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Comparison between a Hybrid Digital and Analog Beamforming System and a Fully Digital Massive MIMO System with Adaptive Beamsteering Receivers in Millimeter-Wave Transmissions

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Abstract—Massive MIMO systems are known to be a very promising solution for future 5G systems. The attractiveness of using such a system for millimeter Wave (mmWave) transmissions comes partly from the reduced size of a many antenna base station. Furthermore, the beamforming gains that they allow is highly suited to combat the high path losses experienced at such wavelengths. Unfortunately the complexity to implement a mmWave Massive MIMO system comes with the difficulty to have a high number of stacked Radio Frequency (RF) chains. Hybrid Analog and Digital Beamforming systems have then emerged to retain a high number of antennas without as many RF chains in order to keep high beamforming gains. In this paper we first describe a User Equipment (UE) solution allowing the system to form a beam that adapts to its own movement so that it always focuses its energy toward the base station, using an on board analog array and an Inertial Measurement Unit. Then we compare the performance of the known Hybrid solution with a fully digital Massive MIMO system, having as many RF chains as the Hybrid system, but serving UEs with beamforming abilities. Mostly we emphasize how such a system allows for great flexibility and evolution, both traits being invaluable features in many future networks.

Index Terms—Massive MIMO, mmWave, Conjugate, LOS, Hybrid Beamforming, DoA

I. INTRODUCTION

The infatuation of the past few years for systems with a high number of antennas keeps studies flourishing. Massive MIMO systems [1] are proven highly energy efficient and thus are very well adapted for solutions requiring high data rates, low consumption or both. At the same time, the high frequency communication field, also called millimeter Wave (mmWave), has thrived with researchers exploring the possibility to use these bands for the increased wireless bit rates promised for future communications.

While those bands are indeed wide and available, they raise many questions about the way to use them. Massive MIMO systems in mmWave are considered very complex to implement, although studies start addressing this topic [2], due to the integration of many Radio Frequency (RF) chains. However, high beamforming gains are needed to compensate the important path losses occurring at these frequencies. Thus Hybrid solutions have emerged to address such a problem.

They allow the number of antennas to remain high without as many RF chains [3], [4]. Our study follows such a path which started with the realization that the higher the frequency, the more the channel response depends on the environment geometry [5], e.g. the angular structure of the propagation paths between the transmitter and the receiver. Also, the use of beamforming techniques are prone to reduce the diversity of the said channel, therefore implying that more adapted solutions need to be shed light on.

Our work revolves around the use of precoders based on the angular structure of the channel instead of its frequency or impulse response, as conventionally done in the literature. Indeed in mmWave communications with high path losses, only the direction of arrival (DoA) of the direct path of the wave carries much energy, thus leading to a Beamsteering precoding strategy. We have compared in [6] the performance of such a precoder at 60 GHz against two widely used linear precoding algorithms, namely the Zero-Forcing (ZF) and the Conjugate Beamforming (CB). That study helps to realize how such a simple solution can reach close to optimal performance in the right conditions, those being having the fewest and weakest multi-paths components in a Line of Sight (LOS) environment.

On the terminal end, most Massive MIMO studies consider single antenna devices because the spatial multiplexing process is used to transmit multiple streams simultaneously to multiple users, each receiving only one. Having a steerable antenna array at the terminal side, on the other hand, would give many benefits, such as higher gains and weaker reflected paths. This however stands problematic due to the random movement of the device.

This is where the Inertial Measurement Unit (IMU), accelerometers and gyroscopes, comes into play. Nowadays most mobile devices have an on-board IMU that give a measure of its acceleration, in up to 3 dimensions with a 3-axis accelerometer, and of its angular velocity, in up to 3 dimensions with a 3-axis gyroscope. Both give measurements that, once combined, offer quick and precise information about the device inclination and position. The validity of such measurements is well noted in [7] where is introduced a way

to estimate the DoA using a single antenna combined with rotation and position information. Our study describes a way of using an IMU to allow the User Equipment (UE) to form a beam that is always directed toward the BS, whatever its change of position or inclination. On that basis, the aim of this paper is to highlight the benefit of such a strategy compared to the known hybrid beamforming solutions.

