frequency is 2 GHz. All the BSs are equipped with directional antenna elements with a horizontal half power beam width (HPBW) of 90º and a vertical HPBW of 20º. All the antennas are vertically polarized with a maximum gain of 13.3 dBi. The 3D beam pattern of the antenna used is shown in Fig. 1. The total transmit power before the application of maMIMO power allocation schemes is 43 dBm over a 20 MHz bandwidth. The user equipment (UE) consists of a single omni-directional antenna with vertical polarization located 1.5 m above the ground level. Only outdoor users are simulated in the results presented belowThe users are always connected to the BS that provides the best received power, i.e. the best server as shown in Fig. 2.

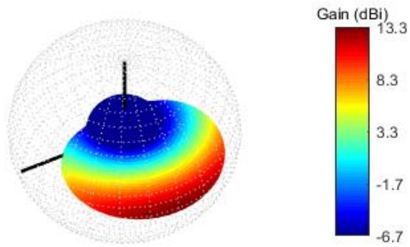

Fig. 1. Directional antenna array pattern of each antenna element of the maMIMO array.

The complex propagation environment creates rich multi-path components, which are predicted by the physical Volcano Urban ray-based model [7]. Multi-paths from reflections and diffractions on the building façade, as well as rooftop diffraction. They affect the maMIMO performance, either by creating spatial separability of users located close to each other, or on the contrary, by producing cross-correlation between users reached by the same canyoning or diffracting phenomenon. The use of a physical channel model does intrinsically bring all correlation factors, between cells and users, which are required for accurate maMIMO assessment. The channel properties are predicted from an antenna element at the center of the BS array and then extrapolated to the whole array, by assuming the multi-paths are stationary (i.e., persistent along with constant amplitude).

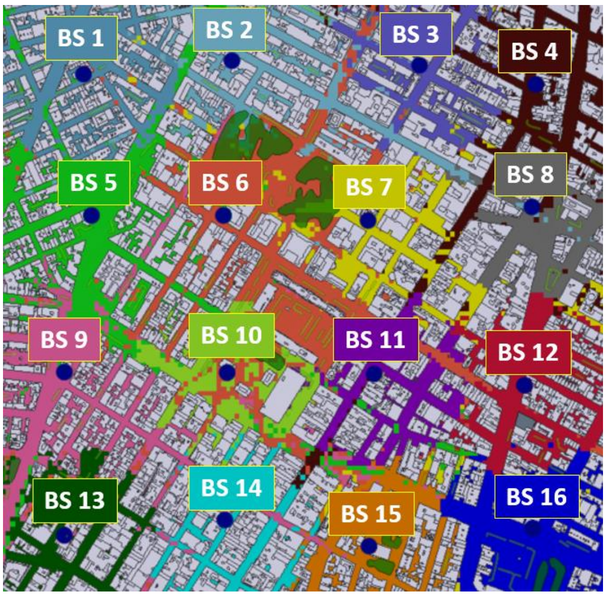

Fig. 2. Massive MIMO BS deployment area. The BSs are depicted by blue dots. The study area is 1.35 km^2. The different colours in the streets represent the color corresponding to their best serving BS for that area.

The performance statistics are obtained from a Monte-Carlo procedure. For the area covered by the 16 cells in Fig. 2, 150 users are randomly dropped at each iteration. These user positions are a subset of 320 random user positions that are uniformly distributed in the entire computation area. The maMIMO propagation from all BS's to all 320 user positions are pre-computed. Then each iteration is conducted in two successive steps; first the maMIMO channel matrices are created for all BS-user combinations (based on pre-computed data); then the system-level simulation is run as described in Section II, including cell selection, precoding, power allocation optimization, and computation of achievable rates.

In a maMIMO multi-cell channel, the individual user channels, even in close proximity can vary significantly based on the propagation conditions. In Fig. 3, an example of two different users connected to the same BS is shown. The significantly different user channels, caused due to the open square and street canyon environments for User 1 and 2 respectively, may be required to be served by the BS simultaneously. This is achieved by jointly selecting the precoding and power allocation at the BS to serve multiple users with different propagation channels. In this work, the maximum product SINR power allocation scheme is used along with the RZF transmit precoder.

In Fig. 4 gives another illustration of the predicted channel heterogeneity, where a same user is reached by two different BS having very distinct propagation conditions.

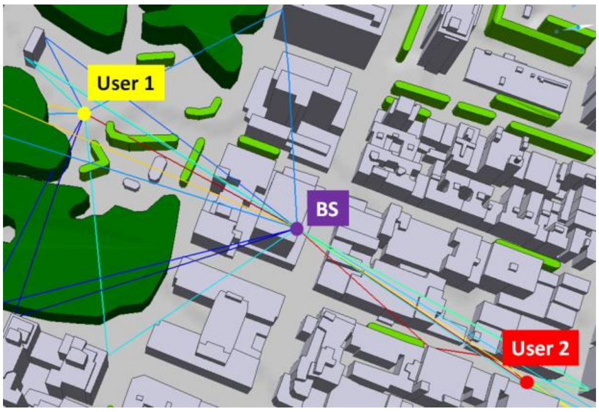

Fig. 3. Example of two users connected to the same BS having very different propagation paths.

