DISTRIBUTED HYBRID BEAMFORMING FOR MMWAVE CELL-FREE MASSIVE MIMO

Nuan Song and Tao Yang

Nokia Bell Labs China
Email: {nuan.song and tao.a.yang}@nokia-sbell.com

ABSTRACT

The cell-free massive Multiple Input Multiple Output (MIMO) architecture is considered for millimeter Wave (mmWave) bands to overcome propagation challenges at higher frequencies such as significant pathloss, easy blockage, and shadowing. Instead of using a single and co-located extreme large antenna array, multiple large arrays with a smaller dimension in a hybrid architecture can be efficiently deployed over multiple Access Points (APs) in a distributed way. We propose a distributed hybrid beamforming concept for mmWave cell-free massive MIMO systems, which supports multi-antenna or even hybrid array based User Equipments (UEs) and multi-stream transmissions. Analog beamforming at both APs and UEs can be obtained in a joint and multi-phase manner to maximize the total effective array gain in the cell-free system. We also develop an interference aware digital precoding method to deal with multi-user/multi-stream transmissions, achieving a high multiplexing gain. Simulation results show a good potential of using the distributed hybrid beamforming in cell-free systems.

1. INTRODUCTION

The cell-free/distributed massive Multiple Input Multiple Output (MIMO) has been considered as one of the most promising candidates for 6G technologies [1, 2]. Cell-free massive MIMO systems (c.f. Figure 1) employ a large number of Access Points (APs) distributed over a wide area that jointly and coherently serve a smaller number of User Equipments (UEs). Such a different form of massive MIMO is able to deal well with the inter-cell interference and achieve uniformly good services for all UEs [3]. It also shows an enhanced performance as compared to the small cell scheme where each UE is served by a dedicated AP, especially under the spatially correlated shadow fading environment.

The millimeter Wave (mmWave) massive MIMO system, which employs a centralized array with a considerable number of antenna elements, can substantially increase the system throughput [4], by exploring both the array gain and the spatial multiplexing gain. The very large array at mmWave frequencies leads to a high level of power consumption, complexity, and costs. The hybrid array architecture and beamforming concepts have thus been mostly considered for mmWave massive MIMO [5]. However, mmWave communications always have coverage issues, due to propagation limitations such as large pathloss, easy blockage, as well as shadowing [6].

Therefore, applying cell-free massive MIMO at mmWave bands turns out to be quite attractive. It can overcome the propagation challenges at higher frequencies by exploring the marco-diversity from distributed APs [7]. The hardware complexity and power consumption can also be considerably alleviated by separating the very large centralized array into smaller arrays mounted at multiple distributed APs. One key problem to be solved is the energy efficient transmit beamforming design, i.e., hybrid beamforming. Some work on different hybrid beamforming architectures for cell-free mmWave massive MIMO has been carried out. References [8, 9, 10] consider the architecture of distributed analog beamforming but centralized digital precoding (c.f. Figure 1 (a)). However, centralized digital precoding requires more efforts at Central Processing Unit (CPU) to handle all the signals and channels to/from APs, which is also quite critical for the fronthaul load. Reference [11] considers the architecture of distributed hybrid analog and digital precoding (c.f. Figure 1 (b)) with multi-antenna UEs but only studies the single-stream transmission.

In this paper, we propose a complete distributed hybrid analog-digital beamforming solution that can be generally applied in cell-free mmWave massive MIMO systems with multi-antenna and even hybrid-array based UEs, supporting multi-beam/stream transmissions. The proposal includes a joint AP-UE analog beamforming procedure to achieve the total effective array gain in the whole cell-free area. We also develop an interference aware digital precoding algorithm, named Successive Interference Rejection Minimum Mean Square Error (SIR-MMSE), which outperforms the existing methods such as Localized MMSE (L-MMSE) and Conjugate Beamforming (CB) with a simple power control scheme. The proposed algorithm does not have any dimensionality constraint on the number of Radio Frequency (RF) chains and on its relationship with UE antennas. We evaluate the performance and compare with various cell-free algorithms as well as the traditional small cell concept.

