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Experimental Study of the Benefits of a Second Antenna at the User Side in a Massive MIMO System

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ABSTRACT Massive MIMO is commonly described as a large number of base station (BS) antennas serving a smaller number of single-antenna users. However, adding a second antenna to the user handset opens the possibility to exploit multiplexing techniques and obtain higher throughput. This paper is based on a measurement campaign comprising a BS with 64 elements reconfigurable into three shapes: 1) a very large array with 6-m aperture; 2) a large array with 2m aperture; and 3) a compact two dimensional array with 25 cm by 28 cm sides. We study the throughput in single-user and multi-user scenarios using both non-linear optimal and linear precoders. The experimental results show that the throughput increases when adding a second antenna, but the increase is lower than in Gaussian channels due to the intra-user correlation. However, increasing the number of BS antennas, massive MIMO achieves more benefits from the second antenna. A large number of users in the system and the inter-user correlation reduce the benefits of a second antenna in the user handset.

INDEX TERMS Massive MIMO, multi-user MIMO, channel measurements, indoor propagation, antenna arrays.

I. INTRODUCTION

Massive MIMO was first described in the seminal work of Marzetta as a time-division-duplexing (TDD) cellular system comprising a very large number of Base Station (BS) antennas serving a smaller number of single-antenna users in the same time-frequency resource [1]. In the recent years it has been considered an essential technology for 5G, since it claims high gains in throughput, reliability and energy efficiency [2]. The excess number of BS antennas renders a large number of degrees of freedom in the system that can be exploited by signal processing techniques. For example, when the number of BS antennas grows large, the channel vectors of the users become asymptotically orthogonal, which makes linear precoding techniques to achieve close to optimal performance [3].

Extending the definition of massive MIMO to users with multiple antennas, the degrees of freedom of the system can be utilized to multiplex several data streams to the same user. Hence, the throughput gain of massive MIMO can be increased. However, the close distance between antennas in the same device can reduce the degrees of freedom of the channel and lead to only small improvements in multiplexing gain. Although most of the massive MIMO research has been focused on single-antenna users, some work derived the benefits of multiple antennas users in theoretical channels [4]. We go beyond those studies by focusing on multi-antenna handsets in measured massive MIMO propagation channels. Specifically, we study the broadcast channel where the BS serves multiple users simultaneously.

Several massive MIMO measurement campaigns have been performed recently, but due to the difficulty of measuring such a large number of antennas simultaneusly, most of them use virtual antenna arrays (e.g. [5]). The measurements for the current work were performed at 5.8 GHz in a large indoor environment similar to a shopping mall to reflect the new scenarios of 5G [2]. Such scenarios can integrate very large BS arrays into their structures. The measurement has 64 BS elements reconfigurable into three array shapes: A very long aperture (6 m) array, a long aperture (2 m) array, and a rectangular (25 cm by 28 cm) array. The array serves 8 users with 2 antennas each. Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) scenarios are measured. We focus

on indoor scenarios where moving users hold a handset mockup. The study of multi-antenna users' throughput is only possible because of the simultaneous user antenna measurements achieved by the Aalborg University channel sounder. The data of the measurements was also analyzed in [6]–[8].

Another measurement campaign studying user handsets with multiple antennas was performed in [9]. It uses 100 BS antennas, but only one static handset with 3 antennas, from which only 2 are used at a time. The main difference from our present work is that [9] focus on the uplink pilot transmission schemes to achieve diversity gain, whereas here the focus is on the downlink broadcast multiplexing. Also, in [9] user antenna power imbalance is studied, while here the throughput is evaluated versus SNR and the number of antennas. In addition, we consider dynamics in the channel generated by the movement of the users and their handgrip.

A. CONTRIBUTION

The data from the measurement campaign used in this study was previously analysed in [6]–[8]. These publications focus on the characteristics of the massive MIMO channel without giving results on the throughput performance. These publications present results on the degree of multi-user multiplexing, the orthogonality of the channel vectors, the channel hardening, etc. Although, most of the results are for single-antenna users, they also show the condition number of the channel with the two antennas in the same user handset.

In contrast here we study the benefit of adding a second antenna to the user handset. This is a novel result because the analysed measured channels are the only ones having multiple users with multiple antennas each. In addition, this publication presents results on the performance of the system using various linear and non-linear precoders. We compare the throughput of the system with single-antenna users and double-antenna users and we study the impact of the number of antennas and the signal-to-noise ratio (SNR). We also show statistics of the sum rate for different users.

The results show that dual-antenna users have higher throughput than single-antenna ones, but the improvement is smaller than that for Gaussian channels due to the higher correlation between the antennas in the user handset. In single-user systems the improvement of adding a second antenna to the handset is larger than in multi-user systems, because in multi-user systems the load is higher and the channel experiences a saturation effect. In addition, multi-user systems suffer from intra-user interference. We observe that in massive MIMO increasing the number of antennas at the BS reduces the correlation and inter-user interference and makes the performance of measured channels similar to the performance of Gaussian channels. For example, for 32 BS antennas, the results show a 37 % average increase in dirty paper coding capacity at 10 dB SNR when adding the second antenna, compared to a 55 % increase in Gaussian channels. Doubling the number of BS antennas to 64, the improvement becomes 53 % and 65 % for the measured channels and the Gaussian ones respectively. In the indoor measured channels with 8 double-antenna users and an SNR range from −10 to 14 dB, massive MIMO achieves more benefits from adding a second antenna to the user due to the large number of BS antennas.

