Joint Precoding and Scheduling Optimization in Downlink Multicell Satellite Communications

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***Abstract*—Mobile satellite communications are expected to play an increasing role in future wireless communications. In this paper, we consider the joint optimization of multibeam precoding and scheduling in a downlink multicell satellite communication system where the users in each cell share the link in a time-division multiple access fashion. Multicell satellite precoding is considered in conjunction with user time resource allocation to minimize the overall satellite transmit power while satisfying the communication capacity requirement for all users. We also derive an alternative optimization problem using the signal-to-leakage ratio to facilitate parallel optimization with reduced computational complexity.**

keywords: Satellite communications, multibeam precoding, user scheduling, optimization.

I. INTRODUCTION

Mobile satellite communications (SATCOM) are expected to play an increasing role in future wireless communications [1]–[4]. In some applications, e.g., where mobile terminals are deployed in areas that are difficult to be reached through terrestrial links due to physical or cost reasons, communications through satellites become the only choice to keep the terminals connected. A communication satellite commonly functions as a relay which receives data packets from ground stations or terminal users, repeats or regenerates the received packets, and then routes them to the other terminal users or ground stations. To make effective use of the frequency spectrum, the coverage area of a satellite is divided into small cells and each cell is covered by a spotbeam.

We consider a SATCOM system using satellites located on the geostationary Earth orbit (GEO), which constitute the main infrastructure for the current SATCOM networks. With an orbit of height 35,786 km above the surface of the Earth, a GEO satellite remains in a stationary position relative to the Earth. A GEO satellite covers a large footprint, which amounts to approximately one-third of the Earth surface except for the polar regions. In this way, GEO SATCOM systems offer near-global coverage with a minimum of three satellites. Because of the stationary satellite constellations, GEO SATCOM systems do not require satellite handover and allow accurate beam steering with no need to consider Doppler effects due to satellite motion.

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Next-generation high-throughput SATCOM systems are required to offer much higher throughput and data rates [5]. Toward this end, a promising technology is to use multiple array beams to enable high resource reuse over the coverage area. For example, a multibeam SATCOM system with more than 300 fixed beams are being considered under the European project on Broadband Access via Integrated Terrestrial and Satellite Systems (BATS) [6]. With the more capable onboard processing capability in the future, communication satellites will allow adaptive multibeam beamforming and support flexible and optimized packet delivery [7]–[9].

In this paper, we consider optimized multibeam precoding and scheduling in a downlink SATCOM system where the users in each cell share the link using the time-division multiple access (TDMA) scheme. One of the key differences of SATCOM systems from typical terrestrial array systems [10]–[12] is the high coherency of channels associated with nearby ground users, particularly those in the same cell and share a common satellite spotbeam. Downlink satellite multibeam precoding is considered in conjunction with user time resource allocation to optimize the overall communication capacity and, at the same time, guarantee the required quality of service for all users. We also derive an alternative optimization problem using the output signal-to-leakage ratio to facilitate parallel optimization with reduced computational complexity. In many communication scenarios, the latter achieves a similar optimization performance with much lower complexity.

Notations. Lower-case (upper-case) bold characters are used to denote vectors (matrices). In particular, $\mathbf{I}_K$ stands for the $K \times K$ identity matrix, $\mathbf{1}$ and $\mathbf{0}$ denote vectors of all 1 elements and all 0 elements, respectively, with a proper dimension. $(\cdot)^*$, $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\mathrm{H}}$ denote complex conjugation, transpose and Hermitian transpose, respectively. $\mathrm{E}(\cdot)$ stands for statistical expectation, and $||\mathbf{a}||$ denotes the Euclidean norm of vector $\mathbf{a}$. $\mathbf{A} \succeq \mathbf{0}$ implies that matrix $\mathbf{A}$ is positive semidefinite, whereas $\mathbf{a} \geq \mathbf{0}$ denotes that all elements in vector $\mathbf{a}$ are nonnegative.

