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# Experimental Evaluation of the Effect of BS Antenna Inter-Element Spacing on MU-MIMO Separation

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***Abstract*—In this paper, multiple-input multiple-output (MIMO) channel measurements in an outdoor micro-cell environment are used to study the effect of base-station (BS) inter-element spacing on multi-user MIMO signal separation. Users with two dual-polarized patch antennas at the mobile station (MS), and four equally-spaced dual-polarized patch antennas at the BS are considered. At the BS, the inter-element spacing (i.e., the spacing between the four dual-polarized patch antennas), is varied from half a wavelength to $8$ m. For each BS inter-element spacing, the $4 \times 8$ MIMO channels are used to evaluate the system's capability separating closely located users. This evaluation is done by means of the correlation matrix distance metric (between each pair of closely located users) and the sum-rate capacity of the system (when $8$ equally-spaced closely located users are served simultaneously). It is found that the system is capable of separating closely located users as long as the distance between them and the BS is less than the Fraunhofer distance associated with the BS antenna array. In the measured environment, for both LOS and NLOS propagation conditions, users located as close as $0.5$ m from each other, having the same orientation, are separated successfully in the multi-user MIMO sense.**

***Index Terms*—Multi-user MIMO separation, MIMO measurements, users spatial separation, multi-user MIMO.**

## I. Introduction

Multi-user MIMO (MU-MIMO) is identified as one of the main key technologies in LTE-Advanced that can contribute to achieving high spectral efficiency [1], [2]. In MU-MIMO, the spatial properties of the users' communication channels are utilized to serve multiple users simultaneously over the same time-frequency resource [3]. The amount of overlap among the subspaces of the users' MIMO channels determines their mutual interference and consequently the MU-MIMO performance [4]. When the served users are closely located, the effect of the overlap among their subspaces becomes more pronounced and results in significant degradation of performance.

Up to date, only few measurements were performed to study the performance degradation of MU-MIMO systems in realistic channels when the users are closely located. In [5], it was demonstrated that in outdoor-to-indoor channels, the spatial subspaces of users can have significantly different structures even for closely located users (in the same room). However, for outdoor scenarios, it was shown in [6] that, for closely located users with LOS propagation conditions, the system's capacity degrades significantly to the point that there becomes no difference in the performance of single-user MIMO (SU-MIMO) and MU-MIMO. The work reported in [7] attempted to relate the multi-user separation in the signal-space sense to their geographical separation based on outdoor measurements. It was found in [7] that multiple users can be considered to be separated if they are physical apart from each other by a distance of 5 to 10 meters or an angle of 2 degrees.

In the case of LOS SU-MIMO, a strong dependency between the assumptions used to model the MIMO channel and both the size of the Tx antenna array and its distance to the user is found. It is reported that there is a threshold distance below which the spherical wave model should be used instead of the plane wave model in order to avoid under estimating the capacity of LOS MIMO; therefore, even in LOS conditions, the MIMO channel can enjoy a rich spatial subspace and be full rank [8], [9].

In this work, we address the following questions: To what degree does increasing the inter-element spacing at the BS improve the system's capability to separate closely located users? How can the required inter-element spacing at the BS be related to the geometry of the service area? Can increasing the BS inter-element spacing help in separating closely located LOS users, which is known to be the most difficult scenario for MU-MIMO? Therefore, we utilize our measurements to quantify the MU-MIMO improvement that can be achieved when the inter-element spacing at the BS is changed from as small as half a wavelength up to 8 m under both LOS and NLOS scenarios. The MU-MIMO separability is evaluated by means of the correlation matrix distance metric (quantifying the differences in the subspace structures of the users) and the system's sum-rate capacity (quantifying the overall system performance).

This paper is organized as follows. In Section II, a detailed overview about the measurement campaign is given. In Section III, the steps used to analyze the measurement data including extracting the MIMO channels of the different users and their corresponding Tx correlation matrices are explained. The metrics used to evaluate the system's capability to separate multiple users are detailed in Section IV. The main results of this study are demonstrated in Section V. Finally, the conclusions are stated in Section VI.