In that perspective, Section II first describes the conventional Hybrid Analog and Digital beamforming approach with its limitations in a multi-user transmission scheme. Section III then introduces and describes the requirements followed by the process for the terminal to be able to direct its own beam at all times toward the base station, whatever its inclination and position. Finally Section IV compare the performance of the known Hybrid system against a fully digital Massive MIMO base station, having as many RF chain but fewer antennas and serving UEs with as many analogically steered antennas as the Analog stage of the Hybrid system. With these results we highlight how such multi-user solutions gain from deporting the analog stage on the user terminal. Conclusions are drawn in Section V.

II. HYBRID DIGITAL AND ANALOG BEAMFORMING

The purpose of a Hybrid system, first described in [3], is to allow a Base Station (BS) to have a high number of antennas without being too complex to implement. This complexity comes mostly from the fact that integrating many RF chains in mmWave is very difficult, although studies such as [2] have found some promising results.

A. System model

Various hybrid system architectures are presented in [4] and each have their own pros and cons but few can be used for multi-user transmissions. One such is illustrated on Fig. 1 and the multiple user precoding MIMO system translates into a decomposition of the $M \times K$ precoding matrix \mathbf{W} into two matrices denoted as $\mathbf{W}_D \in \mathbb{C}^{N_D \times K}$ for the baseband processing and $\mathbf{W}_A \in \mathbb{C}^{M \times N_D}$ for the analog stage. K is the number of users to serve simultaneously and M is the total

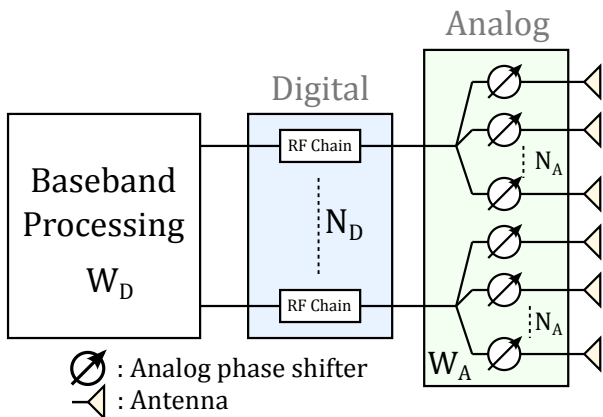


Figure 1. Hybrid Analog and Digital Beamforming system. N_D is the number of RF chains and N_A is the number of antennas steered analogically per RF chain.

number of antennas. From the figure, we denote as N_A the number of antenna elements analogically controlled through phase adjustment beyond each of the N_D RF chains. Such phase shifts lead to a beamsteering effect at the level of each RF chain. Then, we clearly have $M = N_A \times N_D$, and the vector gathering the precoded information $\mathbf{x} \in \mathbb{C}^{M \times 1}$ can finally be written as:

$$\mathbf{x} = \mathbf{W}_A \mathbf{W}_D \mathbf{s} \quad (1)$$

with $\mathbf{s} \in \mathbb{C}^{K \times 1}$ the vector of data symbols intended to the K users. For instance, considering a uniform linear array (ULA) of elements, matrix \mathbf{W}_A takes the form of a block diagonal matrix, i.e. $\mathbf{W}_A = \text{diag}[\mathbf{a}_1(\phi_1), \dots, \mathbf{a}_{N_D}(\phi_{N_D})]$, with vector \mathbf{a}_i defined as:

$$\mathbf{a}_i(\phi_i) = \left[1, e^{jk d_A \sin(\phi_i)}, \dots, e^{j(N_A-1)k d_A \sin(\phi_i)} \right]^T \quad (2)$$

where d_A is the antenna element spacing, $k = \frac{2\pi}{\lambda}$ with λ the transmission wavelength, and ϕ_i is the angular direction toward which the analog beam produced through the i th antenna array is steered.