II. SIGNAL MODEL

A. Channel Model

A downlink multibeam satellite, depicted in Fig. 1, receives signals from a single gateway, and a total number of N feed signals are transformed into K beams toward ground users. The ground users are clustered into K cells, and there are Q_k

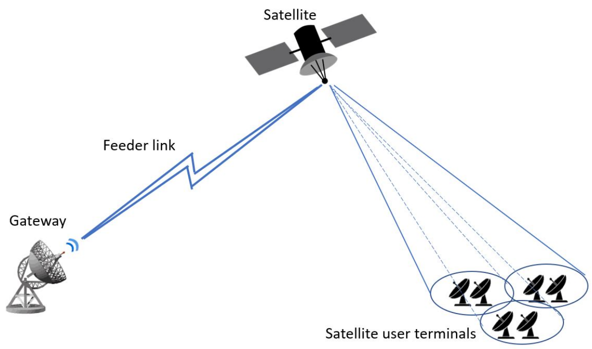


Fig. 1. Multibeam satellite communications structure.

single-antenna users in the kth cell. For simplicity, we only consider the case with $Q_1 = \cdots = Q_K = Q$. Therefore, the total number of ground users is KQ. In addition, we consider the multi-frequency scheme where the entire frequency band is divided into multiple subcarriers. Multicell beamforming is considered only for one of the subcarriers without loss of generality. Each subcarrier can practically be treated as narrowband from array processing perspective.

Denote $\mathbf{x}(t) \in \mathbb{C}^{N\times 1}$ as the feed signal vector. Then, the signal vector received at the KQ users, $\mathbf{y}(t) \in \mathbb{C}^{KQ\times 1}$, is expressed as

$$\mathbf{y}(t) = \mathbf{H}\mathbf{x}(t) + \mathbf{n}(t), \tag{1}$$

where $\mathbf{H} \in \mathbb{C}^{KQ\times N}$ is the channel matrix linking the N satellite feeders and the KQ ground users which are clustered into K cells, and $\mathbf{n}(t) \in \mathbb{C}^{KQ\times 1} \sim \mathcal{CN}(\mathbf{0}, \sigma_n^2\mathbf{I}_{KQ})$ is the additive noise vector, whose elements are modeled as independent and identically distributed complex Gaussian random variables with zero mean and variance σ_n^2.

The elements of the channel matrix $\mathbf{H}$ are determined by several factors. The channel vector $\mathbf{h}_{q_k} \in \mathbb{C}^{N\times 1}$ associated with user q_k (i.e., the qth user in the kth cell) can be expressed as [8], [9]:

$$\mathbf{h}_{q_k} = \frac{\alpha_{q_k}\lambda}{4\pi d_{q_k}}\sqrt{G^t_{q_k}G^r_{q_k}}\exp(j\phi_{q_k})\mathbf{a}_{q_k}, \tag{2}$$

where α_{q_k} is the atmospheric attenuation factor, λ is the wavelength, d_{q_k} is the distance between the satellite and the q_kth ground user, and $G^t_{q_k}$ and $G^r_{q_k}$ are the transmit and receive antenna gains, respectively. In addition, ϕ_{q_k} is the phase difference of the qth user with respect to the reference point in the kth cell, and $\mathbf{a}_{q_k} \in \mathbb{C}^{N\times 1}$ is the transmit steering vector of the antenna array in the satellite.

Stacking the channel vectors for the Q users in the kth cell yields

$$\mathbf{H}_k = [\mathbf{h}_{1_k}, \cdots, \mathbf{h}_{Q_k}]^{\mathrm{T}} \in \mathbb{C}^{Q\times N}, \tag{3}$$

and the channel matrix $\mathbf{H}$ for all the K cells can be expressed as

$$\mathbf{H} = [\mathbf{H}_1^{\mathrm{T}}, \cdots, \mathbf{H}_K^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{C}^{KQ\times N}. \tag{4}$$

The diameter of a ground cell is typically in the order of tens to hundreds of kilometers. Because of the large distance between the GEO satellite and the Earth surface, channel vectors associated with ground users within the same cell typically exhibit a high spatial correlation, rendering matrices $\mathbf{H}_k, k = 1, \cdots, K$, to be low rank (the rank is often equal or close to one [13]). Such high coherency is a major difference of the SATCOM system to terrestrial communication systems whose propagation channel characteristics are often defined by the multipath fading. On the other hand, the physical separation between ground users within a cell are still large enough for them to experience different attenuation conditions due to different atmospheric and weather conditions.

