Joint User Scheduling and Hybrid Beamforming Design for Cooperative mmWave Networks

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2021 IEEE Wireless Communications and Networking Conference (WCNC) | 978-1-7281-9505-6/20/$31.00 ©2021 IEEE | DOI: 10.1109/WCNC49053.2021.9417429

***Abstract*—This paper investigates hybrid beamforming for cooperative multi-user millimeter-wave (mmWave) multiple-input multiple-output (MIMO) networks. We aim to jointly design the user scheduling and hybrid beamforming to maximize the sum-rate subject to the transmit power of each base station. Due to the non-convexity of constant modulus of phase shifters and objective function, the problem is mathematically intractable. We propose a low-complexity two-step scheme, in which user scheduling and analog beamforming are first obtained to maximize the sum-beamforming-gain, followed by digital beamforming calculation based on weighted minimum-mean-square-error (wMMSE) approach. We further extend the hybrid beamforming design to dynamic sub-array architecture, where a novel antenna selection algorithm is developed. Simulation results demonstrate the effectiveness of the proposed algorithms, which can outperform other state-of-the-art approaches.**

***Index Terms*—Millimeter-wave (mmWave) communications, cooperative multi-user, hybrid beamforming, user scheduling, dynamic sub-array.**

I. Introduction

To meet the exponentially growing demand of wireless communication capacity, millimeter-wave (mmWave) communication has been deemed as a promising technology owing to its capability of providing larger available bandwidth and higher data rate [1], [2]. However, the severe pathloss of mmWave channels has become the major challenge to deploy mmWave communications in reality. Thanks to the short wavelength of mmWave, a large number of antenna elements can be packed into a small dimension device. Therefore, multiple-input multiple-output (MIMO) technology has been a key enabling technique for mmWave communications, which can provide enough beamforming gain to compensate for the pathloss [3], [4].

Due to the high hardware cost and energy consumption, the conventional full digital beamforming architecture, in which each antenna should be equipped with a radio frequency (RF) chain, is difficult to be implemented in mmWave MIMO systems. To tackle this problem, hybrid beamforming has been proposed to make a trade-off between system performance and hardware cost [5]. In the widely considered fully connected hybrid beamforming architecture, numerous phase shifters are required, which may still cause relatively high energy consumption and hardware cost [6]. In order to further reduce hardware complexity and improve the energy efficiency, dynamic sub-array architecture has attracted a lot of attention and has been investigated recently [7].

On the other hand, cooperative transmission is another promising and practical approach to further enhance the throughout and reliability of mmWave communications. In the cooperative network, multiple base stations (BSs) can coordinate their precoding operations to jointly manage the inter-cell interference and overcome the pathloss [8]. Meanwhile, the cooperation of BSs also provides the possibility for the better user scheduling design in multi-user mmWave systems. Therefore, cooperative transmission networks have drawn significant attention in recent years [9]-[11]. Furthermore, the mmWave MIMO communications with fully connected hybrid beamforming architecture have been also applied in the cooperative transmission networks [12], [13]. In [13], the authors jointly researched user scheduling and hybrid beamforming in the cloud radio access network (C-RAN). Particularly, the analog beamformer and user selection are jointly designed by a pre-defined codebook, and digital beamformer is calculated by semidefinite relaxation (SDR) technologies. Moreover, the authors in [14] further indicated the significance of user selection in eliminating multi-user interference (MUI) for mmWave massive MIMO systems. Motivated by these literatures, we attempt to take full advantages of both dynamic sub-array hybrid beamforming architecture and the interference management ability of user scheduling scheme to further enhance the achievable sum-rate performance.

In this paper, we study the hybrid beamforming design based on two antenna array architectures, i.e., fully connected and dynamic sub-array connected, for cooperative multi-user mmWave MIMO systems. We aim to jointly design the user scheduling and hybrid beamforming to maximize the downlink sum-rate subject to the transmit power of each BS. A low-complexity two-step algorithm is proposed to efficiently obtain the hybrid beamforming design. To be specific, jointly user

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This work is supported in part by the National Natural Science Foundation of China (Grant No. 61971088, 62071083, U1808206, and U1908214), in part by the Fundamental Research Funds for the Central Universities (Grant No. DUT20GJ214), in part by Dalian Science and Technology Innovation Project (Grant No. 2020JJ25CY001), and in part by the Open Research Fund of National Mobile Communications Research Laboratory, Southeast University (Grant No. 2021D08).

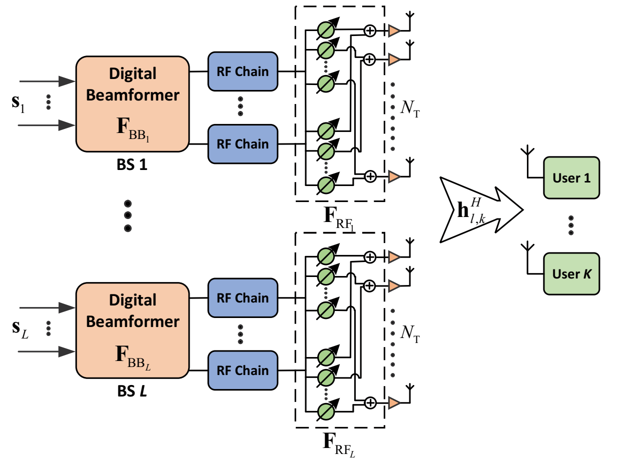

Fig. 1. Cooperative mmWave MIMO network with hybrid beamforming.

scheduling and analog beamforming design is first obtained to maximize the sum-beamforming-gain. Then, based on the effective baseband channel, digital beamformer is calculated by weighted minimum mean-square-error (wMMSE) approach. Simulation results demonstrate that the proposed algorithms can achieve satisfactory performance compared to other state-of-the-art approaches and validate the effectiveness of proposed dynamic sub-array based design.