## II. Measurement Description

### A. Scenario

The propagation measurements took place on the campus of Lund University, Lund, Sweden, in an area which can be best characterized as suburban microcell environment. The chosen setup consists of a mobile receive unit (MS), provided with two dual-polarized patch antennas, and a BS provided with four transmit units (TxU), each of which has a dual-polarized patch antenna. This setup results in having $4 \times 8$

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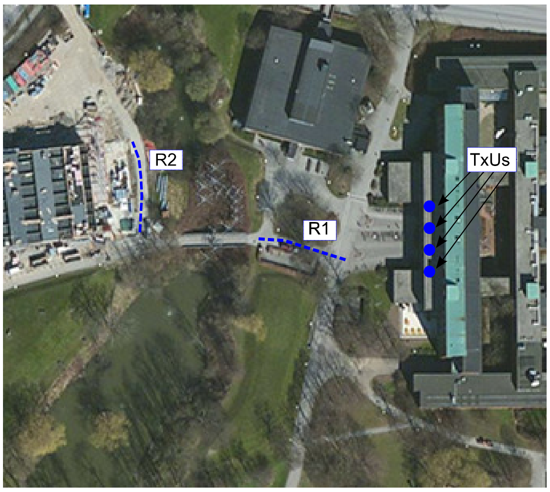


Fig. 1. Aerial photo of the measurement area. TxUs are indicated with the blue circles. The measurement routes are plotted in dashed blue lines: route 1 (R1), and route 2 (R2).

MIMO channels between the MS and the BS. The TxUs are placed on the rooftop of a four story building (about 15 m above ground) in an equally-spaced linear configuration. The patch antenna of each TxU is mounted on a tripod to facilitate adjusting the inter-element spacing, which is defined as the distance between two adjacent patch antennas. The inter-element spacing is varied to the following 8 values: $\lambda/2$, $\lambda$, 0.25 m, 0.50 m, 1 m, 2 m, 4 m, and 8 m. The measurement scenarios include both LOS and NLOS propagation conditions. For each inter-element spacing value, the MS is moved (at 0.5-1 m/s) in two routes each of which is about 40 m long: route 1 is *mainly* LOS with a starting point at about 43 m from the BS, and route 2 is *mainly* NLOS with starting point at about 114 m from the BS. In the measurement area, there are only few buildings; however, the main interacting objects are heavy leafy trees. Therefore, in both measurement routes, the propagation conditions may alter from LOS to NLOS, or visa versa, due to the sudden appearance or disappearance of heavy branches between the MS and the TxUs. See Fig. 1.

### B. Measurement Equipment

The measurement campaign was carried out with the RUSK LUND channel sounder [10] at a center frequency of 2.6 GHz and a measurement bandwidth of 40 MHz. At the BS, each of the four TxUs is equipped with a patch antenna with dual-polarized antenna elements. See Fig. 2b and 2c. The signal broadcasted by the TxUs is received by a single MS equipped with 64 dual-polarized antenna elements in a stacked uniform cylindrical array configuration, consists of four rings each of which with 16 dual-polarized antenna elements; see Fig. 2a. The transmit-receive channels are sounded in a time-multiplexed fashion such that all of the receive antenna elements are visited in succession prior to switching to the next transmit antenna element, where a 6.4 $\mu$s sounding signal is used. The data results from this operation is referred to as a snapshot, consists of 1024 wideband transmit-receive channels (128 MS antenna elements $\times$ 8 BS antenna elements), each of which with 257 frequency bins. A distance wheel is used to trigger the acquisition of the MIMO snapshots every $\lambda$, which

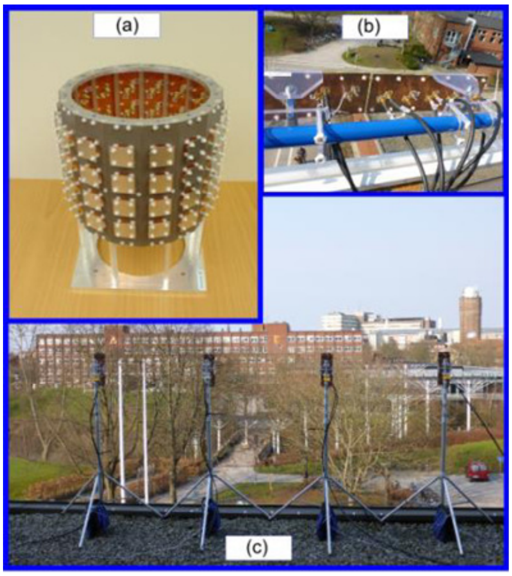


Fig. 2. Antennas at the MS and at the TxUs. (a) MS antenna: stacked uniform cylindrical array with 64 dual-polarized antenna elements arranged in four rings, (b) TxUs' antennas, inter-element spacing of $\lambda$ (back view), and (c) TxUs' antennas, inter-element spacing of 1 m (back view).

results in collecting 350 snapshots per measurement route. The measured snapshots are used to extract the users' $4\times8$ MIMO channels as detailed in the next section.