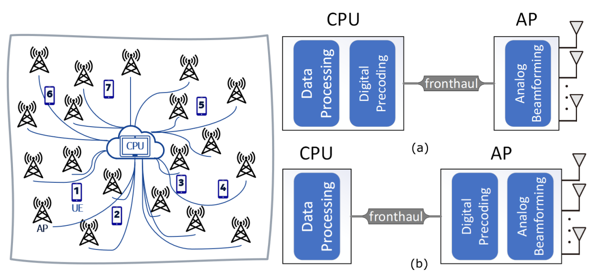


Fig. 1. A cell-free massive MIMO system with two different beamforming architectures. CPU: Central Processing Unit.

2. SYSTEM MODEL

We consider the scenario where all APs are serving all UEs and the simple architecture with both analog and digital beamforming functions being implemented in a distributed fashion at each AP (c.f. Figure 1 (b)). Figure 2 shows the block diagram of cell-free mmWave massive MIMO using distributed processing in the case where each AP is serving multiple UEs for downlink. There are M APs in the system serving K UEs. Each AP is mounted with M_t transmit antennas that all connect to N_t RF chains, where $N_t < M_t$ holds for the hybrid design. The total number of antennas and RF chains for all APs are $M_T = M{\cdot}M_t$ and $N_T = M{\cdot}N_t$, assuming APs have the same array dimension. Similarly, for the k-th UE ($k = 1, \cdots, K$), the number of receive antennas is denoted by M_{R_k} and the corresponding number of RF chains satisfies $N_{R_k} < M_{R_k}$, if a hybrid array is also considered at UE. Accordingly, we denote the total number of antennas for all users by $M_R = \sum_{k=1}^{K} M_{R_k}$ and that of the RF chains by $N_R = \sum_{k=1}^{K} N_{R_k}$. The received signal at all UEs after combining is given by

$$\boldsymbol{y} = \boldsymbol{W}_{BB}^H \boldsymbol{W}_{RF}^H \boldsymbol{H} \boldsymbol{F} \boldsymbol{P} \boldsymbol{s} + \boldsymbol{n} \in \mathbb{C}^r, \tag{1}$$

where $r = \sum_{k=1}^{K} r_k$ is the total number of data streams with r_k being the stream number per UE and $\boldsymbol{s} = [\ \boldsymbol{s}_1^T, \ \cdots, \ \boldsymbol{s}_K^T\ ]^T \in \mathbb{C}^r$ is a vector of data symbols from all UEs. For the distributed hybrid beamforming case, the matrix $\boldsymbol{F}_m \in \mathbb{C}^{M_t \times N_t}$ is the m-th AP's analog RF beamformer and all constitute a block diagonal matrix $\boldsymbol{F} = \mathrm{diag}\{\boldsymbol{F}_1, \ldots, \boldsymbol{F}_M\} \in \mathbb{C}^{M_T \times N_T}$ as the total analog beamforming matrix. $\boldsymbol{P} \in \mathbb{C}^{N_T \times r}$ represents the digital baseband precoder. The channel matrix is $\boldsymbol{H} \in \mathbb{C}^{M_R \times M_T}$. At the k-th UE, the analog combiner and the digital decoder are denoted by $\boldsymbol{W}_{\mathrm{RF}}^{(k)} \in \mathbb{C}^{M_{R_k} \times N_{R_k}}$ and $\boldsymbol{W}_{\mathrm{BB}}^{(k)} \in \mathbb{C}^{N_{R_k} \times r_k}$, constructing the block diagonal matrices $\boldsymbol{W}_{\mathrm{RF}} = \mathrm{diag}\{\boldsymbol{W}_{\mathrm{RF}}^{(1)}, \ldots, \boldsymbol{W}_{\mathrm{RF}}^{(K)}\} \in \mathbb{C}^{M_R \times N_R}$ and $\boldsymbol{W}_{\mathrm{BB}} = \mathrm{diag}\{\boldsymbol{W}_{\mathrm{BB}}^{(1)}, \ldots, \boldsymbol{W}_{\mathrm{BB}}^{(K)}\} \in \mathbb{C}^{N_R \times r}$, respectively. The vector $\boldsymbol{n}$ is the complex Additive White Gaussian Noise (AWGN) with variance σ_n^2.