II. System Model and Problem Formulation

A. System Model

We consider a cooperative multi-user mmWave MIMO system with L BSs and K single-antenna users, where all BSs share the data and channel state information (CSI) of users commonly, as shown in Fig. 1. Each BS is equipped with N_{T} antennas and N_{RF} RF chains to implement hybrid beamforming. Let $\mathcal{L} \triangleq \{1,\ldots,L\}$ and $\mathcal{K} \triangleq \{1,\ldots,K\}$ denote the sets of all BSs and users, respectively. Note that the maximum number of users served by each BS is limited by the number of RF chains. We assume the number of users served by each BS is N_{RF} and the total number of users is $K = LN_{\mathrm{RF}}$. Then, the signal y_k received at the k-th user is

$$y_k = \sum_{l\in\mathcal{L}} \mathbf{h}_{l,k}^H \mathbf{x}_l + n_k, \tag{1}$$

where $\mathbf{x}_l \in \mathbb{C}^{N_{\mathrm{T}}\times 1}$ denotes the transmit signals after beamforming at the l-th BS, $\mathbf{h}_{l,k} \in \mathbb{C}^{N_{\mathrm{T}}\times 1}$ is the channel vector from BS-l to user-k, and $n_k \sim \mathcal{CN}(0,\sigma_k^2)$ indicates the Gaussian additive noise at the k-th user.

Based on the hybrid beamforming architecture at each BS, the transmitted signal of the l-th BS is first processed by digital beamformer $\mathbf{F}_{\mathrm{BB}_l} \triangleq [\mathbf{f}_{\mathrm{BB}_{l,1}},\ldots,\mathbf{f}_{\mathrm{BB}_{l,N_{\mathrm{RF}}}}]$, followed by analog beamformer $\mathbf{F}_{\mathrm{RF}_l} \triangleq [\mathbf{f}_{\mathrm{RF}_{l,1}},\ldots,\mathbf{f}_{\mathrm{RF}_{l,N_{\mathrm{RF}}}}]$. Thus, the transmitted signal $\mathbf{x}_l$ from BS-l can be written as

$$\mathbf{x}_l = \sum_{k\in\mathcal{U}_l} \mathbf{F}_{\mathrm{RF}_l} \mathbf{f}_{\mathrm{BB}_{l,k}} s_k, \tag{2}$$

where s_k is the transmitted symbol for user-k, satisfying $\mathbb{E}\{s_k s_k^*\} = 1$ and $\mathbb{E}\{s_i s_j^*\} = 0$, $\forall i \neq j$. $\mathcal{U}_l$ represents the set of users served by the l-th BS, and $|\mathcal{U}_l| = N_{\mathrm{RF}}$. By substituting the expression of $\mathbf{x}_l$ (2) into (1), we can rewrite the received signal of the k-th user as

$$\begin{aligned} y_k &= \sum_{l\in\mathcal{L}} \mathbf{h}_{l,k}^H \mathbf{x}_l + n_k, \\ &= \sum_{l\in\mathcal{L}} \mathbf{h}_{l,k}^H \mathbf{F}_{\mathrm{RF}_l} \sum_{k\in\mathcal{U}_l} \mathbf{f}_{\mathrm{BB}_{l,k}} s_k + n_k, \\ &= \underbrace{\mathbf{h}_{l,k}^H \mathbf{F}_{\mathrm{RF}_l} \mathbf{f}_{\mathrm{BB}_{l,k}} s_k}_{\text{desried signal}} + \underbrace{\sum_{i\neq l, i\in\mathcal{L}} \mathbf{h}_{i,k}^H \mathbf{F}_{\mathrm{RF}_i} \sum_{j\in\mathcal{U}_i} \mathbf{f}_{\mathrm{BB}_{i,j}} s_j}_{\text{inter-cell interference}} \\ &\quad + \underbrace{\mathbf{h}_{l,k}^H \mathbf{F}_{\mathrm{RF}_l} \sum_{j\neq k, j\in\mathcal{U}_l} \mathbf{f}_{\mathrm{BB}_{l,j}} s_j}_{\text{intra-cell interference}} + n_k. \end{aligned} \tag{3}$$

We consider a multi-path mmWave channel model so that the channel vector between the l-th BS and the k-th user can be described as [1]:

$$\mathbf{h}_{l,k} = \sqrt{\frac{N_{\mathrm{T}}}{N_{\mathrm{ray}}}} \sum_{n=1}^{N_{\mathrm{ray}}} \alpha_n \mathbf{a}(\theta_n), \tag{4}$$

where α_n denotes the complex gains of the n-th propagation path, N_{T} and N_{ray} denote the number of transmit antennas and paths, respectively. We assume that the uniform linear array (ULA) is employed, and the array response vector $\mathbf{a}(\theta)$ with the angles of departure (AoDs) θ is:

$$\mathbf{a}(\theta) = \frac{1}{\sqrt{N_{\mathrm{T}}}} [1, e^{j\frac{2\pi}{\lambda} d\sin(\theta)}, \ldots, e^{j(N_{\mathrm{T}}-1)\frac{2\pi}{\lambda} d\sin(\theta)}]^T, \tag{5}$$

where λ represents the signal wavelength, and d is the distance between antenna elements.

