# Joint Optimization of Analog Beam and User Scheduling for Millimeter Wave Communications

Shiwen He, Yongpeng Wu, Derrick Wing Kwan Ng, and Yongming Huang

***Abstract*— Millimeter wave (mmWave) technology is a promising candidate for future wireless communication systems to provide gigabit data rates to meet the stringent quality of service requirements of multimedia applications. Analog beam selection and user scheduling are two key problems for realizing multiuser mmWave communication in practical systems. We focus on the joint optimization of analog beam selection and user scheduling based on limited effective channel state information. Two codebook-based effective methods are developed to address this problem. Numerical results show the developed suboptimal methods achieve a considerable achievable sum rate performance of the optimal exhaustive search method, but with a fairly low computational complexity.**

***Index Terms*— Millimeter wave communication, hybrid precoding, analog codeword selection, user scheduling.**

## I. Introduction

Millimeter wave (mmWave) communication technology is a promising candidate for future wireless communication systems to address the challenge of spectrum shortage [1]. However, the ten-fold increases in carrier frequency in mmWave frequency band implies that the mmWave signals experience severe path loss compared to signals in sub-6 GHz frequency bands. To compensate the signal attenuation due to large path loss, large-scale multiple-input multiple-output (MIMO) technology is adopted for mmWave communication systems [2], as it offers massive antenna array gains.

Conventionally, fully digital beamforming is implemented in MIMO systems where a dedicated baseband and a radio frequency (RF) chain are needed for each antenna. However, the associated hardware cost/complexity and power consumption are prohibitive for mmWave systems. Consequently, a digital-analog hybrid structure, which the precoder composes of a low-dimension digital precoder and an analog phase shifter network, has been proposed. Ayach *et al.* exploited the sparsity of mmWave channels to investigate the design of hybrid precoder for maximizing the throughput of a point-to-point communication system [3]. The hybrid precoder design for physical layer multicasting was investigated in [4]. Alkhateeb *et al.* studied the design problem of hybrid precoder in [5] based on the predefined codebook for multiuser mmWave systems [6], [7].

Despite the research on the design of hybrid precoder, most of the existing works, e.g., [3]–[7], were based on the assumption of a given user set. In practice, when the number of users requiring communication services is more than the maximum number of supportable users, some user scheduling techniques should be used to improve the system performance. However, the existing literatures mainly focus on the research of user scheduling for multiuser in sub-6 GHz communication systems [8]. Specifically, the existing scheduling designs for sub-6 GHz cannot be applied directly to mmWave systems, as they do not fully exploit the features of the propagation of the mmWave and do not consider the hybrid antenna architecture.

In fact, due to the hybrid antenna architecture of mmWave communication systems, in general, the physical channel coefficients cannot be directly obtained for scheduling design and the user scheduling decision also depends on the design of analog precoder. Also the joint design of analog precoder and user scheduling has attracted little research for multiuser mmWave systems. In this letter, the joint analog beam selection and user scheduling (JBSUS) problem is formulated as a nonconvex and combinatorial optimization problem, which takes into account the limited effective channel state information (ECSI). We propose two codebook based methods with low complexity to address this problem. Numerical results show that our methods can achieve a considerable achievable sum rate performance of the exhaustive search method with a fairly low computational complexity.

## II. System Model

Consider a single-cell multiuser multiple-input single-output (MISO) downlink network as shown in Fig. 1. There is a fully connected hybrid architecture base station (BS) equipped with $N_{\rm RF}$ RF chains, each of which connects with $N_t$ antennas uniform linear array (ULA) via analog phase shifting networks. Assume that there are $N_u > N_{\rm RF}$ users which randomly distribute in the coverage area served by the BS. In this letter, the channel between the BS and each user is modeled as a narrowband clustered channel based on the extended Saleh-Valenzuela model which has been widely used in mmWave communications. The channel coefficients between the BS and the $u$th user, $\mathbf{h}_u$, is modeled by a sum of the contributions of $N_{\rm cl}$ scattering clusters, each of which includes $N_{\rm ray}$ propagation paths, and is expressed as [3]

$$\mathbf{h}_u = \sqrt{\frac{N_t}{N_{\rm cl} N_{\rm ray}}} \sum_{m=1}^{N_{\rm cl}} \sum_{n=1}^{N_{\rm ray}} \alpha_{m,n} \mathbf{a}\left(\phi_{m,n}\right), \tag{1}$$