## III. Data Analysis

### A. MIMO Channel Matrices Extraction

As described earlier, each measured snapshot has a size of 128 MS antenna elements $\times$ 8 BS antenna elements $\times$ 257 frequency bins. For the work presented in this paper, not all the MS antenna elements are considered at once. We assume that: (a) each user is equipped with two dual-polarized patch antennas, and (b) each user may have different orientation. Hence, each two dual-polarized vertically adjacent (with a $\lambda/2$ vertical spacing) patch antennas from the MS uniform cylindrical array (i.e., four antenna elements) are considered at a time to represent a user. This results in 32 transmit-receive channels (4 MS antenna elements $\times$ 8 BS antenna elements), each of which has 257 frequency bins, represents the wideband MIMO channel for a user with the same orientation as the selected MS patch antennas. At each frequency bin, the $4\times8$ MIMO channel represents the narrowband MIMO channel for a user. Among the 257 narrowband MIMO channels of each user, only those channels with SNR$\geq$10 dB are considered to be valid for further processing. In this work, only the lower two rings of the MS uniform cylindrical antenna array are considered, which results in having 16 $4\times8$ MIMO channels at each snapshot.

To mimic the multi-user scenario and given that distance trigger is used in this measurement campaign, we assume the position of the MS at each snapshot to represent the position of a user. Therefore, each user is assumed to be spaced by an integer multiple of $\lambda$ from the adjacent users. For each position (i.e., snapshot index), due to the MS antenna geometry, we consider 16 orientations at equally-spaced angles ($360/16 = 22.5$ degrees) spanning the azimuth plane. Therefore, a user at a specific position can experience any of these 16 orientations. The snapshot indices together with the orientation indices are used to signify the different users. In order to study the effect of the different orientations on the spatial structure of the MIMO channel while eliminating the effect of the orientation on the strength of the received signal, we assume that each user receives the same power from each BS antenna element regardless of its orientation (i.e., each column of the $4 \times 8$ MIMO channel matrices had a unity norm). In this work, when the MU-MIMO separation is evaluated, we considere the worst case scenario in terms of the users' orientation and frequency where we assume that all the concerned users to have the same orientation and to use the same frequency.

It should be noted that as a result of selecting two patch antennas from the MS cylindrical array to represent a user, and due to the different possible orientations of these patches in the azimuth plane, even at the same MS position (i.e., snapshot index), not all users will have the same propagation conditions (i.e., LOS vs. NLOS). For example, in route 1, which is described as *mainly* LOS, users that are not oriented towards the direction of the BS are in NLOS condition. Also, in route 2, which is described as *mainly* NLOS, some of the patch antennas at specific orientations (for very short time intervals during the route) are in LOS condition due to the disappearance of the tree branches that obstruct the LOS signal (or obstructed LOS condition if the first Fresnel zone is not clear). Therefore, the main difference between the two routes is the probability of a user with arbitrary orientation to have an optical LOS with one or more BS antennas. This probability is higher in route 1 compared to route 2.

### B. MIMO Correlation Matrices Extraction

The frequency bins of the $4 \times 8$ MIMO channels are used to estimate the Tx correlation matrix (i.e., at the BS) for each user at each location (i.e., snapshot), and at each orientation. Given a set of $N$ MIMO channels (for this calculation, we consider only 10 frequency bins, equally-spaced over the whole bandwidth), the Tx correlation matrices, $\mathrm{R}$, are estimated by:

$$\mathrm{R} = \frac{1}{N}\sum_{n=1}^{N} \mathrm{H}^T \mathrm{H}^*. \tag{1}$$

where, $\mathrm{H}$ is a $4 \times 8$ MIMO channel. $(.)^T$, and $(.)^*$ are the transpose and the conjugate of a matrix, respectively.