We design a joint precoding and scheduling scheme such that the users in the same cell share a beam in the TDMA manner. That is, at any time instant, only one user is activated in each cell. Denote p_{q_k} as the proportion of the shared time for user q_k to be activated, and let $\mathbf{p}_k = [p_{1_k}, ..., p_{Q_k}]^{\mathrm{T}}$. Clearly, $\sum_{q=1}^{Q} p_{q_k} = \mathbf{1}^{\mathrm{T}}\mathbf{p}_k = 1, \forall k$ should be satisfied to keep each cell link fully utilized.

B. User Capacity

The precoder $\mathbf{W} = [\mathbf{w}_1, \cdots, \mathbf{w}_K] \in \mathbb{C}^{N\times K}$ transforms the K incoming streams, $\mathbf{s}(t) = [s_1(t), \cdots, s_K(t)]^{\mathrm{T}} \in \mathbb{C}^{K\times 1}$, into an N-feed satellite output as vector $\mathbf{x}(t) \in \mathbb{C}^{N\times 1}$, i.e.,

$$\mathbf{x}(t) = \mathbf{W}\mathbf{s}(t), \tag{5}$$

where $\mathrm{E}[\mathbf{s}(t)\mathbf{s}^{\mathrm{H}}(t)] = \mathbf{I}_K$ is assumed. In addition, $\mathbf{w}_k$ is the kth column of $\mathbf{W}$ and denotes the beamforming vector of the satellite array toward the kth cell, and its power is given as $||\mathbf{w}_k||^2$.

In satellite communications, the onboard processing capability is limited and is difficult to be updated. Therefore, it is often more convenient to perform the above precoding at the ground gateway. This is feasible when the channel state information between the satellite and the ground users is forwarded to the gateway so that the precoder optimization (to be detailed in Section III) and the precoding operation (Eq. (5)) are carried out in the gateway. The gateway forwards the precoder output (i.e., vector $\mathbf{x}(t)$) to the satellite for the N satellite antennas to transmit.

The output signal for the qth user in the kth cell is expressed as

$$\begin{aligned} y_{q_k}(t) &= \mathbf{h}^{\mathrm{H}}_{q_k}\mathbf{x}(t) + n_{q_k}(t) = \mathbf{h}^{\mathrm{H}}_{q_k}\mathbf{W}\mathbf{s}(t) + n_{q_k}(t) \\ &= \mathbf{h}^{\mathrm{H}}_{q_k}\mathbf{w}_k s_k(t) + \sum_{l\neq k}^{K}\mathbf{h}^{\mathrm{H}}_{q_k}\mathbf{w}_l s_l(t) + n_{q_k}(t). \end{aligned} \tag{6}$$

The three terms at the right-hand side respectively represent the desired signal, inter-cell interference, and noise. As a result, the output signal-to-interference-plus-noise ratio (SINR) is given as

$$\mathrm{SINR}_{q_k} = \frac{\mathrm{E}\left|\mathbf{h}^{\mathrm{H}}_{q_k}\mathbf{w}_k s_k(t)\right|^2}{\mathrm{E}\left|\mathbf{h}^{\mathrm{H}}_{q_k}\sum\limits_{l\neq k}^{K}\mathbf{w}_l s_l(t) + n_{q_k}(t)\right|^2} = \frac{|\mathbf{h}^{\mathrm{H}}_{q_k}\mathbf{w}_k|^2}{\sum\limits_{l\neq k}^{K}|\mathbf{h}^{\mathrm{H}}_{q_k}\mathbf{w}_l|^2 + \sigma_n^2}. \tag{7}$$

Denote B as the constant signal bandwidth in the underlying subcarrier. Then, the channel capacity of user q_k is

$$C_{q_k} = p_{q_k} B \log_2(1 + \mathrm{SINR}_{q_k}). \tag{8}$$

III. Joint Precoding and Scheduling Optimization

We consider an optimization problem which optimizes $\mathbf{w}_k$ and $\mathbf{p}_k$, $k = 1, \cdots, K$, to minimize the total transmit power whereas the individual capacity requirement of each user is satisfied, i.e.,