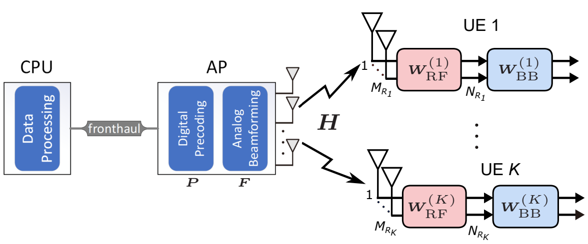


Fig. 2. Block diagram of cell-free mmWave massive MIMO with the transmission involving one AP to multiple UEs.

3. DISTRIBUTED HYBRID ANALOG AND DIGITAL BEAMFORMING

In the mmWave massive MIMO system with hybrid array architecture, an efficient way to design beamforming is to break the joint optimization into two stages, i.e., the analog part and the digital part [12]. In the mmWave cell-free case, where each AP has a hybrid array with a large number of antennas, it is also straightforward to carry out the split hybrid beamforming concept. The analog beamformer/combiner technique aims at maximizing the total effective array gain, while the digital precoder/decoder processing is to handle the interference and exploit the spatial multiplexing gain.

3.1. Proposed joint AP-UE multi-phase analog beamforming

Since all APs are serving all UEs in our considered cell-free system, the analog beamforming problem targets at solving the maximization of the total effective array gain, which can be formulated by

$$\begin{aligned} &\max_{\boldsymbol{F}_m, \boldsymbol{W}_{RF}^{(k)}} \mathbb{E}\left\{\left\|\boldsymbol{W}_{RF}^H \boldsymbol{H} \boldsymbol{F}\right\|_F^2\right\}, \\ &\text{s.t.} |\boldsymbol{F}_m(i,j)| = 1, |\boldsymbol{W}_{RF}^{(k)}(i,j)| = 1\ \forall m, \forall k, \end{aligned} \tag{2}$$

where the AP m's analog beamformer $\boldsymbol{F}_m$ is defined in Section 2 and $\|\cdot\|_F$ denotes the operation of the Frobenius norm. The phase shifter based energy-efficient beamforming network is assumed with constant modulus constraint.

To solve the optimization problem in (2), we propose a joint AP-UE analog beamforming scheme by alternating calculations of analog beamformers and combiners between APs and UEs in a multi-phase manner. The proposed scheme is based on the following decoupled optimization problems, by relaxing the constant modulus constraint for simplicity.

With a fixed $\boldsymbol{W}_{RF}$, each AP solves its own optimization problem that maximizes the effective array gain between the m-th AP and all UEs, written by

$$\max_{\boldsymbol{F}_m} \mathbb{E}\left\{\left\|\boldsymbol{W}_{RF}^H \boldsymbol{H}_m \boldsymbol{F}_m\right\|_F^2\right\}, \ \text{s.t.} \boldsymbol{F}_m^H \boldsymbol{F}_m = \boldsymbol{I}_{N_T}, \tag{3}$$

where the matrix $\boldsymbol{H}_m \in \mathbb{C}^{M_R \times N_t}$ represents the channel between the AP m to all UEs. This optimization can be equivalently reformulated as

$$\begin{aligned} &\max_{\boldsymbol{F}_m} \mathrm{trace}\left(\boldsymbol{F}_m{}^H \underbrace{\mathbb{E}\left\{\boldsymbol{H}_m^H \boldsymbol{W}_{RF} \boldsymbol{W}_{RF}^H \boldsymbol{H}_m\right\}}_{\boldsymbol{Q}_m} \boldsymbol{F}_m\right), \\ &\text{s.t.} \boldsymbol{F}_m^H \boldsymbol{F}_m = \boldsymbol{I}_{N_T}. \end{aligned} \tag{4}$$