II. MEASUREMENTS AND DATA

In the following we briefly depict the measurement campaign. For more details refer to [6].

A. SET-UP

Three BS arrays are tested, all consisting of 64 monopole elements. The monopoles are arranged in eight linear arrays, named sets in the following, each with eight elements separated by $\lambda/2$.

The array sets are grouped in three dispositions. The VLA (i.e. very large aperture) array is a linear 6 m long array where the antenna sets are placed longitudinally with a separation of 50 cm between them. The LA (large aperture) array is a linear 2 m long array where the antenna sets are placed longitudinally with no separation between them. The C2D (i.e. compact 2D array) is a square array of dimension 25 cm by 28 cm where the antenna sets are placed next to each other, along the long edges. The C2D array is shown in Fig. 1(b).

(a) (b)

FIGURE 1. Scenario and array shown in the results. (a) Scenario with spread users in NLoS, S-NLoS. (b) Compact 2D array, C2D.

The measurements involve eight mock-up handsets with two antennas separated $\lambda/2$. The total of 16 channels originating at the user side are all measured simultaneously. Eight users hold the handsets in front of them imitating "data mode" as if using a smartphone for browsing.

In the following *scenarios* denotes the dispositions of the users or handsets. Seven scenarios are tested, each one with specific propagation properties, with LoS and NLoS and with a specific distribution of the devices. The details of the scenarios are descrived in [6]. Fig. 1(a) shows the NLoS scenario with spread users.

B. CHANNEL SOUNDER: QUASI-SIMULTANEOUS MEASUREMENTS

The measurements were made with a correlation based channel sounder operating at 5.8 GHz and with a bandwidth of about 100 MHz. The sounder measures a 8 × 16 MIMO channel fully in parallel, which is further extended by connecting the elements of each antenna set (see above) via a fast switch, so that the 64 elements are multiplexed onto the

8 parallel Rx channels of the channel sounder. During the measurements the users move randomly in a 1 m^2 area while the massive MIMO channel is sampled at a rate of 60 Hz during 20 s, for a total of 1200 time realizations of the channel in the measurement run.

C. NARROWBAND CHANNEL AND NORMALIZATION

We focus on the analysis of a narrowband channel of 2 MHz bandwidth obtained via Fourier transform of the measured impulse responses. We denote $\mathbf{h}_k^{(n)}(r) \in \mathbb{C}^{M\times 1}$ as the channel vector from antenna $n \in \{a, b\}$ in the handset of user $k \in \{1, ..., K\}$ to the BS array at channel realization $r \in \{1, ..., R\}$, where $M = 64$ is the number of BS elements, $K = 8$ is the number of users and $R = 1200$ is the number of channel realizations.

Normalizing the channel we create a virtual power gain control, where the received energy from each user is normalized as

$$\overline{\mathbf{h}}_k^{(n)}(r) = \frac{\mathbf{h}_k^{(n)}(r)}{\sqrt{\sum_{r=1}^{R}\sum_{n=1}^{N}\left\|\mathbf{h}_k^{(n)}(r)\right\|^2}}\sqrt{MRN} \tag{1}$$

where $\|\cdot\|$ is the Euclidean norm, and N ($N = 1$ or 2) is the number of antennas per user.

With this normalization, we remove the user power imbalance but we keep the differences among BS elements, channel realizations, and handset antennas' power imbalance. We denote $\overline{\mathbf{H}}^{(1)}(r) \in \mathbb{C}^{M\times K}$ the channel made out of concatenating the normalized vectors in (1) using antenna a of each user. $\overline{\mathbf{H}}_k(r) \in \mathbb{C}^{M\times N}$ is the channel of user k using 1 or 2 antennas and $\overline{\mathbf{H}}(r) \in \mathbb{C}^{M\times KN}$ is the whole system channel matrix concatenating the channel of the users using both antennas.

III. CHANNEL THROUGHPUT

Channel throughput is used as a mean to quantify the performance of the system. We compare sub-optimal linear precoders with capacity achieving techniques (i.e. dirty paper coding) in the broadcast channel where the BS serves multiple users simultaneously.

A. DIRTY PAPER CODING

Dirty paper coding is a capacity achieving non-linear precoding technique first described in [10]. We compute such capacity using the waterfilling algorithm described in [11] which exploits the multiple access channel (MAC) - broadcast channel (BC) duality to obtain the optimal transmission policies. The achieved capacity becomes

$$\boldsymbol{C}_{\text{DPC}}^{\text{sum rate}}(P, \overline{\mathbf{H}}(r)) = \max_{\left\{\boldsymbol{P}_j\geq 0, \sum_{i=1}^{K}\text{Tr}(\boldsymbol{P}_i)\leq P\right\}} \log\left|\boldsymbol{I} + \sum_{i=1}^{K}\overline{\mathbf{H}}_i(r)^{\dagger}\boldsymbol{P}_i(r)\overline{\mathbf{H}}_i(r)\right| \tag{2}$$

as described in [12]. P is the total transmitted power, $\boldsymbol{P}_j$ is the MAC covariance matrix of user j, $\boldsymbol{I}$ is the identity matrix, $|\cdot|$ is the determinant operator and $\cdot^{\dagger}$ is the transpose conjugate operator.