[Problem 1]

$$\begin{aligned} &\min_{\mathbf{w}_k, \mathbf{p}_k, \forall k} \sum_{k=1}^{K} ||\mathbf{w}_k||^2 \\ \text{s.t.} \;\; & p_{q_k} B \log_2 \left(1 + \frac{|\mathbf{h}_{q_k}^{\mathrm{H}} \mathbf{w}_k|^2}{\sum_{l \neq k}^{K} |\mathbf{h}_{q_k}^{\mathrm{H}} \mathbf{w}_l|^2 + \sigma_n^2} \right) \geq \tilde{C}_{q_k}, \forall k, \forall q, \\ & \mathbf{p}_k \geq \mathbf{0}, \; \mathbf{1}^{\mathrm{T}} \mathbf{p}_k = 1, \; \forall k, \end{aligned} \tag{9}$$

where $\tilde{C}_{q_k}$ denotes the minimum capacity requirement for the qth user in the kth cell. The problem is feasible when the total realized transmit power satisfies $\sum_{k=1}^{K} ||\mathbf{w}_k||^2 \leq \tilde{P}$, where $\tilde{P}$ is the maximum allowed transmit power.

Because of the coupling of the precoder and the scheduling coefficients, the above optimization is highly non-convex and NP-hard. In the following, we simplify the problem by iteratively optimize the precoding vectors $\mathbf{w}_k$ and the scheduling vectors $\mathbf{p}_k, \forall k$.

A. Optimization of Precoding Vectors

We first optimize the precoding vectors, $\mathbf{w}_k, k = 1, \cdots, K$, using the semidefinite relaxation (SDR) approach. For each cell, the initial values of p_{q_k}, $q = 1, ..., Q$, are chosen to be proportional to the required user capacity, expressed as

$$p_{q_k} = \frac{\tilde{C}_{q_k}}{\sum_{q'=1}^{Q} \tilde{C}_{q'_k}}. \tag{10}$$

Define $\mathbf{X}_k = \mathbf{w}_k \mathbf{w}_k^{\mathrm{H}}$ as the transmit covariance matrix of the beamformer toward the kth cell, and the corresponding transmit power is given as $\mathbf{w}_k^{\mathrm{H}} \mathbf{w}_k = \mathrm{trace}(\mathbf{X}_k)$. Further, we denote $\mathbf{Z}_{q_k} = \mathbf{h}_{q_k} \mathbf{h}_{q_k}^{\mathrm{H}}$, and let $\tilde{\gamma}_{q_k} = 2^{\tilde{C}_{q_k}/(p_{q_k} B)} - 1$ to be the required output SINR. Then, Problem 1 can be reformulated as:

[Problem 1a]

$$\begin{aligned} &\min_{\mathbf{X}_k, \forall k} \sum_{k=1}^{K} \mathrm{trace}(\mathbf{X}_k) \\ \text{s.t.} \;\; & \mathrm{trace} \left(\mathbf{Z}_{q_k} \left(\frac{1}{\tilde{\gamma}_{q_k}} \mathbf{X}_k - \sum_{l \neq k}^{K} \mathbf{X}_l \right) \right) - \sigma_n^2 \geq 0, \forall k, \forall q, \\ & \mathbf{X}_k \succeq \mathbf{0}, \; \mathrm{rank}(\mathbf{X}_k) = 1, \; \forall k. \end{aligned} \tag{11}$$

Problem 1a can be relaxed into a convex problem by dropping the rank-1 constraint, yielding the following semidefinite programming problem:

[Problem 1a′]

$$\begin{aligned} &\min_{\mathbf{X}_k, \forall k} \sum_{k=1}^{K} \mathrm{trace}(\mathbf{X}_k) \\ \text{s.t.} \;\; & \mathrm{trace} \left(\mathbf{Z}_{q_k} \left(\frac{1}{\tilde{\gamma}_{q_k}} \mathbf{X}_k - \sum_{l \neq k}^{K} \mathbf{X}_l \right) \right) - \sigma_n^2 \geq 0, \forall k, \forall q, \\ & \mathbf{X}_k \succeq \mathbf{0}, \; \forall k. \end{aligned} \tag{12}$$

When the rank of the obtained solution of $\mathbf{X}_k$ is 1, the precoding vector $\mathbf{w}_k$ is obtained as the primary eigenvector of $\mathbf{X}_k$. On the other hand, when the obtained rank is higher than 1, Gaussian randomization is commonly used to obtain the closest rank-1 solution [10].