Indeed, an efficient way to share the same time and frequency resource between users is to have all analog arrays controlled so that they steer their beam in the same direction, that is $\phi_i = \bar{\phi}, \forall i$. Within this beam, users can be addressed simultaneously if they don't outnumber the RF chains at the BS. In other words, UEs can communicate simultaneously with the BS if there are more RF chains than them and if the analog beam, formed by the analog stage of the Hybrid system, covers them all in its main lobe. Therefore the fewer antennas are in the analog stage, the wider the beam and thus the more UEs to be included in the spatial multiplexing but the lower the beamforming gain and thus the lower the link quality. The tradeoff chosen for each solution between N_D and N_A is going to depend very closely on the use cases they are applied to.

The following process describes the solution followed in this paper to compute the direction $\bar{\phi}$ toward which steering the analog beam:

- 1) The width of the beam is determined from the number of analog antennas N_A . In this paper, we consider square antenna arrays which means $\sqrt{N_A}$ horizontal and vertical elements, therefore the minimum beam width in azimuth or elevation is :

$$\Delta\theta_{-3dB} \approx \frac{\lambda}{\sqrt{N_A} d_A} 0.886 \quad (3)$$

where $\Delta\theta_{-3dB}$ is the angular span within which the amplitude of the main lobe is between $\frac{\sqrt{N_A}}{2}$ and $\sqrt{N_A}$. This beam width stands for a transverse beam therefore it will get wider as soon as it is steered;

- 2) The user around which are gathered the most other UEs, within the angular span defined in equation (3), is found and a group \mathcal{K} is made out of all these UEs;
- 3) The direction of the steered analog beam is then derived from the average value of all the DoA of the users in the group. Denoting as ϕ_k the DoA of user k , the angular

direction then expresses as:

$$\bar{\phi} = \frac{1}{\text{Card}\{\mathcal{K}\}} \sum_{k \in \mathcal{K}} \phi_k \quad (4)$$

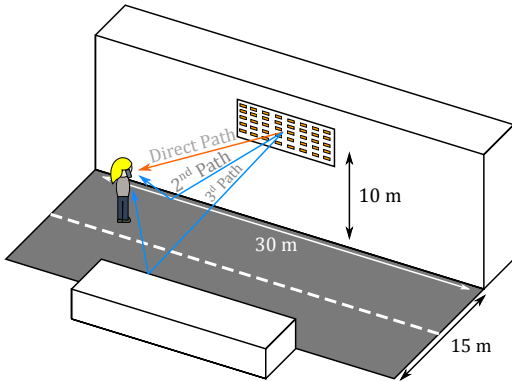


Figure 2. Cell configuration.

The environment used for this paper's simulations, illustrated on Fig. 2, is a short street section of 30m long and 15m wide. The BS, implemented with 16 RF chains at 60 GHz, is placed in the middle of the street at 10m from the ground on a building wall and we consider two reflections adding up to the direct path, one on the ground and one on the building on the opposite side of the street. This model is developed more extensively in [8].

Two precoders maximizing the transmitted energy toward each user have been chosen to demonstrate the performance of such systems:

- The Conjugate Beamforming (CB) derived from the baseband equivalent frequency channel response $\mathbf{H} \in \mathbb{C}^{K \times N_D}$:

$$\mathbf{W}_D = \mathbf{H}^H \quad (5)$$

Note that the channel is viewed at the level of the baseband unit. Therefore, matrix \mathbf{H} is of size $K \times N_D$ and conveys the equivalent channel gains experienced at the RF chains as a consequence of the analog beamsteering effect obtained at the analog precoding level.

- The Digital BeamSteering (DBS) using the DoA ϕ_k of the users gathered into one steering matrix $\mathbf{A} \in \mathbb{C}^{K \times N_D}$:

$$\mathbf{W}_D = \mathbf{A}^H \quad (6)$$

the k th column of \mathbf{A} being the steering vector \mathbf{a}_k computed from (2) and using the DoA of user k . Note that such a precoding is strictly equal to the CB in a pure LOS environment (no reflected path).