B. ZERO-FORCING PRECODER

We use a Zero-forcing precoder (ZF) to compute the linear precoder throughput for single-antenna users. ZF eliminates the inter-user interference by nulling the signal to unintended users [13]. Such precoder is defined as

$$\mathbf{W}_{ZF}(r) = \overline{\mathbf{H}}^{(1)}(r)^{\dagger}(\overline{\mathbf{H}}^{(1)}(r)\overline{\mathbf{H}}^{(1)}(r)^{\dagger})^{-1}. \tag{3}$$

Each column of $\mathbf{W}_{ZF}$ (i.e. $\mathbf{W}_{ZF,i}$) is normalized to unit power [13] $\overline{\mathbf{W}}_{ZF,i}(r) = \frac{\mathbf{W}_{ZF,i}(r)}{\sqrt{\|\mathbf{W}_{ZF,i}(r)\|_F^2}}$.

The system model becomes

$$\mathbf{y}(r) = \overline{\mathbf{H}}^{(1)}(r)^{\dagger}\overline{\mathbf{W}}_{ZF}(r)\mathbf{P}(r)\mathbf{x}(r) + \mathbf{n}(r). \tag{4}$$

With $\mathbf{y}(r)$ the receive signal, $\mathbf{x}(r)$ the transmit signal, $\mathbf{P}(r)$ a diagonal matrix with the power allocated to each user using water filling algorithm, and $\mathbf{n}(r)$ an additive white Gaussian noise. The sum rate of this system is computed as the sum of the throughput for each user $R_k = \log(1 + \text{SINR}_k)$. Where SINR_k is the signal power to noise plus interference ratio of user k ($\text{SINR}_k = \frac{P_k}{I_k+N_0}$).

C. BLOCK DIAGONALIZATION PRECODER

In systems with multiple antenna users the goal is to reduce the inter-user interference at the same time that several data streams are multiplexed for each user. The solution is a block-diagonal precoder [14]. A block diagonalization precoder (BD) transmits the signal for the intended user into the null space of the interfering user, and projects this signal to the channel of the intended user. Hence, the multiplexing gain is exploited while the inter-user interference is reduced. The power is allocated to the data streams using a water filling algorithm.

We use BD to compute the linear precoder throughput for double-antenna users.

IV. RESULTS

A. SINGLE USER

We begin the analysis by considering a channel with a single user in order to keep the load of the system low (i.e. the number of user antennas is much lower than the number of BS antennas). In this way we also avoid the effects of inter-user interference and we can focus on the impact of other properties of the channel, such as the intra-user correlation.

Fig. 2 shows the DPC capacity averaged over 1200 channel realizations of two correlated channels with independent identically distributed (i.i.d.) Gaussian entries. We refer to these simulated channels for comparison purposes.

In the following we plot the results of measured channels together with the results of simulated channels with independent identically distributed (i.i.d.) Gaussian entries, which we call "Gaussian channels." We show results considering 20 consecutive antennas at the BS and all 64 antennas to show

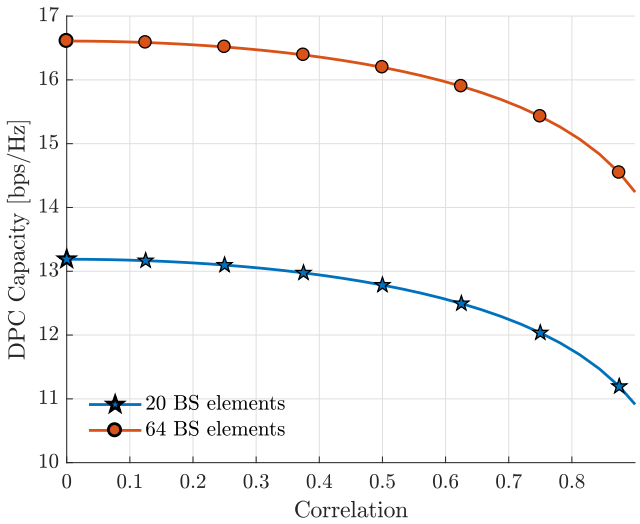

FIGURE 2. DPC capacity averaged over 1200 realizations of simulated correlated Gaussian channels.

the effects of the number of antennas and the array aperture. The capacity is computed for a 10 dB SNR, unless otherwise stated.

Fig. 3 shows the cumulative distribution function (CDF) of the DPC capacity over the 1200 channel realizations. The results presented here are for the S-NLoS scenario, C2D, user 7, but they are very similar to other users, arrays and scenarios.