## IV. Multi-User Separation

The MU-MIMO separation is evaluated by means of the correlation matrix distance metric and the system's sum-rate capacity as detailed below.

### A. Correlation Matrix Distance (CMD)

The Correlation Matrix Distance (CMD) is a metric that provides information about the alignment of the subspaces of two matrices [11]. In our analysis, if two users have Tx correlation matrices $\mathrm{R}_1$, and $\mathrm{R}_2$, then CMD($\mathrm{R}_1$,$\mathrm{R}_2$) describes the differences between their subspaces. The CMD metric takes values between 0 and 1. When $\mathrm{CMD} = 0$, it signifies the case when the subspaces of the two users are identical (up to a multiplicative factor). In this case, the system is expected to fail separating the users based on the spatial domain. On the other side, a $\mathrm{CMD} = 1$ means that the two users have subspaces that are different to the maximum. The CMD describing the difference between two matrices $\mathrm{R}_1$, and $\mathrm{R}_2$ is expressed as:

$$\mathrm{CMD}(\mathrm{R}_1,\mathrm{R}_2) = \frac{\mathrm{tr}(\mathrm{R}_1\mathrm{R}_2)}{\|\mathrm{R}_1\|_F \|\mathrm{R}_2\|_F} \tag{2}$$

where, $\mathrm{tr}(.)$ and $\|.\|_F$ are the trace and the Frobenius norm of a matrix, respectively.

### B. Sum-Rate Capacity (SRC)

The Sum-Rate Capacity (SRC) of the narrow-band MU-MIMO downlink channel with full channel state information at the BS and the users' sides, and a sum-power constraint, $P$, is addressed in [12]. For each considered BS inter-element spacing, SRC, calculated based on iterative water-filling [13], is used to describe the system performance in serving different closely located users using the same time-frequency resource under the following assumptions: (1) the number of served users is 8 (same as the number of the BS antenna elements), (2) the served users are equally spaced (the inter-user distance varies between a wavelength to 4.6 m as detailed in the next section), (3) all users have the same orientation, (4) the channel matrices of all users have columns with unity vectors, (5) the total power constraint applied in [13] is $P = 10$, and (6) the noise is i.i.d. Gaussian with unit variance.

It should be noted that the CMD metric describes the difference between the spatial structure of two matrices; however, it can not be analytically related to the spatial multiplexing performance of a communication system [4]. The CMD metric evaluate the alignment of the subspaces of only two users, while the SRC evaluate the overall performance of the whole system without considering fairness among the served users. In this work, we use both metrics to evaluate the system performance; however, no claim is made to relate the evaluation performance of these two metrics.

## V. Results

The CMD and SRC are used to study the effect of the BS inter-element spacing on the MU-MIMO separation (Subsection V-A), and the effect of the users' orientation on the system's capability separating the different users (Subsection V-B).

### A. Effect of the BS Inter-Element Spacing on MU-MIMO Separation

#### 1) Using the CMD Metric

For each of the considered BS inter-element spacings ($\mathrm{d_{BS}} = \lambda/2$, $\lambda$, 0.25 m, 0.50 m, 1 m, 2 m, 4 m, and 8 m), the CMD values between users as a function of the inter-user distance ($\mathrm{d_U}$), averaged over all orientations, are calculated as follows. First, the CMD between the correlation matrices of each two users that are separated by a distance $\mathrm{d_U}$ and having the same orientation is calculated according to (2). Second, the average CMD (over all available pairs of users that are separated by a distance $\mathrm{d_U}$ with the same orientation) is estimated. Finally, in order to eliminate the effect of the orientation of the users, these CMD values are averaged over all the 16 orientations. The resulted CMD values indicate the