Then with a fixed $\boldsymbol{F}_m$, each UE solves the maximization problem of the effective array gain from all APs by

$$\max_{\boldsymbol{W}_{RF}^{(k)}} \sum_{m=1}^{M} \mathbb{E}\left\{\left\|\boldsymbol{W}_{RF}^{(k)H} \boldsymbol{H}_{m,k} \boldsymbol{F}_m\right\|_F^2\right\}, \ \text{s.t.} \boldsymbol{W}_{RF}^{(k)H} \boldsymbol{W}_{RF}^{(k)} = \boldsymbol{I}_{N_R}, \tag{5}$$

where $\boldsymbol{H}_{m,k} \in \mathbb{C}^{M_{R_k} \times M_t}$ is the channel between the AP m and the UE k. It can also be reformulated as

$$\begin{aligned} &\max_{\boldsymbol{W}_{RF}^{(k)}} \mathrm{trace}\left(\boldsymbol{W}_{RF}^{(k)H} \underbrace{\mathbb{E}\left\{\sum_{m=1}^{M} \boldsymbol{H}_{m,k}^H \boldsymbol{F}_m^H \boldsymbol{F}_m \boldsymbol{H}_{m,k}\right\}}_{\boldsymbol{T}_k} \boldsymbol{W}_{RF}^{(k)}\right), \\ &\text{s.t.} \boldsymbol{W}_{RF}^{(k)H} \boldsymbol{W}_{RF}^{(k)} = \boldsymbol{I}_{N_R} \end{aligned} \tag{6}$$

By iteratively solving (4) and (6) and calculating $\boldsymbol{F}_m$ and $\boldsymbol{W}_{RF}^{(k)}$, the total effective array gain can be maximized. The joint/iterative AP-UE analog beamforming procedure is shown as follows.

a) Initialize: $\boldsymbol{W}_{\mathrm{RF}}^{(k)}(i) = [\ \boldsymbol{I}_{N_{R_k}}, \ \ \boldsymbol{0}_{N_{R_k}, M_{R_k} - N_{R_k}}\ ]^T, \forall k = 1 \cdots K$, the iteration index i, and the threshold $\epsilon \in \mathbb{R}$ is an arbitrary small number.

b) Set $i = i + 1$, compute $\boldsymbol{Q}_m(i)$ as

$$\boldsymbol{Q}_m(i) = \mathbb{E}\left\{\boldsymbol{H}_m^H \boldsymbol{W}_{RF}(i) \boldsymbol{W}_{RF}^H(i) \boldsymbol{H}_m\right\}, \tag{7}$$

solve the optimization problem in (4) using Singular Value Decomposition (SVD) of $\boldsymbol{Q}_m(i)$, and obtain $\boldsymbol{F}_m(i) = \boldsymbol{U}_{Q_m}(:, 1 : N_t)$, which represents the first N_t left singular vectors of $\boldsymbol{Q}_m(i)$.

c) For each user k, compute $\boldsymbol{T}_k(i)$ as

$$\boldsymbol{T}_k(i) = \mathbb{E}\left\{\sum_{m=1}^{M} \boldsymbol{H}_{m,k}^H \boldsymbol{F}_m^H(i) \boldsymbol{F}_m(i) \boldsymbol{H}_{m,k}\right\}, \tag{8}$$

solve the optimization problem in (6) using SVD of $\boldsymbol{T}_k(i)$ and obtain $\boldsymbol{W}_{\mathrm{RF}}^{(k)}(i) = \boldsymbol{U}_{T_k}(:, 1 : N_{R_k})$, which are the first N_{R_k} left singular vectors of $\boldsymbol{T}_k(i)$.

d) Calculate $|\mathrm{AG}(i) - \mathrm{AG}(i-1)|$ via (2) with

$$\mathrm{AG}(i) = \mathbb{E}\left\{\left\|\boldsymbol{W}_{RF}^H(i) \boldsymbol{H} \boldsymbol{F}(i)\right\|_F^2\right\}, \tag{9}$$

if it is greater than ϵ, go to Step b); otherwise, the convergence is achieved.

3.2. Proposed Interference-Aware Digital Precoding

The digital precoding will be calculated based on the equivalent channel after the analog beamforming is obtained. Since we consider the distributed beamforming at each AP, the designed digital precoding should well handle the inter-UE and/or inter-stream interferences. The existing schemes such as L-MMSE [13] and CB [3] cannot work well when UE is equipped with multiple antennas and also in the case of multi-stream transmissions. Reference [14] considers UEs with multiple antennas but the precoding design has no interference-aware functionality.