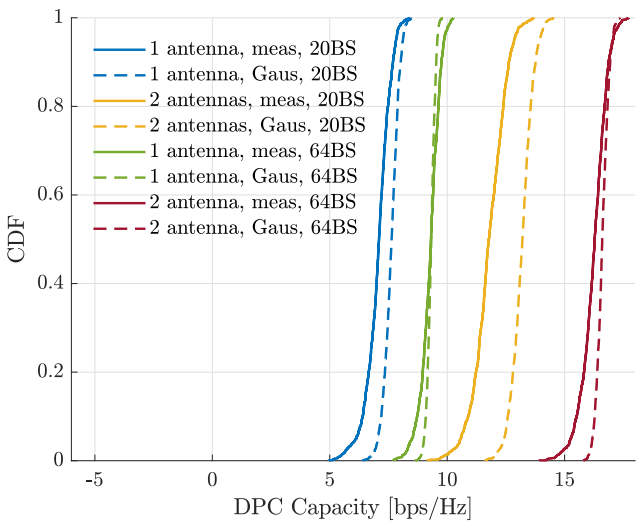

FIGURE 3. CDF of the DPC capacity at 10dB with 1 and 2 antennas, S-NLoS, C2D, User 7.

The results in Fig. 3 show a smaller difference between measured channels and Gaussian channel when increasing the number of BS antennas. This is in accordance with the theoretical result that increasing the number of BS antennas makes the channel vectors of different users asymptotically orthogonal, and therefore more similar to the Gaussian channel [1]. For a fixed number of BS antennas, a second antenna in the handset increases the differences between measured channels and Gaussian channels. This is due to the large correlation between the antennas that can not be compensated by increasing the number of BS antennas.

The steepness of the curves shows the channel hardening effect. The more hardened channel, experiences less fading and the capacity has small variations over time. In Fig. 3 we observe that the measured channels have less hardening than the Gaussian channel, due to the intra-user correlation.

We also notice that the measured channels can achieve higher DPC capacity than the Gaussian channel. This can happen due to the fading, because even if the total gain of the measured channel and the Gaussian channel is the same, the amount of fades and their deepness can be different. Due to the non-linearity of the logarithm function of the DPC capacity equation, even if the average power is the same for measured and Gaussian channels, the average DPC capacity does not need to be the same.

In terms of DPC capacity there is a clear benefit of adding a second antenna to the user handset. Although the curves show some variations on the capacity due to the fading, the double-antenna users have always a higher capacity than single-antenna users with the same number of BS antennas.

For the rest of the results we show the ergodic capacity averaging the instantaneous capacity over the 1200 channel realizations.

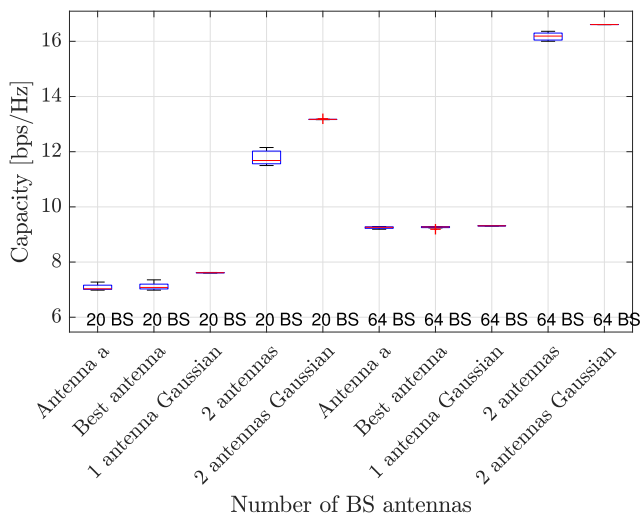

FIGURE 4. Throughput at 10dB with 1 and 2 antennas users expanding the BS array, S-NLoS, C2D array.

For a better understanding of the diversity of results among different users Fig. 4 shows the statistics over the 8 users of the DPC capacity in the S-NLoS scenario and C2D. The boxplot shows the quartiles, whiskers and outliers. It divides the data in 4 regions each one containing 25 % of the results (i.e. 25th, 50th and 75th percentiles), the whiskers contain the values 1.5 times the inter-quartile range, above or below the 75th and 25th percentiles, and the rest of the data are outliers (i.e. crosses in red).

The results show that all the 8 users benefit of adding a second antenna in their handset regardless the number of antennas in the BS. The median capacity for channels with 20 BS antennas and users with two antennas is 13.2 bps/Hz for the Gaussian channel and 11.7 bps/Hz for the measured one corresponding to the case of 0 and 0.8 correlation respectively, as observed in Fig. 2. For channels with 64 BS antennas, the median capacity is 16.6 bps/Hz and 16.2 bps/Hz for the Gaussian and the measured channels respectively which correspond to 0 and 0.5 correlation. Fig. 5. shows that the correlation is 0.41 and 0.36 for 20 and 64 antennas respectively so the capacity not only depends on the correlation but also depends on other factors. For example, unequal branch powers will have an impact on the capacity.

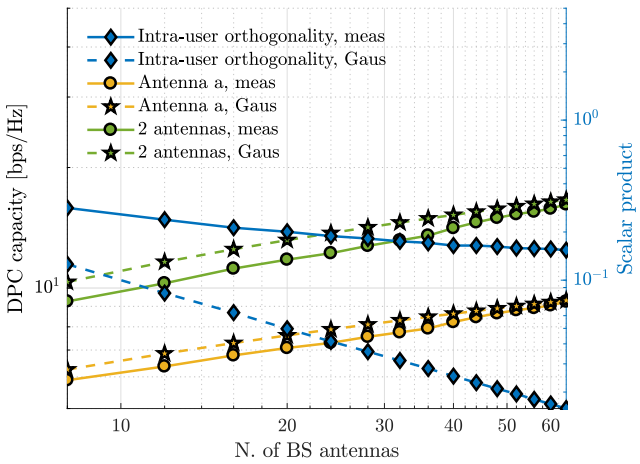

FIGURE 5. Scalar product and DPC capacity at 10dB with 1 and 2 antenna users expanding the BS array, S-NLoS, C2D array.

