Antenna Array Configurations for Massive MIMO Outdoor Base Stations

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Abstract—**Massive MIMO predicts unprecedented capacity and energy efficiency improvements in future networks, by the use of base stations with hundreds of antennas. However the crucial question of determining suitable, or even optimal, antenna hardware solutions for deploying such a large number of antennas in constrained physical spaces is still open. Here we analyse the potential benefits of using compact arrays, dual-polarized arrays, and 2D arrays in outdoor scenarios using a realistic 3D spatial channel model. In particular we show that it is detrimental to reduce the distance between elements below λ/3. Actually, better performances can be achieved by increasing the number of antennas using dual polarization instead. We also show that good performance can be achieved by using 2D arrays, but at the expense of an increased number of total elements when compared to horizontal linear arrays.**

I. Introduction

Massive MIMO is considered a key enabler technology for drastically improving the spectral efficiency of 5G and beyond mobile networks while reducing energy consumption and thus reducing the carbon footprint [1-3]. Massive MIMO is based on a multi-user MIMO scheme in which the base stations (BS) are equipped with a number of antennas well over the number of active users. In this way, different data streams can be simultaneously sent to different users by forming very narrow beams. The resulting array gains provide improved throughputs and reduced transmitted powers.

The first measurements campaigns with large arrays showed that with about ten BS antennas per user terminal, a stable performance not far from the theoretical limits can be obtained by using simple pre-coding schemes [3, 4]. Therefore it is envisaged that base stations with hundreds of antennas will be needed to serve tens of users. However, a solution for accommodating hundreds of antennas in the constrained spaces of traditional BS towers is required.

Several works addressed this problem recently. The benefits of compacting the antenna elements with spacings below half wavelength were shown in [5]. However, only the mutual coupling effects between immediate neighbour elements was considered there, resulting in overestimated performances as demonstrated in this work. Another solution is to use full-dimension arrays, in which the elements are arrayed not only in the horizontal dimension but also in the vertical one [6, 7]. In contrast to traditional BSs, the vertical beamforming is not fixed for a uniform coverage area around the station, but it is dynamically adjusted forming beams to the different users.

In our prior work [8], we studied the solution of using full-dimension compact arrays with multi-polarized elements. However, the modelling assumptions there limited the validity of the results to rich scattering indoor scenarios. Therefore, the aim of this paper is to extend these results by studying the use of compact, multi-polarized and full-dimension arrays *in realistic outdoor environments*. To this end, a 3D spatial channel model based on the outcomes of the WINNER+ project [9] is used, and the antenna radiation characteristics and the mutual coupling between elements are accurately modelled using electromagnetic full-wave simulations.

II. System Model

A single 120º sector with a BS equipped with M antennas serving K single-antenna active users is considered. We focus on the downlink transmission, for which the multi-user MIMO system model can be written as

$$\boldsymbol{y} = \boldsymbol{G}\boldsymbol{s} + \boldsymbol{w} \quad (1)$$

where $\boldsymbol{y}$ is a $K \times 1$ received vector containing the stack of the received signals at all user terminals and $\boldsymbol{w}$ is a $K \times 1$ vector denoting the stack of all received noise components, which are modelled as independent and identically distributed (i.i.d.) complex circular symmetric Gaussian random variables with zero mean and variance σ^2_w. The channel matrix $\boldsymbol{G}$ is of size $K \times M$. Its component G_{km} refers to the channel gain from the mth transmit antenna to user terminal k. The $M \times 1$ transmit signal vector $\boldsymbol{s}$ complies with a transmit power constraint so that

$$E[\boldsymbol{s}^{\mathrm{H}}\boldsymbol{s}] \leq P \quad (2)$$

where P denotes the total power injected to the antenna ports. The ratio between the injected power and the receiver noise variance is denoted by $\rho = \frac{P}{\sigma_w^2}$.

