User Grouping for Sum-rate Maximization in Multiuser Multibeam Satellite Communications

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***Abstract*—Aiming at maximizing the sum-rate of multiuser multibeam satellite communications, user grouping algorithms are studied. Different users are divided into several groups, where the users in the same group are simultaneously served by the satellite via space division multiple access (SDMA) and different groups of users are served in different time slots via time division multiple access (TDMA). A sum-rate maximization user grouping (SMUG) algorithm is proposed. Given the number of total time slots, the SMUG algorithm sequentially selects users one by one from the candidate users to maximize the current sum-rate and to guarantee the increase of sum-rate in each time slot. Simulation results verify the effectiveness of our work and show that the proposed SMUG algorithm outperforms the existing algorithms.**

***Index Terms*—Satellite communications, user grouping, sum-rate maximization, multibeam satellite precoding**

I. Introduction

Satellite communications will play an important role in the next generation wireless communications [1]. Compared with terrestrial wireless communication, satellite communication has wider signal coverage without any restrictions in geographical conditions. For example, satellite communication is a good candidate to provide signal coverage for mountain areas. In fact, satellite communications have already been widely used in personal mobile communications and military communications [2]. Recently, multibeam satellite communication is drawing more attention from both the industry and academia because of its high spectral efficiency and energy efficiency [3] [4]. In order to provide larger bandwidth for each user, full frequency reuse among different beams can be used, which is typically adopted in terrestrial wireless communications. However, it may result in the inter-beam interference. To mitigate the inter-beam interference, a common approach is joint preprocessing the signal before the transmission, i.e., precoding [5] [6].

Due to the large number of users on the ground, user selection algorithms are often used to select a small part of users to be served by the satellite under certain criteria. In [7], the random user selection and the best user selection schemes based on the received signal-to-interference-plus-noise-ratio (SINR) are presented and analyzed in terms of coverage probability. In [8], a location-based user selection scheme exploiting the satellite system architecture is described. However, the aforementioned user selection schemes can not guarantee the fairness of every user, meaning that some users are frequently served, while some users are seldom served. By introducing user grouping, where different users are divided into multiple groups to be served by the satellite consecutively, the user fairness can be improved, compared to the straightforward user selection without grouping. In [9], a user grouping algorithm based on the correlation of different user channel coefficients is proposed, which can guarantee a fair distribution of the available resources among different users. However, the existing work does not consider the user grouping algorithms to maximize the sum-rate of multiuser satellite communications systems.

In this paper, aiming at maximizing the sum-rate of multiuser multibeam satellite communications, we consider the user grouping algorithms. Different users are divided into several groups, where the users in the same group are simultaneously served by the satellite via space division multiple access (SDMA) and different groups of users are served in different time slots via time division multiple access (TDMA). We propose a sum-rate maximization user grouping (SMUG) algorithm. Given the number of total time slots, the SMUG algorithm sequentially selects a user from the candidate users to maximize the current sum-rate and to guarantee the increase of sum-rate in each time slot.

The remainder of this paper is organized as follows. Section II formulates the system model of sum-rate maximization for multiuser multibeam satellite communications. Section III analyzes the sum-rate maximization problem. Based on the analysis, the SMUG algorithm is then proposed. Simulation results are provided in Section IV. Finally, Section V concludes the paper.

The notations used in this paper are defined as follows. Symbols for matrices (upper case) and vectors (lower case) are in boldface. $[\cdot]_{m,n}$, $(\cdot)^T$, $(\cdot)^H$, $\boldsymbol{I}_L$, $\mathbb{C}^M$, $\mathbb{R}^M$, $\mathbb{E}\{\cdot\}$, tr$\{\cdot\}$, $\mathcal{CN}$, $\cup$, $\setminus$ and $\varnothing$, denote the entry on the m th row and nth column of a matrix, the matrix transpose, the matrix conjugate transpose (Hermitian), the identity matrix of size L, the set of complex vectors with dimension M, the set of real vectors with dimension M, expection, trace of a matrix, the complex Gaussian distribution, union operator, except operator and the empty set, respectively.