Manuscript received August 10, 2017; accepted August 21, 2017. Date of publication August 29, 2017; date of current version December 8, 2017. This work was supported by National Natural Science Foundation of China under Grants 61471120, 61422105 and 61720106003, the Research Project of Jiangsu Province under Grant BE2015156. The work of D. W. K. Ng is supported under Australian Research Council's Discovery Early Career Researcher Award funding scheme under Grant DE170100137. The associate editor coordinating the review of this letter and approving it for publication was L. Wang. *(Corresponding author: Yongming Huang.)*

S. He is with the State Key Laboratory of Millimeter Waves, School of Information Science and Engineering, Southeast University, Nanjing 210096, China (e-mail: shiwenhe@seu.edu.cn).

Y. Wu is with the Department of Electronic Engineering, Shanghai Jiao Tong University, China, Minhang 200240, China (e-mail: yongpeng.wu@sjtu.edu.cn).

D. W. K. Ng is with the School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, NSW 2052, Australia (e-mail: w.k.ng@unsw.edu.au).

Y. Huang is with the National Mobile Communications Research Laboratory, School of Information Science and Engineering, Southeast University, Nanjing 210096, China (e-mail: huangym@seu.edu.cn).

Digital Object Identifier 10.1109/LCOMM.2017.2745570

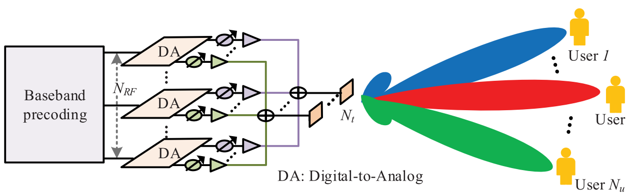


Fig. 1. System model for multiuser mmWave communication.

where $\alpha_{m,n}$ is a complex Gaussian random variable with zero mean and variance $\sigma_{\alpha,m}^2$. $\phi_{m,n}$ is the angle of departure (AoD) for the $n$th ray in the $m$th scattering cluster. $\mathbf{a}\left(\phi_{m,n}\right)$ is the normalized array response vector at an azimuth angle of $\phi_{m,n}$ and is given by

$$\mathbf{a}\left(\phi_{m,n}\right)=\sqrt{\frac{1}{N_t}}\left[1,e^{j\psi},\cdots,e^{j(N_t-1)\psi}\right]^T, \tag{2}$$

where $\psi=\frac{2\pi}{\lambda_s}d\sin\left(\phi_{m,n}\right)$ and $\lambda_s$ is the signal wavelength and $d$ is the antennas spacing. The AoD $\phi_{m,n}$ within the $m$th scattering cluster follows the Laplacian distributions with a mean angle of $\phi_m$ and a standard deviation of $\sigma_\phi$ [3].

Considering linear receivers are adopted at users, only a subset of users can be simultaneously served due to limited radio resource. Let $\mathcal{S}\subset\mathcal{U}=\{1,\cdots,N_u\}$ be the set of users to whom the BS simultaneously transmits data over the same radio resources. For the hybrid architecture of interest, we have $1\leqslant|\mathcal{S}|\leqslant N_{\mathrm{RF}}$, where $|\mathcal{S}|$ denotes the cardinality of $\mathcal{S}$. The transmitter applies a hybrid precoder $\mathbf{F}$ to symbol $\mathbf{x}\in\mathbb{C}^{|\mathcal{S}|}$ with $\mathbb{E}\left[\mathbf{x}\mathbf{x}^*\right]=\mathbf{I}_{|\mathcal{S}|}$, where $\mathbf{I}_{|\mathcal{S}|}$ is an $|\mathcal{S}|\times|\mathcal{S}|$ identity matrix. The hybrid precoder $\mathbf{F}=\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}$ is composed of an RF precoder $\mathbf{F}_{\mathrm{RF}}\in\mathbb{C}^{N_t\times N_{\mathrm{RF}}}$ and a baseband digital precoder $\mathbf{F}_{\mathrm{BB}}\in\mathbb{C}^{N_{\mathrm{RF}}\times|\mathcal{S}|}$. In mmWave communication systems, the RF precoder is implemented via an analog phase shifter network, implying that each element of $\mathbf{F}_{\mathrm{RF}}$ is constrained to have a constant modulus and only its phase can be adjusted. Thus, the system model can be expressed as