We assume linear precoding at the BS, such that the transmitted vector is rewritten as

$$\boldsymbol{s} = \boldsymbol{F}\boldsymbol{a} \quad (3)$$

where the $K \times 1$ vector $\boldsymbol{a}$ contains the stack of the K information symbols intended for the K user terminals. Independent unit energy constellation symbols are assumed, that is, $E[\boldsymbol{a}\boldsymbol{a}^{\mathrm{H}}] = \boldsymbol{I}_K$, such that the power constraint can be rewritten in terms of the $M \times K$ precoding matrix $\boldsymbol{F}$ as

$$trace(\boldsymbol{F}\boldsymbol{F}^{\mathrm{H}}) \leq P \quad (4)$$

Two linear precoding strategies are considered throughout the paper: (i) the maximum ratio transmission (MRT), which was found to be optimum when the number of BS antennas tends to infinity [1] and is computationally low–demanding; and (ii) the Zero-Forcing which aims the complete cancellation of the inter-user interference but at the expense of increased computational requirements. The expressions of the precoding matrices can be found in [8].

The metric used to compare the different array configurations is the sector average sum rate which in the case of the MRT is calculated as

$$sum\ rate_{MRT} = \sum_k log_2(1 + SINR_k) \quad (7)$$

where $SINR_k$ is the signal-to-noise-plus-interference ratio of the kth user which, and denoting $\boldsymbol{A}=(1/M)\boldsymbol{GG}^{\mathrm{H}}$ is expressed as [8]

$$SINR_k = \frac{\rho A_{kk}^2}{\frac{trace(\boldsymbol{A})}{M} + \rho \sum_{l=1,l\neq k}^{k} |\boldsymbol{A}_{kl}|^2} \quad (8)$$

The ZF equalizes the signal-to-noise ratio (SNR) among users, so the sector average sum rate in this case is directly

$$sum\ rate_{ZF} = K log_2(1 + SNR) \quad (9)$$

where the equalized SNR is [8]

$$SNR = \frac{\rho}{trace\left(\left(GG^H\right)^{-1}\right)} \quad (10)$$

A. Channel and antenna modelling

The spatial channel model SCM and its extensions SCME and WINNER have been widely used by the wireless community for analysing the performance of new developed standards (e.g. 3GPP-LTE). These are 2D geometry based stochastic channel models in which only the horizontal cross-section of wireless channels is considered, so they cannot be used for analysing beamforming in elevation. Although 3D extensions of these models are being studied by standardization bodies there is no accepted version available yet. Therefore in this work use a 3D extension developed in the WINNER+ project [9] but with the parameters extracted in [10] that correct the problem of having non-positive definite cross-correlation matrices of large scale parameters. The correction on the polarization of LOS components proposed in [10] is also applied.

The radiation properties of the antennas are included by means of their radiated field patterns. For an accurate modelling, we extract these patterns from full-wave electromagnetic simulations carried out with Ansys HFSS. In order to include the mutual coupling effects between elements we compute the so-called *embedded* pattern of each element, i.e. the radiation field pattern of each antenna element surrounded by its neighbours terminated by the system reference impedance. Two BS antenna elements are considered throughout the paper: vertical dipoles backed by a perfect conductor at a distance around a quarter wavelength for directing the radiation to the desired sector; and dual-polarized 45º slanted crossed dipoles also backed with a perfect conductor. In both cases the antennas are designed to be matched to 50Ω in isolation conditions at 2.5 GHz. It is worth mentioning that the entire analysis is carried out at the single frequency of 2.5GHz so bandwidth issues are not considered. For the user terminals ideal omnidirectional radiators are assumed.

Since the objective is to compare different array configurations and not power allocation strategies, the pathloss and shadowing effects are not taken in account and a uniform power allocation among users is assumed. The channel gains are normalized by the channel gain obtained when using isolated vertical dipoles at the BS and vertically polarized omnidirectional antennas at the user side.

III. Simulations results

The analysis is focused to a 120º cell sector of urban macro scenario with cell radius of 500m in which K=10 users are served. For each array configuration the sum rates of 1000 realizations are averaged. In each realization the users are uniformly distributed inside the sector but keeping a minimum distance from the BS of 50m in order to fulfil the channel model assumptions. The BS and user terminal heights are 25m and 1.5m, respectively. LOS and NLOS conditions are set according to the probabilities defined in the WINNER+ model.