II. System Model

Consider a multibeam satellite communication system where a single broadband multibeam satellite serving K users

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on the ground, as shown in Fig. 1. We assume the array fed reflector on the satellite has a single-feed-per-beam (SFPB) architecture [10], which means that the array fed reflector can transform the N feed signal into N transmitted signal, where the coverage of each signal on the ground forms a beam. Full frequency reuse is commonly considered in existing work to improve the spectral efficiency [6].

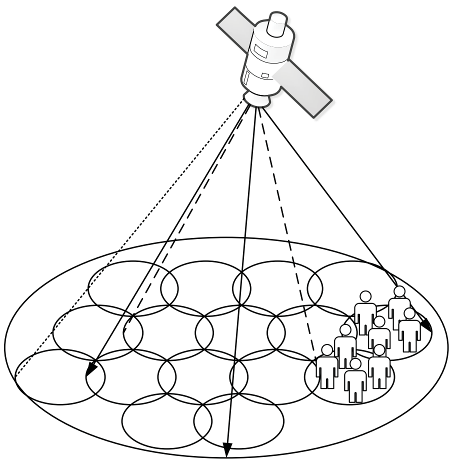

Fig. 1. Illustration of multibeam satellite communication system.

Suppose the K users are uniformly distributed over all the N beams on the ground. In practice, there are several users in each beam, resulting in $N \ll K$. To simultaneously serve multiple users, the multibeam satellite adopts both the TDMA and SDMA. Based on TDMA, the satellite serves multiple users in unit of frames, where each frame includes T time slots. For the $t(t = 1, 2, \ldots, T)$th time slot, $L_t(L_t \leq N < K)$ users are selected from totally K users, where at most one user is selected from each beam to guarantee that the selected L_t users can be simultaneously served by the multibeam satellite via SDMA. Note that L_t can be different for different t so that an optimal L_t can be obtained to maximize the sum-rate at the tth time slot. Suppose the indices of all the K users form a set $\mathcal{K}$, i.e., $\mathcal{K} = \{1, 2, \ldots, K\}$. The indices of the selected L_t users at the $t(t = 1, 2, \ldots, T)$th time slot form a set $\mathcal{S}_t$. We have

$$(\mathcal{S}_1 \cup \mathcal{S}_2 \cup \cdots \cup \mathcal{S}_T) \subseteq \mathcal{K}. \tag{1}$$

To ensure the fairness of different users, we set

$$\mathcal{S}_i \cap \mathcal{S}_n = \emptyset,\ i \neq n,\ i = 1, 2, \ldots, T,\ n = 1, 2, \ldots, T \tag{2}$$

which indicates that each user can be served within each frame at most once. In this context, the user grouping problem is converted into the problem on how to select L_t users, i.e., how to determine $\mathcal{S}_t$ at the tth time slot.

The downlink channel matrix between the multibeam satellite and the K ground users is denoted as $\boldsymbol{H} \in \mathbb{C}^{K\times N}$, which can be expressed as

$$\boldsymbol{H} = \boldsymbol{\Phi}\boldsymbol{C} \tag{3}$$

where $\boldsymbol{\Phi} \in \mathbb{C}^{K\times K}$ denotes the signal phase matrix caused by different propagation paths among the satellite and users, $\boldsymbol{C} \in \mathbb{R}^{K\times N}$ denotes the multibeam antenna pattern. Since the distance between the neighbouring satellite antenna feeds is relatively small compared with the distance between the satellite and the users, it is common to assume that the phase among the user and all the antenna feeds are the same [11]. Therefore, $\boldsymbol{\Phi}$ is a diagonal matrix with the $i(i = 1, 2, \ldots, K)$th diagonal entry being $[\boldsymbol{\Phi}]_{i,i} = e^{j\phi_i}$, where ϕ_i denotes a random variable obeying the uniform distribution in $(0, 2\pi)$. The off-diagonal entries of $\boldsymbol{\Phi}$ are all zero, i.e., $[\boldsymbol{\Phi}]_{i,l} = 0$ for $i \neq l$. The entry on the $k(k = 1, 2, \ldots, K)$th row and $n(n = 1, 2, \ldots, N)$th column of $\boldsymbol{C}$ can be modeled as

$$[\boldsymbol{C}]_{k,n} = \frac{\sqrt{G_R G_{k,n}}}{4\pi \frac{d_k}{\lambda}\sqrt{\kappa T_R B_W}} \tag{4}$$

where d_k denotes the the distance between the satellite and the kth user, G_R denotes the receiving antenna gain, and $G_{k,n}$ denotes the gain between the nth antenna feed and the kth user. λ, B_W, κ and T_R represent the wavelength, the bandwidth, the Boltzman constant, and the clear sky noise temperature at the receiver, respectively.