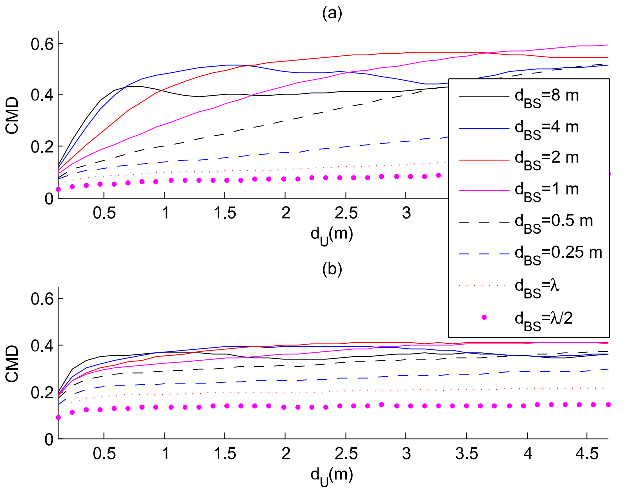


Fig. 3. The CMD values, averaged over all orientations, versus the distance among users ($\mathrm{d_U}$), for all considered inter-element spacings ($\mathrm{d_{BS}}$). (a) route 1, and (b) route 2.

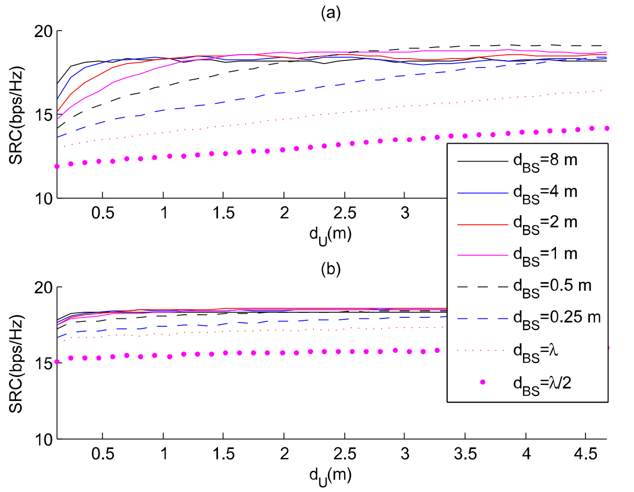


Fig. 4. The SRC values, averaged over all orientations, versus the distance among users ($\mathrm{d_U}$), for all considered inter-element spacings ($\mathrm{d_{BS}}$). (a) route 1, and (b) route 2.

difference between the subspace structures of the correlation matrices of two randomly selected users as a function of $\mathrm{d_U}$ given that both of them have the same, but arbitrary, orientation. The calculated CMD values are plotted in Fig. 3 for the different values of $\mathrm{d_{BS}}$, where $\mathrm{d_U}$ varies between $\lambda$ and $40\lambda$ in steps of $\lambda$ (between $0.11$ m and $4.6$ m in steps of $0.11$ m). From Fig. 3 the following points can be deduced:

- The higher the BS inter-element spacings, the higher the CMD value. However, it should be noticed that the relative CMD gain due to increasing the BS inter-element spacings becomes insignificant after a certain *large enough* inter-element spacing. For example, in route $1$, Fig. 3.a, with BS inter-element spacing of $1$ and $2$ meters, a CMD value of $0.4$ can be achieved at inter-user distances of $1.75$ m, and $0.93$ m, respectively. On the other hand, for both BS inter-element spacings of $4$ and $8$ meters, a CMD value of $0.4$ can be achieved almost at the same inter-user distance, $0.54$ m, and $0.59$ m, respectively. The same trend is noticed in route $2$, but the values of CMD are smaller than those of route $1$ (see Fig. 3.b).
- When the BS inter-element spacing is greater than $0.5$ m, with very few exceptions, the higher the probability of being in LOS (e.g., route $1$ compared to route $2$), the higher the value of CMD for the same inter-user distance. This can be concluded when comparing Fig. 3a, and 3b. For example, in route $2$, for all considered BS inter-element spacings, the CMD values saturate around $0.4$ for all inter-user distances. However, in route $1$, the CMD values reach as high as $0.6$ in half of the considered BS inter-element spacings.

