Multi-UE Multi-AP Beam Alignment in mmWave Cell-Free Massive MIMO Exploiting Channel Sparsity

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***Abstract*—This paper considers the problem of beam-alignment (BA) in a cell-free massive MIMO system in a scenario where multiple user equipments (UEs) simultaneously estimate the direction of arrival and departure of the strongest propagation paths arriving from the surrounding access points (APs). Building on the single-UE, single-AP procedure recently proposed by Song, Haghighatshoar and Caire in [1], we develop a protocol that permits one-shot joint BA for all the UEs and all the APs in the considered system. The proposed procedure relies on the existence of a reliable control channel at sub-6 GHz frequency, so as to enable exchange of estimated values between the UEs and the network, and assumes that APs can be identified based on the prior knowledge of the set of carriers and transmit beamforming codebooks. In order to manage the simultaneous transmissions from the APs, the orthogonality between the resources used by these transmitters in the BA procedure is obtained exploiting both orthogonal subcarriers and orthogonal pilot sequences. Numerical results show the effectiveness of the proposed detection strategies, with the strategy exploiting the two levels of orthogonality performing better than that relying only on subcarriers.**

***Index Terms*—cell-free massive MIMO, user-centric, beam alignment, millimeter wave**

I. INTRODUCTION

In the recent past, the mmWave spectrum has been widely considered for adoption in wireless cellular communications due to the availability of large bandwidths as compared to conventional sub-6 GHz frequencies. The large path-loss, typical of such frequencies, can be overcome using multiple antennas and narrow beams so as to concentrate radiated energy along spatial directions associated with the strongest propagation paths [2]. The term "*beam alignment*" (BA) referd to the procedure aimed at finding these beamforming directions. Since, due to the large path-loss, transmitting with low-gain wide beams does not permit to achieve a sufficiently strong useful signal power level, implementing an efficient and fast BA procedure is a pre-requisite in order to have reliable data transmission. As a consequence, BA has been widely investigated in recent literature – see for instance [1], [3]–[6]. Reference [1] proposes a BA algorithm wherein a (single) base station transmits constant power using a sequence of pseudo-random multi-finger beam patterns and the UEs, in receive mode, estimate the directions of arrival (DoAs) and directions of departure (DoDs) of the strongest beams. More precisely, [1] proposes a formulation that makes the channel sparsity explicit, and proposes the use of the non-negative constrained least-squares algorithm at the UE to estimate the DoA and DoD of the strongest beam. It should be noted that the majority of existing BA algorithms refer to a scenario involving a single AP and a single UE, and the BA procedure is performed usually using a protocol that consists in several interactions between the AP and the UE, aimed at successive refinements. On the other hand, it is expected that future beyond-5G and 6G wireless networks will heavily rely, at least in area with high traffic demand, on a set of several low-complexity APs, jointly serving, with overlapping clusters, the UEs in the system. This deployment is currently known as cell-free massive MIMO (CF-mMIMO) [7], [8], and is credited to be one of the main evolutions of first-generation massive MIMO systems. Accordingly, it is of the utmost interest to devise BA procedures that do not have the constraint to work in a single-AP single-UE scenario.

The aim of this paper is to address the BA problem in the relevant multi-AP multi-UE scenario. Departing from the procedure in [1], we develop a protocol, where, thanks to the aid of a sub-6 GHz uplink/downlink control channel, BA is performed *simultaneously* for all the UEs in the system, using the same set of carrier frequencies. In order to be able to distinguish the several APs, we define a set of orthogonal resources known as data-patterns. We consider two types of data-patterns; in the *pilot-less* case, data-patterns are simply sets of disjoint subcarriers; in the *pilot-based* one, data-patterns are given by set of disjoint carrier frequencies and orthogonal pilots, so that APs that use the same set of subcarriers transmit orthogonal pilots during the BA procedure. The use of data-patterns based only on orthogonal subcarriers was reported in the companion paper [9], while this paper investigates on the adoption of data-patterns that exploit the pilot-based doubled degree of orthogonality. Clearly, the adoption of pilot-based orthogonality permits to increase the number of available data-patterns, thus increasing the distance between APs that use the same data-patterns and reducing thus

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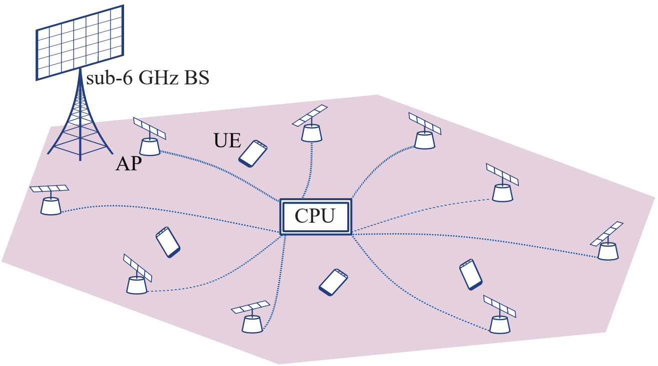

Fig. 1: Considered scenario.

the interference level.

