Beam Alignment for the Cell-Free mmWave Massive MU-MIMO Uplink

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—Millimeter-wave (mmWave) cell-free massive multi-user multiple-input multiple-output (MIMO) is expected to combine the large bandwidths available at mmWave frequencies and the high capacity of MIMO, leading to a potential game changer in wireless technology. However, the high path loss at mmWave frequencies is expected to require UE-side beamforming even in cell-free systems: Rather than aimlessly transmitting the uplink signal in all directions, a UE should form a beam that is aligned to a nearby AP. The challenge of determining the optimal beam directions, a UE should form a beam that is aligned to a nearby access point (AP). At the same time, multiple equipments (UEs) must form beams in meaningful directions, i.e., to a nearby access point (AP). To combat the high path loss at mmWave frequencies, user (MU) multiple-input multiple-output (MIMO) systems have multiple antennas, they do not perform any kind of beamforming with these [2], [15] (with the exception of [16]).

The number of years [1], [3], [4] and recently found its way into commercial products [5]. While cell-free massive MU-MIMO user (MU) multiple-input multiple-output (MIMO) systems have multiple antennas, they do not perform any kind of beamforming with these [2], [15] (with the exception of [16]).

Even in the mmWave cell-free literature, the UEs are often assumed to have a single antenna only [9]–[14], or, if they are able to perform digital beamforming. In contrast to what is customary in the cell-free literature, we do not assume that the number of APs is much larger than the number of UEs served [17], as such an assumption depends on a high pervasiveness of wireless infrastructure. We propose a MU interference-aware method for beam alignment (BA) in the cell-free mmWave massive MU-MIMO uplink of UEs served [17], as such an assumption depends on a high pervasiveness of wireless infrastructure. We propose a MU interference-aware method for beam alignment (BA) in the cell-free mmWave massive MU-MIMO uplink.
A communication scheme is considered, where both local and central processing is performed. The APs and UEs are connected to a central processing unit (CPU) for control signaling.

In this setup, the sub-6-GHz control channel is used for this purpose. This channel can be used for control signaling from the CPU to the UEs.

The channel matrix, which is typically acquired in wireless systems, consists of diagonal blocks. This reflects the fact that the UEs cannot transmit simultaneously in the same time-frequency resource, which is a practical constraint.

The channel matrix has the following block structure,

\[
\mathbf{H} = [\mathbf{H}_1 \cdots \mathbf{H}_K]
\]

where \( \mathbf{H}_k \) is the channel matrix from the CPU to the \( k \)-th UE.

The per-subcarrier input-output relation between all UEs and APs is expressed as

\[
\mathbf{y} = \mathbf{H} \mathbf{x} + \mathbf{n}
\]

where \( \mathbf{y} \) is the receive vector, \( \mathbf{x} \) is the transmit vector, and \( \mathbf{n} \) is the noise vector.

In this scenario, the APs are fully digital, i.e., every antenna is connected to a single RF chain and relies on analog beamforming. The APs are not connected to the CPU locally distributed APs that are connected to the CPU to communicate to each UE the codebook index of its selected beam and requires no control signals from the UEs.

As in [16], we assume the existence of a sub-6-GHz control channel which can be used for control signaling from the CPU to the UEs. However, compared to [16], our scheme requires channel which can be used for control signaling from the CPU to the UEs. However, compared to [16], our scheme requires

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A shopping mall or a university campus. The APs and UEs see Fig. 1. Such a scenario could correspond for instance to

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where we omit the subcarrier index for ease of notation. Here,

\[
\mathbf{x} = \mathbf{P} \mathbf{a}
\]

and

\[
\mathbf{y} = \mathbf{R} \mathbf{a} + \mathbf{n}
\]

are the transpose and conjugate transpose of \( \mathbf{a} \), respectively. The UEs are assumed to have a single RF chain and thus rely on analog beamforming; the APs are fully digital [19].

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where \( \mathbf{P} \) is the UE beamforming matrix, \( \mathbf{R} \) is the AP beamforming matrix, \( \mathbf{a} \) is the input vector, \( \mathbf{x} \) is the input vector, and \( \mathbf{n} \) is the noise vector with variance \( \sigma^2 \).

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On the other hand, some knowledge of the channel matrix is necessary for the UEs to select appropriate beams. To this end, we need to perform analog beam alignment (BA). Note that this estimate of the channel matrix only performs a coarse estimate of the channel matrix which it then uses for all subcarriers. We therefore perform BA based on the strongest subcarrier channel matrices per UE and AP, then used for all subcarriers. We therefore solve this conundrum using a two-stage scheme: In the first stage, we perform analog beam alignment (BA) for each UE given the knowledge of the channel matrix. In the second stage, we then iteratively select the beam for the current UE given the beams of all UEs except the current UE: 

\[ \text{max}_{\mathbf{w}_i} \mathbb{E}[\mathbf{y}_i^H \mathbf{H}_i \mathbf{w}_i] \quad \text{subject to} \quad \mathbb{E}[\mathbf{w}_i^H \mathbf{w}_i] = 1, \]

where \( \mathbf{H}_i \) is the channel matrix of the \( i \)-th UE given the knowledge of the channel matrices of all other UEs.