*2) Using the Sum-Rate Capacity (SRC)*

The effect of the inter-element spacing, $d_{BS}$, on the SRC is evaluated as follows. For each BS inter-element spacing, $8$ users separated by equal distances, $d_U$, (where $d_U$ takes values between $\lambda$ and $40\lambda$ ($\approx$ $4.6$ m) in steps of $\lambda$) are selected, all with the same orientation. Then the corresponding SRC is estimated (as detailed in Subsection IV-B). For each BS inter-element spacing, for each inter-user distance, the reported SRC is calculated as the average of $200$ realizations. Then, to eliminate the effect of the orientation of the users, the calculated SRC are averaged over all the $16$ orientations. Fig. 4 depicts the SRC as a function of the inter-user distance, where the following points can be deduced:

- The SRC has a monotonic increase as a function of the inter-user distance regardless of the value of the BS inter-element spacing.
- Increasing the BS inter-element spacing results in higher SRC; however, this effect is more pronounced when the probability of LOS is higher (route $1$ compared to route $2$).
- In route $2$ (low probability of LOS), there is almost no difference in the achieved SRC when the BS inter-element spacing equals to $1$, $2$, $4$, or $8$ m regardless of the value of the inter-user distance; however, in route $1$ (high probability of LOS), the difference among them diminishes only when the inter-user distance if greater than $1.2$ m.

Based on the results of Fig. 3, and Fig. 4, it can be concluded that, in the case of very closely spaced BS elements, the subspaces of closely located LOS users are almost identical (i.e., the performance of SU-MIMO and MU-MIMO is the same), which has been reported in [6]. However, by increasing the BS inter-element spacings, the Fraunhofer distance associated with the BS antenna array increases. If the Fraunhofer distance becomes larger than the distance between the BS and the users, then the spherical wave model should be used to model the users' MIMO channels instead of the plane wave model [8], [9]. In this case, the differences among the angles of departure of the LOS signals transmitted from each BS antenna element becomes more sensitive to the users' positions. These differences affect the structure of the MIMO channels of the different users, where the $n$th column of the MIMO channel of a user is determined by the relative positions of the $n$th BS element and the user. The Fraunhofer distance is calculated as [14, p. 42]:

$$\mathrm{d} = \frac{2\mathrm{D}^2}{\lambda} \tag{3}$$

where, D is the largest dimension of the antenna array.

Therefore, the relative locations of the users and the BS can be used to estimate the minimum BS inter-element spacing required for MU-MIMO systems. Any inter-element spacing makes the users become closer to the BS than the Fraunhofer distance is expected to make the system able to separate closely located users. In our case, the furthest user is located 143 m from the BS, and an inter-element spacing of 1 m (i.e., $\mathrm{D} = 3$ m) results in a Fraunhofer distance of 156 m. The performance is comparable when the BS inter-element spacing is 1, 2, 4, or 8 m.

### *B. Effect of the Orientation of the Users on MU-MIMO Separation*

In Subsection V-A, the effect of the user's orientation is eliminated by averaging the values of CMD and SRC over the different orientations. In this subsection, the values of CMD and SRC are calculated per orientation, which allows us to evaluate the performance of the system as the orientation of the users changes. Fig. 5 to 8 illustrate the CMD and the SRC for routes 1 and 2 at the different orientations, where orientations indexed 8 to 12 in route 1, and orientations indexed 10 to 16 in route 2 are not facing the BS (i.e., users with these orientations are in NLOS conditions). From these figures, the following points can be concluded.

- Without any exception, increasing the BS inter-element spacing results in increasing the system's performance in terms of CMD and SRC. This improvement is much more pronounced when we consider the orientations that are facing the BS i.e., higher probability to be in LOS (e.g., orientations indexed 1 to 7 and 13 to 16 in route 1, and 1 to 9 in route 2).
- Increasing the BS inter-element spacing results in increasing the system's robustness against the degradation that might result from the arbitrary orientation of the users. For example, the minimum SRC for users separated by 1 m is 12 (16) bps/Hz and 17.6 (17.6) bps/Hz with $\mathrm{d}_{\mathrm{BS}}$ values of $\lambda$ and 1 m, respectively, for route 1 (route 2). Compare Fig. 6.h (8.h) versus Fig. 6.d (8.d).
- When examining Subfigures a to d in Fig. 5 to 8, we can conclude that, in the measured environment, there is no significant gain that can be achieved, especially if the users are separated by 1 m or more, by increasing the BS inter-element spacing more than 1.5 m.