This paper is organized as follows. Next section contains the system model description, while the proposed BA procedure is detailed in Section III. Section IV contains the numerical results, showing the performance gains obtained when the additional protection granted by the use of orthogonal pilots is exploited. Finally, concluding remarks are provided in Section V.

II. SYSTEM DESCRIPTION

Consider a CF-mMIMO system where M APs simultaneously serve K UEs on a shared channel. We focus on the BA procedure and, for the sake of simplicity, consider a bidimensional layout. It is assumed that the adopted modulation format is the orthogonal frequency division multiplexing (OFDM); the OFDM symbol duration is denoted by t_0, B denotes the overall available bandwidth, while the subcarrier spacing for the OFDM signal id denoted by Δf. This implies that the number of subcarriers is $N_C = B/\Delta f$. The OFDM symbol duration is $1/\Delta f + \tau_{CP}$, with τ_{CP} the length of the cyclic prefix. The BA phase will span T *beacon slots*, each made of S consecutive OFDM symbols. We denote by N_{UE} and N_{AP} the numbers of antennas and by $n_{\mathrm{UE}} < N_{\mathrm{UE}}$ and $n_{\mathrm{AP}} < N_{\mathrm{AP}}$ the numbers of RF chains at the generic UE and AP, respectively. Both the APs and the UEs are equipped with uniform linear arrays (ULAs) with random orientations, and the steering angles are assumed to take value in the range $[-\pi/2, \pi/2]$. See Fig. 1 for a sample scenario realization.

Channel model

The downlink channel between the m-th AP and the k-th UE in the s-th beacon slot is represented by an $(N_{\mathrm{UE}} \times N_{\mathrm{AP}})$-dimensional matrix-valued linear time invariant (LTI) system with impulse response

$$\mathbf{H}_{k,m}^{(s)}(\tau)=\sum_{\ell=0}^{L_{k,m}}\alpha_{k,m}^{(s)}(\ell)\mathbf{a}_{\mathrm{UE}}(\varphi_{k,m,\ell})\mathbf{a}_{\mathrm{AP}}^{H}(\theta_{k,m,\ell})\delta(\tau-\tau_{k,m,\ell}) \,, \tag{1}$$

where $L_{k,m}$ represents the number of paths for the channel between the k-th UE and the m-th AP, $\alpha_{k,m}^{(s)}(\ell) \sim \mathcal{CN}(0, \gamma_{k,m}(\ell))$ is the complex gain associated to the ℓ-th path in the s-th beacon slot, $\gamma_{k,m}(\ell)$, $\varphi_{k,m,\ell}$, $\theta_{k,m,\ell}$ and $\tau_{k,m,\ell}$ are the variance of the complex gain (including path loss and shadow fading), the DoA, DoD and the propagation delay associated to the ℓ-th path between the k-th UE and the m-th AP, respectively, and $\mathbf{a}_{\mathrm{AP}}(\cdot)$ and $\mathbf{a}_{\mathrm{UE}}(\cdot)$ are the ULA array responses at the AP and at the UE, respectively. Notice that $L_{k,m}$ depends on the geometry of the system, usually we have that $L_{k,m} << \min\{N_{\mathrm{AP}}, N_{\mathrm{UE}}\}$. Notice also that the complex gains $\alpha_{k,m}^{(s)}(\ell)$ depend on the beacon slot index s, while the other parameters are assumed to vary over much larger timescales.

III. BEAM ALIGNMENT PROCEDURE

A. Preliminaries

Before the BA procedure starts, a set of orthogonal resources, referred to as *data-patterns*, are to be defined and assigned to the APs. Obviously, since in large system the number of orthogonal data-patterns can be reasonably assumed to be smaller than the number of APs, the same data-pattern is to be reused across the network.

Two different types of data-patterns will be considered in this paper. With regard to the former type, we define as data-pattern a set of subcarriers and beamforming vectors, which the APs use to transmit *constant* signals. Since each AP is equipped with n_{AP} RF chains, i.e., it can simultaneously transmit n_{AP} data streams using different beamforming vectors. In order to permit data stream separation at the UEs without having knowledge of the AP locations and antenna array orientation, it is needed that the transmitted data streams are orthogonal *before* beamforming. One way of achieving this is through the use of non-overlapping subcarriers for the parallel data-streams. In order to be able to understand how many different data-patterns can be built with the described approach, the following reasoning can be made: denoting by Q the number of subcarriers assigned to each AP RF chain, we can accordingly define $D = \lfloor \lfloor N_C/Q \rfloor / n_{\mathrm{AP}} \rfloor$ disjoint sets of carrier frequencies; the corresponding D data-patterns will be denoted by $\mathcal{D}_1, \ldots, \mathcal{D}_D$. The generic set $\mathcal{D}_d$ will thus specify, for each of the n_{AP} transmit RF chains, the Q subcarriers *and* the beamformers to be used in each slot. more precisely, letting $\mathcal{L}_{d,s,i}$ denote the set of Q subcarriers to be used by the APs that are assigned the d-th data-pattern in the s-th beacon slot and on the i-th RF chain, the data-pattern $\mathcal{D}_d$ is in this case formally described as