Therefore, we propose a SIR-MMSE beamforming to support multi-antenna UEs and multi-stream transmissions. The key concept to deal with the interference is to decompose the digital precoding design problem into the Multi-User Interference (MUI) suppression and the Single-User (SU) MIMO optimization, i.e., $\boldsymbol{P}_m = \boldsymbol{P}_{m,1}\boldsymbol{P}_{m,2}$, where $\boldsymbol{P}_{m,1}$ and $\boldsymbol{P}_{m,2}$ are MUI processing matrix and SU precoding matrix, respectively. The most important feature is including the interference rejection capability in MUI precoding design ($\boldsymbol{P}_{m,1}$). It deals with each UE antenna independently and rejects the interference successively user by user.

In the following for simplicity, we remove the index m in the subscripts of matrices such as $\boldsymbol{H}_{m,k}, \boldsymbol{P}_{m,1}, \boldsymbol{P}_{m,2}$. We firstly reformulate the channel matrix by re-arranging the channel vector of each desired UE by

$$\bar{\boldsymbol{H}}_k^{(i)} = \left[\begin{array}{c} \boldsymbol{h}_{k,i}^T, \boldsymbol{H}_1^T, \dots, \boldsymbol{H}_{k-1}^T, \boldsymbol{H}_{k+1}^T, \dots, \boldsymbol{H}_k^T \end{array}\right]^T, \quad (10)$$

where $\boldsymbol{h}_{k,i}^T$ is the i-th row of $\boldsymbol{H}_k$, denoting the channel of i-th antenna at UE k. The interference rejection matrix is defined by removing the channel matrix of the current desired UE

$$\tilde{\boldsymbol{H}}_k^{(i)} = \left[\begin{array}{c} \boldsymbol{H}_1^T, \dots, \boldsymbol{H}_{k-1}^T, \boldsymbol{H}_{k+1}^T, \dots, \boldsymbol{H}_k^T \end{array}\right]^T. \quad (11)$$

Then the intermediate precoding matrix is obtained by

$$\bar{\boldsymbol{P}}_1^{(k,i)} = \left(\tilde{\boldsymbol{H}}_k \tilde{\boldsymbol{H}}_k^H + \alpha \boldsymbol{I}\right)^{-1} \bar{\boldsymbol{H}}_k^{(i)H}, \quad (12)$$

where $\alpha = \sigma_n^2/P_t$ with P_t being the transmit power. Then the n-th column of $\bar{\boldsymbol{P}}_1^{(k,i)}$ will construct the n-th column of $\boldsymbol{P}_1$.

We assume that the precoder $\boldsymbol{P}_1$ decouples the UEs and the SU-MIMO precoding can be considered to obtain $\boldsymbol{P}_2$. By calculating the SVD of the k-th UE's effective channel $\check{\boldsymbol{H}}_k = \boldsymbol{H}_k \boldsymbol{P}_{1,k}$ and taking the first r_k left singular vectors from $\check{\boldsymbol{U}}_k$, we get $\boldsymbol{P}_{2,k} = \check{\boldsymbol{U}}_k(:, 1:r_k)$. The precoding matrices for all UEs constitute $\boldsymbol{P}_2 = \mathrm{diag}\{\boldsymbol{P}_{2,1}, \dots, \boldsymbol{P}_{2,K}\}$.

Remarks: The proposed SIR-MMSE digital precoding is independent of the analog beamforming design. It can be applied in cell-free massive MIMO systems with multi-antenna UEs and multi-stream transmissions at any frequencies.

3.3. Power Control

The received signal at UE k is written as

$$\boldsymbol{y}_k = \sum_{m=1}^{M} \sum_{k=1}^{K} \sqrt{\rho_{m,k}} \boldsymbol{H}_{m,k} \boldsymbol{F}_m \boldsymbol{P}_{m,k} \boldsymbol{s}_k + \boldsymbol{n}_k, \quad (13)$$

where $\rho_{m,k}$ is the power coefficient used to control the transmit power from AP m to UE k. The optimal power allocation is to find all power coefficients $\rho_{m,k}, \forall m, \forall k$ that maximize the minimum Signal to Interference and Noise Ratio (SINR) for UE k, subject to the transmit power constraint from each AP ρ_t. However, the optimal power control problem which requires the problem reformulation and bisection method leads to a very high complexity especially for a large number of antennas considered at mmWave frequencies.