$$\mathbf{y}=\mathbf{H}\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}\mathbf{x}+\mathbf{n}, \tag{3}$$

where $\mathbf{y}=\left[y_1,\cdots,y_u,\cdots,y_{|\mathcal{S}|}\right]^T$ with $y_u$ being the received signal of the $u$th user. $\mathbf{H}^H=\left[\mathbf{h}_1,\cdots,\mathbf{h}_u,\cdots,\mathbf{h}_{|\mathcal{S}|}\right]$ is a supermatrix of $\mathbf{h}_u$, and $\mathbf{n}\sim\mathcal{CN}\left(\mathbf{0},\sigma^2\mathbf{I}_{|\mathcal{S}|}\right)$ is an additive white Gaussian noise (AWGN) vector with independent identically distributed (i.i.d.) entries of zero mean and variance $\sigma^2$.

## III. ECSI Feedback

From the implementation point of view, we assume that each column of the RF precoder $\mathbf{F}_{\mathrm{RF}}$ comes from a predefined codebook $\mathcal{F}=\left[\mathbf{f}_1,\cdots,\mathbf{f}_c,\cdots,\mathbf{f}_{N_c}\right]$, where $N_c$ denotes the number of the codewords in $\mathcal{F}$. In what follows, we focus on the joint optimization of the JBSUS problem based on the effective channel information, and therefore the baseband precoder matrix is regarded as an identity matrix [5]. We further assume that the $N_c$ codewords in $\mathcal{F}$ are independent of each other and each element in $\mathcal{F}$ has a constant modulus. In order to realize high speed, long range, and reliable data transmission in mmWave communication systems, beam training consisting of link establishment, sector level searching, and beam level searching is a necessary process [6]. Assume that the first two steps, i.e., link establishment and sector level searching, have been performed. Then, the proposed JBSUS scheme based on the beam level searching includes three stages:

*Beam Training Stage*: The BS transmits a training sequence with a single RF chain using each codeword in $\mathcal{F}$ as analog steering vector sequentially in time.

*Feedback Stage*: Each user feeds back the ECSI, which includes the effective channel gain (ECG) and the corresponding codeword index, based on the measurement of the received signal carried on each codeword.

*JBSUS Stage*: The BS exploits the collected ECSI to finish the JBSUS procedure based on certain performance criterions.

To facilitate the presentation in the sequel, we define $\mathbf{P}\in\mathbb{R}_+^{N_u\times N_c}$ as the ECG matrix with $[\mathbf{P}]_{u,c}=p_{u,c}$ and $p_{u,c}=P\left|\mathbf{h}_u^H\mathbf{f}_c\right|^2/\sigma^2$ as the ECG between the $u$th user and the BS with codeword $c$, where $P$ is the transmitted power. After obtaining the ECSI, one naive JBSUS method is to select the $N_{\mathrm{RF}}$ largest ECGs which comes from different rows and different columns of $\mathbf{P}$ to be the scheduled user-codeword pairs. Note that this naive JBSUS method is a simple method but without considering the impact of inter-user interference on the system performance. As a result, the performance of this JBSUS method may be unsatisfied. Therefore, a careful design of JBSUS method is needed to improve the performance.

## IV. Problem Formulation and Solution

In this section, we focus on designing an effective method to address the JBSUS problem. Specifically, the JBSUS problem is formulated as a mixed non-convex and combinatorial optimization problem. From (3), we see that the rank of matrix $\mathbf{H}\mathbf{F}_{\mathrm{RF}}$ is not larger than the rank of $\mathbf{H}$ and that of $\mathbf{F}_{\mathrm{RF}}$. Therefore, to transmit independent data streams to $|\mathcal{S}|$ users with a linear receiver, it is necessary that the column rank of the RF precoder $\mathbf{F}_{\mathrm{RF}}$ is not less than $|\mathcal{S}|$, i.e., $\mathbf{F}_{\mathrm{RF}}$ includes at least $|\mathcal{S}|$ independent codewords. In addition, for the hybrid architecture mmWave system of interest, we have $|\mathcal{S}|\leqslant N_{\mathrm{RF}}$. Thus, the optimal JBSUS for maximizing the achievable sum rate can be designed via solving the following problem:

$$\max_{\mathcal{I}}\ \sum_{u=1}^{N_u}\sum_{c=1}^{N_c}\log_2\left(1+\mathrm{SINR}_{u,c}\right) \tag{4a}$$

$$\text{s.t.}\ \sum_{c=1}^{N_c}I_{u,c}\leqslant 1,\quad\forall u\in\mathcal{U},\sum_{u=1}^{N_u}I_{u,c}\leqslant 1,\ \forall c\in\mathcal{C}, \tag{4b}$$

$$I_{u,c}\in\{0,1\},\quad\forall u\in\mathcal{U},c\in\mathcal{C}, \tag{4c}$$

$$\sum_{u=1}^{N_u}\sum_{c=1}^{N_c}I_{u,c}\leqslant N_{\mathrm{RF}}. \tag{4d}$$

In (4a), $\mathcal{I}$ is the set of $I_{u,c},\forall u\in\mathcal{U},\ c\in\mathcal{C}=\{1,\cdots,N_c\}$. $I_{u,c}$ is the user-codeword pair $(u,c)$ indicator, e.g., $I_{u,c}=1$ means that the $u$th user that pairs with codeword $c$ is scheduled by the BS, otherwise, $I_{u,c}=0$. The signal-to-interference-plus-noise ratio (SINR) of the $u$th user paired with codeword $c$ is

$$\mathrm{SINR}_{u,c}=\frac{I_{u,c}p_{u,c}}{\phi_{u,c}+1}, \tag{5}$$

where $\phi_{u,c}=\sum_{u'=1}^{N_u}\sum_{c'=1}^{N_c}I_{u',c'}p_{u,c'}-I_{u,c}p_{u,c}$ denotes the inter-user interference. Constraints (4b) and (4c) ensure that each codeword can only be assigned to at most one user and each user can only occupy at most one codeword. Due to the limited number of RF chains equipped at the BS, the number of scheduled users must satisfy constraint (4d). Note that the fairness among users is not taken into account in problem (4), which is left as our future work.

To design an effective JBSUS method to address the non-convex problem (4), we first rewrite the problem into its equivalent form by introducing auxiliary optimization variables $\alpha_{u,c}, \beta_{u,c}, \forall u \in \mathcal{U}, c \in \mathcal{C}$.

$$\max_{I,\alpha,\boldsymbol{\beta}} \sum_{u=1}^{N_u}\sum_{c=1}^{N_c}\log_2\left(1+\frac{\alpha_{u,c}}{\beta_{u,c}}\right), \quad \text{s.t. (4b), (4c), (4d),} \tag{6a}$$
$$\alpha_{u,c} \leqslant I_{u,c}p_{u,c}, \phi_{u,c}+1 \leqslant \beta_{u,c}, \quad \forall u \in \mathcal{U}, c \in \mathcal{C}, \tag{6b}$$

where $\boldsymbol{\alpha}$ is the set of $\alpha_{u,c}$ and $\boldsymbol{\beta}$ is the set of $\beta_{u,c}, \forall u \in \mathcal{U}$, $c \in \mathcal{C}$. It is easy to prove that all inequality constraints in (6b) are activated when the solution of problem (6) is obtained.

The optimization problem (6) is a complex combinatorial optimization problem. In general, the globally optimal solution to (6) can only be obtained by the exhaustive search (ES) method with considerable computational complexity of $\sum_{i=1}^{N_{\rm RF}} C_{N_u}^i C_{N_c}^i A_i^i$ where $C_a^b = \frac{a!}{b!(a-b)!}$ and $A_a^b = \frac{a!}{(a-b)!}$, $a \geqslant b$. Therefore, we need to develop a low computational complexity optimization method to address (6).