$$\begin{aligned}\mathcal{D}_d = \; & \{\{\mathcal{L}_{d,s,i},\ s=1,\ldots,T,\ i=1,\ldots,n_{\mathrm{AP}}\}, \\ & \{\mathcal{B}_{d,s,i},\ s=1,\ldots,T,\ i=1,\ldots,n_{\mathrm{AP}}\}\} \ ,\end{aligned} \tag{2}$$

where $\mathcal{B}_{d,s,i}$ denotes the beamformer used by the APs that have been assigned the d-th data-pattern in the s-th beacon slot and on the i-th RF chain. These beamformers will be specified later.

The above definition of data-patterns is a *pilot-less* one, i.e., APs are assumed to transmit a constant signal on their assigned subcarriers. Based on this consideration, an alternative *pilot-based* definition of data-pattern can be thus introduced that leads to a larger number of orthogonal data-patterns, and permits increasing the distance between conflicting APs that will have to be assigned the same data-pattern. In this case, in each beacon slot, APs assigned the same data-pattern of the first kind may be differentiated by transmitting orthogonal pilots of length S. Since up to S different orthogonal pilots of length S can be generated, this strategy increases to SD the number of available orthogonal data-patterns. The ℓ-th pilot sequence, $\boldsymbol{\phi}_\ell$ say, of length S is in particular defined as

$$\boldsymbol{\phi}_\ell = \left[\sqrt{\beta} e^{\mathrm{i}\widetilde{\phi}_\ell(1)}, \ldots, \sqrt{\beta} e^{\mathrm{i}\widetilde{\phi}_\ell(S)}\right]^T \tag{3}$$

where i is the imaginary unit, and

$$\boldsymbol{\phi}_\ell^H \boldsymbol{\phi}_{\ell'} = S\beta\delta(\ell - \ell'), \tag{4}$$

with β the power transmitted by the APs in each beacon-slot and on each subcarrier.

B. Timing of the BA procedure

Similarly to what is assumed in [1], a general frame synchronization information is available in the system. This can be ensured by exploiting the fronthaul connection between the APs and the CPU, and by using a control-plane connection with the UEs at a sub-6 GHz carrier frequency. The BA procedure with consequent user association is made of the following phases:

a) All the APs transmit simultaneously proper signals on their assigned data-patterns and the UEs gather information and estimate the DoAs and DoDs corresponding to the strongest received paths for each data-pattern.
b) Using the sub-6 GHz uplink control channel, each UE communicates to the network its position and, for each of the data-patterns[1], the DoA and DoD of the strongest beam and a strength indicator.
c) Based on the information gathered from all the UEs, the network makes user-centric AP-UE association and communicates AP-UE associations to the APs and to the UEs (via the sub-6 GHz control channel).

Finally, the downlink/uplink communication between the BSs and the UEs can start using the beams that have been estimated in the above phases.

IV. BEAM ALIGNMENT SIGNAL MODEL

A. Signal model

Let us focus on the signal transmitted in the s-th beacon slot, i.e. for $t \in [sTt_0, (s+1)Tt_0]$. The baseband equivalent of the signal transmitted in the s-th beacon slot by the m-th AP can be expressed through the following N_{AP}-dimensional vector-valued waveform:

$$\mathbf{x}_{m,s}(t) = \sum_{i=1}^{n_{\mathrm{AP}}} x_{m,s,i}(t)\mathbf{u}_{m,s,i} \ , \tag{5}$$

where $x_{m,s,i}(t)$ is the signal corresponding to the i-th data stream from the m-th AP in the s-th beacon interval; the N_{AP}-dimensional vector $\mathbf{u}_{m,s,i}$ is the corresponding transmit beamformer[2]. The signal received at the k-th UE, before the receive beamforming is applied, after some algebraic manipulations, can be then written as

$$\begin{aligned} \mathbf{r}_{k,s}(t) = \ & \sum_{m=1}^{M} \int \mathbf{H}_{k,m}^{(s)}(\tau)\mathbf{x}_{m,s}(t-\tau)d\tau + \mathbf{z}_{k,s}(t) = \\ & \sum_{m=1}^{M} \sum_{\ell=0}^{L_{k,m}} \sum_{i=1}^{n_{\mathrm{AP}}} \alpha_{k,m}^{(s)}(\ell) g_{k,m,\ell,s,i}^{(AP)} \times \\ & x_{m,s,i}(t-\tau_{k,m,\ell})\mathbf{a}_{\mathrm{UE}}(\varphi_{k,m,\ell}) + \mathbf{z}_{k,s}(t) \ , \end{aligned} \tag{6}$$

with $g_{k,m,\ell,s,i}^{(AP)} = \mathbf{a}_{\mathrm{AP}}^H(\theta_{k,m,\ell})\mathbf{u}_{m,s,i}$ and $\mathbf{z}_{k,s}(t)$ an N_{MS}-dimensional vector waveform representing the AWGN contribution at the k-th UE receiver in the s-th beacon interval.