B. Problem Formulation

Given the received signal at each user in (3), the signal to interference-plus-noise ratio (SINR) of the k-th user γ_k can be expressed as

$$\gamma_k = \frac{\left|\mathbf{h}_{l,k}^H \mathbf{F}_{\mathrm{RF}_l} \mathbf{f}_{\mathrm{BB}_{l,k}}\right|^2}{\sum_{i\neq l, i\in\mathcal{L}} \sum_{j\in\mathcal{U}_i} \left|\mathbf{h}_{i,k}^H \mathbf{F}_{\mathrm{RF}_i} \mathbf{f}_{\mathrm{BB}_{i,j}}\right|^2 + \sum_{j\neq k, j\in\mathcal{U}_l} \left|\mathbf{h}_{l,k}^H \mathbf{F}_{\mathrm{RF}_l} \mathbf{f}_{\mathrm{BB}_{l,j}}\right|^2 + \sigma_k^2}. \tag{6}$$

The achievable rate of the k-th user is

$$R_k = \log_2(1+\gamma_k). \tag{7}$$

In this paper, we aim to jointly optimize the set of users $\{\mathcal{U}_l\}_{l\in\mathcal{L}}$ served by each BS and the corresponding hybrid beamformer $\{\mathbf{F}_{\mathrm{RF}_l}, \mathbf{F}_{\mathrm{BB}_l}\}_{l\in\mathcal{L}}$ to maximize the achievable sum-rate, subject to the constraints of maximum transmit power $P_{\max_l}$ of the l-th BS and constant modulus of phase shifters. The objective function can be formulated as:

$$\max_{\{\mathbf{F}_{\mathrm{RF}_l}, \mathbf{F}_{\mathrm{BB}_l}, \mathcal{U}_l\}_{l\in\mathcal{L}}} \sum_{k\in\mathcal{K}} R_k \tag{8a}$$

$$\text{s.t.} \quad |\mathcal{U}_l| = N_{\mathrm{RF}}, \ \forall l, \tag{8b}$$

$$\mathcal{U}_i \cap \mathcal{U}_j = \varnothing, \ \forall i,j, i\neq j, \tag{8c}$$

$$\left\|\mathbf{F}_{\mathrm{RF}_l} \mathbf{F}_{\mathrm{BB}_l}\right\|_F^2 \leq P_{\max_l}, \ \forall l, \tag{8d}$$

$$\left|\mathbf{F}_{\mathrm{RF}_l}(m,n)\right| = 1, \ \forall m,n,l. \tag{8e}$$

However, it is difficult to solve problem (8) directly due to the non-convexity of objective function (8a) and constant modulus constraints (8e). In the following, we propose a low-complexity algorithm, which divides the design of (8) into two sub-problems: *i*) joint analog beamforming and user scheduling design to maximize the sum-beamforming-gain; *ii*) digital beamforming calculation. We first consider the design in (8) for fully connected architecture. Then, in order to further reduce hardware complexity and power consumption, the hybrid beamforming design for dynamic sub-array architecture is also studied.

III. Proposed Design For Fully Connected Architecture

In this section, we introduce the low-complexity algorithm for user scheduling and hybrid beamforming design for fully connected architecture. As we mentioned before, we propose to divide the original problem (8) into two sub-problems and then separately obtain the analog and digital beamformer. Next, we first present an efficient joint user scheduling and analog beamforming design followed by digital beamforming calculation.

A. User Scheduling and Analog Beamforming Design

Due to the directionality of mmWave channel, the SINR of each user is highly dependent on the beamforming gain. Thus, we propose to determine the user sets $\{\mathcal{U}_l\}_{l\in\mathcal{L}}$ and analog beamforming matrix $\mathbf{F}_{\mathrm{RF}_l} = [\mathbf{f}_{\mathrm{RF}_{l,\mathcal{U}_l(1)}}, \ldots, \mathbf{f}_{\mathrm{RF}_{l,\mathcal{U}_l(N_{\mathrm{RF}})}}]$ of each BS to maximize the sum-beamforming-gain, which is formulated as

$$\max_{\{\mathbf{f}_{\mathrm{RF}_{l,k}}\}_{l,k},\{\mathcal{U}_l\}_{l\in\mathcal{L}}} \sum_{l\in\mathcal{L}}\sum_{k\in\mathcal{U}_l} |\mathbf{h}_{l,k}^H \mathbf{f}_{\mathrm{RF}_{l,k}}|^2 \tag{9a}$$
$$\text{s.t.} \quad |\mathcal{U}_l| = N_{\mathrm{RF}},\ \forall l, \tag{9b}$$
$$\mathcal{U}_i \cap \mathcal{U}_j = \varnothing,\ \forall i,j, i\neq j, \tag{9c}$$
$$\left|\mathbf{f}_{\mathrm{RF}_{l,k}}(m)\right| = 1,\ \forall m,k,l. \tag{9d}$$

The above design is still a combinatory non-convex problem whose optimal solution is difficult to obtain. We thus propose to further decompose the design of (9) and obtain a sub-optimal solution with low-complexity, in which we first introduce a successive user selection scheme based on channel gains. Then, we propose a novel analog beamforming design scheme to maximize the sum-beamforming-gain.