## VI. Conclusion

In this paper, MIMO propagation measurements in outdoor micro-cell environment have been used to evaluate the performance of MU-MIMO systems. We assume a single-cell system and we focus on evaluating the effect of increasing the BS inter-element spacing on: (a) increasing the differences among the spatial structures of MIMO channels of closely located users, and (b) improving the sum-rate capacity of MU-MIMO systems. It is found that:

- When increasing the BS inter-element spacing, the performance of the system improves. However, the relative locations of the users to the BS determines an inter-element spacing value beyond which no significant improvement can be achieved. This value is the inter-element spacing that makes the distance between the BS and the users becomes less than the Fraunhofer distance of the BS antenna.
- The higher the probability of the closely located users to be in LOS, the better the performance in separating them (given that they are located closer than the Fraunhofer distance) due to benefiting from the different angle of departures of the LOS signals transmitted from the different BS elements (i.e., spherical wave model).
- In the measured environment, with four BS dual-polarized antennas, the system is able to separate closely located users that are as close as 0.50 m with limited loss in the achieved sum-rate capacity compared to users that are far from each other (about 5 meters apart).

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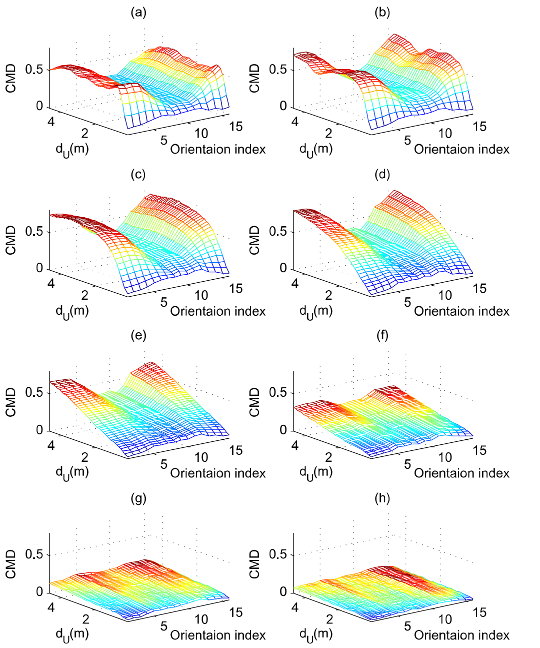


Fig. 5. Route 1: CMD as a function of the inter-user distance ($\mathrm{d_U}$), and the orientation of the users. (a) $\mathrm{d_{BS}}$=8 m, (b) $\mathrm{d_{BS}}$=4 m, (c) $\mathrm{d_{BS}}$=2 m, (d) $\mathrm{d_{BS}}$=1 m, (e) $\mathrm{d_{BS}}$=0.5 m, (f) $\mathrm{d_{BS}}$=0.25 m, (g) $\mathrm{d_{BS}}=\lambda$, and (h) $\mathrm{d_{BS}}=\lambda/2$. Orientations indexed 8 to 12 are not facing the BS (i.e., always in NLOS conditions).

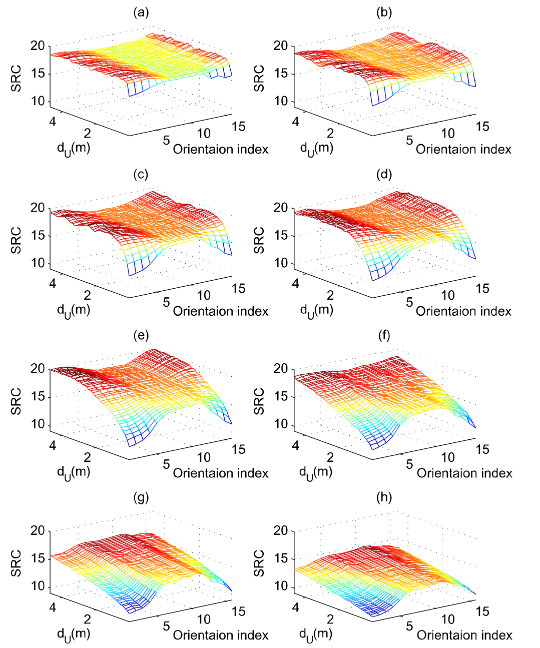


Fig. 6. Route 1: SRC as a function of the inter-user distance ($\mathrm{d_U}$), and the orientation of the users. (a) $\mathrm{d_{BS}}$=8 m, (b) $\mathrm{d_{BS}}$=4 m, (c) $\mathrm{d_{BS}}$=2 m, (d) $\mathrm{d_{BS}}$=1 m, (e) $\mathrm{d_{BS}}$=0.5 m, (f) $\mathrm{d_{BS}}$=0.25 m, (g) $\mathrm{d_{BS}}=\lambda$, and (h) $\mathrm{d_{BS}}=\lambda/2$. Orientations indexed 8 to 12 are not facing the BS (i.e., always in NLOS conditions).