The k-th UE can apply n_{UE} different receive beamforming vectors to the received signal (6). Denoting by $\mathbf{v}_{k,s,j}$ the j-th beamformer (with $j = 1, \ldots, n_{\mathrm{UE}}$) used by the k-th UE in the s-th beacon slot, the following set of observables is available at the k-th UE after beamforming:

$$\begin{aligned} y_{k,s,j}(t) = \ & \frac{1}{\sqrt{n_{\mathrm{UE}}}} \mathbf{v}_{k,s,j}^H \mathbf{r}_{k,s}(t) = \\ & \sum_{m=1}^{M} \sum_{\ell=0}^{L_{k,m}} \sum_{i=1}^{n_{\mathrm{AP}}} \frac{1}{\sqrt{n_{\mathrm{UE}}}} \alpha_{k,m}^{(s)}(\ell) g_{k,m,\ell,s,i}^{(AP)} g_{k,\ell,s,j}^{(UE)} \times \\ & x_{m,s,i}(t-\tau_{k,m,\ell}) + z_{k,s,j}(t) \ , \end{aligned} \tag{7}$$

for $j = 1, \ldots, n_{\mathrm{UE}}$, with $g_{k,\ell,s,j}^{(UE)} = \mathbf{v}_{k,s,j}^H \mathbf{a}_{\mathrm{UE}}(\varphi_{k,m,\ell})$ and $z_{k,s,j}(t) = \frac{1}{\sqrt{n_{\mathrm{UE}}}} \mathbf{v}_{k,s,j}^H \mathbf{z}_{k,s}(t)$. The waveforms $y_{k,s,j}(t)$, for all j, undergo the usual OFDM receiver processing, and every OFDM symbol in $y_{k,s,j}(t)$ is converted into an N_C-dimensional vector. Focusing on the generic p-th OFDM symbol, and letting $s(p) = \lfloor p/S \rfloor$ denote the beacon slot index associated with the p-th OFDM symbol, the A/D conversion leads to the scalar entries say $Y_{k,p,j}(0), \ldots, Y_{k,p,j}(N_C - 1)$. In particular, it is easy to see that the q-th entry of such vector is expressed as

$$\begin{aligned} Y_{k,p,j,i}(q) = \ & \frac{1}{\sqrt{n_{\mathrm{UE}}}} \sum_{m=1}^{M} \mathbf{v}_{k,s(p),j}^H \mathcal{H}_{k,m}^{(s)}(q) \times \\ & X_{m,p,i}(q)\mathbf{u}_{m,s(p),i} + Z_{k,p,j,i}(q) \ , \end{aligned} \tag{8}$$

where $X_{m,p,i}(q)$ is the q-th data symbol transmitted in the p-th OFDM slot on the i-th transmit RF chain, $Z_{k,p,j,i}(q)$ contains the AWGN contribution and $\mathcal{H}_{k,m}^{(s)}(q)$ is the matrix-valued Fourier transform of the channel impulse response $\mathbf{H}_{k,m}^{(s)}(\tau)$ computed at the frequency $q/(t_0)$, i.e.,

$$\mathcal{H}_{k,m}^{(s)}(q) = \sum_{\ell=0}^{L_{k,m}} \alpha_{k,m}^{(s)}(\ell) \mathbf{a}_{\mathrm{UE}}(\varphi_{k,m,\ell}) \mathbf{a}_{\mathrm{AP}}^H(\theta_{k,m,\ell}) e^{-\mathrm{i}2\pi \frac{q}{t_0} \tau_{k,m,\ell}} \ .$$

As already said, during the BA phase, each AP transmits a pilot sequence that allows to distinguish APs using the

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[1] Remember that the number of data-patterns is either D, if the pilotless definition is used, or SD, if the pilot-based definition of data-pattern is used.

[2] Notice that we are here implicitly assuming that the transmit beamformer is kept constant over an entire beacon slot, i.e. for S consecutive OFDM symbols.

same data-pattern. Otherwise stated, the m-th AP transmits $X_{m,p,i}(q) = \sqrt{\beta} e^{\mathrm{i}\widetilde{\phi}_{\ell(m)}(p \mod s)}$, where $\ell(m)$ is the index of the pilot sequence assigned to the m-th AP, on its assigned subcarriers for T consecutive beacon slots. Otherwise stated, assuming that m-th AP uses the data-pattern $\mathcal{D}_d$, $q \in \mathcal{L}_{d,s,i}$, $s = 1, \ldots, T$. Each UE can rely on the knowledge of the data-patterns $\mathcal{D}_1, \ldots, \mathcal{D}_D$, and of the orthogonal pilot sequences $\boldsymbol{\phi}_1, \ldots, \boldsymbol{\phi}_S$. Based on this information, it has to determine the DoA and DoD of the strongest multipath components to be used for data communication. Notice that no information on the APs location or on the network topology is needed at the UE.

