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Aslan, Y.; Roederer, A.G.; Yarovoy, Alexander

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Yanki Aslan
Department of Electrical Engineering
Delft University of Technology
Delft, The Netherlands
Y.Aslan@tudelft.nl

Antoine Roederer
Department of Electrical Engineering
Delft University of Technology
Delft, The Netherlands
A.G.Roederer@tudelft.nl

Alexander Yarovoy
Department of Electrical Engineering
Delft University of Technology
Delft, The Netherlands
A.Yarovoy@tudelft.nl

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***Abstract*—The system effects and trade-offs of varying the minimal angular separation among multiple simultaneous co-frequency users are investigated for a high-capacity multibeam communication scenario. Through the statistical system simulations, it is demonstrated that the optimal (non-zero) value of the required separation depends on the base station array size, number of users, precoding technique, desired probability of coverage and intended quality of service.**

***Index Terms*—base station antennas, next-generation communications, radio resource management, space division multiplexing, system analysis.**

I. Introduction

The demanding capacity and connectivity criteria of beyond-5G systems can only be satisfied with true multibeam antenna arrays at the base stations, which are able to communicate with several users within a single time-frequency-code resource block [1], [2].

In a full frequency reuse scenario, it is an important task to select the particular users to be served concurrently so as to achieve a high Quality of Service (QoS) in the statistical sense. In the signal processing field, this selection is often wrongly made by a random pick. However, in the antenna community, it is well-known that the beam resolution of the base station antenna puts a restriction on the angular separation among the simultaneous co-frequency users [3]–[5].

Radio Resource Management (RRM) resolves this issue by allowing us to define a minimal user separation criterion in the network [4]. The overall population of users is then served via time slicing or frequency slicing in sub-bands.

In this paper, we investigate the impacts of varying the minimal angular separation among multiple users on the system performance in terms of the QoS and the sector coverage. The rest of the paper is organized as follows. Section II presents the system model. The simulation results are given in Section III. The conclusions are provided in Section IV.

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II. System Model

Consider a communication sector in which a base station (BS) with N antenna elements is serving K single antenna users in pure Line-of-Sight (LoS) simultaneously in the same narrow frequency sub-band using Space Division Multiple Access (SDMA) [5]. Let us assume $\boldsymbol{q} \in \mathbb{C}^{Kx1}$ is the input signal vector at the BS. Then, the precoded signal vector $\boldsymbol{x} \in \mathbb{C}^{Nx1}$ is given by

$$\boldsymbol{x} = \boldsymbol{W}\boldsymbol{q} \tag{1}$$

where $\boldsymbol{W} \in \mathbb{C}^{NxK}$ is the precoding matrix.

The received signal vector at the users $\boldsymbol{y} \in \mathbb{C}^{Kx1}$ is

$$\boldsymbol{y} = \sqrt{\boldsymbol{\rho}} \cdot (\boldsymbol{H}\boldsymbol{x}) + \boldsymbol{n} \tag{2}$$

where $\boldsymbol{\rho} \in \mathbb{C}^{Kx1}$ is a vector proportional to the maximal Signal-to-Noise ratios (SNRs) at the users, $\boldsymbol{H} \in \mathbb{C}^{KxN}$ is the channel matrix with normalized entries, and $\boldsymbol{n} \in \mathbb{C}^{Kx1}$ is the unit-variance Additive White Gaussian Noise (AWGN).

Assuming a common embedded element pattern at the BS and omnidirectional antennas at the users, the entries of the channel matrix $\boldsymbol{H}$ are given by

$$H_{k,n} = \beta_{k,n} G(\hat{r}_k) \frac{e^{-j\frac{2\pi}{\lambda}|r_k - r_n|}}{|r_k - r_n|} \tag{3}$$

where $G(\hat{r}_k)$ is the far-field of a BS element in the direction of the k^{th} user. $|r_k - r_n|$ is the distance between the n^{th} BS element and the k^{th} user, with the coordinate center located at the center of the BS array. $\beta_{k,n}$ is the normalization constant.

Two commonly applied precoding techniques are used for precoding: Conjugate Beamforming (CB) and Zero Forcing (ZF). The generalized (LoS / non-LoS) expressions of $\boldsymbol{W}$ for the two techniques are given by

$$\boldsymbol{W} = \begin{cases} \boldsymbol{H}^{\dagger} & for\ CB \\ \boldsymbol{H}^{\dagger}(\boldsymbol{H}\boldsymbol{H}^{\dagger})^{-1} & for\ ZF \end{cases} \tag{4}$$

where † denotes the Hermitian transpose. It is further considered that $\boldsymbol{W} \in \mathbb{C}^{NxK}$ satisfies the per-user power normalization condition, i.e. $\sum_{n=1}^{N} |W_{n,k}|^2 = 1$ for $\forall k \in \{1, \ldots, K\}$.