The user scheduling problem is formulated as:

$$\max_{\{\mathcal{U}_l\}_{l\in\mathcal{L}}} \sum_{l\in\mathcal{L}}\sum_{k\in\mathcal{U}_l} |\mathbf{h}_{l,k}^H \mathbf{h}_{l,k}|^2 \tag{10a}$$
$$\text{s.t.} \quad |\mathcal{U}_l| = N_{\mathrm{RF}},\ \forall l, \tag{10b}$$
$$\mathcal{U}_i \cap \mathcal{U}_j = \varnothing,\ \forall i,j, i\neq j. \tag{10c}$$

Problem (10) can be solved via exhaustive search but with exponentially computational complexity. In order to further reduce the complexity while maintaining a satisfactory performance, we propose to successively determine the BS-user link to maximize the channel gain. To be specific, the successive BS-user pairing procedure is described in the following Steps 1-3.

Step 1: Initialize the sets $\mathcal{K} = \{1,\ldots,K\}$, $\mathcal{L} = \{1,\ldots,L\}$, and $\mathcal{U}_l = \varnothing$, $\forall l$, respectively. Calculate the channel gains of all BS-user pairs and select the pair $\{k^\star, l^\star\}$ which has the maximum gain:

$$\{k^\star, l^\star\} = \max_{k\in\mathcal{K}, l\in\mathcal{L}} |\mathbf{h}_{l,k}^H \mathbf{h}_{l,k}|^2. \tag{11}$$

Step 2: If the condition $|\mathcal{U}_{l^\star}| = N_{\mathrm{RF}}$ has been satisfied, let $\mathcal{L} = \mathcal{L} - l^\star$ and go back to Step 1; otherwise, update the user sets as $\mathcal{K} = \mathcal{K} - k^\star$ and $\mathcal{U}_{l^\star} = \mathcal{U}_{l^\star} \cup k^\star$.

Step 3: Repeat Steps 1-2 until $\mathcal{K} = \varnothing$.

It can be observed that the searching complexity is reduced to $\mathcal{O}(KL)$ level.

Given fixed BS-user pairing, our next focus is the design of analog beamformer to maximize the sum-beamforming-gain:

$$\max_{\{\mathbf{f}_{\mathrm{RF}_{l,k}}\}_{l,k}} \sum_{k\in\mathcal{U}_l} |\mathbf{h}_{l,k}^H \mathbf{f}_{\mathrm{RF}_{l,k}}|^2 \tag{12a}$$
$$\text{s.t.} \quad \left|\mathbf{f}_{\mathrm{RF}_{l,k}}(m)\right| = 1,\ \forall m,k,l. \tag{12b}$$

The optimal analog beamformer of (12b) can be immediately obtained by matching the phase of each analog beamformer $\mathbf{f}_{\mathrm{RF}_{l,k}}$ to the corresponding user channel vector as

$$\mathbf{f}_{\mathrm{RF}_{l,k}}^\star = e^{-j\angle(\mathbf{h}_{l,k})},\ \forall l\in\mathcal{L}, k\in\mathcal{U}_l. \tag{13}$$

B. Digital Beamforming Design

With the user sets $\{\mathcal{U}_l\}_{l\in\mathcal{L}}$ and optimal analog beamformer $\{\mathbf{F}_{\mathrm{RF}_l}^\star\}_{l\in\mathcal{L}}$ obtained in Sec. III-A, the digital beamforming design problem can be formulated as follows:

$$\max_{\{\mathbf{F}_{\mathrm{BB}_l}\}_{l\in\mathcal{L}}} \sum_{k\in\mathcal{K}} R_k \tag{14a}$$
$$\text{s.t.} \quad \left\|\mathbf{F}_{\mathrm{RF}_l}^\star \mathbf{F}_{\mathrm{BB}_l}\right\|_F^2 \leq P_{\max_l},\ \forall l. \tag{14b}$$

While the non-convexity of objective function (14a) makes the direct solution intractable, we propose to transform problem (14) to an equivalent sum mean-square error (MSE) problem and optimize the variables iteratively.