B. Directions discretization

The DoAs and DoDs, $\varphi_{k,m,\ell}$ and $\theta_{k,m,\ell}$ in Eq. (1), respectively, take continuous values, but in the BA procedure we use the approximate finite-dimensional (discrete) beamspace representation following the approaches in [1], [2]. We consider the discrete set of DoDs and DoAs

$$\begin{aligned} \Theta &= \left\{ \widehat{\theta} : \frac{1+\sin(\widehat{\theta})}{2} = \frac{u-1}{N_{\mathrm{AP}}},\ u = 1, \ldots, N_{\mathrm{AP}} \right\}, \\ \Phi &= \left\{ \widehat{\varphi} : \frac{1+\sin(\widehat{\varphi})}{2} = \frac{u'-1}{N_{\mathrm{UE}}},\ u' = 1, \ldots, N_{\mathrm{UE}} \right\} \end{aligned} \tag{9}$$

and use the corresponding array responses $\mathcal{F}_{\mathrm{AP}} = \left\{ \mathbf{a}_{\mathrm{AP}}(\widehat{\theta}) : \widehat{\theta} \in \Theta \right\}$ and $\mathcal{F}_{\mathrm{UE}} = \{ \mathbf{a}_{\mathrm{UE}}(\widehat{\varphi}) : \widehat{\varphi} \in \Phi \}$ as a discrete dictionary to represent the channel response. For the ULAs considered in this approach the dictionaries $\mathcal{F}_{\mathrm{AP}}$ and $\mathcal{F}_{\mathrm{UE}}$, after suitable normalization, yield orthonormal bases corresponding to the columns of the unitary discrete Fourier transform (DFT) matrices $\mathbf{W}_{N_{\mathrm{AP}}}$ and $\mathbf{W}_{N_{\mathrm{UE}}}$ defined as

$$[\mathbf{W}_N]_{p,p'} = \frac{1}{\sqrt{N}} e^{\mathrm{i}2\pi(p-1)\left(\frac{p'-1}{N} - \frac{1}{2}\right)} \quad p, p' = 1, \ldots, N, \tag{10}$$

with $N \in \{N_{\mathrm{AP}}, N_{\mathrm{UE}}\}$. The columns of $\mathbf{W}_{N_{\mathrm{AP}}}$ ($\mathbf{W}_{N_{\mathrm{UE}}}$) represent an orthonormal basis for $\mathcal{C}^{N_{\mathrm{AP}}}$ ($\mathcal{C}^{N_{\mathrm{UE}}}$); as a consequence, we can define

$$\begin{aligned} &\mathbb{v}_{k,s,j} = \mathbf{W}^H_{N_{\mathrm{UE}}} \mathbf{v}_{k,s,j}, \quad \mathbb{u}_{m,s,i} = \mathbf{W}^H_{N_{\mathrm{AP}}} \mathbf{u}_{m,s,i} \\ &\mathbb{H}^{(s)}_{k,m}(q) = \mathbf{W}^H_{N_{\mathrm{UE}}} \mathcal{H}^{(s)}_{k,m}(q) \mathbf{W}_{N_{\mathrm{AP}}}. \end{aligned} \tag{11}$$

The vector $\mathbb{u}_{m,s,i}$, to be used at the m-th AP in the s-th beacon slot and on the i-th RF chain, is defined by the data-pattern. More precisely, letting $\mathcal{A}_d \in \{1, 2, \ldots, M\}$ denote the set of APs that have been assigned the d-th data-pattern[3], $\mathbb{u}_{m,s,i}$ follows

$$\mathbb{u}_{m,s,i} = \mathbb{d}_{d,s,i},\ \forall\, m \in \mathcal{A}_d\,, \tag{12}$$

i.e., all the APs using the d-th data-patterns in the s-th beacon slot and on the i-th RF chain use the transmit beamformer $\mathbb{d}_{d,s,i}$.

V. BEAM ALIGNMENT OPERATIONAL PHASE

Given the definitions in Section IV, Eq. (8) can be shown to be written as

$$\begin{aligned} Y_{k,p,j,i}(q) = \ &\frac{1}{\sqrt{n_{\mathrm{UE}}}} \sum_{m=1}^{M} \mathbb{v}^H_{k,s(p),j} \mathbb{H}^{(s)}_{k,m}(q) \mathbb{u}_{m,s(p),i} \times \\ &X_{m,s(p),i}(q) + Z_{k,p,j,i}(q)\,. \end{aligned} \tag{13}$$

The beamforming vector $\mathbf{u}_{m,s,i}$ to be used at the m-th AP in the s-th beacon slot and on the i-th RF chain is defined by the data-pattern associated at the AP. We use pseudo-random multi-finger transmit and receive beamformers which offer good performance in presence of channel sparsity [1], [3]. Thus, it is an all-zero vector with ν_{AP} entries equal to one; the positions of the ones are pseudo-random and defined by the data-pattern. Similarly, the beamformer $\mathbf{v}_{k,s,j}$ to be used at the k-th UE in the s-th beacon slot and on the j-th RF chain is an all-zero vector with ν_{UE} ones placed in pseudo-random positions.