The results in Fig. 4 also show a higher dispersion in the users with 2 antennas. The position and handgrip of the users has a high impact in the orthogonality of its antennas. There is a decrease in the spread of the results when increasing the number of BS antennas. This is more evident in LoS scenarios and it shows the effects of channel hardening. Also by increasing the number of BS antennas the results of measured channels become more similar to the Gaussian channel. This is due to the asymptotic orthogonality achieved by increasing the number of BS antennas in massive MIMO.

Fig. 4 also shows the DPC using the best antennas (i.e. a or b for all the channel realizations), however the results are very similar to always using antenna a. This means that there is no consistent difference in the channel of both antennas. For a single channel realization the fading properties of the channel can make the capacity in one antenna much better than in the other. However the randomness of the channel makes the ergodic capacity after 1200 channel realizations very similar for both antennas.

To compare single-antenna users and double-antenna users Fig. 5 shows the DPC capacity averaged over the 8 users when increasing the number of BS antennas and increasing the aperture of the array. The results presented here are for the S-NLoS scenario, C2D, but they are very similar to other measured scenarios and arrays. Notice that both axes are in logarithmic scale.

To evaluate the impact of the channel vector orthogonality of the two antennas in the same handset of the user we add to the plot the intra-user scalar product squared and averaged over channel realizations and users, which is computed as

$$SPS = \frac{1}{KR}\sum_{k=1}^{K}\sum_{r=1}^{R}\left(\frac{\left|\mathbf{h}_k^{(a)}(r)\mathbf{h}_k^{(b)}(r)\right|}{\left\|\mathbf{h}_k^{(a)}(r)\right\|\left\|\mathbf{h}_k^{(b)}(r)\right\|}\right)^2 \tag{5}$$

Since the Gaussian channel has zero mean, this metric shows the variance of the sample correlation and it is equal to $\frac{1}{M}$ [3]. The results of the measured channels are also proportional to $\frac{1}{M}$ but with less slope than the Gaussian channel, because the short distance between the antennas in the same handset makes their channel vectors highly correlated.

The capacity shows a direct proportionality with the number of BS antennas. This is a clear effect of the array gain. To double the antennas in the handset, doubles the slope of the capacity. The single-antenna users present a slope of 0.05 bps/Hz per antenna and the double-antenna users present a slope of 0.1 bps/Hz per antenna. The effect of the orthogonality between antennas is reflected on the distance between the capacity of the measured channel and the Gaussian channel.

To compare the different measured scenarios, Fig. 6 shows the DPC ergodic capacity averaged over the 8 users. The results presented here are for the C2D array but they are very similar to other arrays. Notice that only the length of the bar shows the DPC capacity, whereas the width is set to improve the visualization.

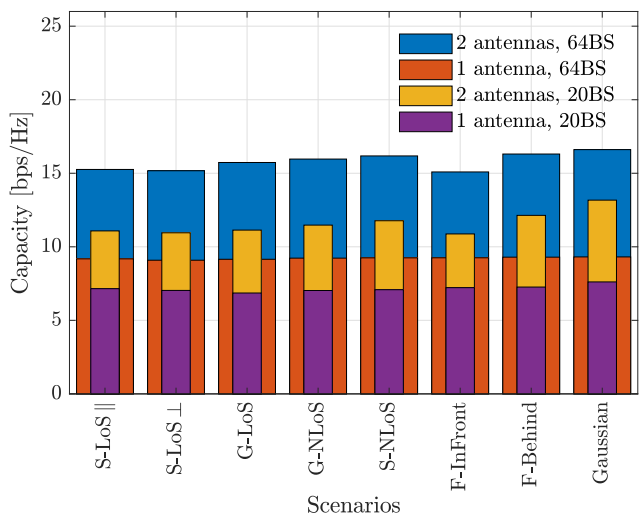

FIGURE 6. DPC capacity averaged over users with 1 and 2 antennas at 10dB, C2D array.

When considering single-antenna users, all the scenarios lead to very similar results. The reason is that in single-antenna single-user channels the capacity depends on the

attenuation of the channel. Since the measured channels are normalized to remove the users' power imbalance using eq. 1, the averaged capacity presents small fluctuations among the scenarios. These fluctuations are due to the fading.

For dual-antenna users we observe higher variations of the DPC capacity among the measured scenarios. Although the variations are larger than for single-antenna users, the results are similar to the Gaussian channel. The reason for the variations is the correlation between the antennas in the same handset. The amount of scatterers in the environment and their distribution have an impact on decorrelating the channel vectors. This effect is even more visible in multi-user channels like the ones presented in Fig. 11, discussed below.