Particularly, let us define the modified MSE matrix at the k-th user as

$$\begin{aligned} E_k &\triangleq \mathbb{E}\{(u_k^* y_k - s_k)(u_k^* y_k - s_k)^*\}, \\ &= u_k^*\left(\mathbf{h}_k^H \mathbf{F}_{\mathrm{RF}}^\star \left(\sum_{k\in\mathcal{K}} \mathbf{f}_{\mathrm{BB}_k}\mathbf{f}_{\mathrm{BB}_k}^H\right)(\mathbf{F}_{\mathrm{RF}}^\star)^H \mathbf{h}_k + \sigma^2\right) u_k \\ &\quad - u_k^* \mathbf{h}_k^H \mathbf{F}_{\mathrm{RF}}^\star \mathbf{f}_{\mathrm{BB}_k} - u_k \mathbf{f}_{\mathrm{BB}_k}^H (\mathbf{F}_{\mathrm{RF}}^\star)^H \mathbf{h}_k + 1, \end{aligned} \tag{15}$$

where $u_k, \forall k$, is an auxiliary variable for the k-th user. We define $\mathbf{h}_k^H \triangleq [\mathbf{h}_{1,k}^H, \ldots, \mathbf{h}_{l,k}^H] \in \mathbb{C}^{1\times LN_{\mathrm{T}}}$, $\mathbf{F}_{\mathrm{RF}}^\star \triangleq \mathrm{blkdiag}\{\mathbf{F}_{\mathrm{RF}_1}^\star, \ldots, \mathbf{F}_{\mathrm{RF}_l}^\star\} \in \mathbb{C}^{LN_{\mathrm{T}}\times LN_{\mathrm{RF}}}$, and $\mathbf{f}_{\mathrm{BB}_k} \triangleq [\mathbf{f}_{\mathrm{BB}_{1,k}}^H, \ldots, \mathbf{f}_{\mathrm{BB}_{l,k}}^H]^H \in \mathbb{C}^{LN_{\mathrm{RF}}\times 1}$ to denote the aggregated channel vector, analog beamforming matrix, and digital beamforming matrix from all BSs to user-k, respectively. By introducing the weighted parameters w_k, $\forall k \in \mathcal{K}$, problem

(14) can be equivalently transformed into [15]:

$$\max_{\{u_k, w_k > 0\}_{k\in\mathcal{K}}, \{\mathbf{F}_{\mathrm{BB}_l}\}_{l\in\mathcal{L}}} \sum_{k\in\mathcal{K}} \left(\ln(w_k) - w_k E_k + 1\right) \tag{16a}$$

$$\text{s.t.} \quad \left\|\mathbf{F}^{\star}_{\mathrm{RF}_l}\mathbf{F}_{\mathrm{BB}_l}\right\|_F^2 \le P_{\max_l},\ \forall l. \tag{16b}$$

Then, the newly formulated problem (16) is convex with respect to each variable and can be solved by iteratively updating each block until convergence. In the following part, we will introduce the solution of each variable in detail.

1) Update variables $\{w_k\}_{k\in\mathcal{K}}$: With fixed digital beamformer $\{\mathbf{F}_{\mathrm{BB}_l}\}_{l\in\mathcal{L}}$ and $\{u_k\}_{k\in\mathcal{K}}$, the sub-problem of weighted parameters $\{w_k\}_{k\in\mathcal{K}}$ to optimize (16) can be expressed as

$$\max_{\{w_k\}_{k\in\mathcal{K}}} \sum_{k\in\mathcal{K}} \left(\ln(w_k) - w_k E_k + 1\right), \tag{17}$$

whose optimal solution can be obtained by

$$w_k^{\star} = E_k^{-1},\ \forall k \in \mathcal{K}. \tag{18}$$

2) Update variables $\{u_k\}_{k\in\mathcal{K}}$: When the other variables are fixed, the sub-problem of $\{u_k\}_{k\in\mathcal{K}}$ is to minimize the MSE in (15), which is a convex problem. Thus, the optimal solution of $\{u_k\}_{k\in\mathcal{K}}$ can be obtained by setting the first-order derivative of expression (15) to zero, which is given by

$$u_k^{\star} = \frac{\mathbf{h}_k^H \mathbf{F}^{\star}_{\mathrm{RF}} \mathbf{f}_{\mathrm{BB}_k}}{\sum_{j\in\mathcal{K}} |\mathbf{h}_k^H \mathbf{F}^{\star}_{\mathrm{RF}} \mathbf{f}_{\mathrm{BB}_j}|^2 + \sigma^2},\ \forall k \in \mathcal{K}. \tag{19}$$

3) Update digital beamformer $\{\mathbf{f}_{\mathrm{BB}_k}\}_{k\in\mathcal{K}}$: Given fixed $\{w_k, u_k\}_{k\in\mathcal{K}}$, the sub-problem of digital beamforming design can be presented as

$$\max_{\{\mathbf{F}_{\mathrm{BB}_l}\}_{l\in\mathcal{L}}} \sum_{k\in\mathcal{K}} \left(\ln(w_k) - w_k E_k + 1\right) \tag{20a}$$

$$\text{s.t.} \quad \left\|\mathbf{F}^{\star}_{\mathrm{RF}_l}\mathbf{F}_{\mathrm{BB}_l}\right\|_F^2 \le P_{\max_l},\ \forall l, \tag{20b}$$

which is a convex problem and can be easily solved. Although problem (20) can be solved with the convex optimization solver, e.g., CVX, the solver has high computational complexity. Therefore, we firstly provide an unconstrained optimal solution of $\mathbf{f}_{\mathrm{BB}_k}$ as:

$$\mathbf{f}^{\star}_{\mathrm{BB}_k} = \left(\sum_{i=1}^{K} w_i^* |u_i|^2 (\mathbf{F}^{\star}_{\mathrm{RF}})^H \mathbf{h}_i \mathbf{h}_i^H \mathbf{F}^{\star}_{\mathrm{RF}}\right)^{-1} \times w_k^* u_k (\mathbf{F}^{\star}_{\mathrm{RF}})^H \mathbf{h}_k,\ \forall k \in \mathcal{K}. \tag{21}$$