First of all, we notice that since each data-pattern adopts a disjoint set of subcarriers, the UE can operate on D different sets of observables. More precisely, the observables in Eq. (13) can be regrouped in D disjoint sets to be separately processed. The d-th set of observables available at the k-th UE, that we denote by $\mathcal{O}^{(d)}_k$, is thus expressed as

$$\begin{aligned} \mathcal{O}^{(d)}_k = &\Big\{ \overline{Y}^{(d)}_{k,p,j,i}(q),\ q \in \mathcal{L}_{d,s,i},\ s = 1, \ldots, T, \\ &p = 1, \ldots, ST,\ i = 1, \ldots, n_{\mathrm{AP}},\ j = 1, \ldots, n_{\mathrm{UE}} \Big\}, \end{aligned}$$

with

$$\begin{aligned} \overline{Y}^{(d)}_{k,p,j,i}(q) = \ &\frac{\sqrt{\beta}}{\sqrt{n_{\mathrm{UE}}}} \sum_{m \in \mathcal{A}_d} \mathbb{v}^H_{k,s(p),j} \mathbb{H}^{(s)}_{k,m}(q) \mathbb{u}_{m,s(p),i} \times \\ &e^{\mathrm{i}\widetilde{\phi}_{\ell(m)}(p \mod s)} + \overline{Z}^{(d)}_{k,p,j}(q)\,. \end{aligned} \tag{14}$$

Based on the above data, the following averaged quadratic observable is built:

$$c^{(d,\ell)}_{k,s,j,i} = \frac{1}{QS} \sum_{p=(s-1)S+1}^{sS} \sum_{q \in \mathcal{L}_{d,s,i}} \left| \overline{Y}^{(d)}_{k,p,j,i}(q) e^{-\mathrm{i}\widetilde{\phi}_{\ell}(p \mod s)} \right|^2, \tag{15}$$

for all $d = 1, \ldots, D$, $\ell = 1, \ldots, S$, $s = 1, \ldots, S$, $i = 1, \ldots, n_{\mathrm{AP}}$, $j = 1, \ldots, n_{\mathrm{UE}}$, $k = 1, \ldots, K$.

At the k-th UE the measurements in Eq. (15) are collected for all the values of i, j and s and grouped into the following vector:

$$\mathbf{c}^{(d,\ell)}_k = \left[c^{(d,\ell)}_{k,1,1,1}, \ldots, c^{(d,\ell)}_{k,1,n_{\mathrm{UE}},n_{\mathrm{AP}}}, c^{(d,\ell)}_{k,2,1,1}, \ldots, c^{(d,\ell)}_{k,T,n_{\mathrm{UE}},n_{\mathrm{AP}}} \right]^T. \tag{16}$$

Next, let

$$\mathbb{b}^{(d)}_{k,s,j,i} = \frac{\mathbb{d}_{d,s,i} \otimes \mathbb{v}^H_{k,s,j}}{\|\mathbb{d}_{d,s,i}\| \|\mathbb{v}^H_{k,s,j}\|}\,, \tag{17}$$

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[3] Note that in the pilot-based case this set corresponds to APs using the same set of subcarriers during the BA procedure, but assigned to different pilot-sequences.

and form the $(n_{\rm AP}n_{\rm UE}T \times N_{\rm AP}N_{\rm UE})$-dimensional matrix

$$\begin{aligned}\mathbf{B}_k^{(d)} = \; & \Big[\mathbb{b}_{k,1,1,1}^{(d)}, \ldots, \mathbb{b}_{k,1,n_{\rm UE},n_{\rm AP}}^{(d)}, \\ & \mathbb{b}_{k,2,1,1}^{(d)}, \ldots, \mathbb{b}_{k,T,n_{\rm UE},n_{\rm AP}}^{(d)}\Big]^T \; . \end{aligned} \tag{18}$$

Note that the matrix $\mathbf{B}_k^{(d)}$ depends only on the beamforming vectors used in the d-th data-pattern and not on the pilot sequences used by the APs.

Based on the above notation, the following optimization problem can be considered:

$$\boldsymbol{\xi}_k^{(d,\ell)} = \arg \min_{\mathbf{x}} \left\| \mathbf{B}_k^{(d)}\mathbf{x} + \sigma^2 \mathbf{1}_{n_{\rm AP}n_{\rm UE}T\times 1} - \mathbf{c}_k^{(d,\ell)} \right\|^2 \; . \tag{19}$$