At the $t(t = 1, 2, \ldots, T)$th time slot, we suppose the indices of the selected L_t users are denoted as $m_1, m_2, \ldots, m_{L_t}$ with $1 \leq m_1 < m_2 < \cdots < m_{L_t} \leq K$. We have

$$\mathcal{S}_t = \{m_1, m_2, \ldots, m_{L_t}\}. \tag{5}$$

Then the received signal by the L_t users in $\mathcal{S}_t$ is denoted as $\boldsymbol{y} \triangleq [y_{m_1}, y_{m_2}, \ldots, y_{m_{L_t}}]^T \in \mathbb{C}^{L_t}$, which can be expressed as

$$\boldsymbol{y} = \boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{x} + \boldsymbol{\eta} \tag{6}$$

where $\boldsymbol{H}_{\mathcal{S}_t} \triangleq [\boldsymbol{h}_{m_1}^T, \boldsymbol{h}_{m_2}^T, \ldots, \boldsymbol{h}_{m_{L_t}}^T]^T \in \mathbb{C}^{L_t\times N}$ denotes the downlink channel matrix between the satellite and the L_t users in $\mathcal{S}_t$, with $\boldsymbol{h}_{m_l} \in \mathbb{C}^{1\times N}$ representing the channel vector between the satellite and the m_lth user, $l = 1, 2, \ldots, L_t$. We use $\boldsymbol{x} \in \mathbb{C}^N$ to denote the transmitted signal by the satellite at the tth time slot. $\boldsymbol{\eta} \triangleq [\eta_1, \eta_2, \ldots, \eta_{L_t}]^T \in \mathbb{C}^{L_t}$ denotes an additive white Gaussian noise (AWGN) vector, where each entry of $\boldsymbol{\eta}$ independently obeys the complex Gaussian distribution with zero mean and variance being σ^2, i.e., $\mathbb{E}\{\boldsymbol{\eta}\boldsymbol{\eta}^H\} = \sigma^2\boldsymbol{I}_{L_t}$. To mitigate the inter-beam interference caused by the channel matrix, a common preprocessing technique is introducing a precoding matrix to combat the channel distortion. We suppose

$$\boldsymbol{x} = \boldsymbol{W}\boldsymbol{s} \tag{7}$$

where $\boldsymbol{W} \triangleq [\boldsymbol{w}_1, \boldsymbol{w}_2, \ldots, \boldsymbol{w}_{L_t}] \in \mathbb{C}^{N\times L_t}$ denotes the precoding matrix. $\boldsymbol{s} = [s_{m_1}, s_{m_2}, \ldots, s_{m_{L_t}}]^T \in \mathbb{C}^{L_t}$ denotes the transmitted data, where s_{m_l} is the data intended for the m_lth user, $l = 1, 2, \ldots, L_t$. The entries of $\boldsymbol{s}$ are assumed to be mutually uncorrelated and $\boldsymbol{s}$ is assumed to be normalized, i.e., $\mathbb{E}\{\boldsymbol{s}\boldsymbol{s}^H\} = \boldsymbol{I}_{L_t}$. Substituting (7) into (6) leads to the following expression as

$$\boldsymbol{y} = \boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{W}\boldsymbol{s} + \boldsymbol{\eta}. \tag{8}$$

The received signal by the m_lth user, $l = 1, 2, \dots, L_t$, can be expressed as

$$y_{m_l} = \boldsymbol{h}_{m_l}\boldsymbol{w}_l s_{m_l} + \sum_{\substack{m_i \in \mathcal{S}_t \\ i \neq l}} \boldsymbol{h}_{m_l}\boldsymbol{w}_i s_{m_i} + \eta_l. \tag{9}$$