B. Performance

Fig. 3 shows how implementing an analog stage on a Massive MIMO system impacts the performance of the CB and the DBS. The Channel State Information (CSI) is assumed perfectly known and the basic Massive MIMO performance with no analog stage is represented by the dotted curves while the plain curves represent the hybrid systems with $N_A = 4$ and $N_A = 16$ having respectively no marker and the star marker.

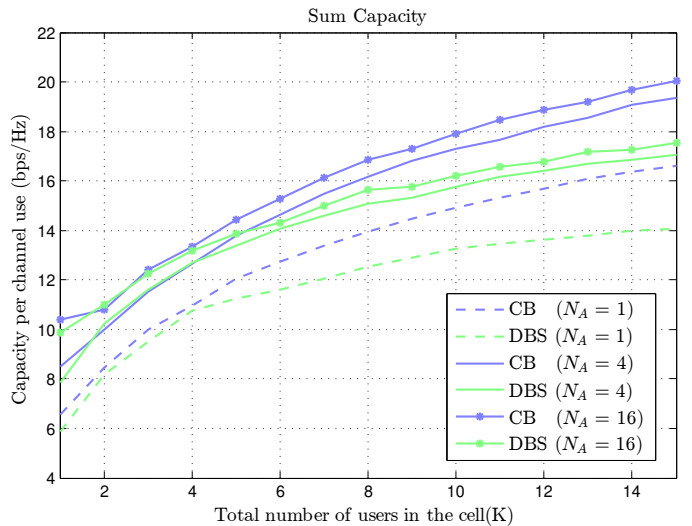


Figure 3. Performance comparison between Hybrid Analog and Digital Beamforming systems, one with $N_A = 4$ (no marker), one with $N_A = 16$ (star marker) and a Massive MIMO system ($N_A = 1$). The two precoders used are the Conjugate Beamforming (CB) in blue using the channel frequency responses and the Digital Beamsteering (DBS) in green using the DoA. The number of RF chains remains $N_D = 16$ in the BS and 1 in a UE.

Note that the CB remains more effective than the DBS, especially when the number of simultaneously served users grows. This is due to the fact that it uses the CSI instead of just the direction of the direct path (used by the DBS), therefore also exploiting the reflections of the wave to improve its focus on each user.

We can see that there is an obvious gain to implement an analog stage, whether using the CB or the DBS precoder, since the plain curves are well above the dotted curves. On the other hand having many analogically steered antennas does not seem to increase much the multi-user system performance. Indeed, the higher the number of antennas in the analog stage, the fewer the users targeted by the beam and thus the lower the sum capacity.

To summarize, such Hybrid solutions can increase the performance of multi-user transmission systems to a certain degree that depends on the density of population in the cell since the more users there are, the more interesting it is to focus precisely with the analog stage to have an average of users high enough that sum capacity reaches high peaks. Also, this analog focus makes them particularly suited for multi-stream point-to-point MIMO solutions, as presented in [4].

III. SELF-ADAPTING ANALOG ARRAY

Most often in Massive MIMO systems, UEs are described as single antenna terminals since they simply receive the signal from the base station without channel knowledge, therefore not implementing any traditional point-to-point MIMO techniques that require a plurality of antennas on the terminal.

In such techniques, however, what is behind the terms single and multiple antennas is actually the number of RF chains. Indeed a terminal with one RF chain and many antennas steered analogically is considered a single antenna terminal

with the particularity that this antenna is directive and the direction of its beam controlled.

This section explains how a terminal can adjust the direction of its beam in real time so that it constantly focuses toward the BS to get the highest beamforming gain.

A. Description

This method is based on the hypothesis that the UE has an antenna array whose beam can be steered analogically or digitally. The following procedure aims at adapting the direction of the terminal's beam depending on its inclination at any time.