A. Compact arrays

We first analyse compact arrays by considering horizontal linear arrays of vertical dipoles at the BS and vertically polarized omnidirectional antennas at the users. The total size of the array is fixed to 10λ and the number of BS antennas is increased from 10 to 80, so the inter-element distance is reduced from d=1λ to d=λ/8.

Figures 1 and 2 show the results obtained in regimes with high (ρ=20dB) and low (ρ=0dB) injected powers (in transmission) to received noise variances ratios, respectively. The performance of ZF and MRT precoders are compared using: (i) the embedded radiation pattern for fully modelling the mutual coupling between elements; (ii) and the isolated radiation pattern for only taking in account the limited aperture but not the mutual couplings. An array with an unconstrained size and fixed inter-element distances of d=λ/2 is also included as a reference.

It can be observed that, independently of the regime, the use of unconstrained arrays logically lead to a monotonically increasing sum rates with the increasing number of antennas. Actually, in the case of the ZF and thanks to its interference cancelling capabilities, the unconstrained array curves approach the theoretical interference free sum rate $K\log_2(1+\rho N/K)$ i.e. 96.5b/s/Hz for ρ=100 and 31.7b/s/Hz for ρ=1. However, the limited aperture and mutual coupling effects of constrained arrays limit the sum rate improvement above 20 BS antennas (or d=λ/2). The most limiting factor is the reduction in the transmitted power due to mutual coupling between elements which not only limits the sum rate scaling up but even produce a decrease above 30 BS antennas (d=λ/3). An exception is found for the MRT in ρ=20dB regime, since the transmitted power reduction affects both the desired signal and the interference so the mutual coupling effects are masked by the high SNR. When the mutual coupling is not considered, the limited aperture does not allow producing narrower beams by increasing the number of antennas, but still provides an increasing sum rate due to fictitious array gains.

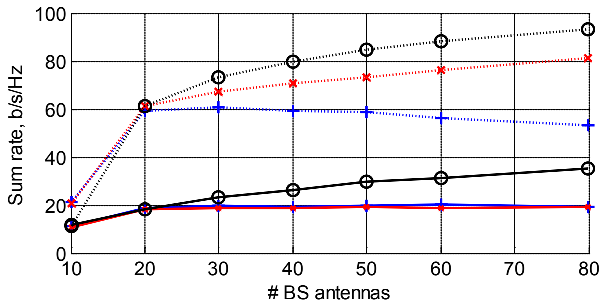

Fig. 1. Sector sum rate for ρ=100: (--) ZF; (-) MRT; (+) embedded pattern; (x) isolated pattern; (o) isolated pattern in unconstrained arrays with d=λ/2.

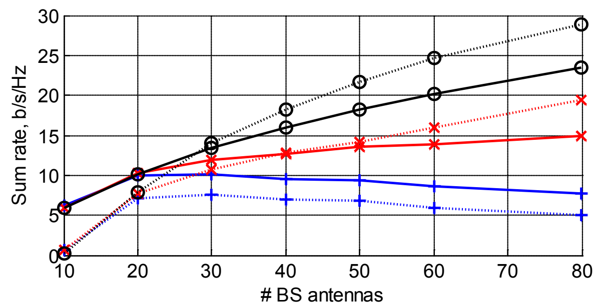

Fig. 2. Sector sum rate for ρ=1: (--) ZF; (-) MRT; (+) embedded pattern; (x) isolated pattern; (o) isolated pattern in unconstrained arrays with d=λ/2.

As expected, the ZF performs better than the MRT for the ρ=20dB regime while the contrary occurs in the ρ=0dB one. Only when unconstrained arrays are considered, the array gain makes the ZF perform better than the MRT even for ρ=0dB.

In high SNR regimes, massive MIMO can be used for improving the energy efficiency by using the high array gains for reducing the transmitted power instead of increasing the SNR. This feature is analysed in Fig. 3, in which the power injected to the BS antennas is scaled down by the number of antennas, so that $\rho=100/N$. In this case, the effects of limited aperture and mutual coupling are more pronounced. Increasing the number of antennas beyond 20 (d=λ/2) does not provide any sum rate improvement when the limited aperture is artificially considered alone, whereas it results in drastic sum rate reductions when the mutual coupling effects are also considered.