Then the SINR of the m_lth user is

$$\Gamma_{m_l} = \frac{|\boldsymbol{h}_{m_l}\boldsymbol{w}_l|^2}{\sum_{m_i \in \mathcal{S}_t, i \neq l} |\boldsymbol{h}_{m_l}\boldsymbol{w}_i|^2 + \sigma^2}. \tag{10}$$

The achievable rate of the m_lth user is given by

$$R_{m_l} = \log_2(1 + \Gamma_{m_l}). \tag{11}$$

The sum-rate of the selected L_t users which can be simultaneously served by the satellite via SDMA can be expressed as

$$R_{\mathcal{S}_t} = \sum_{l=1}^{L_t} R_{m_l}. \tag{12}$$

Then the sum-rate of totally T time slots, where T groups of users are served by the satellite via TDMA, can be expressed as

$$R_{\text{total}} = \sum_{t=1}^{T}\sum_{l=1}^{L_t} R_{m_l}. \tag{13}$$

The maximization of R_{total} is essentially to maximize the sum-rate at each time slot, i.e.

$$\max_{\mathcal{S}_t} R_{\mathcal{S}_t} \tag{14}$$

which is determined by the selected L_t users at the tth time slot. Note that L_t can be different for different t so that an optimal L_t can be obtained to maximize the sum-rate at the tth time slot.

III. User Grouping Algorithm

It is seen that the straightforward method to solve (14) is sequentially setting $L_t = 1, 2, \dots, N$ in order, where given each L_t we exhaustively select L_t users from all candidate users. Since the exhaustive selection method is usually computational intractable, in the following we will propose a low computational user grouping algorithm.

We denote the precoding matrix $\boldsymbol{W}$ in (7) as

$$\boldsymbol{W} = \alpha\boldsymbol{F} \tag{15}$$

where $\boldsymbol{F}$ denotes zero-forcing (ZF) precoding matrix as

$$\boldsymbol{F} = \boldsymbol{H}_{\mathcal{S}_t}^H(\boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{H}_{\mathcal{S}_t}^H)^{-1} \tag{16}$$

and α is a positive factor to satisfy the total power constraint as

$$\alpha = \sqrt{\frac{\rho}{\text{tr}\{\boldsymbol{F}\boldsymbol{F}^H\}}}. \tag{17}$$

Note that ρ in (17) denotes the total transmitting power of the satellite. Based on (16), we have

$$\begin{aligned}\text{tr}\{\boldsymbol{F}\boldsymbol{F}^H\} &= \text{tr}\left\{\boldsymbol{H}_{\mathcal{S}_t}^H(\boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{H}_{\mathcal{S}_t}^H)^{-1}(\boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{H}_{\mathcal{S}_t}^H)^{-1}\boldsymbol{H}_{\mathcal{S}_t}\right\} \\ &= \text{tr}\left\{\boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{H}_{\mathcal{S}_t}^H(\boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{H}_{\mathcal{S}_t}^H)^{-1}(\boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{H}_{\mathcal{S}_t}^H)^{-1}\right\} \\ &= \text{tr}\left\{(\boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{H}_{\mathcal{S}_t}^H)^{-1}\right\}\end{aligned} \tag{18}$$

Then (17) can be converted to

$$\alpha = \sqrt{\frac{\rho}{\text{tr}\left\{(\boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{H}_{\mathcal{S}_t}^H)^{-1}\right\}}}. \tag{19}$$

Then the SINR of m_lth user can be expressed as

$$\Gamma_{m_l} = \frac{\alpha^2|\boldsymbol{h}_{m_l}\boldsymbol{F}_l|^2}{\alpha^2\sum_{m_i \in \mathcal{S}_t, i \neq l}|\boldsymbol{h}_{m_l}\boldsymbol{F}_i|^2 + \sigma^2} = \frac{\alpha^2}{\sigma^2} \tag{20}$$

where $\boldsymbol{F}_l$ denotes the $l(l = 1, 2, \dots, L_t)$th column of $\boldsymbol{F}$. Substituting (17) and (20) into (11) leads to

$$R_{m_l} = \log_2\left(1 + \frac{\rho}{\sigma^2\text{tr}\left\{(\boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{H}_{\mathcal{S}_t}^H)^{-1}\right\}}\right). \tag{21}$$