The right-inverse is used in the case of ZF for computational complexity reduction [4]. Yet, it is worth noting that ZF, due to the matrix inversion, is more complex to compute reliably and more sensitive to the channel impurities [6].

Thus, the downlink SINR of the k-th user is given by

$$SINR_k = \frac{\rho_{k,k}|\boldsymbol{H}_{k,:}\boldsymbol{W}_{:,k}|^2}{\sum_{j\neq k}^{K}\rho_{k,j}|\boldsymbol{H}_{k,:}\boldsymbol{W}_{:,j}|^2 + 1} \tag{5}$$

where $\rho_{k,j}$ is proportional to the SNR at the k-th user while serving the j-th user.

In this work, we assume a LoS communication scenario with a constant maximal SNR per user (via adaptive power transmission depending on the user distance, within a maximal cell range of 200 meters with higher probability of occurrence at larger distances as applied in [5]), which occurs in the case of CB with maximum possible array gain. N = 256 in a 16 by 16, 0.5λ-spaced square grid topology. K = 8 and the sector is formed by a $\pm$60 / $\pm$15 degree window in azimuth / elevation (i.e. a 2(sin60^o) / 2(sin15^o) window in the uv-plane) [7]. The maximal per user SNR is varied between 0 to 20 dB for parametric studies. A minimal user separation, δ (in the uv-plane, in units), is also defined by the RRM. δ is varied between 0 to 0.3 units (note that λ/D = 0.13 units, where D is the array edge length). The main focus of this paper is to investigate the impact of δ on the system performance in terms of the BS array radiation pattern, sector coverage and the statistical user SINRs which gives a measure of the QoS.

III. Simulation Results

A. Impact on the Array Pattern

First, to give insight, the effect of user separation on the BS multibeam array radiation pattern is visualized at the v = 0 cut. Let us assume a subset of SDMA users positioned at u = {0, 0.17, -0.34, -0.02}. Fig. 1(a) shows the beams with CB precoding. Taking the user at broadside (u = 0) as reference, it can be seen that a huge interference occurs towards the closest user at u = -0.02. This level decreases as the interfering user is located further away from the reference user and reaches near the first and second side lobe of the reference pattern at u = 0.17 and -0.34, respectively. For a ZF-like precoding, it is seen that the interference problem is completely resolved by placing nulls. However, the array gain is seriously affected when two concurrent/co-frequency users are closeby. Fig. 1(b) shows that the broadside gain at the reference pattern drops significantly while forcing a null at the interfering user at u = -0.02. On the other hand, the gain remains almost unaffected for a null at the far-away users.

This simple feasibility study highlights the importance of setting a user separation constraint in RRM for high-capacity multiuser communications, regardless of the type of precoding.

B. Impact on the Sector Coverage

For statistical studies, the K = 8 user positions are quasi-randomly (i.e. satisfying the minimal separation criterion, δ) selected 10,000 times within the fully-populated sector. The

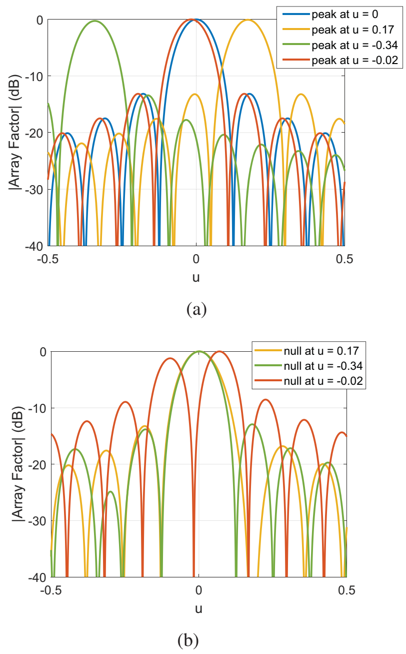


Fig. 1. Sample BS array radiation patterns: (a) multiple beams with CB precoding, (b) null forming with ZF-like precoding.

histograms of uv-plane user locations for varying δ values are provided in Fig. 2. It is seen that with increasing δ, the probability of selecting users close to the sector corners increases. In fact, such an effect might lead to "blind spots" within the sector. Fig. 3 quantifies the number of blind spots with respect to a threshold, μ, on the number of occurrence. For relatively high δ values, Fig. 4 visualizes the blind spots which are selected less than 10 times out of 8 x 10,000 total occurrences (i.e. μ = 10).