Table 1. Simulation parameters of the channel model

Parameters	Values
Carrier Frequency	28 GHz
Pathloss at distance d m $PL = \alpha + 10\beta \log_{10}(d) + \xi$ [dB]	NLOS: $\alpha = 72, \beta = 2.92$ LOS: $\alpha = 61.4, \beta = 2$
Lognomal shadowing $\xi \sim (0, \sigma^2)$	NLOS: $\sigma = 8.7$ dB LOS: $\sigma = 5.8$ dB
NLOS-LOS-Outage	$\frac{1}{a_{\text{out}}} = 30$ m, $b_{\text{out}} = 5.2$ $\frac{1}{a_{\text{LOS}}} = 67.1$ m

Therefore, we consider a simple power control concept, using the fixed power for each AP and uniform power allocation for each UE. Accordingly, the power coefficient can be calculated by

$$\rho_{m,k} = \rho_m = \frac{\rho_t}{\sum_{k=1}^{K} \|\boldsymbol{F}_m \boldsymbol{P}_{m,k}\|_F^2}, \text{ for } m = 1, \dots, M, \quad (14)$$

where the transmit power ρ_t for each AP can be selected as the maximal transmit power per AP. For multi-stream transmissions, power loading across different streams within one UE could also be considered and we assume equal power loading for different streams, under the power control (14).

4. SIMULATION RESULTS

In this section we evaluate the performance of the proposed distributed hybrid beamforming for mmWave cell-free massive MIMO systems and compared with the small-cell scheme as well as the cell-free algorithms including various beamforming functions. For the small-cell scheme, each UE is served by only one AP and the available AP is chosen based on the best channel quality. If one AP has already been selected by other UE, the next available AP with the second best channel quality will be chosen. APs that are not selected will be inactive.

The mmWave channels are modeled at 28 GHz according to [6], where each channel link could be one of the three states, i.e., line-of-sight, non-line-of-sight, and outage. The probability calculation for distance d follows $p_{\text{out}}(d) = \max\{0, 1 - e^{-a_{\text{out}} d + b_{\text{out}}}\}$, $p_{\text{LOS}}(d) = [1 - p_{\text{out}}(d)] e^{-a_{\text{LOS}} d}$, and $p_{\text{NLOS}} = 1 - p_{\text{out}}(d) - p_{\text{LOS}}(d)$, respectively. The large-scale propagation pamameters are shown in Table 1. We assume that $M = 20$ APs are uniformly distributed within a square area of dimension 200 m $\times$ 200 m and the minimum separation between any two APs is set as 40 m. UEs are also randomly distributed in this area, as shown in Figure 3. We consider the fixed AP distribution and 1000 realizations of random UE positions in the simulation. Each AP has a Uniform Rectangular Array (URA) of size 4×8 and fully-connected to 4 RF chains. Each UE also has a hybrid array, i.e., Uniform Linear Array (ULA) with 4 antenna elements and 2 RF chains.

Figure 4 shows the Cumulative Distribution Function (CDF) of the spectral efficiency performance for various schemes when the number of UEs is set as $K = 6, 14$. For all the schemes, analog beamforming is carried out exclusively at each AP in the distributed way. In the small cell case, only one AP serves one UE according to the criterion that the serving AP provides the best receive power level to the desired UE and meanwhile is not serving other UEs. One difference of the compared cell-free schemes lies in whether the digital precoding is carried out in the centralized or distributed manner (Figure 1 (a) or (b)). For the cell-free centralized scheme, Regularized Block Diagonalization (RBD) is applied [15]. While in the distributed case, our proposed SIR-MMSE algorithm will be