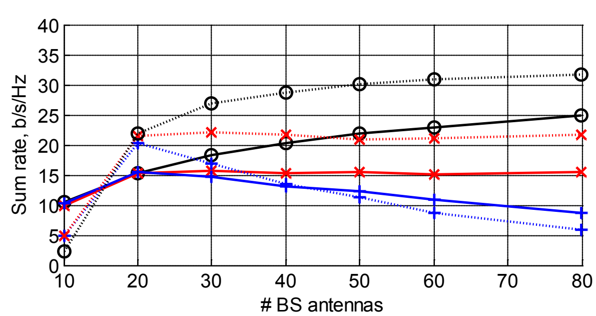

Fig. 3. Sector sum rate for $\rho=100/N$: (--) ZF; (-) MRT; (+) embedded pattern; (x) isolated pattern; (o) isolated pattern in unconstrained arrays with d=λ/2.

B. Dual-polarized arrays

From the previous section it can be concluded that there is no benefit in using inter-element distances below λ/2 or λ/3. However, it is well-known that using dual-polarized elements allow doubling the number of antenna ports without increasing the physical space and avoiding mutual coupling effects. Besides, it also provides polarization diversity so that the impact of polarization losses due to the misalignment of the user antennas and the BS antennas is reduced. The main drawback of dual-polarized arrays in massive MIMO is that the elements in orthogonal polarization do not contribute to the formation of narrower beams.

Figures 4 and 5 show the performance of dual-polarized arrays when the array gains are used for increasing the received SNR or for reducing transmitted power, respectively.

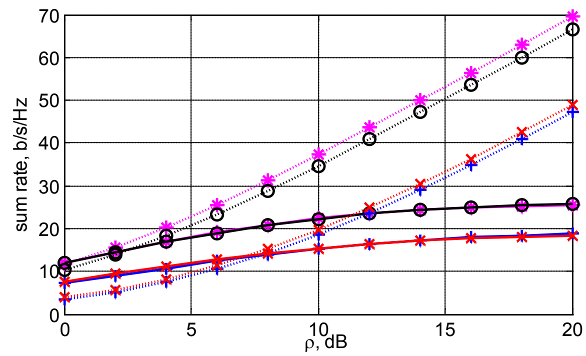

Fig. 4. Sector sum rate vs ρ: (--) ZF; (-) MRT; (+) 40 vertical dipoles (d=λ/4); (x) 20 vertical dipoles (d=λ/2); (o) 40 vertical dipoles (d=λ/2); (*) 20 dual-pol. dipoles (d=λ/2).

We consider10λ linear horizontal arrays formed by: (i) 20 dual-polarized 45º slanted crossed dipoles (40 antenna ports) with a distance between elements of d= λ/2; (ii) 40 vertical dipoles with d= λ/4; and (iii) 20 vertical dipoles with d= λ/2. A 20λ array with 40 vertical dipoles and d= λ/2 is also included as a reference. The polarization of user terminal antennas is assumed to be random in order to include polarization losses in the analysis.

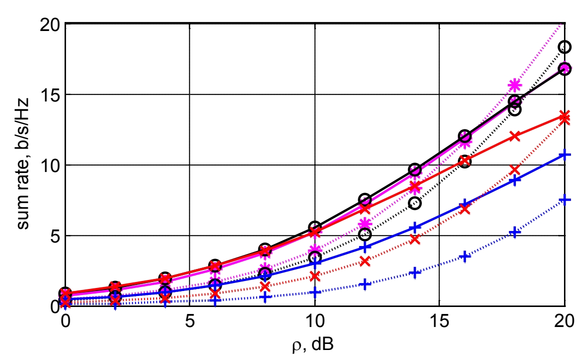

Fig. 5. Sector sum rate vs ρ with transmitted power scaled by N: (--) ZF; (-) MRT; (+) 40 vertical dipoles (d=λ/4); (x) 20 vertical dipoles (d=λ/2); (o) 40 vertical dipoles (d=λ/2); (*) 20 dual-pol. dipoles (d=λ/2).

Regardless of the precoder or the power scaling strategy, the dual-polarized solution clearly surpasses the other 10λ arrays. It even performs slightly better than the 20λ array of single polarized dipoles when ZF is used whereas the performance of both solutions is similar for the MRT. A physical explanation is that the benefits of using polarization diversity for reducing the polarization losses exceed the increased array gains provided by the larger array.