The following parameters need to be known from the UE to implement the solution:

- The inclination of the BS antenna array in relation to the wall, see α on Fig. 5 - a)
- The DoA used by the BS to form its beam toward the UE (θ, φ)
- The terminal own inclination with its integrated accelerometers and gyroscopes (A_X, A_Y, A_Z on Fig. 4 - a)

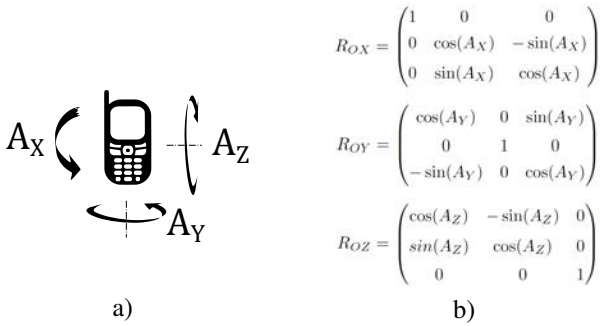


Figure 4. UE rotation parameters.

The study in [4] introduces a DoA estimation technique which involves mapping directions on each subcarriers so that the entire spectrum covers the cell area. By using this method, the UE can extract the optimum DoA used by the BS without knowing anything except the mapping table linking the DoA to the subcarriers used for the estimation process.

B. Beam targeting process

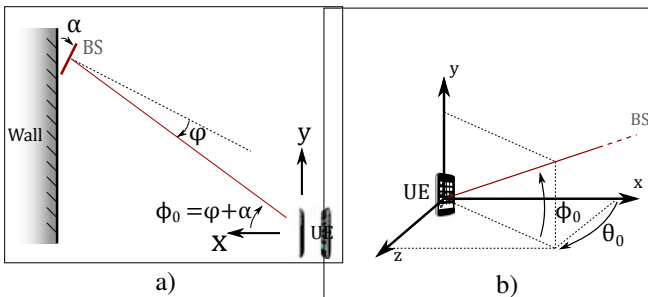


Figure 5. This geometric system representation includes α as the inclination angle of the BS with (θ, φ) its DoA used to focus energy toward the UE. The angles (θ_0, ϕ_0) correspond to the direction from which the UE sees the BS when it faces the wall.

The steps needed by the UE to focus energy toward the BS in real time are the following:

- 1) The UE learns the direction used by the BS (θ, φ)
- 2) An initial system of reference that corresponds to the user facing the wall where is positioned the BS (Fig. 5 - b)) is chosen. Then the initial DoA that the terminal would need to use to form a beam directed toward the BS is calculated, as illustrates Fig. 5 - a) and b) ($\theta_0 = \theta$, $\phi_0 = \varphi + \alpha$)
- 3) The inclination information is learned from the UE's IMU (see A_X, A_Y, A_Z on Fig. 4 - a))
- 4) The rotation matrix R_{OX}, R_{OY} and R_{OZ} , illustrated on Fig. 4 - b), allows the determination of the new coordinates of a point from the initial reference system to the final reference system, the latter being the reference system of the UE. The initial point has the coordinates (x_0, y_0, z_0) in the initial reference system and they become (x_{UE}, y_{UE}, z_{UE}) in the UE reference system. The steps leading to the knowledge of the couple of angles the UE needs to focus its beam toward the BS are the following:

- a) The objective is to determine the coordinates of an arbitrary point placed on the axis formed by the DoA (θ, ϕ_0) . We arbitrarily choose $x_0 = 1$ which gives the other coordinates $y_0 = \frac{\tan(\phi_0)}{\cos(\theta)}$ and $z_0 = \tan(\theta)$

- b) Then the new coordinates of this point after rotation of the terminal are:

$$\begin{pmatrix} x_{UE} \\ y_{UE} \\ z_{UE} \end{pmatrix} = R_{OX} R_{OY} R_{OZ} \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} \quad (7)$$