Finally we focus on the conditions of the channel for which the two antennas of the handset are active. For this purpose we study the waterfilling power allocation to the antennas when performing eigenvalue decomposition. Due to the fading characteristics of the channel the power allocation to the antennas varies in each channel realization, therefore we compute the proportion of channel realizations that both antennas are allocated power. In order to avoid the effect of the array gain we scale the transmitted power by the number of links in the system.

$$\mathbf{y} = \sqrt{\beta}\sqrt{\frac{P_t}{\text{numel}(\overline{\mathbf{H}}_k)}}\overline{\mathbf{H}}_k\mathbf{x} + \mathbf{n} \tag{6}$$

where $\mathbf{y}$ denotes the received signal by the user, β is the path loss, P_t is the transmitted power before removing the array gain, numel$(\cdot)$ is the number of elements of a matrix, $\mathbf{x}$ is the transmitted signal after precoding and $\mathbf{n}$ is an additive white Gaussian noise.

The results are averaged over the users and they are presented in Fig. 7. This figure presents the results for the S-NLoS scenario and VLA. Other scenarios and arrays present different results according to the different correlation characteristics.

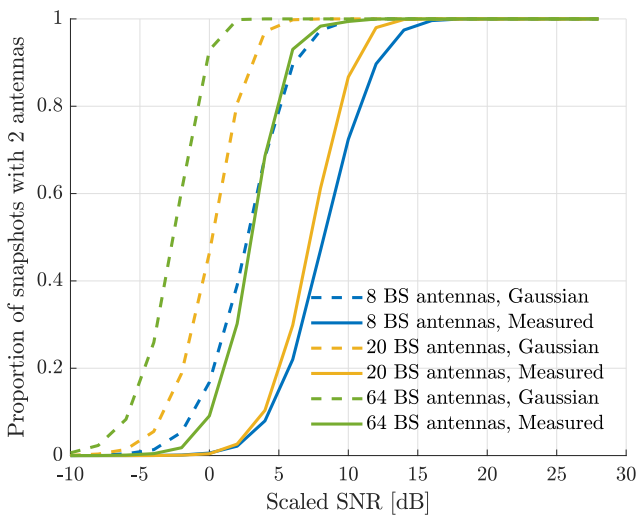

FIGURE 7. Proportion of snapshots that 2 antennas of the user are active, averaged over the users, removing the array gain, S-NLoS, VLA array.

The results show an increase of number of channel snapshots where 2 antennas are active when increasing the number of BS antennas for a fixed SNR. For example at 6 dB SNR with 8 BS antennas only 22 % of the channel realizations use 2 antennas, while this percentage grows to 30 % and 93 % for 20 and 64 antennas respectively. This is the consequence of decorrelating the two antennas in the handset which makes the eigenvalues more similar to each other and the waterfilling algorithm allocates power to both antennas. This result can be seen in Fig. 5, as the number of BS antennas increases the capacity of the measured channels becomes more similar to the Gaussian channel, because the two antennas become more uncorrelated and power is allocated to both of them.

B. MULTIPLE USERS

In the following we consider a system with 8 users. In such scenario a small number of BS antennas means a large load of the system and it can have an impact on the result. The throughput is affected by the inter-user interference.

To illuminate the benefits of a second antenna in the user handset Fig. 8 shows the throughput for DPC and linear precoders for single-antenna users and double-antenna users in the S-NLoS scenario and C2D. As the difference between curves changes for each SNR, we take 10 dB as a reference point for the following comparisons.

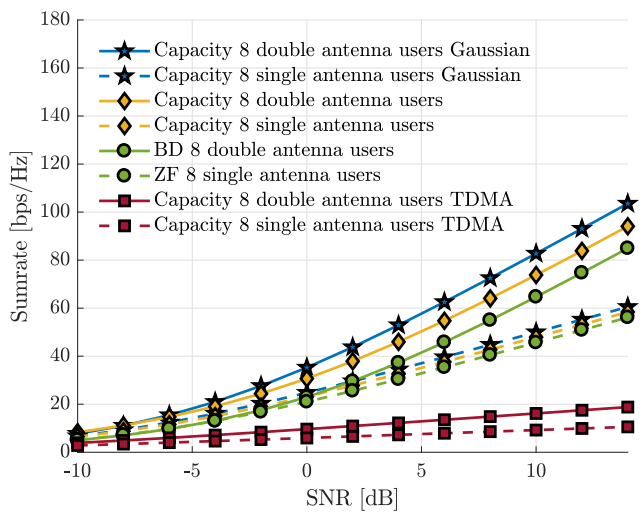

FIGURE 8. Throughput with 1 and 2 antenna users, S-NLoS, C2D.

In this figure we observe an improvement of 50 % DPC sum rate when adding a second antenna to the users. Although the signal in the second antenna of the device is not completely orthogonal with the first antenna, there is a benefit of adding it. The improvement is smaller than the observed in single user systems. For example Fig. 4 shows a 75 % increase in capacity. This is because multi-user systems are limited by the inter-user correlation, apart from the intra-user correlation. For linear precoders the result is similar with a sum rate increase of 36 %. In average, among all the scenarios and arrays (i.e. $7 \times 3 = 21$ combinations), there

is an improvement of adding a second antenna of 53 % and 43 % for non-linear and linear precoders, respectively. For less than −4 dB SNR the performance of single stream per user is similar to the double stream per user, using linear precoders.