After obtaining the digital beamformer $\{\mathbf{f}^{\star}_{\mathrm{BB}_k}\}_{k\in\mathcal{K}}$ for each user, we can obtain $\{\mathbf{F}^{\star}_{\mathrm{BB}_l}\}_{l\in\mathcal{L}}$, which denotes the digital beamformer from all BSs to corresponding users. Then, we normalize it for each BS to satisfy the transmit power constraints and the sub-optimal solution is

$$\mathbf{F}^{\star}_{\mathrm{BB}_l} = \sqrt{P_{\max_l}} \frac{\mathbf{F}^{\star}_{\mathrm{BB}_l}}{\|\mathbf{F}^{\star}_{\mathrm{BB}_l}\mathbf{F}^{\star}_{\mathrm{RF}_l}\|_{\mathrm{F}}},\ \forall l. \tag{22}$$

Hence, given appropriate initializations of each variable block $\{w_k, u_k, \mathbf{f}_{\mathrm{BB}_k}\}_{k\in\mathcal{K}}$, we can iteratively update three blocks until convergence.

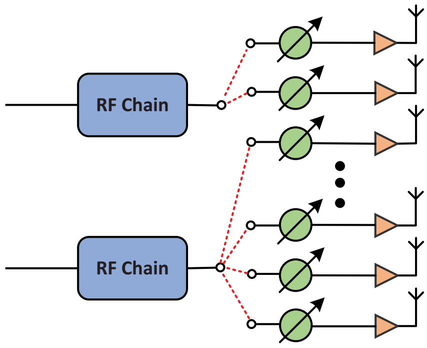

Fig. 2. Hybrid beamforming architecture based on dynamic sub-array.

IV. Proposed Design For Dynamic Sub-Array Architecture

It is well known that the advantage of sub-array architecture is to reduce hardware complexity and power consumption. However, the fixed sub-array architecture based on equally antenna array partition cannot satisfy the various requirements for users. In this section, we consider the hybrid beamforming design for dynamic sub-array architecture, as shown in Fig. 2, where each RF chain connects to a part of the antennas and the number of antennas per sub-array can be dynamically adjusted according to the different channel conditions. Based on this structure, the analog beamforming matrix $\mathbf{F}_{\mathrm{RF}_l}$, $\forall l$, at each BS has the following block diagonal form:

$$\mathbf{F}_{\mathrm{RF}_l} = \begin{bmatrix} \mathbf{f}_{\mathrm{RF}_{l,1}} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{f}_{\mathrm{RF}_{l,2}} & & \mathbf{0} \\ \vdots & & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{f}_{\mathrm{RF}_{l,N_{\mathrm{RF}}}} \end{bmatrix}, \tag{23}$$

where $\mathbf{f}_{\mathrm{RF}_{l,q}} \in \mathbb{C}^{|M_{l,q}|\times 1}$ is the q-th sub-array with $M_{l,q}$ antennas at the l-th BS.

Similarly, we aim to jointly design user scheduling and hybrid beamforming to maximize the sum-rate performance. The optimization problem has the same form as (8) except for the constraints of dynamic sub-array hybrid beamforming architecture. To solve this combinatory problem, we still first determine the user scheduling and analog beamformer. After that, digital beamformer is calculated. Specifically, the user scheduling results $\{\mathcal{U}_l\}_{l\in\mathcal{L}}$ can be fast determined through Steps 1-3 proposed in Sec. III-A. Notice that, we assume that the difference of antenna architectures has no effect on user scheduling result.

Then, for analog beamformer $\{\mathbf{F}_{\mathrm{RF}_l}\}_{l\in\mathcal{L}}$ design, we propose to optimize each sub-analog beamformer and the corresponding number of antennas per sub-array to maximize the sum-beamforming-gain:

$$\max_{\{\mathbf{F}_{\mathrm{RF}_l}\}_{l\in\mathcal{L}}, \mathbf{M}} \sum_{l\in\mathcal{L}} \sum_{k\in\mathcal{U}_l} |\tilde{\mathbf{h}}_{l,k}^H \mathbf{f}_{\mathrm{RF}_{l,k}}|^2 \tag{24a}$$

$$\text{s.t.} \quad \|\mathbf{M}(:,j)\|_1 = N_{\mathrm{T}},\ \forall j, \tag{24b}$$

$$\left|\mathbf{f}_{\mathrm{RF}_{l,k}}(m)\right| = 1,\ \forall l, k, m, \tag{24c}$$

where we define $\mathbf{M} \in \mathbb{N}^{*\,N_{\mathrm{RF}}\times L}$ as the distribution of antennas and $\mathbf{M}(i,j)$ represents the number of antennas connect to the i-th user in the j-th BS. $\tilde{\mathbf{h}}_{l,k}$ denotes the corresponding sub-channel vector. Note that aiming to solve (24), the key point is to determine the number of antennas per sub-array at BSs, i.e., the design of $\mathbf{M}$. With fixed $\mathbf{M}$, each sub-analog beamformer can be obtained by using a similar method as (13). Next, we introduce a novel antenna allocation method which first roughly allocates the antennas based on channel gains followed by fine adjustment to further improve the sum-beamforming-gain.