The solution $\boldsymbol{\xi}_k^{(d,\ell)}$ to Problem (19) is a $(N_{\rm AP}N_{\rm UE})$-dimensional vector that can be arranged in a $(N_{\rm AP} \times N_{\rm UE})$-dimensional matrix, $\boldsymbol{\Xi}_k^{(d,\ell)}$ say, where each entry can be associated to a pair (DoD, DoA) associated to a possible propagation path coming from the APs using the d-th data-pattern and the ℓ-th pilot sequence. Each entry of $\boldsymbol{\Xi}_k^{(d,\ell)}$ contains, for each possible pair (DoD, DoA), an estimate of the channel power; it thus follows that the largest entry of $\boldsymbol{\Xi}_k^{(d,\ell)}$ is an indicator of the dominant path between the k-th UE and the APs using the d-th data-pattern and the ℓ-th pilot sequence. In order to perform the proposed BA procedure, each UE needs to solve DS optimization problems, i.e., the k-th UE solves Problem (19) $\forall d = 1, \ldots, D$ and $\ell = 1, \ldots, S$. The k-th UE chooses the $N_D \leq DS$ *strongest* (DoD, DoA) pairs which can be thus used for data communication. This procedure is independently implemented by each UE, i.e., $k = 1, \ldots, K$.

VI. NUMERICAL RESULTS

In our simulation setup, we assume a communication bandwidth $W = 250$ MHz centered over the carrier frequency $f_0 = 28$ GHz. The OFDM subcarrier spacing is 480 kHz and assuming that the length of the cyclic prefix is 7% of the OFDM symbol duration, i.e., $\tau_{\rm CP}\Delta_f = 0.07$, we obtain $t_0 = 2.23$ μs and $N_C = 512$ subcarriers. A beacon slot contains $S = 16$ OFDM symbols and the random access slot, used to share the results of the BA procedure, also contains 16 OFDM symbols [1]. The antenna height at the AP is 10 m and at the UE is 1.65 m. The additive thermal noise is assumed to have a power spectral density of -174 dBm/Hz, while the front-end receiver at the APs and at the MSs is assumed to have a noise figure of 9 dB. We consider a square area of 400 m × 400 m; the APs and UEs are equipped with ULAs of $N_{\rm AP} = 32$ and $N_{\rm UE} = 16$ antennas, respectively, the number of RF chains at the APs and UEs are $n_{\rm AP} = 8$ and $n_{\rm UE} = 4$, respectively. We assume a number of total scatterers, $N_{\rm s} = 1000$ say, common to all the APs and UEs and uniformly distributed in the simulation area. In order to model the signal blockage, we assume that the communication between the m-th AP and the k-th UE takes place via the n-th scatterer, i.e., the n-th scatterer is one of the effective $L_{k,m}$ contributing in the channel in Eq. (1), if the rays between the m-th AP and the n-th scatterer and the k-th UE and the n-th scatterer *simultaneously* exist. We assume that a link exists between two entities, in our case one AP/UE and one scatterer, if they are in LoS, with a LoS probability given by [10], [11]. For the channel model in Eq. (1), the variance of the complex gain associated to the ℓ-th path between the k-th user and the m-th AP, $\gamma_{k,m}(\ell)$ is obtained as reported in [10]. The total power transmitted by the APs over all the subcarriers during the BA phase is denoted as $P_{\rm BA}$, and consequently $\beta = P_{\rm BA}/N_C$. In the following, we assume $P_{\rm BA} = 10$ dBW.

The considered performance measure is the probability of correct detection at the UE of the DoD and DoA of the N_D strongest paths (one for each AP), i.e. the probability that a UE detects the correct DoD and DoA for the strongest path from the N_D best APs. The correct DoD and DoA between the m-th AP and the k-th UE is obtained as follows. We firstly define the $(N_{\rm UE} \times N_{\rm AP})$-dimensional matrix $\mathbf{E}_{k,m}$ whose (r,t)-th entry is defined as as

$$[\mathbf{E}_{k,m}]_{(r,t)} = \sum_{q=1}^{N_C} \left| [\mathbf{W}_{N_{\rm UE}}]_{(:,r)}^H \, \mathcal{H}_{k,m}^{(s)}(q) \, [\mathbf{W}_{N_{\rm AP}}]_{(:,t)} \right|^2 , \tag{20}$$

with $[\mathbf{W}_{N_{\rm UE}}]_{(:,r)}$ and $[\mathbf{W}_{N_{\rm AP}}]_{(:,t)}$ the r-th and t-columns of the matrices $\mathbf{W}_{N_{\rm UE}}$ and $\mathbf{W}_{N_{\rm AP}}$, respectively. Assume that the maximum entry of the matrix $\mathbf{E}_{k,m}$ is in the position (r^*, t^*), the correct DoD is the t^*-th element of the set Θ, discrete set of DoDs, and the correct DoA is the r^*-th element of the set Φ, discrete set of DoAs, as defined in (9).