### A. DC Program Based Solution

Note that the difficulties in solving problem (6) are the binary optimization variable constraints and the non-convex objective function. To overcome these difficulties, we first rewrite constraint (4c) to its equivalent form:

$$0 \leq I_{u,c} \leq 1, \forall u \in \mathcal{U}, c \in \mathcal{C}, \sum_{u=1}^{N_u}\sum_{c=1}^{N_c} I_{u,c} - \sum_{u=1}^{N_u}\sum_{c=1}^{N_c} I_{u,c}^2 \leq 0. \tag{7}$$

Now, the variables $I_{u,c}$ in (7) are continuous values between zero and one while constraint (7) is in DC (difference of two convex functions) form. Thus, we further rewrite (6) to the following equivalent DC programming problem [9].

$$\min_{I,\boldsymbol{\alpha},\boldsymbol{\beta}} \ g_1(\boldsymbol{\alpha},\boldsymbol{\beta}) - g_2(\boldsymbol{\beta}), \quad \text{s.t. (4b), (4d), (6b), (7).} \tag{8}$$

where $g_1(\boldsymbol{\alpha},\boldsymbol{\beta}) \triangleq -\sum_{u=1}^{N_u}\sum_{c=1}^{N_c}\log_2\left(\alpha_{u,c}+\beta_{u,c}\right)$ and $g_2(\boldsymbol{\beta}) \triangleq -\sum_{u=1}^{N_u}\sum_{c=1}^{N_c}\log_2\left(\beta_{u,c}\right)$. According to [10, Proposition 2], it is easy to show that the problem in (8) can be solved by solving the following program by appropriately choosing $\mu > 0$.

$$\min_{I,\boldsymbol{\alpha},\boldsymbol{\beta}} \ g_1(\boldsymbol{\alpha},\boldsymbol{\beta}) + \mu g_3(I) - g_2(\boldsymbol{\beta}) - \mu g_4(I), \tag{9a}$$
$$\text{s.t. (4b), (4d), (6b), (7),} \tag{9b}$$

where $g_3(I) \triangleq \sum_{u=1}^{N_u}\sum_{c=1}^{N_c} I_{u,c}$ and $g_4(I) \triangleq \sum_{u=1}^{N_u}\sum_{c=1}^{N_c} I_{u,c}^2$.

In general, an iterative procedure is adopted to address the DC programming problem. Here, we use the iterative successive convex approximation (SCA) method to obtain a stationary point of (9). Let $I^{(\kappa)}$, $\boldsymbol{\alpha}^{(\kappa)}$, and $\boldsymbol{\beta}^{(\kappa)}$ be an initial feasible solution of (9) at the $\kappa$th iteration. Since $g_2(\boldsymbol{\beta})$ and $g_4(I)$ are convex functions, we have $g_2(\boldsymbol{\beta}) \geqslant \overline{g}_2(\boldsymbol{\beta})$ and $g_4(I) \geqslant \overline{g}_4(I)$ where $\overline{g}_2(\boldsymbol{\beta})$ and $\overline{g}_4(I)$ are given by:

$$\overline{g}_2(\boldsymbol{\beta}) \triangleq g_2\left(\boldsymbol{\beta}^{(\kappa)}\right) - \sum_{u=1}^{N_u}\sum_{c=1}^{N_c}\frac{1}{\beta_{u,c}^{(\kappa)}\ln 2}\left(\beta_{u,c}-\beta_{u,c}^{(\kappa)}\right),$$
$$\overline{g}_4(I) \triangleq g_4\left(I^{(\kappa)}\right) + 2\sum_{u=1}^{N_u}\sum_{c=1}^{N_c} I_{u,c}^{(\kappa)}\left(I_{u,c}-I_{u,c}^{(\kappa)}\right).$$

**Algorithm 1** DC Program Based JBSUS Method

1: Initialize iteration index $\kappa = 0$ and $I^{(\kappa)}$, then compute the initial value of $\boldsymbol{\alpha}^{(\kappa)}$ and $\boldsymbol{\beta}^{(\kappa)}$.
2: Solve problem (10) for given $I^{(\kappa)}$, $\boldsymbol{\alpha}^{(\kappa)}$, and $\boldsymbol{\beta}^{(\kappa)}$ and obtain the intermediate solution $I^{(\kappa+1)}$, $\boldsymbol{\alpha}^{(\kappa+1)}$ and $\boldsymbol{\beta}^{(\kappa+1)}$.
3: If $\frac{\left|\psi\left(\boldsymbol{\alpha}^{(\kappa+1)},\boldsymbol{\beta}^{(\kappa+1)}\right)-\psi\left(\boldsymbol{\alpha}^{(\kappa)},\boldsymbol{\beta}^{(\kappa)}\right)\right|}{\left|\psi\left(\boldsymbol{\alpha}^{(\kappa)},\boldsymbol{\beta}^{(\kappa)}\right)\right|} \leqslant \zeta$, then output $I^{(\kappa+1)}$, $\boldsymbol{\alpha}^{(\kappa+1)}$, and $\boldsymbol{\beta}^{(\kappa+1)}$, otherwise go to step 4.
4: Set $\kappa = \kappa + 1$ and go to step 2.