Particularly, we first transform the objective function (24a) into

$$\max_{\mathbf{M}} \sum_{k\in\mathcal{K}} |\tilde{\mathbf{h}}_{l,k}^H \mathbf{f}_{l,k}|^2 = \sum_{l\in\mathcal{L}} \max_{\mathbf{M}(:,l)} |\tilde{\mathbf{h}}_{l,k}^H \mathbf{f}_{l,k}|^2, k \in \mathcal{U}_l. \tag{25}$$

With known $\mathcal{U}_l$, we can transform (25) into L sub-problems and assign the antennas to RF chains for each BS based on the maximum sum-beamforming-gain. For the l-th BS, we calculate the channel gains of all users in $\mathcal{U}_l$, sort the results, and then store as β_l. Hence, the initial antenna allocation according to the channel gains ratio can be given by

$$\mathbf{M}^0(i,j) = \frac{\beta_l(p)}{\sum_{q=1}^{N_{\mathrm{RF}}} \beta_l(q)} N_{\mathrm{T}}, \ \forall i,j, \tag{26}$$

where $p = N_{\mathrm{RF}} - i + 1$. In fact, this initialization method will allocate fewer antennas to users with better channel gains, and on the contrary, more antennas will be allocated to users with poorer channel states to improve performance. The advantage of this method is to optimize the maximum sum-rate while ensuring fairness among users. Then, we propose a heuristic algorithm to dynamically adjust the number of antennas of each sub-array until obtain the maximum sum-beamforming-gain. To be specific, the antenna dynamic adjustment process is described in the following Steps 1-4.

Step 1: Initialize $\mathcal{L} = \{1,\ldots,L\}$ and obtain the user sets $\{\mathcal{U}_l\}_{l\in\mathcal{L}}$. Calculate the channel gains of all users in $\mathcal{U}_l$ and initialize $\mathbf{M}^0(:,l)$ by (26) for l-th BS.

Step 2: Dynamically adjust the antennas for each RF chain in l-th BS. Firstly, take an appropriate adjustment step length h, e.g., $h = 1$. Then, find the $N_{\mathrm{RF}}/2$ users with the minimum channel gains and add h antennas to each of these users. Meanwhile, reduce h antennas for $N_{\mathrm{RF}}/2$ users with the maximum channel gains. Finally, update $\mathbf{M}(:,l)$ through this adjustment result.

Step 3: Update $\mathbf{F}_{\mathrm{RF}_l}$ and sum-beamforming-gain by (13). Repeat Steps 2-3 until sum-beamforming-gain achieves maximum. Then, update the BSs set as $\mathcal{L} = \mathcal{L} - l$.

Step 4: Repeat Steps 1-3 until $\mathcal{L} = \varnothing$.

After the design of analog beamformer, the digital beamformer is similarly designed by the algorithm proposed in Sec. III-B.

V. Simulation Results

In this section, we provide simulation results to evaluate the performance of proposed hybrid beamforming algorithms in the cooperative multi-user mmWave MIMO systems. We consider that $L = 4$ BSs and $K = 8$ single-antenna users are randomly distributed over a square area. Each BS is equipped with $N_{\mathrm{T}} = 64$ antennas and $N_{\mathrm{RF}} = 2$ RF chains. For all the simulations, the complex gain α_n of n-th propagation path is generated by a complex Gaussian distribution $\alpha_n \sim \mathcal{CN}(0, 10^{-0.1\kappa})$ and $\kappa = \kappa_a + 10\kappa_b \log10(d) + \kappa_c$ with $\kappa_a = 32$, $\kappa_b = 2$, $\kappa_c \sim \mathcal{CN}(0,\sigma_c^2)$ and $\sigma_c^2 = 8.7$dB. The Gaussian additive noise $\sigma_k^2, \forall k$, is set to 1. Besides, we assume that all BSs have the same maximum transmit power $P_{\max_l} = P_{\max}, \forall l$.

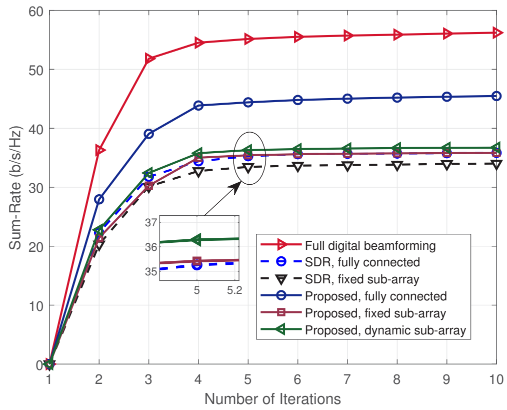

Fig. 3. Achievable sum-rate versus the number of iterations ($L = 4, K = 8$, $N_{\mathrm{RF}} = 2$, $N_{\mathrm{T}} = 64$, $P_{\max} = 20$ dB).