C. Full-dimension arrays

So far only horizontal linear arrays were considered. However, clearly many mechanical and esthetical issues may arise when trying to attach large (i.e. several meters long) horizontal arrays to traditional slim vertical BS towers. Therefore, here we analyse the benefits of arraying the antenna elements not only in the horizontal dimension but also in the vertical one. Such 2D arrays allow reducing the horizontal dimension and thus minimizing the mechanical and esthetical impacts, while maintaining good performances due to their beamforming capabilities in both azimuth and elevation dimensions.

We consider dual-polarized arrays with inter-element distances of $\lambda/2$ to avoid mutual coupling effects. We focus on a high SNR regime with the transmitted power scaled down by the number of BS antennas for energy saving ($\rho=100/N$) and the use of ZF. The results in other scenarios are qualitatively similar so they are omitted due to space constraints. Figure 6 depicts the performance obtained with the following array configurations: (i) linear horizontal array with horizontal dimension of $Hd=N/2*\lambda/2$; (ii) linear vertical array with $Hd=\lambda/2$; (iii) square array with $Hd=\sqrt{N/2}\lambda/2$; and (iv, v, vi) rectangular arrays with $Hd=5\lambda/2$, $10\lambda/2$ and $20\lambda/2$. For easy interpretation of the results, the sum rates are expressed in percentage of the maximum stable sum rate obtained by the linear horizontal array.

It is clear that the best performance is obtained by the linear horizontal array. In fact, with about 60 antenna elements 90% of the maximum achievable sum rate is already reached with a horizontal linear array of length 15λ, whereas around 160 elements are needed for the array with horizontal dimension of 10λ, and near 200 elements are needed for the arrays with more reduced horizontal dimensions. The reason is that in the azimuth plane the users are uniformly distributed in a 120º sector, whereas in the elevation domain the sector reduces to 24º, so much more vertical antennas are needed to produce narrower beams in order to obtain a similar equalized SNR.

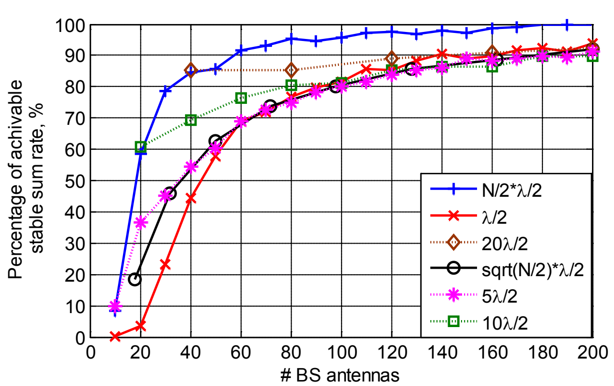

Fig. 6. Sector sum rate for 2D arrays with different horizontal dimensions.

Another interesting result is that for 2D arrays, as the number of vertical elements increase the sum rate converge to the sum rate obtained by the linear vertical array, but is still clearly below the horizontal one. Therefore, with respect to the vertical linear arrays, 2D arrays provide improved performances for low number of elements whereas they only provide reduced vertical dimensions for large number of elements.

IV. Conclusion

A solution for accommodating the large number of BS antenna elements required for massive MIMO in constrained physical spaces is needed. In this paper we demonstrated that compacting single-polarized elements with inter-element distances below $\lambda/3$ is not beneficial, and that this solution is clearly surpassed by the use of dual-polarized elements with $\lambda/2$ spacings, not only due to their reduced mutual coupling effects but also because of the induced polarization diversity. Finally we showed that though horizontal linear arrays provide the best performances, 2D arrays can reach a big percentage of this performance with reduced horizontal dimensions but with a notable increase on the total number of radiating elements.

Acknowledgment

This work received funding from the Spanish Ministry of Economy and Competitiveness (TEC2011-29006-C03-02 GRE3N-LINKMAC) and from the Catalan Government (2009SGR0891). The authors would like to thank Dr. Martin Haardt for providing access to the WINNER+ channel model.

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