In comparison, the improvement in the Gaussian channels is 65 %, which is a larger percentage due to the larger orthogonality between the two antennas of the user. Although the theoretical Gaussian channels present a lower correlation between antennas, the throughput of the measured channel is similar, showing the benefit of the massive number of antennas decorrelating the user channels. Nevertheless this improvement is still lower than the 75 % achieved in single user systems observed in Fig. 4 , it is a result of the saturation effect of the high load of the system.

In the same Fig. 8 it is interesting to compare the sum rate achieved by linear precoders and DPC for a fixed number of user antennas. Both for single-antenna users and double-antenna users there is a small gap between linear precoders and optimal ones. This is due to the asymptotically orthogonal user channels achieved by an excess of BS antennas, which renders linear precoders close to optimal. However, we observe a larger difference for double-antenna users, where the ratio between BS antennas and total number of user antennas is lower (i.e. $\frac{64}{16} = 4$ compared to $\frac{64}{8} = 8$).

Additionally we compute the capacity for a time division multiplexing (TDMA) system instead of the broadcast channel in order to compare to the results without the effect of the load of the system. These results correspond to the results presented in section IV-A.

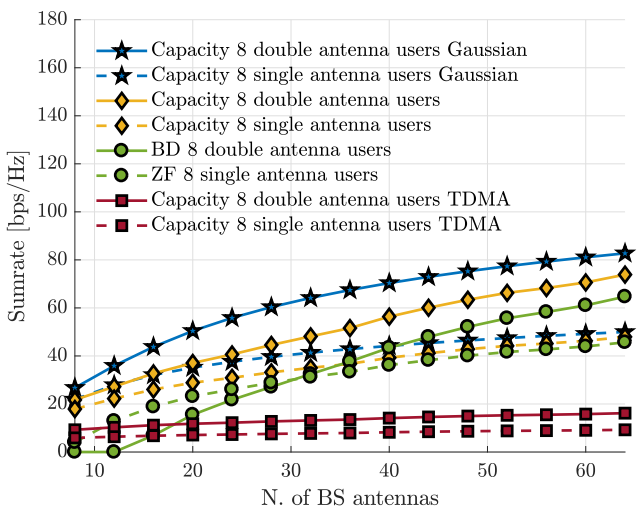

FIGURE 9. Multi-user throughput at 10dB with 1 and 2 antenna users expanding the BS array, S-NLoS, C2D.

In order to investigate the impact of the number of antennas, and more specifically, the ratio between BS antennas and user antennas, Fig. 9 shows the sum rate achieved at 10 dB SNR when increasing the number of BS antennas in the S-NLoS scenario and C2D. The antennas are selected in a consecutive order starting from the antennas closer to the bridge, and the aperture of the array is increased with the number of antennas. The TDMA curves are the same as presented in Fig. 5.

First we observe that adding a second antenna to the user has more benefits when the number of BS antennas is large. Increasing the number of BS antennas decorrelates the two antennas in the handset and more information can be transmitted to the second antenna. For example, using 32 BS antennas there is a 37 % increase averaged over the scenarios and arrays in DPC capacity, whereas the Gaussian channel presents a 55 % capacity increase. The difference between measured and Gaussian channels is larger than when using 64 BS antennas that the increase in DPC is 53 % and 65 % for measured and Gaussian channels respectively.

As expected from the results in Fig. 8, Fig. 9 shows, for the linear precoders, a better performance of single-antenna users compared to the double-antenna users when the number of BS antennas is low. This is due to the ratio between BS antennas and user antennas. To fully exploit the benefits of massive MIMO, an excess of BS antennas is necessary. Hence, double-antenna users need more BS antennas than single-antenna users. The crossing point of the two linear precoder curves corresponds to the ratios $\frac{25}{16} = 1.6$ compared to $\frac{25}{8} = 3.1$. Hence, in this scenario, to achieve massive MIMO performance, the number of BS's antennas has to be around 60 % higher than the number of user antennas. The linear precoders rely on the extra degrees of freedom to eliminate the inter-user interference. If the number of BS antennas is similar to the number of interfering users there are not enough degrees of systems to eliminate the inter-user interference. If the number of BS antennas is smaller then the number of user antennas the precoders can not work and the capacity becomes 0, as observed for less than 16 antennas in the BD curve. Other scenarios present similar results, however the crossing point varies among scenarios and arrays.

The impact of the number of antennas ratio is smaller in the DPC capacity than in the linear precoders. The double-antenna users have a better performance regardless the number of BS antennas. In addition, the DPC capacity increases at a higher rate for double-antenna users. Therefore, the benefit of the second user antenna increases with the number of BS antennas. It is also important to notice that increasing the number of BS antennas reduces the gap between the linear precoders and the DPC. Again, this is the effect of achieving asymptotically orthogonal user channels.

For small number of BS antennas, the correlation between user antennas in the measured channel is high, and the sum rate is lower than for the Gaussian channels. Increasing the number of BS antennas reduces the correlation and the sum rate of measured channels approaches the sum rate of the Gaussian channel. Specially for single-antenna users, the performance of the linear precoders becomes close to the DPC and Gaussian channel. For double-antenna users the difference in performance is larger, because of the smaller ratio between number of BS antennas and user antennas.