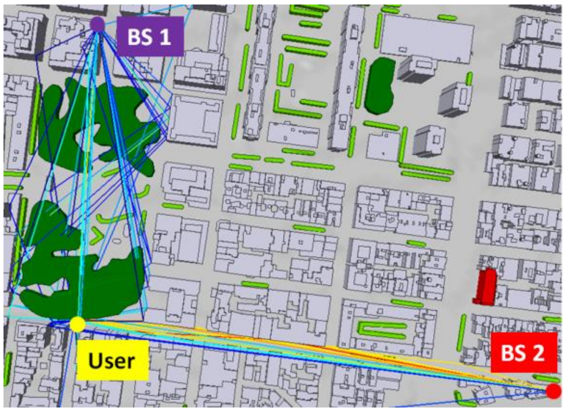

Fig. 4. Example of single user connected to multiple BSs by different propagation paths (canyoning/open square).

4. Massive MIMO Multi-cell System-level Channel Predictions

The system-level simulator presented in [5] is applied to the multi-cell maMIMO scenario described in Section II. The channel data is obtained either from the statistical model (i.i.d. Rayleigh) or from importing the channel realizations created by the deterministic ray-based Volcano Urban model. Several antenna array configurations are implemented and tested: linear, planar, circular and cylindrical. Communication-theoretic data rate expressions given in [5] are used to evaluate the maMIMO performance.

Different antenna configurations are considered: linear, circular, planar and cylindrical. All the considered arrays are uniform and each antenna element is separated by half-wavelength. The linear array is a single row of 192 antenna elements that are all directed in the same direction of 135˚ and has the largest single dimension among all the considered antennas. The circular array is a single circular row of 192 antennas that face outwards from the circle with different but uniform orientations around the circle. The planar array consists of 24 antenna elements in each of the 8 rows for a total of 192 antenna elements. The cylindrical array is obtained similarly by considering a 24 x 8 setup with circular shape. The cylindrical antenna has the smallest dimensions among all the antennas considered.

In Fig. 7, the cumulative distributive function (CDF) of the downlink (DL) throughput/rate per UE [5] is given for different antenna array configurations. Here all the 16 BSs are considered. In each simulation, the users are randomly dropped in the considered area and the corresponding deterministic maMIMO user channels are used to calculate the throughput. At the median percentile, the linear array performs the best with a throughput per UE of 76 Mbit/s. The cylindrical array performs the worst with a throughput per UE of 52 Mbit/s. This difference can be explained by the spatial aperture of each antenna array. The cylindrical array containing 192 antennas (24x8) has the smallest radius (dimension) of all the selected configurations. This is followed by the planar, circular and linear arrays which have similar median performance. At the highest percentiles, however, the performance of all different array configurations converges when the users all have good/favourable channel conditions. The difference in performance observed between the different arrays also depends on the distribution of the users. In Fig. 7, only outdoor users located at street-level at a height of 1.5 m above the ground are considered. In such a scenario, it is expected that the antenna elements of the planar and cylindrical arrays in the vertical dimension are unable to contribute towards the separation of the outdoor users. In Fig. 7, at the lower percentiles this incapability of the planar and cylindrical arrays to separate the users impacts the performance. If indoor users (located at different floors in tall buildings) are also considered, we could expect better performance from the planar and cylindrical arrays. Infact, the performance of the linear and circular arrays is also expected to degrade if the same number of users are located also in the vertical dimension. Therefore, considering this kind of 3-dimensional user distribution is an interesting aspect to this study. This is currently an ongoing perspective.

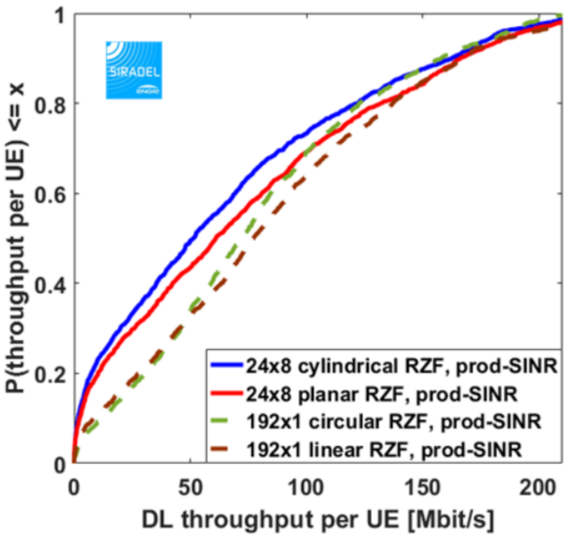

Fig.7. The DL throughput per UE for different antenna configurations considering regularized zero-forcing precoding and prod-SINR power control optimization.