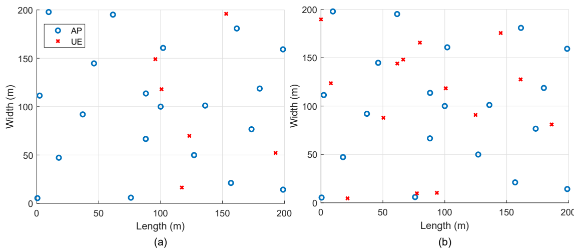
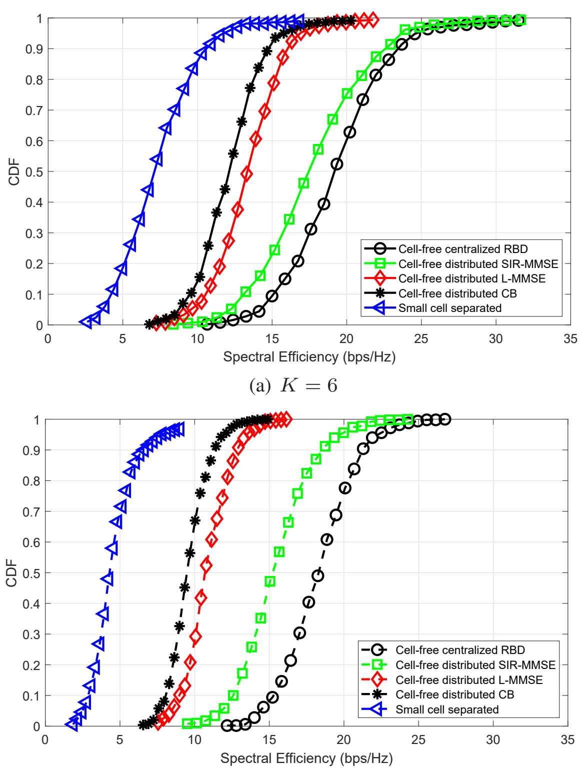


Fig. 3. Examples of the AP and UE distribution within the considered area for (a) $K = 6$ and (b) $K = 14$.

compared with the existing L-MMSE and CB methods. It is also assumed that the uniform power control is used for APs, subject to the maximal per-AP power. We can observe that in general the cell-free scheme significantly outperforms the small cell counterpart at both the median and 5% levels. The centralized digital precoding is more efficient to deal with MUI, i.e., smaller gap between the case of $K = 6$ and the denser UE scenario with $K = 14$. The proposed method achieves 2.4-3.4 times spectral efficiency at median and 3.5-4.5 times at 5%. The distributed "SIR-MMSE" digital precoding exhibits a much higher robustness against MUI and inter-stream interference as compared to L-MMSE and CB counterparts, and its performance is quite close to the cell-free centralized RBD scheme when the number of serving UEs is moderate.



(a) $K = 6$

(b) $K = 14$

Fig. 4. Spectral efficiency performance of various considered schemes using hybrid beamforming.

We also evaluate the performance of using hybrid beamforming and compare with the fully digital counterpart. Figure 5 shows the performance of the proposed hybrid analog-digital beamforming in architectures of Figure 1 (a, b) and compares with the fully digital case, where no analog beamforming is applied and the number of RF chains equals to the number of antenna elements. We can observe that for the distributed processing shown in Figure 1 (b), analog beamforming exhibits almost no performance loss to the fully digital case for the moderate number of UEs.

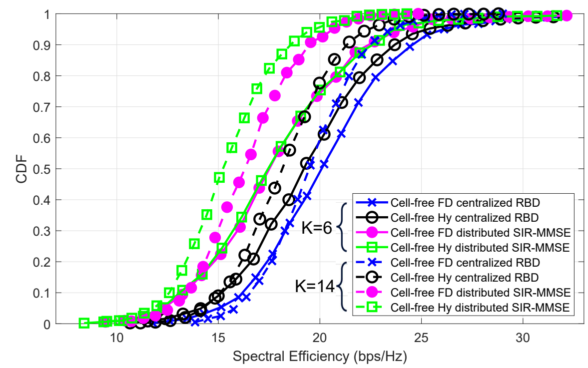


Fig. 5. Performance comparison of using hybrid ("Hy") and fully digital ("FD") beamforming.

5. CONCLUSIONS

This paper proposes a distributed hybrid beamforming scheme for mmWave cell-free massive MIMO systems, which is a generalized solution that can support multi-antenna and hybrid array based UEs, as well as multi-beam/stream transmissions. The proposed joint AP-UE analog beamforming procedure efficiently solves the beam alignment problem of maximizing the total effective array gain in the cell-free system at mmWave frequencies. The proposed digital precoding concept has the interference aware functionality, which reformulates each UE's channel at the antenna (port) level and applies successive interference rejection to handle the MUI. It is independent of the analog beamforming design and can be directly applied in the general cell-free massive MIMO systems once UE has multiple antennas. Simulation results show an enhanced performance of the proposed distributed cell-free scheme, i.e., 3 to 4 times of the small-cell counterpart. It can also be observed that the proposed SIR-MMSE precoding outperforms the existing distributed precoding schemes such as L-MMSE and CB. The proposed analog beamforming showing a comparable performance as the fully digital counterpart, can be effectively applied in the cell-free hybrid beamforming architecture. This work indicates the potential of using the cell-free concept at mmWave and distributed beamforming solutions could bring a satisfying performance.