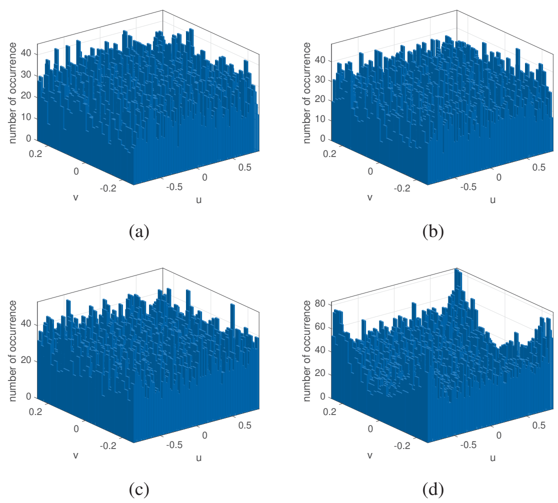


Fig. 2. Histogram of selected user positions: (a) δ = 0, (b) δ = 0.1, (c) δ = 0.2, (d) δ = 0.3 units. (Bin width = 0.017 units)

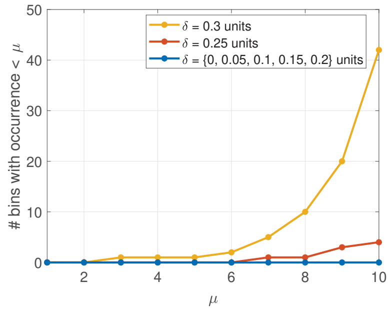
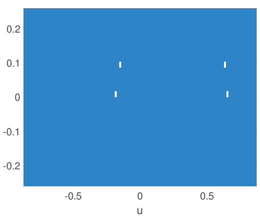
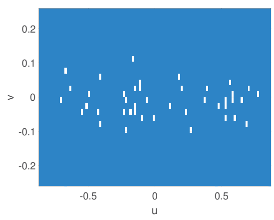


Fig. 3. Number of blind spots for varying δ, with respect to a threshold, μ, on the number of occurrence.



(a)



(b)

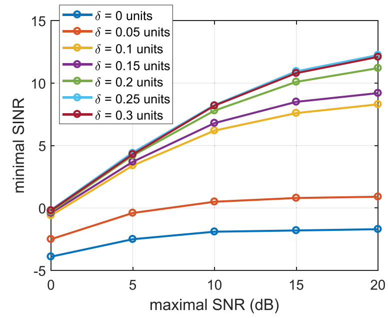
Fig. 4. Locations of the blind spot which are selected less than 10 times out of 8 x 10,000 total occurrences (i.e. μ = 10): (a) δ = 0.25, (b) δ = 0.3 units.

This analysis clearly shows that there is a side effect of increasing δ, which is the undesired blind spots within the field of view. Note that better coverage can be achieved for less number of users with the high δ values, but this comes at the expense of reduced spectral efficiency.

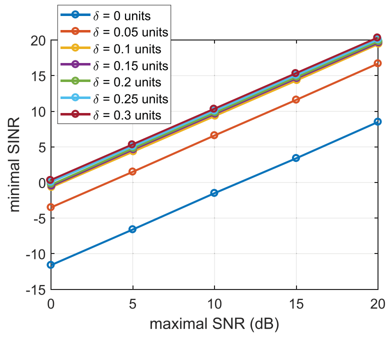
C. Impact on the QoS

Last, using the previously obtained user distributions in the simulation model described in Section II, SINR values at the users are computed for different δ values. As a measure of the statistical QoS, the minimal SINR value obtained in 99% of the total occurrences is used. In other words, it is guaranteed that the given SINR value is obtained in 99% of the 80,000 cases for the corresponding maximal SNR and δ.

The results are given in Fig. 5(a) and Fig. 5(b) for the CB and ZF precoding, respectively. In CB, it can be seen that δ should be large enough to suppress the interference. Yet, as explained previously, choosing δ too large could yield blind spots. Therefore, selecting δ = 0.2 (i.e. $1.5\lambda/D$) seems to be a good trade-off. In ZF, a near-optimal performance (i.e. SINR $\approx$ SNR) is achieved for $\delta \geq 0.1$ (i.e. $0.75\lambda/D$). Thus, as compared to the CB precoding, a smaller δ value can be used in RRM with ZF, which is also favorable for effective coverage. However, as mentioned before, ZF is more complex to apply and less reliable in comparison to the CB under realistic conditions.



(a)



(b)

Fig. 5. Minimal SINR obtained in 99% of the total occurrences for varying δ at different maximal SNR values: (a) CB precoding, (b) ZF precoding.

IV. Conclusion

The effects of setting a minimum user separation constraint in RRM for the next-generation SDMA-based communications are discussed. Based on a system model, the discussion is tailored to the impacts on the base station array pattern, sector coverage and the overall QoS. It is explained that due to the limited beam resolution, satisfying a certain minimal user spacing is a must. However, there is a trade-off between the inter-user distance and effective coverage of the communication sector. The optimal value of the minimal user separation depends on the size of the array, the number of simultaneous co-frequency users, the precoding strategy used and the desired performance criteria on the coverage.

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