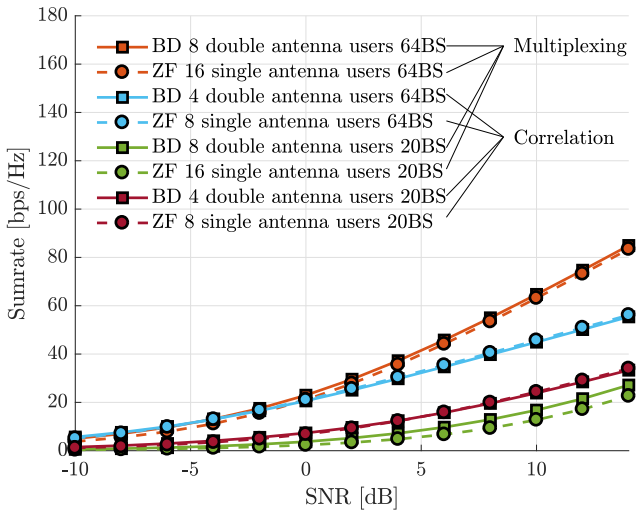

FIGURE 10. Mean multi-user throughput at 10dB with 1 and 2 antenna users and fixed load of the system, S-NLoS, C2D array.

Fig. 10 compares systems with the same load. First a system with 16 user antennas; grouped in 8 users so multiplexing is possible, or separated in 16 users so user antennas can not cooperate. The antennas used are the same in both cases so there are no difference in correlation. Second a system with 8 user antennas; chosen from 4 users so there is high correlation in the two antennas in the same user, or chosen from 8 users so there is low correlation between the antennas. Under this comparison, BD and ZF are almost the same, which means that neither the collaboration of antennas grouped two-by-two (BD) nor the decorrelated user antennas (ZF) shows a dominant performance. Reducing the number of BS antennas reduces the sum rate in both systems, but increases the difference between BD and ZF for the 'multiplexing' cases.

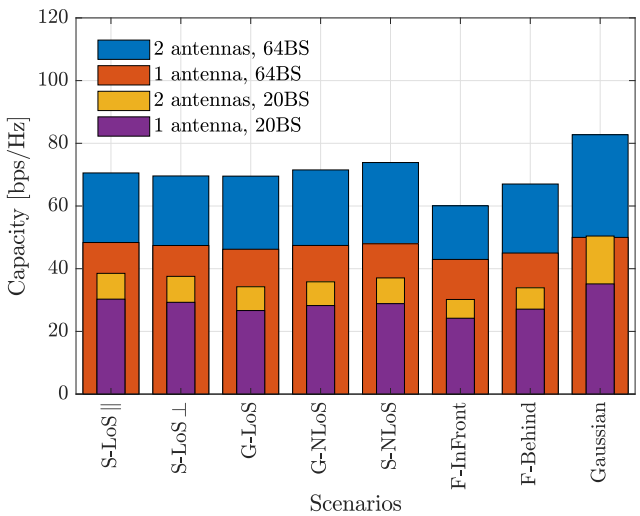

FIGURE 11. Mean multi-user DPC Capacity with 1 and 2 antenna users at 10dB, C2D array.

Fig. 11 compares the mean DPC capacity of the measured scenarios. The figure shows the results with double-antenna users and single-antenna users as well as with 20 BS antennas and 64 BS antennas.

First, we observe a larger variation of the results compared with the single user scenario presented in Fig. 6 because the multiuser scenario is affected by the inter-user interference, so the position of the users has a higher impact. Both for single-antenna users and double-antenna users the Free space scenarios show the lowest capacity. This is due to the short distance between the devices tied to the table. In addition the F-InFront scenario already presented high intra-user correlation in Fig. 6 .

There is an increase of capacity in NLoS scenarios because the large amount of scatterers decorrelates the channel vectors of the users, even if they are grouped. This result is the same for the LA, however the VLA shows a decrease in capacity in NLoS scenarios, probably because some parts of the array are far away from the entrance of the room where the users are located.

V. CONCLUSION

A massive MIMO measurement campaign has been used to investigate the benefits of having two antennas in the user handset. The measurement campaign was carried out in a large indoor environment and involved 3 array shapes with 64 elements each, 8 users holding a double-antenna mockup handset, and 7 scenarios including LoS, NLoS, spread users, grouped users, and without users.

Considering a single user scenario we observe the benefits of adding a second antenna to the handset. The second antenna increases the capacity, but it also increases the variation of the results. A larger number of BS antennas makes the two antennas in the handset more orthogonal and the measured channels becomes more similar to the simulated Gaussian channel.

In multi-user scenarios the results show a 53 % average increase in dirty paper coding capacity at 10 dB SNR when adding the second antenna. There is also an improvement using linear precoders, though slightly less (43 %). We also show the importance of the ratio between the number of BS antennas and user antennas in linear precoders. Even though the user antennas in the measurements can be correlated, increasing the number of BS antennas achieves the massive MIMO asymptotic orthogonality and the gap between the throughput of i.i.d. Gaussian channels, non-linear precoders, and linear precoders asymptotically vanishes.

We conclude that the benefits of adding a second antenna to the user vary in each channel realization due to the fading, but in massive MIMO, by increasing the number of BS antennas, the proportion of channel realizations that allocate power to both antennas increases. Overall the sum-rate improves by adding a second antenna.

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