Since the achievable rate of each user is the same in the each group, which reflects the user fairness, we have

$$R_{\mathcal{S}_t} = \sum_{l=1}^{L_t} R_{m_l} = |\mathcal{S}_t|\log_2\left(1 + \frac{\rho}{\sigma^2\text{tr}\left\{(\boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{H}_{\mathcal{S}_t}^H)^{-1}\right\}}\right) \tag{22}$$

where $|\mathcal{S}_t|$ denotes the number of entries in $\mathcal{S}_t$, i.e., $|\mathcal{S}_t| = L_t$. Then (14) can be rewritten as

$$\max_{\mathcal{S}_t} \ |\mathcal{S}_t|\log_2\left(1 + \frac{\rho}{\sigma^2\text{tr}\left\{(\boldsymbol{H}_{\mathcal{S}_t}\boldsymbol{H}_{\mathcal{S}_t}^H)^{-1}\right\}}\right). \tag{23}$$

To solve (23), instead of using the exhaustive search which is computationally intractable, we may incrementally select users one by one to substantially reduce the computational complexity. We first set $|\mathcal{S}_t| = 1$ and select the first user. We add the selected user index into $\mathcal{S}_t$, meanwhile removing it from $\mathcal{K}$ and updating $\mathcal{K}$. Then we set $|\mathcal{S}_t| = 2$. We test each user in current $\mathcal{K}$ by temporarily adding its index to $\mathcal{S}_t$ and computing (22). From all the user tests, we select the user that achieves the largest value of (22). Then we formally add the index of the selected user into current $\mathcal{S}_t$, meanwhile removing it from current $\mathcal{K}$ and updating $\mathcal{K}$. We repeat these steps until we can no longer increase (22) any more. In this way, we can obtain the largest $R_{\mathcal{S}_t}$ at the tth time slot, where the corresponding $\mathcal{S}_t$ is also obtained.

At each step, given $|\mathcal{S}_t|$ with $|\mathcal{S}_t| - 1$ users already selected in the previous step, we only select one user from the candidate users to maximize (22). Note that although $\mathcal{S}_t$ is not

Algorithm 1 Sum-rate Maximization User Grouping (SMUG) algorithm

Input: $\boldsymbol{H}, N, K, T, \rho, \sigma^2$.
Initialization: $\mathcal{K} \leftarrow \{1, 2, ..., K\}$. $t \leftarrow 1$.
for $t = 1, 2, \ldots, T$ **do**
  Obtain m^* via (27).
  $\mathcal{S}_t \leftarrow \{m^*\}$. $\mathcal{K} \leftarrow \mathcal{K} \backslash m^*$.
  Compute $R_{\mathcal{S}_t}$ via (22).
  while $|\mathcal{S}_t| \leq N$ **do**
    Obtain m^* via (26).
    $\overline{\mathcal{S}}_t \leftarrow \mathcal{S}_t \cup \{m^*\}$. $\mathcal{K} \leftarrow \mathcal{K} \backslash m^*$.
    Compute $R_{\overline{\mathcal{S}}_t}$ via (22).
    if $R_{\overline{\mathcal{S}}_t} \leq R_{\mathcal{S}_t}$ **then**
      Break.
    else
      $\mathcal{S}_t \leftarrow \overline{\mathcal{S}}_t$. $R_{\mathcal{S}_t} \leftarrow R_{\overline{\mathcal{S}}_t}$.
    end if
  end while
end for
Output: $\mathcal{S}_t, t = 1, ..., T$.

determined, $|\mathcal{S}_t|$ is given before the user selection at each step, implying that (23) can be convert to

$$\max_{\mathcal{S}_t} \ \log_2 \left(1 + \frac{\rho}{\sigma^2 \text{tr}\left\{ (\boldsymbol{H}_{\mathcal{S}_t} \boldsymbol{H}_{\mathcal{S}_t}^H)^{-1} \right\}} \right) \tag{24}$$

which is equivalent as

$$\min_{\mathcal{S}_t} \ \text{tr}\left\{ (\boldsymbol{H}_{\mathcal{S}_t} \boldsymbol{H}_{\mathcal{S}_t}^H)^{-1} \right\}. \tag{25}$$