Thus, the $\kappa$th iteration of the iterative procedure that yields an iterative solution $\boldsymbol{\alpha}^{(\kappa+1)}$, $\boldsymbol{\beta}^{(\kappa+1)}$, and $I^{(\kappa+1)}$ of problem (9) is obtained by solving the following problem:

$$\min_{I,\boldsymbol{\alpha},\boldsymbol{\beta}} \ g_1(\boldsymbol{\alpha},\boldsymbol{\beta}) + \mu g_3(I) - \overline{g}_2(\boldsymbol{\beta}) - \mu \overline{g}_4(I), \tag{10a}$$
$$\text{s.t. (4b), (4d), (6b), (7).} \tag{10b}$$

Now, (10) is a convex optimization problem and can be easily solved via classical optimization methods, such as the interior point method. The proposed iterative JBSUS method is summarized as Algorithm 1 where $\psi(\boldsymbol{\alpha},\boldsymbol{\beta}) = g_1(\boldsymbol{\alpha},\boldsymbol{\beta}) - g_2(\boldsymbol{\beta})$ and $\zeta > 0$ is the maximum tolerable level.

*Remark 1:* In problem (10), $\mu$ acts as a large penalty factor for penalizing the objective function for any $I_{u,c}$ that is not equal to 0 or 1. With a larger value of $\mu$, $I_{u,c}$ that is not equal to 0 or 1 converges to 0 or 1 more quickly. A smaller value of $\mu$ helps to find a better solution of (9) for the same initial solution, but the values of $I$ may be between zero and one. Accordingly, we first solve (9) via Algorithm 1 with any feasible initial solution and a smaller value of $\mu$ named as $\mu_s$. Let $I^{(\mu_s)}$ be the solution of (9) with fixed $\mu_s$. Note that the elements of $I^{(\mu_s)}$ may be still not binary but only approach binary, i.e., may be zero or nonzero. Let $I_{u,c}^{(\mu_s)} = 1$ if $I_{u,c}^{(\mu_s)} \geqslant \zeta$, otherwise, $I_{u,c}^{(\mu_s)} = 0$, $\forall u \in \mathcal{U}, c \in \mathcal{C}$. Then for a larger $\mu_m > \mu_s$, we again solve (9) via Algorithm 1 using $I^{(\mu_s)}$ as the initial solution, and obtain the final solution of (6) with similar rounding operation.

The convergence of Algorithm 1 can be guaranteed by the theory of SCA as stated in [9]. Note that in (10), there are totally $3N_uN_c$ optimization variables and there are $\Omega \triangleq 4N_uN_c + N_u + N_c + 1$ convex linear constraints. Thus its computational complexity is $\mathcal{O}\left((3N_uN_c)^3\,\Omega\right)$, where $\mathcal{O}(\cdot)$ stands for the big-O notation. Thus, the computational complexity of Algorithm 1 is $\mathcal{K}\mathcal{O}\left((3N_uN_c)^3\,\Omega\right)$, where $\mathcal{K}$ is the number of the operation times of Step 2 in Algorithm 1.

### B. Greedy Based Solution

It is not difficult to find that the computational complexity of Algorithm 1 is still prohibitive for massive MISO multiuser networks in practice. To further reduce the computational complexity, in this section, we present a greedy JBSUS method

**Algorithm 2** Greedy Based JBSUS Method

1: Let $\mathcal{S} = \mathcal{C}_s = \Phi$, $I_{u,c} = 0, \forall u \in \mathcal{U}, c \in \mathcal{C}$. Select the user-codeword pair $(u^*, c^*)$ such that $(u^*, c^*) = \max_{u\in\mathcal{U}, c\in\mathcal{C}} p_{u,c}$. Let $I_{u^*,c^*} = 1$, $\mathcal{S} = \mathcal{S} \cup \{u^*\}$ and $\mathcal{C}_s = \mathcal{C}_s \cup \{c^*\}$. If $|\mathcal{S}| < N_{\mathrm{RF}}$, then let flag $= 1$, otherwise let flag $= 0$.