B. Optimization of Scheduling Vectors

After the precoding vectors $\mathbf{w}_k, k = 1, \cdots, K$, are obtained, we turn to the optimization of the scheduling vectors, $\mathbf{p}_k, k = 1, \cdots, K$. Denote

$$\theta_{q_k} = B \log_2 \left(1 + \frac{|\mathbf{h}_{q_k}^{\mathrm{H}} \mathbf{w}_k|^2}{\sum_{l \neq k}^{K} |\mathbf{h}_{q_k}^{\mathrm{H}} \mathbf{w}_l|^2 + \sigma_n^2} \right) \tag{13}$$

as the capacity of the qth user in the kth cell if it is activated, where $\mathbf{w}_k$ and $\mathbf{w}_l$ are the precoder vectors obtained in the previous subsection. Thus, given the activation proportion p_{q_k}, the achieved capacity of this user is given by $\theta_{q_k} p_{q_k}$.

For each cell k, the optimization of $\mathbf{p}_k$ is to allocate the users' active time share such that their capacity requirements are satisfied in an efficient manner, while the entire time slot is fully utilized. Toward this end, we first minimize the value of $\mathbf{1}^{\mathrm{T}} \mathbf{p}_k$ while meeting the capacity requirement for each user, and then scale the time share distribution proportionally.

The optimization problem of the scheduling vectors is separately formulated for each cell k, expressed as

[Problem 1b]

$$\begin{aligned} &\min_{\mathbf{p}_k} \mathbf{1}^{\mathrm{T}} \mathbf{p}_k \\ \text{s.t.} \;\; & \theta_{q_k} p_{q_k} - \tilde{C}_{q_k} \geq 0, \quad \forall q_k, \\ & p_{q_k} \geq 0, \quad \forall q_k. \end{aligned} \tag{14}$$

It is clear that the solution to this problem is simply given as $p_{q_k} = \tilde{C}_{q_k} / \theta_{q_k}$ for each q_k.

After we obtain the values of $\mathbf{p}_k, k = 1, \cdots, K$, with the sum of it elements being smaller than 1, we proportionally scale the obtained results by $\mathbf{p}_k \leftarrow \mathbf{p}_k / (\mathbf{1}^{\mathrm{T}} \mathbf{p}_k)$ so that $\mathbf{1}^{\mathrm{T}} \mathbf{p}_k = 1$ is maintained to keep the cell frame time fully utilized.

The optimization steps of the precoding vectors and scheduling vectors, as depicted in Problem 1a and Problem 1b, are iterated. Convergence is typically achieved in 2 to 3 iterations.

IV. Alternative Optimization Using Signal-to-Leakage Ratio

In the above discussion, the original precoder optimization problem in (9) is relaxed into a convex $\text{Problem 1a}'$ in (12), but its computational complexity remains high because it involves all precoders corresponding to the K cells. An alternative approach is to use the output signal-to-leakage ratio (SLR) [14], [15], in lieu of the output SINR, in the precoder optimization. Toward this end, we change Problem 1 in (9) as

[Problem 2]

$$\begin{aligned}&\min_{\mathbf{w}_k,\mathbf{p}_k,\forall k}\sum_{k=1}^{K}||\mathbf{w}_k||^2\\ \text{s.t.}\ \ & p_{q_k}B\log_2\left(1+\frac{|\mathbf{h}_{q_k}^{\rm H}\mathbf{w}_k|^2}{\sum_{l\neq k}^{K}|\mathbf{h}_{q_l}^{\rm H}\mathbf{w}_k|^2+\sigma_n^2}\right)\geq\tilde{C}_{q_k},\forall k,\forall q,\\ &\mathbf{p}_k\geq\mathbf{0},\ \mathbf{1}^{\rm T}\mathbf{p}_k=1,\ \forall k,\end{aligned} \quad (15)$$

in which only a single precoding vector $\mathbf{w}_k$ is involved.