More specifically, for a given $\mathcal{S}_t$, a new user can be selected by

$$m^* \leftarrow \arg \min_{\substack{m \in \mathcal{K} \\ \mathcal{S}_t^* = \mathcal{S}_t \cup \{m\}}} \ \text{tr}\left\{ (\boldsymbol{H}_{\mathcal{S}_t^*} \boldsymbol{H}_{\mathcal{S}_t^*}^H)^{-1} \right\} \tag{26}$$

where a user index m is selected from current $\mathcal{K}$ and temporarily added into $\mathcal{S}_t$ to form a new set $\mathcal{S}_t^*$, i.e., $\mathcal{S}_t^* = \mathcal{S}_t \cup \{m\}$. From all the selection, we obtain the user index m^* that achieves the minimum in (26). Then we formally add m^* into current $\mathcal{S}_t$ and obtain $\overline{\mathcal{S}}_t$, i.e., $\overline{\mathcal{S}}_t \leftarrow \mathcal{S}_t \cup \{m^*\}$. Meanwhile we remove m^* from current $\mathcal{K}$ and updating $\mathcal{K}$ by $\mathcal{K} \leftarrow \mathcal{K} \backslash m^*$. Then we compute $R_{\overline{\mathcal{S}}_t}$ via (22). Although we select a best candidate user m^* to group with $\mathcal{S}_t$, it does not guarantee the monotonically increase of the sum-rate, which means that $R_{\overline{\mathcal{S}}_t}$ might be smaller than $R_{\mathcal{S}_t}$. If $R_{\overline{\mathcal{S}}_t}$ is no larger than $R_{\mathcal{S}_t}$, we break from the iterations, discard $\overline{\mathcal{S}}_t$ and output $\mathcal{S}_t$; otherwise, we replace $\mathcal{S}_t$ and $R_{\mathcal{S}_t}$ by $\overline{\mathcal{S}}_t$ and $R_{\overline{\mathcal{S}}_t}$, respectively. We repeat the procedure until the number of selected users equals the number of the satellite beams, i.e., $|\mathcal{S}_t| = N$.

Note that the number of users to select is not fixed to be N, which means the maximal sum-rate might be achieved by less than N users. The reason lies in the fact that different user channels might be correlated, which causes the low rank of $\boldsymbol{H}_{\mathcal{S}_t} \boldsymbol{H}_{\mathcal{S}_t}^H$ or very small singular value of $\boldsymbol{H}_{\mathcal{S}_t} \boldsymbol{H}_{\mathcal{S}_t}^H$, and further leads to large $\text{tr}\{(\boldsymbol{H}_{\mathcal{S}_t} \boldsymbol{H}_{\mathcal{S}_t}^H)^{-1}\}$ and small $R_{\mathcal{S}_t}$. To ensure that the matrix inversion can always be done for $\boldsymbol{H}_{\mathcal{S}_t} \boldsymbol{H}_{\mathcal{S}_t}^H$, in practice we have to add $\boldsymbol{H}_{\mathcal{S}_t} \boldsymbol{H}_{\mathcal{S}_t}^H$ with a small positive term $\epsilon \boldsymbol{I}$, e.g., $\epsilon = 0.001$.

Therefore, we have to determine the optimal number of users to maximize the sum-rate. When sequentially selecting users one by one, we always compare the current sum-rate with that in the previous iteration to guarantee the continuous increase of sum-rate. In practice, it is impossible to put all the power of the satellite on single one beam, even if only this beam works while the other beams do not work. In fact the power is put on all the beams in average even if some beams do not work. As a consequence, in (24) we should replace ρ by $|\mathcal{S}_t|\rho/N$ when performing the user selection for multiuser multibeam satellite communications [9].

We iteratively run the user selection for each time slot, until finishing the user grouping for all the T time slots, which is summarized in **Algorithm 1**. For the first user selection that is a completely new start point at each time slot, we select the user with the largest channel gain as

$$m^* \leftarrow \arg \max_{m \in \mathcal{K}} \|\boldsymbol{h}_m\|_2. \tag{27}$$

where the set of candidate users for the user grouping denoted as $\mathcal{K}$ is getting smaller. Finally we output the results of user grouping as $\mathcal{S}_t, t = 1, ..., T$. Note that it may happen that some users are not selected by the user grouping and thus not served by the satellite. However, we achieve the sum-rate maximization of the multiuser satellite communications.