2: **while** flag $== 1$ **do**

3: Select codeword $\overline{c}$ such that $\overline{c} = \max_{\overline{c}\in\mathcal{C}\setminus\mathcal{C}_s} \sum_{u\in\mathcal{S}} \sum_{c\in\mathcal{C}_s} R_{u,c}$ where $R_{u,c} = \log_2\left(1 + \frac{I_{u,c} p_{u,c}}{\varphi_{u,c} + p_{u,\overline{c}}}\right)$, and then select $\overline{u}$th user such that $\overline{u} = \max_{u\in\mathcal{U}\setminus\mathcal{S}} \frac{p_{u,\overline{c}}}{\sum_{c\in\mathcal{C}_s} p_{u,c}+1}$.

4: If $\sum_{u\in\mathcal{S}} \sum_{c\in\mathcal{C}_s} R_{u,c} + R_{\overline{u},\overline{c}} > \sum_{u\in\mathcal{S}} \sum_{c\in\mathcal{C}_s} \log_2\left(1 + \frac{I_{u,c} p_{u,c}}{\varphi_{u,c}}\right)$ where $R_{\overline{u},\overline{c}} = \log_2\left(1 + \frac{p_{\overline{u},\overline{c}}}{\sum_{c\in\mathcal{C}_s} p_{\overline{u},c}+1}\right)$, then $I_{\overline{u},\overline{c}} = 1$, $\mathcal{S} = \mathcal{S} \cup \{\overline{u}\}$, $\mathcal{C}_s = \mathcal{C}_s \cup \{\overline{c}\}$, and go step 5, otherwise, flag $= 0$ and output $I$.

5: If $|\mathcal{S}| < N_{\mathrm{RF}}$, then flag $= 1$, otherwise, flag $= 0$ and output $I$.

6: **end while**

to pick out a subset of users from the user set $\mathcal{U}$ to be serving user set. Let $\mathcal{C}_s$ be the set of selected codewords from $\mathcal{C}$. We first try to select out the best user-codeword pair that has the maximum $p_{u,c}, \forall u \in \mathcal{U}, c \in \mathcal{C}$. Next, we select the codeword $\overline{c}$ that causes minimum interference to the scheduled user set $\mathcal{S}$ to be the candidate codeword from the remaining codeword set $\mathcal{C}\setminus\mathcal{C}_s$. Then, we select the user that pairs with the candidate codeword $\overline{c}$ resulting in the maximum SINR as the candidate user from the remaining user set $\mathcal{U}\setminus\mathcal{S}$. If the user-codeword pair $(\overline{u}, \overline{c})$ leads to an increasing sum rate, then they are added to $\mathcal{S}$ and $\mathcal{C}_s$, respectively. Accordingly, the greedy based JCSUS method is summarized as Algorithm 2, where $\varphi_{u,c} = \sum_{c'\in\mathcal{C}_s, c'\neq c} p_{u,c'} + 1$. The computational complexity of Algorithm 2 is $\mathcal{O}\left(N_u N_c + \sum_{l=2}^{|\mathcal{S}|} (N_u + N_c - 2(l-1))\right)$, which is substantially lower than Algorithm 1.

## V. Numerical Results

In this section, we present numerical results to demonstrate the performance of the proposed JBSUS methods. A uniform linear array with antenna spacing equal to a half wavelength is adopted. The predesigned codebook $\mathcal{F}$ is the discrete Fourier transform (DFT) codebook. The propagation environment is modeled as $N_{\mathrm{cl}} = 6$ with $N_{\mathrm{ray}} = 8$ for each cluster with Laplacian distributed angles of departure [3]. For simplicity, we assume that all clusters are of equal power, i.e., $\sigma_{\alpha,m}^2 = \sigma_\alpha^2, \forall m$. The mean angle of $\phi_m$ is uniformly distributed over $[-\pi, \pi)$ and the constant angular spread of AoD $\sigma_\phi$ is $7.5^{\circ}$ [3]. The noise power spectral density is $\sigma^2 = \frac{1}{\mathrm{SNR}}$ and the tolerance level is $\zeta = 10^{-5}$. The penalty factor $\mu_s = 0$ and $\mu_m = 100$. The number of codewords $N_c$ in codebook $\mathcal{F}$ is equal to the number of the antennas $N_t$.