We follow the similar approach as in solving Problem 1 by dividing the problem into two separate subproblems, one solving the precoding vectors, and the other solving the scheduling vectors.

When considering the precoder optimization, the weight vectors can be individually optimized for each cell. We similarly compute the value $\tilde{\gamma}_{q_k}$ based on the required user capacity and the assumed ratio of time share. One needs to optimize the following K parallel optimization problems for $k=1,\cdots,K$, thus leading to a lower complexity as compared to Problem 1a:

[Problem 2a]

$$\begin{aligned}&\min_{\mathbf{w}_k}||\mathbf{w}_k||^2\\ \text{s.t.}\ \ &\frac{|\mathbf{h}_{q_k}^{\rm H}\mathbf{w}_k|^2}{\sum\limits_{l\neq k}^{K}|\mathbf{h}_{q_l}^{\rm H}\mathbf{w}_k|^2+\sigma_n^2}\geq\tilde{\gamma}_{q_k},\quad\forall q.\end{aligned} \quad (16)$$

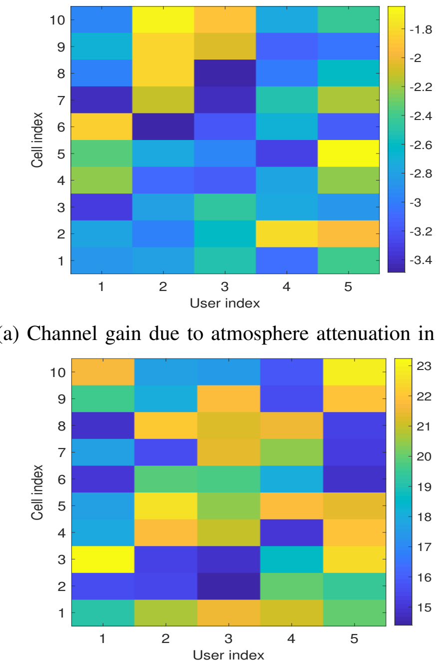
Note that the constrain in the above expression can be reformulated as

$$\mathbf{w}_k^H\left(\frac{1}{\tilde{\gamma}_{q_k}}\mathbf{Z}_{q_k}-\sum_{l\neq k}^{K}\mathbf{Z}_{q_l}\right)\mathbf{w}_k\geq\sigma_n^2,\quad\forall q. \quad (17)$$

By using the SDR with the same notations used in the previous section, the above optimization problem becomes:

[Problem 2a$'$]

$$\begin{aligned}&\min_{\mathbf{X}_k}\text{trace}(\mathbf{X}_k)\\ \text{s.t.}\ \ &\text{trace}\left(\left(\left(\frac{1}{\tilde{\gamma}_{q_k}}\mathbf{Z}_{q_k}-\sum_{l\neq k}^{K}\mathbf{Z}_{q_l}\right)\mathbf{X}_k\right)\geq\sigma_n^2,\ \forall q,\\ &\mathbf{X}_k\succeq\mathbf{0}.\end{aligned} \quad (18)$$



(a) Channel gain due to atmosphere attenuation in dB

(b) Required capacity in Mbps for all users

Fig. 2. Example of channel gain and required capacity.

After obtaining $\mathbf{w}_k$, we can continue to obtain θ_{q_k} as defined in (13), and then proceed with Problem 1b to optimize the scheduling vectors, $\mathbf{p}_k, k=1,\cdots,K$.

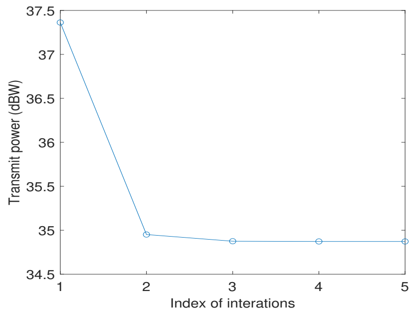
According to [10], in each iteration, the computational complexity for solving $\text{Problem 1a}'$ in (12) is $O(K^3N^6)$, whereas that for solving $\text{Problem 2a}'$ in (18) is $O(KN^6)$, thus yielding a significant reduction of the computational complexity.