The real DoA seen by the UE can then be determined:

$$\theta_{UE} = \arctan\left(\frac{z_{UE}}{x_{UE}}\right) \quad (8)$$

$$\phi_{UE} = \arctan\left(\frac{y_{UE}}{\sqrt{x_{UE}^2 + z_{UE}^2}}\right) \quad (9)$$

- 5) The beam can finally be steered, analogically or digitally, toward the BS. When considering a planar array, as illustrated on Fig. 6, the phase shift to apply to the antenna of coordinate (d_x, d_y) , relatively to the reference antenna coordinates $(0,0)$ chosen arbitrarily in the plane, is:

$$\frac{2\pi}{\lambda} (d_x \cos(\phi_{UE}) \sin(\theta_{UE}) + d_y \sin(\phi_{UE})) \quad (10)$$

C. Multi-layer array extension

In the case of a 3D array, or multi-layer illustrated on Fig. 7, the phase shift linked to the thickness of the layers needs to be taken into account. Thus if we call w the thickness of the layer, the generalized expression of the phase shift to apply per antenna is

$$\frac{2\pi}{\lambda} (\Delta\Phi_{\text{azimuth}} + \Delta\Phi_{\text{elevation}}) \quad (11)$$

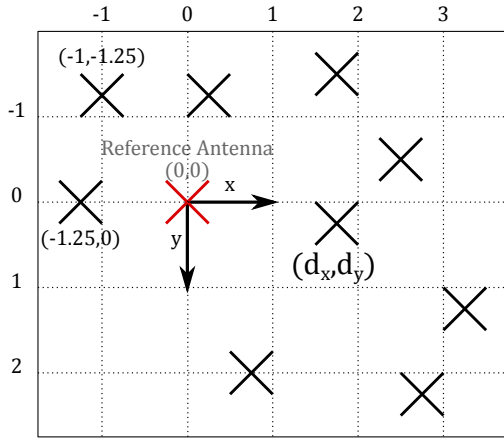


Figure 6. Antenna coordinates in a planar array for beamforming purposes.

with

$$\Delta\Phi_{\text{azimuth}} = (d_x - w \tan \theta \cos \varphi) \sin \theta \cos \varphi + \frac{w}{\cos \theta \cos \varphi}$$

$$\Delta\Phi_{\text{elevation}} = (d_y - w \tan \varphi) \sin \varphi + \frac{w}{\cos \varphi}$$

We notice that for a planar array, $w = 0$ and thus the phase shift falls back to equation (10).

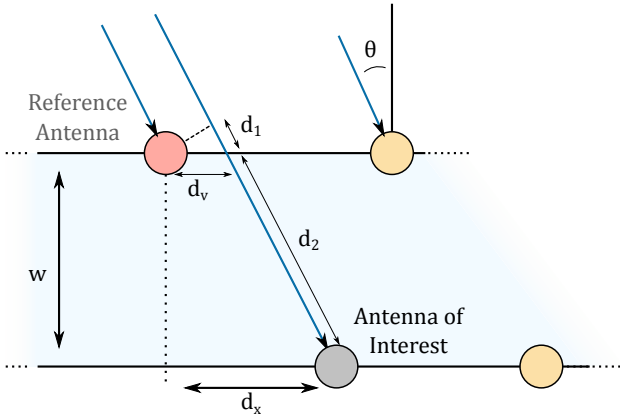


Figure 7. Multi-layer antenna array structure.

IV. HYBRID BS VERSUS MASSIVE MIMO BS WITH BEAM STEERING RECEIVERS

With a Hybrid system such as presented in Section II, the only effective solution to increase the cell capacity lies in the addition of RF chain, which is already the limitation of a fully digital Massive MIMO system.

Also, the fact that such a Hybrid solution needs users to be close enough to be included in the spatial multiplexing scheme lowers the benefits of a multi-user transmission. The main principle of such spatial multiplexing is that the less correlated user channels are, the weaker the inter-user interference and thus the higher the cell capacity. In LOS environments, this means that the further users are from each other, the better their link quality.