6. REFERENCES

[1] E. Björnson, L. Sanguinetti, H. Wymeersch, J. Hoydis, and T. L. Marzetta, "Massive MIMO is a reality What is next?: Five promising research directions for antenna arrays," *Digital Signal Processing*, vol. 94, pp. 3–20, 2019.

[2] J. Zhang, E. Björnson, M. Matthaiou, D. W. K. Ng, H. Yang, and D. J. Love, "Prospective multiple antenna technologies for beyond 5G," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 8, pp. 1637–1660, 2020.

[3] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, "Cell-free massive MIMO versus small cells," *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 1834–1850, 2017.

[4] M. Xiao, S. Mumtaz, Y. Huang, L. Dai, Y. Li, M. Matthaiou, G. K. Karagiannidis, E. Björnson, K. Yang, I. Chih-Lin, et al., "Millimeter wave communications for future mobile networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 1909–1935, 2017.

[5] A. F. Molisch, V. V. Ratnam, S. Han, Z. Li, S. L. H. Nguyen, L. Li, and K. Haneda, "Hybrid beamforming for massive MIMO: A survey," *IEEE Communications Magazine*, vol. 55, no. 9, pp. 134–141, 2017.

[6] M. R. Akdeniz, Y. Liu, M. K. Samimi, S. Sun, S. Ranganp, T. S. Rappaport, and E. Erkip, "Millimeter wave channel modeling and cellular capacity evaluation," *IEEE journal on selected areas in communications*, vol. 32, no. 6, pp. 1164–1179, 2014.

[7] G. R. MacCartney and T. S. Rappaport, "Millimeter-wave base station diversity for 5G coordinated multipoint (CoMP) applications," *IEEE Transactions on Wireless Communications*, vol. 18, no. 7, pp. 3395–3410, 2019.

[8] N. T. Nguyen, K. Lee, and H. Dai, "Hybrid Beamforming and Adaptive RF Chain Activation for Uplink Cell-Free Millimeter-Wave Massive MIMO Systems," *arXiv preprint arXiv:2010.09162*, 2020.

[9] G. Femenias and F. Riera-Palou, "Cell-free millimeter-wave massive MIMO systems with limited fronthaul capacity," *IEEE Access*, vol. 7, pp. 44596–44612, 2019.

[10] J. García-Morales, G. Femenias, and F. Riera-Palou, "Energy-efficient access-point sleep-mode techniques for cell-free mmWave massive MIMO networks with non-uniform spatial traffic density," *IEEE Access*, vol. 8, pp. 137587–137605, 2020.

[11] M. Alonzo, S. Buzzi, A. Zappone, and C. DElia, "Energy-efficient power control in cell-free and user-centric massive MIMO at millimeter wave," *IEEE Transactions on Green Communications and Networking*, vol. 3, no. 3, pp. 651–663, 2019.

[12] A. Alkhateeb, G. Leus, and R. W. Heath, "Limited feedback hybrid precoding for multi-user millimeter wave systems," *IEEE Transactions on Wireless Communications*, vol. 14, no. 11, pp. 6481–6494, 2015.

[13] E. Björnson and L. Sanguinetti, "Making cell-free massive mimo competitive with mmse processing and centralized implementation," *IEEE Transactions on Wireless Communications*, vol. 19, no. 1, pp. 77–90, 2019.

[14] B. Bandemer, M. Haardt, and S. Visuri, "Linear MMSE multi-user MIMO downlink precoding for users with multiple antennas," in *2006 IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications*, 2006, pp. 1–5.

[15] V. Stankovic and M. Haardt, "Generalized design of multi-user MIMO precoding matrices," *IEEE Transactions on Wireless Communications*, vol. 7, no. 3, pp. 953–961, 2008.