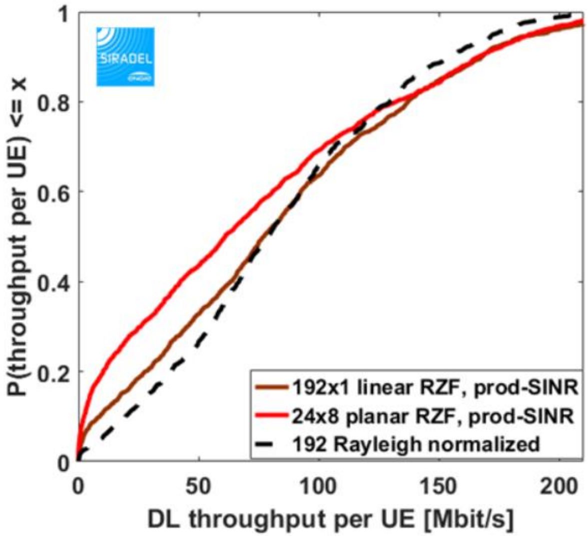

Fig.8. The DL throughput per UE for comparison of ray-based deterministic channel and i.i.d. Rayleigh based channel as applied to system-level simulations.

In Fig. 8, the i.i.d. Rayleigh fading channel is considered with the same multi-cell system-level simulator from [5]. The channel is defined only by the number of antenna elements for each user position and no correlations along the antenna coefficients or between user positions are considered. This model has the advantage of being easily implemented and analyzed, since there are closed-form rate expressions available in the literature [5], but the accuracy of the results is limited. In order to fairly compare the i.i.d. Rayleigh fading results with the deterministic setup, the path-losses obtained from the deterministic setup are also used in the i.i.d. Rayleigh fading setup. This process makes sure that the path-losses between the two different channel models are the same and therefore we are able to compare the impact of the two channel models in terms of angular diversity and cross-link correlation. It can be seen from Fig. 8 that the performance of the normalized i.i.d. Rayleigh channel is similar to that of the deterministic channel in case of the linear array. At the median percentile, both the i.i.d. Rayleigh fading channel and the deterministic channel give a throughput of 80 Mbit/s per UE. However, if we consider the planar array, due to the similarity of the path-losses with the linear model, the normalized i.i.d. Rayleigh model gives results that are very close if not identical to that of the linear array. When considering the deterministic model, a DL throughput/rate per UE of 60 Mbit/s is obtained at the median value for the planar array. This difference of 20 Mbit/s between the planar and linear arrays is not seen in the i.i.d. Rayleigh model. The difference that is not captured by the i.i.d. Rayleigh model is due to the smaller aperture in the horizontal direction of the planar array.

It is also interesting to note that for the sake of comparison, we were able to set the path losses in both deterministic and i.i.d. Rayleigh models to be the same. In reality, if we only consider i.i.d. Rayleigh fading channels, we normally do not have access to accurate models and the path loss information is obtained from more simple approaches (empirical models) which has to be chosen very carefully as small variations in the selection of the model can lead to very different results.

Ongoing simulations have utilized a user distribution in which users are located both outdoors at street-level and indoors. The indoor users are distributed at different floors of buildings. The considered ratio of indoor to outdoor users is typically 80% and is used in these simulations. From preliminary results, it is seen that there is a significant reduction in the datarate due to the weaker indoor channels. Some results of these multifloor user distribution will be provided at the meeting.

5. Conclusions and Perspectives

Practical maMIMO systems will have a large but limited number of antennas which corresponds to limited spatial degrees of freedom and dimensions for the antenna array. The performance of the maMIMO system at the cell and system levels depends on the array structure but also on the propagation characteristics. This work explored new simulation procedures to reach accurate prediction of a maMIMO network. A multi-cell macro deployment of 16 maMIMO BSs in a real complex environment was evaluated.

The maMIMO channel responses from a ray-based deterministic tool that provides realistic 3-dimensional channel correlations between the users were obtained and used for system-level simulations that include precoding and multi-user power allocation. The evaluation is performed by considering the DL throughput per

UE. When considering only outdoor users located on street-level, the performance of the antenna arrays with the largest horizontal dimension (linear) is found to be the best when users are located closer to each other. It is, however, interesting to note here that all the users considered are located at the same street level and these results will change when indoor users located at multiple floors are considered. Then the planar and cylindrical arrays will have an advantage to separate users in the vertical direction.

Further, it is shown that at i.i.d. Rayleigh fading channels whose path losses have been set to the same values as those considered in the deterministic model provide rather similar throughput as the deterministic channel when considering the linear array. This can be explained by the fact that the large size of the linear array is able to see various different channel components that is closer to the uncorrelated channels represented by the i.i.d. channels. In the case of the planar array, the impact due to the limited horizontal dimension of the array is not captured by the i.i.d. Rayleigh model and leads to significantly different results.

This on-going work will continue to include the channels to not only outdoor users but also indoor users located at different floors which are expected to give advantage to the planar and cylindrical arrays. Another perspective of this work is also to predict deterministic maMIMO performance heat-maps, as 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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