This paper means to highlight the benefits of implementing the analog stage in the terminal instead of in the base station

for multi-user communication systems, using the real time beamforming process described in Section III. Not only this keeps the base stations highly flexible due to the potential of baseband processing units, but it also allows an easy evolution in Quality of Service (QoS). Indeed, the only thing that manufacturers need to do to increase this factor with such a solution is to increase the number of antennas in the terminals. Also the processing at the BS remains the same whatever the number of antennas at the UEs which is another really interesting factor.

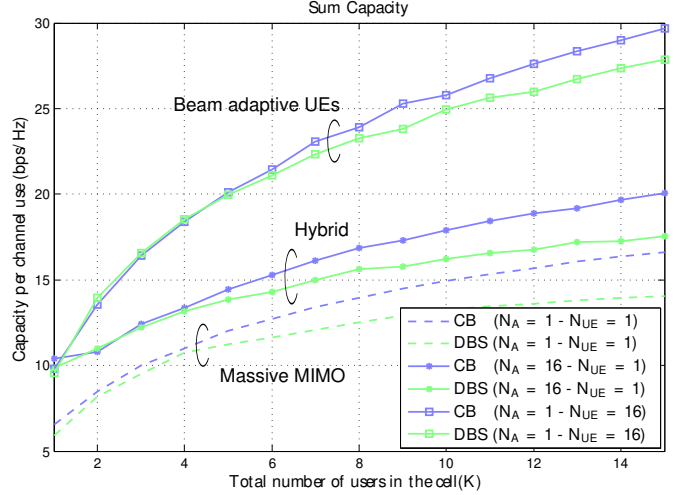


Figure 8. Comparison between a Massive MIMO system ($N_A = 1 - N_{UE} = 1$), Hybrid system ($N_A = 16 - N_{UE} = 1$) and a Massive MIMO system with adaptive receivers ($N_A = 1 - N_{UE} = 16$) using two precoders, the Conjugate Beamforming (CB) based on the channel frequency response and the Digital Beamsteering (DBS) based on the DoA. N_{UE} is the number of antennas on the UE and the number of RF chains is 16 at the BS and 1 at each terminal.

Fig. 8 proves how transferring an analogically steered array of $N_A = 16$ antennas from the BS to the UE changes the cell capacity. Not only are the curves with adaptive receivers (square markers) much better than the ones from the Hybrid system (star markers), but the gap between the CB and DBS performance is slightly reduced. Note that in a pure LOS environment, both precoders have the same performance since the channel matrix is reduced to the steering matrix depending only on the DoA [6]. This illustrates the fact that the more antennas UEs can be implemented with, the lower the channel diversity and the more effective solutions based on DoA such as the DBS are.

V. CONCLUSION

At the dawn of the new era that represents 5G communications where many different systems will need to coexist to address specific needs, Massive MIMO solutions at high frequencies hold promising results for a plurality of small cell scenarios where high energy efficiency is required.

The fact that the coherence time is inversely proportional to the carrier frequency doesn't help the implementation of techniques based on channel impulse or frequency responses. On the other hand the geometry of the channel does not change with the frequency which explains the growing interest

toward solutions based on Directions of Arrival (DoA). These directions, meaning a couple of angles per user, are essential for Hybrid Analog and Digital Beamforming systems to allow the Base Station (BS) to focus toward a specific area in the cell in which the use of spatial multiplexing is made possible. However, such systems lose flexibility and efficiency when a multi-user transmission is implemented.

In this paper we show how to implement a beamforming solution in the terminal so that the beam constantly focuses toward the BS using Inertial Measurement Units, whatever the changes of position and inclination of the device. Then a comparison is made between a Hybrid system addressing single antenna devices and a Massive MIMO system addressing devices each possessing an antenna array steered analogically using real time beam adapting process.

This analysis highlights the need, for multi-user transmission systems at high frequencies, to use fully digital Massive MIMO base stations but with a reduced number of antennas, as long as this reduction is compensated by the use of devices with the hardware to focus energy in real time toward the BS.

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