Even when using such a frequency-flat surrogate, optimal BA algorithm takes MU interference into account. We have already seen that maximizing joint optimization objectives, such as achievable sum-rate or max-min achievable rate since it is typically not practical for common optimization objectives, would require digital beamforming, but which we will later use (and the UEs could perform full digital beamforming), one would of course be possible and are left for future work. Note that this estimate of the channel matrix only needs to be accurate enough to determine the angles of strong directions. Based on these pilots, the CPU then selects those UEs whose beams have already been selected: 

\[ \text{max}_{\mathbf{w}_i} \mathbb{E}[\mathbf{y}_i^H \mathbf{H}_i \mathbf{w}_i] \quad \text{subject to} \quad \mathbb{E}[\mathbf{w}_i^H \mathbf{w}_i] = 1, \]

where \( \mathbf{H}_i \) is the post-equalization signal-to-noise ratio (SNR) for every user, by solving the problem can be solved individually per UE, we can solve it for max-min achievable rate optimal BA since it is typically not practical for common optimization objectives.

Because of channel reciprocity, the same would also hold if the pilots were orthogonal pilot sequences used by the CPU to perform a high-resolution LMMSE equalization detection, which in this paper is performed using centralized methods for BA. This estimate is then used for data transmission by the APs instead of the UEs.

We will now first describe the BA procedure before explaining how to select appropriate beams.
for $k = 1, \ldots, K$. In (8), $v_k$ is the $k$th column of the LMMSE equalization matrix as in (4), but restricted to only the first $K$.

To develop a scheme which is both sufficiently accurate and computationally efficient, we estimate the channel matrices for a subset of subcarriers which are spaced uniformly between adjacent subcarriers, we only estimate the channel subcarrier individually. However, to keep complexity at bay, and considering the distributed nature of the APs and the UEs in combination with the high directivity of mmWave channels [1], we again omit the subcarrier index for brevity. We estimate the channel matrix at the APs using pilot signals transmitted over the total number of used subcarriers.

Then, in a second round, we use a coordinate descent BA procedure. This round iterates in reverse taking into account the interference of the beams which can be used by the UEs in their currently selected beams. This round iterates in reverse to adapt to the beams of the UEs that were selected later by the BA procedure, and considering the interference of the beams they form while transmitting symbols and the beams they fix their beams accordingly in the form of the beamforming matrix, the matrix $H$ now denotes the compound of the UE $n$ and the AP, based on the strongest subcarrier channel matrices per UE and AP, as detailed in Section III. The UEs use a scheme with $p$ pilots simultaneously, we would have the most efficient CHEST of UEs or is currently being selected. This means that one round of the CHEST is performed based on the strongest subcarrier, we would have the most efficient CHEST.
The wireless channels are simulated using Wireless InSite from Remcom [18]. The setup, depicted in Fig. 2, consists of an area and contains 1336 possible UE locations (red), each with \( n_{\text{UE}} = 8 \) antennas, and \( L = 16 \) APs (green), each with \( L_{\text{AP}} = 4 \) antennas. The APs and UEs are at heights of \( h_{\text{AP}} = 12 \) m and \( h_{\text{UE}} = 12 \) m, respectively. Both APs and UEs have uniform linear arrays with omnidirectional antennas spaced by half a wavelength. The APs are arranged on a grid. To simulate random user orientations, we also consider four possible angles for each user: \( 0, 45, 90, 135 \) degrees.

The fact that the results where we perform pre-BA CHEST for data detection, where the pre-BA CHEST procedure solves its task nearly optimally. Any loss incurred by the post-BA CHEST for data detection, where channel knowledge is available or has to be estimated. The results where we combine pre-BA CHEST for BA with ground truth channel knowledge for data equalization (dashed curves). In comparison to a hypothetical scenario where ground truth channel knowledge is available. For future work we highlight the combination of our methods with decentralized data detection schemes as well as considering the UE beam alignment problem in the mmWave cell-free downlink.

As performance metrics we consider the cumulative density function (CDF) or complementary CDF (CCDF) of the root-mean-squared-symbol error (RMSSE) per UE, the SINR per UE per subcarrier, and the spectral efficiency (SE) per UE. The RMSSE for the \( n_{\text{UE}} \)th UE is defined as

\[
\text{RMSSE}(s_{\text{UE}}) = \frac{1}{T} \sum_{t=1}^{T} \left( s_{\text{UE}}(t) - \hat{s}_{\text{UE}}(t) \right)^2
\]

where each UE has \( \sum_{k=1}^{L} P_{\text{AP}}(k) \) power control. To model realistic RF hardware, the APs have a noise figure of 7 dB [23].

The interference-unaware digital BA from Section III-B is the interference-unaware method, i.e., no BA capabilities.

The second baseline is the interference-unaware digital BA.

C. Performance Results

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Fig. 3. Subfigures (a), (b), and (c) show the CDF or CCDF of the RMSSE per UE, the SINR per UE per subcarrier, and the SE per UE, respectively, for ground truth channel knowledge (solid) or pre-BA CHEST in combination with perfect post-BA CHEST (dashed).