IV. Numerical Results

To evaluate the performance of our work, we assume a multibeam multiuser satellite equipped with $N = 16$ beams. Within the coverage of the satellite, $K = 320$ users are uniformly distributed. We consider the scenario of full frequency reuse to improve the spectral efficiency of the satellite communication system. Array fed radiation pattern and the measured channel data used in our simulation is provided by the European Space Agency (ESA), which takes into account the different user locations. The simulation parameters are listed in Table I. The Boltzmann constant is $\kappa = 1.38 \times 10^{-23}$ J/K. Since we normalize the noise power by $\kappa T_R B_W$ in (4), we set $\sigma^2 = 1$ [4].

TABLE I
Simulation Parameters

Parameter	Value
Satellite height	35786km
Carrier frequency	20 GHz (Ka band)
Total bandwidth (B_W)	500 MHz
User antenna gain	41.7 dBi
G/T	17.68 dB/K
Feed Radiation pattern	Provided by ESA

We compare the proposed SMUG algorithm with the existing multiple antenna downlink orthogonal clustering (MADOC) algorithm [9]. We also consider serving all the users, where the user grouping algorithm is named as SMUG

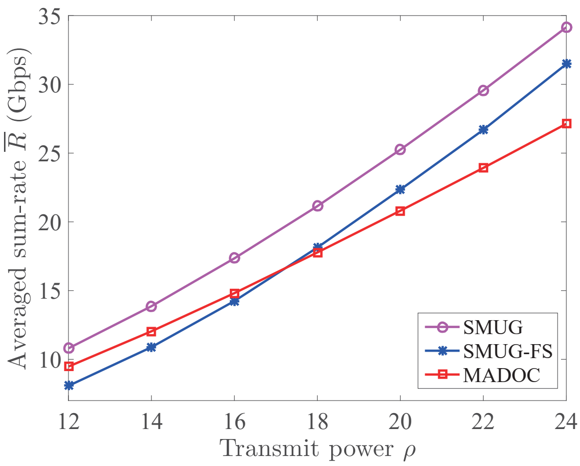

Fig. 2. Comparisons of averaged sum-rate for SMUG, SMUG-FS and MADOC with different transmit power.

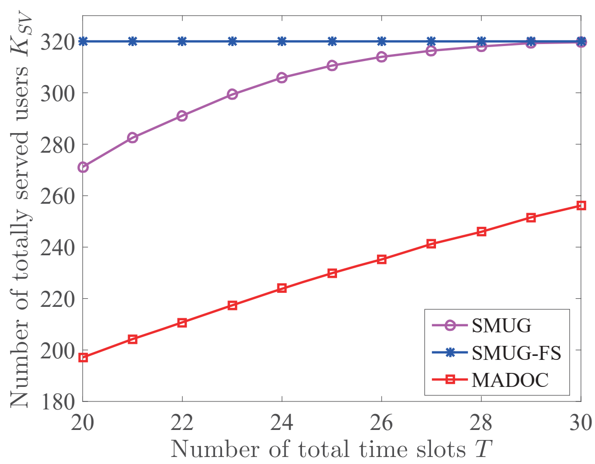

Fig. 4. Comparisons of number of totally served users for SMUG, SMUG-FS and MADOC with different number of time slots.

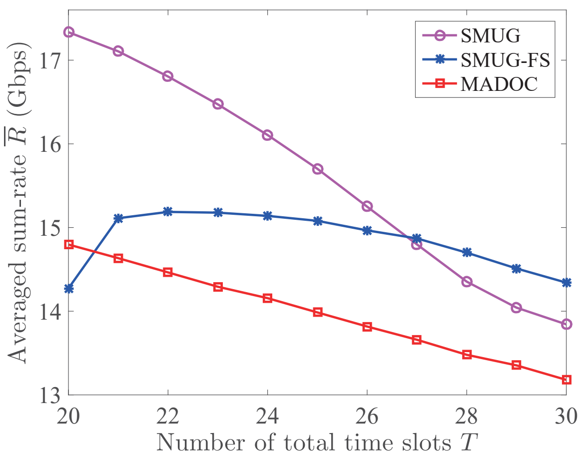

Fig. 3. Comparisons of averaged sum-rate for SMUG, SMUG-FS and MADOC with different number of total time slots.