In order to better verify the effectiveness of proposed algorithms, we consider the following algorithms for comparison:

- *Full digital beamforming*: Full digital beamformer is designed based on wMMSE algorithm, where $N_{\mathrm{T}} = N_{\mathrm{RF}}$.
- *SDR, fully connected* [13]: In such case, each RF chain connects all antennas with a fully connected architecture. Jointly design the user scheduling $\mathcal{U}_l$ and analog beamformer $\mathbf{F}_{\mathrm{RF}}$ with the pre-defined codebook, whose resolution is $N_{\mathrm{c}} = 32$. Then, digital beamformer $\mathbf{F}_{\mathrm{BB}}$ is solved by SDR technique.
- *SDR, fixed sub-array* [13]: Similar to the "SDR, fully connected" algorithm, this algorithm considers the fixed sub-array architecture and performs the hybrid beamforming design with pre-defined codebook and SDR technique.

Notice that, the proposed algorithm uses method in (13) to design analog beamformer $\{\mathbf{F}_{\mathrm{RF}_l}\}_{l\in\mathcal{L}}$ and performs the digital beamformer $\{\mathbf{f}_{\mathrm{BB}_k}\}_{k\in\mathcal{K}}$ by wMMSE method in (21). Besides, the proposed algorithm considers all architectures we have mentioned before to perform hybrid beamforming design.

Fig. 3 shows the convergence performance of all algorithms, where the transmit power is $P_{\max}$ = 20 dB. It can be observed that the achievable sum-rate of these algorithms gradually increases with the number of iterations and finally converges to a stationary point within about six iterations. This indicates that the proposed algorithm is stable and the simulation results are of general significance.

Fig. 4 shows the achievable sum-rate comparison in the cooperative multi-user mmWave MIMO system, where the number of BSs $L = 4$, the number of users $K = 8$, the number of RF chains and antennas are $N_{\mathrm{RF}} = 2$ and $N_{\mathrm{T}} = 64$,

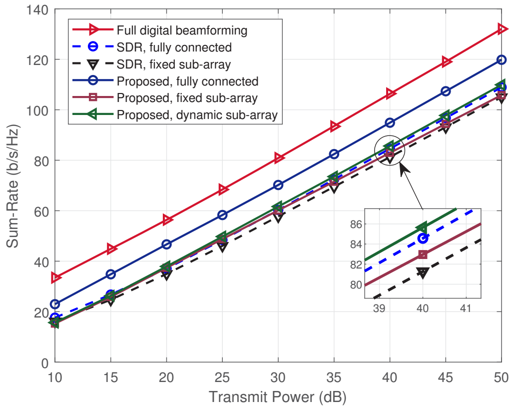

Fig. 4. Achievable sum-rate versus transmit power ($L = 4, K = 8$, $N_{\text{RF}} = 2$, $N_{\text{T}} = 64$).

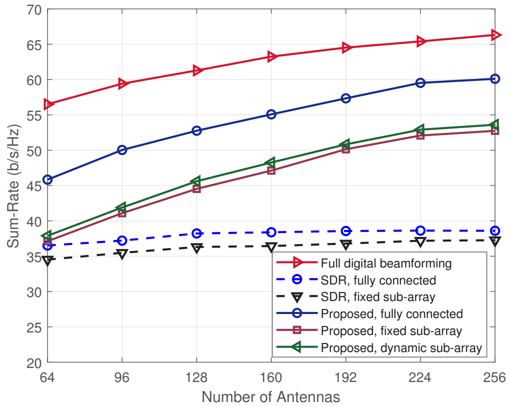

Fig. 5. Achievable sum-rate versus the number of antennas ($L = 4, K = 8$, $N_{\text{RF}} = 2$, $P_{\text{max}} = 20$ dB).

respectively. We observe from Fig. 4 that the proposed hybrid beamforming algorithm always outperforms the SDR based algorithm, no matter the architecture is fully connected or dynamic sub-array. Specifically, the performance of proposed algorithm with a fixed sub-array antenna architecture is s-lightly better than that of SDR based algorithm. Meanwhile, the proposed algorithm with a dynamic sub-array architecture even outperforms SDR based algorithm with a fully connected architecture with the increasing of transmit power, as green and blue curves shown.

Fig. 5 shows the achievable sum-rate comparison against the numbers of antennas N_{T}, where $P_{\text{max}} = 20$ dB. We notice from Fig. 5 that the achievable sum-rate increases with the number of transmit antennas for all algorithms and the advantage of proposed algorithm is gradually prominent with the increasing of antennas. When the number of antennas is $N_{\text{T}} = 64$, the performance of proposed dynamic sub-array algorithm is slightly better than that of SDR based algorithm whose antenna architecture is fully connected, and then the advantages are increasingly prominent. More importantly, the performance of SDR based algorithm increases gradually and saturates when the number of antennas is greater than 128. By contrast, the proposed algorithm has a sustained growth trend, as brown and green curves shown.

VI. Conclusions

In this paper, we studied the joint design of user scheduling and hybrid beamforming design for cooperative multi-user mmWave multiple-input multiple-output (MIMO) systems. Instead of solving the original non-convex problem, we proposed a low-complexity two-step algorithm which first determined the user scheduling scheme and analog beamformer to maximize the sum-beamforming-gain, followed by digital beamforming calculation based on weighted minimum mean-square-error (wMMSE) method. Two hybrid beamforming architectures were considered. Simulation results demonstrated that the proposed algorithm is suitable for all mentioned architectures and has better performance than other algorithms. Moreover, the proposed algorithm has more prominent performance advantages in MIMO systems with large-scale antenna arrays.

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