V. Simulation Results

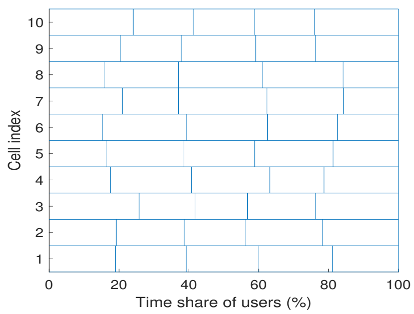
For the convenience of presentation, we consider a simplified satellite system model with $N=15$ antennas that are linearly placed with 6 wavelengths apart. The carrier frequency is 10 GHz, and the signal bandwidth is 36 MHz. $K=10$ cells are linearly separated by 0.63$^{\rm o}$ looking from the satellite (or approximately 393.5 km on ground). There are $Q=5$ users in each cell, which are randomly placed with the respective cell. The satellite transmit antenna gain is 4.5 dB, and the ground receive antenna gain is 41 dB. The receiver noise temperature is assumed to be 150 K.

As we discussed earlier, users in the same cell have similar spatial signatures but they may experience different atmosphere attenuations. Fig. 2(a) illustrates the additional channel gain α_{q_k} due to atmosphere attenuation, shown as negative dB values. Fig. 2(b) shows the required user capacity in Mbps.

Fig. 3(a) shows the optimized transmit power with respect to the index of iterations after solving $\text{Problems 1a}'$ and 1b. It is clear that the transmit power converges as the optimization optimizes, and its value is very close to the optimum solution in the second iteration. During the optimization, the rank of $\mathbf{X}_k$ is always one, implying the optimality of the SDR ap-

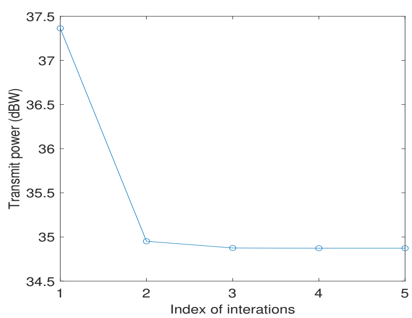


(a) Convergence of the transmit power in dBW

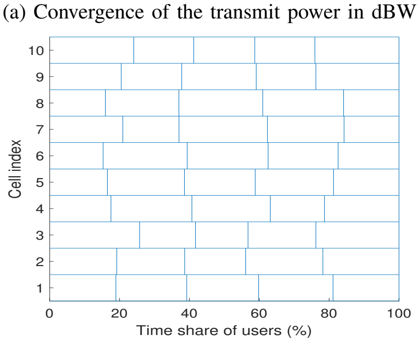


(b) Scheduling diagram after convergence

Fig. 3. Results based on output SINR optimization (Problems $1a'$ and $1b$)



(a) Convergence of the transmit power in dBW



(b) Scheduling diagram after convergence

Fig. 4. Results based on output SLR optimization (Problems $2a'$ and $1b$)

proach in this case. Fig. 3(b) shows the optimized scheduling diagram after the convergence.

Figs. 4(a) and 4(b) show the optimized transmit power with respect to the index of iterations and the optimized scheduling diagram after solving Problems $2a'$ and $1b$. The results closely resemble to those depicted in Fig. 3. During the optimization, the rank of $\mathbf{X}_k$ remains one.

VI. Conclusion

In this paper, we have considered the joint optimization of the precoding and scheduling schemes in a downlink multicell satellite communication system. The problem is first considered to satisfy each user's capacity requirement while minimizing the signal power transmitted from the satellite. The optimization problem is formulated and relaxed into a linear programming problem and is effectively solved. We also develop an SLR-based approach to separately enable parallel optimization for each cell. Simulation results are provided to verify the effectiveness of these methods, and similar performance is achieved for both user capacity- and SLR-based methods.

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