with full selection of users (SMUG-FS). At each time slot, SMUG-FS sequentially selects users one by one in the same manner as SMUG. But even if the sum-rate starts to decrease, we keep on selecting users until the number of selected users reaches a prespecified threshold β, e.g., $\beta = K/T$. We define the averaged sum-rate over all the time slots as

$$\overline{R} = \frac{B_W}{T}\sum_{t=1}^{T} R_{\mathcal{S}_t} \tag{28}$$

where $R_{\mathcal{S}_t}$ is defined in (12).

As shown in Fig. 2, we compare the averaged sum-rate $\bar{R}$ for SMUG, SMUG-FS and MADOC with different transmit power ρ. For the fair comparisons with MADOC, we set ρ to be 12 to 24 dBW, which is the same as that in [9]. The total time slots is set to be $T = 20$. For SMUG-FS, we set $\beta = 16$. It is seen that as the transmit power gets larger, the averaged sum-rate of three different algorithms all increases, where SMUG has the best performance. In the region of large transmit power, e.g., $\rho > 18$ dBW, SMUG-FS outperforms MADOC. The reason lies in the different objective of two algorithms, where SMUG-FS aims to select a new user with the largest contribution to the sum-rate and MADOC aims to select a new user with smaller channel correlation to the selected users. With the small transmit power, the channel correlation of different users is dominant factor for the sum-rate; while with the large transmit power, the channel correlation has less impact on the sum-rate than the transmit power. To achieve the same averaged sum-rate of $\bar{R} = 20$ Gbps, SMUG and MADOC need 17.4 dBW and 19.5 dBW in transmit power, respectively, leading to the transmit power ratio of 2.1 dB for SMUG over MADOC, or equivalently indicating that the transmit power of MADOC is 1.6 times larger than that of MADOC.

As shown in Fig.3, we compare the averaged sum-rate $\bar{R}$ for SMUG, SMUG-FS and MADOC with different number of total time slots T. We fix $\rho = 16$ dBW. For both SMUG and MADOC, as T gets larger, the averaged sum-rate decreases, since T in (28) plays an important role. For SMUG-FS, the averaged sum-rate first increases and then decreases, because the channel correlation of different users in the same group reduces and contributes to the averaged sum-rate more than T when T is not very large, e.g., $T < 22$. It is also observed that SMUG-FS performs even better than SMUG when T is large, e.g., $T > 27$. The reason is that SMUG is too greedy in selecting users in the first several time slots while SMUG-FS is less greedy due to the control of the threshold β. SMUG selects more users in the first several time slots while in the later time slots it selects too few users, leading to lower averaged sum-rate. SMUG-FS selects almost the same number of users for each time slot and has a more stable averaged sum-rate.

As shown in Fig.4, we compare the number of totally served users for SMUG, SMUG-FS and MADOC with different number of total time slots T. We fix $\rho = 16$ dBW. The number of totally served users is defined as

$$K_{SV} = \sum_{t=1}^{T} L_t. \tag{29}$$

Since SMUG-FS is the full selection of all the users, the served users for SMUG-FS is always $K = 320$. For SMUG, where in each time slot the continuous increase in sum-rate should be guaranteed for the user selection, less users than the satellite beams can be selected in each time slot, which needs more time slots to finish selecting all the users.

V. Conclusions

In this paper, aiming at maximizing the sum-rate of multiuser multibeam satellite communications, we have considered the user grouping algorithms. Different users are divided into several groups, where the users in the same group are simultaneously served by the satellite via SDMA and different groups of users are served in different time slots via TDMA. We have proposed a SMUG algorithm, which sequentially selects a user from candidate users to maximize the current sum-rate and to guarantee the increase of sum-rate in each time slot. Future work will be continued with the focus on the user grouping and power allocation in multiuser multibeam satellite communications.

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