Fig. 2 shows such detection probability versus the number of used beacon slots T. In the two sub-figures we compare the performance of the proposed pilot-based BA procedure with a pilot-less BA procedure. A pilot-less BA procedure assumes only the reuse of the data-patterns defined in (2) and no orthogonal pilot sequences are transmitted by the APs assigned to the same data-pattern, i.e., $\widetilde{\phi}_\ell(p) = 0, \; \forall \ell, p = 1, \ldots, S$. We assume an *high-density scenario* with $M = 32, K = 8$, and a *low-density scenario* with $M = 16, K = 4$. We consider two values of D, number of different data-patterns, with a random assignment (RA) of the data-patterns to the APs. The number of active fingers in the beamformers is $\nu_{\rm AP} = 8$ and $\nu_{\rm UE} = 4$. The pilot sequences in the pilot-based BA procedure are Hadamard sequences with length S. Inspecting the figures and firstly focusing on the pilot-less BA procedure, we can see that the increase in the parameter D can improve the detection capability of the system, especially in the case of $N_D = 1$ for low values of T; however D cannot be increased too much since this corresponds to a smaller value of Q, the number of carriers assigned to each AP RF chain. Focusing on the pilot-based BA procedure, we can see that the increasing in D very poorly increases the performance, because the orthogonality between the APs can be obtained exploiting the pilot sequences. Overall, the results show that both the procedures are effective and permit realizing BA in multi-AP multi-UE environments with satisfactory performance. The introduction of the orthogonal pilot sequences helps to

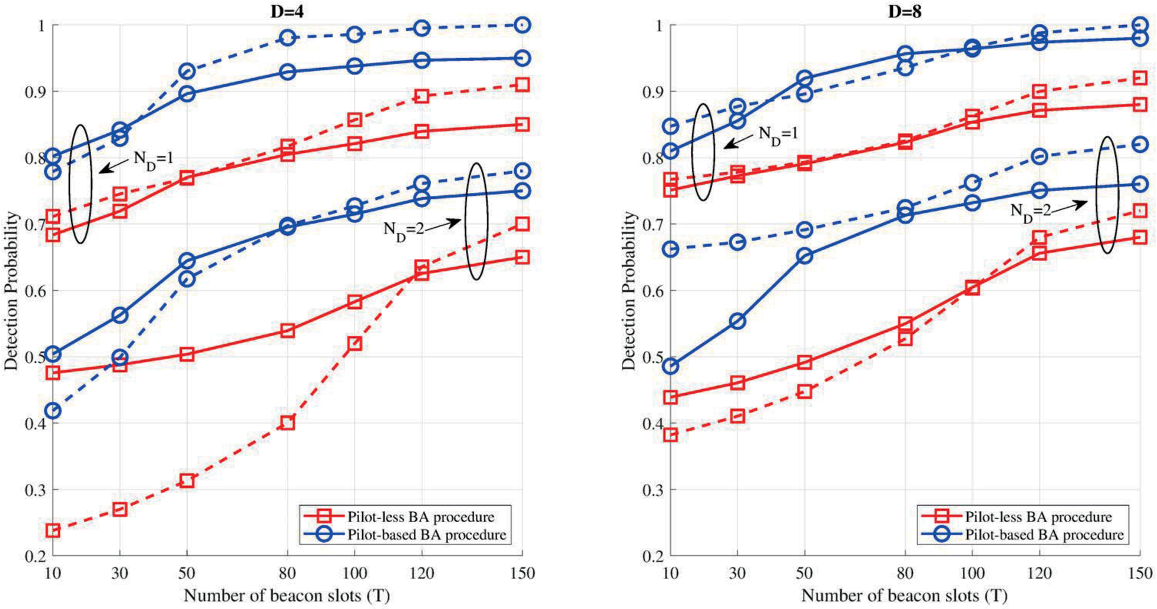

Fig. 2: Detection probability of the proposed pilot-based BA procedure compared with the pilot-less BA procedure versus the number of beacon slots T. Continuous lines are referred to the *high-density scenario* with $M = 32, K = 8$, the dashed lines are referred to the *low-density scenario* with $M = 16, K = 4$. The detection probability results are reported for different values of N_D and D. Parameters: $N_{\text{AP}} = 32$, $N_{\text{UE}} = 16$, $\nu_{\text{AP}} = 8$, $\nu_{\text{UE}} = 4$, $n_{\text{AP}} = 8$, and $n_{\text{UE}} = 4$.

further increase the detection capability performance of the system and to reach the orthogonality of the resources used by different APs without increasing the number of orthogonal data-patterns reused between the simultaneous transmitters.

VII. CONCLUSIONS

This paper has considered the problem of performing a pilot-based BA procedure and user-AP association in a CF-mMIMO network operating at mmWave. The proposed BA procedure amounts to a protocol involving the CPU, the UEs, the APs and a macro-BS managing a control channel at sub-6 GHz frequency. It enables simultaneous BA of each UE with the strongest beams coming from a pre-defined number of strongest APs. The orthogonality between the resources used by the APs is obtained exploiting the data-patterns and the pilot sequences. Numerical results are presented comparing the performance of the pilot-based BA procedure with a pilot-less BA procedure where no orthogonal pilot sequences are used by APs assigned to the same data-pattern. These results have confirmed the effectiveness of the proposed approach, showing that BA can be performed in a shared frequency band with a simultaneous operation of several APs and several UEs.

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