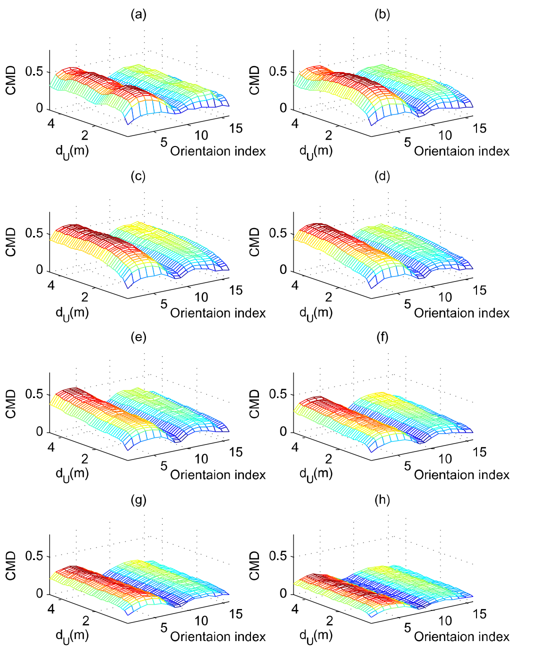


Fig. 7. Route 2: CMD as a function of the inter-user distance ($\mathrm{d_U}$), and the orientation of the users. (a) $\mathrm{d_{BS}}$=8 m, (b) $\mathrm{d_{BS}}$=4 m, (c) $\mathrm{d_{BS}}$=2 m, (d) $\mathrm{d_{BS}}$=1 m, (e) $\mathrm{d_{BS}}$=0.5 m, (f) $\mathrm{d_{BS}}$=0.25 m, (g) $\mathrm{d_{BS}}=\lambda$, and (h) $\mathrm{d_{BS}}=\lambda/2$. Orientations indexed 10 to 16 are not facing the BS (i.e., always in NLOS conditions).

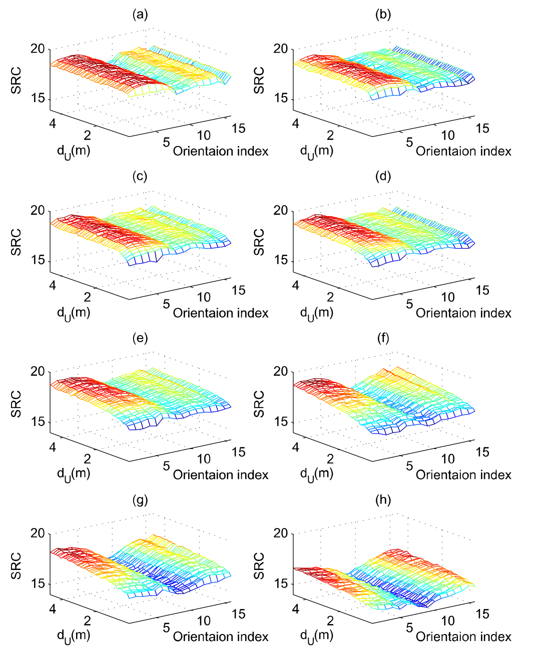


Fig. 8. Route 2: SRC as a function of the inter-user distance ($\mathrm{d_U}$), and the orientation of the users. (a) $\mathrm{d_{BS}}$=8 m, (b) $\mathrm{d_{BS}}$=4 m, (c) $\mathrm{d_{BS}}$=2 m, (d) $\mathrm{d_{BS}}$=1 m, (e) $\mathrm{d_{BS}}$=0.5 m, (f) $\mathrm{d_{BS}}$=0.25 m, (g) $\mathrm{d_{BS}}=\lambda$, and (h) $\mathrm{d_{BS}}=\lambda/2$. Orientations indexed 10 to 16 are not facing the BS (i.e., always in NLOS conditions).