Fig. 2 illustrates the sum rate performance comparison of various mentioned JBSUS methods. As expected, the ES method obtains the best sum rate performance in all the considered SNR operating regimes, at the expense of prohibitively high computational complexity. Besides, it can be observed that both Algorithms 1 and 2 are able to achieve a considerable performance compared to the optimal ES. On the other hand, the sum rate achieved by Algorithm 1 is higher than that achieved by the greedy based JBSUS method and the naive JBSUS method. It is interesting to find that the sum

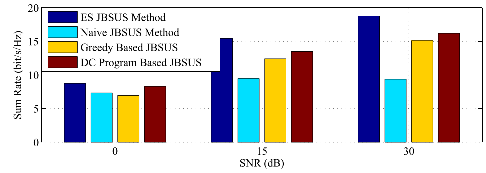


Fig. 2. Sum rate comparison of various JBSUS methods, $N_u = 10$, $N_t = 16$, $N_{\mathrm{RF}} = 4$.

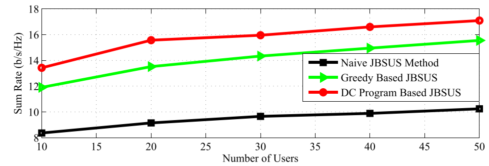


Fig. 3. Sum rate comparison of various JBSUS methods, SNR = 15dB, $N_t = 16$, $N_{\mathrm{RF}} = 4$.

rate performance of the naive JBSUS method is better than that of the greedy based JBSUS method at low SNR region. The reason is that at low SNR region, as noise dominates the inter-user interference, controlling inter-user interference provides only a marginal gain which results in a low sum rate. However, at high SNR region, controlling inter-user interference provides a large gain. Consequently, the greedy based JBSUS method outperforms the naive JBSUS method.

Fig. 3 shows the average sum rate of the considered scheduling algorithms versus $N_u$. It is seen that Algorithm 1 is superior to the other two JBSUS methods. Moreover, we find that the sum rate increases as the number of users, $N_u$, increases. The reason is that the proposed algorithms are able to exploit the multiuser diversity provided by the spatially distributed multiuser structure.

## VI. Conclusion

The codeword selection and user scheduling problem was investigated for downlink multiuser mmWave systems. Two codebook based effective JBSUS methods with ECSI were developed to address the JBSUS problem.

## References

[1] V. W. S. Wong *et al.*, *Key Technologies for 5G Wireless Systems*. Cambridge, U.K.: Cambridge Univ. Press, Mar. 2017.

[2] X. Gao *et al.*, "Energy-efficient hybrid analog and digital precoding for mmWave MIMO systems with large antenna arrays," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 998–1009, Apr. 2016.

[3] O. El Ayach *et al.*, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

[4] M. Dai and B. Clerckx, "Hybrid precoding for physical layer multicasting," *IEEE Commun. Lett.*, vol. 20, no. 2, pp. 228–231, Feb. 2016.

[5] A. Alkhateeb *et al.*, "Limited feedback hybrid precoding for multi-user millimeter wave systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 11, pp. 6481–6494, Nov. 2015.

[6] J. Wang, "Beam codebook based beamforming protocol for multi-Gbps millimeter-wave WPAN systems," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, pp. 1390–1399, Aug. 2009.

[7] Z. Xiao *et al.*, "Codebook design for millimeter-wave channel estimation with hybrid precoding structure," *IEEE Trans. Wireless Commun.*, vol. 16, no. 1, pp. 141–153, Jan. 2017.

[8] L.-N. Tran *et al.*, "Iterative precoder design and user scheduling for block-diagonalized systems," *IEEE Trans. Signal Process.*, vol. 60, no. 7, pp. 3726–3739, Jul. 2012.

[9] Y. Sun *et al.*, "Majorization-minimization algorithms in signal processing, communications, and machine learning," *IEEE Trans. Signal Process.*, vol. 65, no. 3, pp. 794–816, Feb. 2017.

[10] E. Che *et al.*, "Joint optimization of cooperative beamforming and relay assignment in multi-user wireless relay networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 10, pp. 5481–5495, Oct. 2014.