JOINT CARRIER ALLOCATION AND PRECODING OPTIMIZATION FOR INTERFERENCE-LIMITED GEO SATELLITE

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Abstract

The rise of flexible payloads on satellites opens a door for controlling satellite resources according to the user demand, user location, and satellite position. In addition to resource management, applying precoding on flexible payloads is essential to obtain high spectral efficiency. However, these cannot be achieved using a conventional resource allocation algorithm that does not consider the user demand. In this paper, we propose a demand-aware algorithm based on multiobjective optimization to jointly design the carrier allocation and precoding for better spectral efficiency and demand matching with proper management of the satellite resources. The optimization problem is non-convex, and we solve it using convex relaxation and successive convex approximation. Then, we evaluate the performance of the proposed algorithm through numerical results. It is shown that the proposed method outperforms the benchmark schemes in terms of resource utilization and demand satisfaction.

1 Introduction

Modern satellite communication systems employ multi-beam technologies in order to provide broadcast and broadband internet services to urban, rural, and remote areas [1]. Traditional satellites utilize conventional payloads, such that the bandwidth, the carrier frequency, and the transmit power of the transponder are fixed during the lifetime of the satellite. However, this is inefficient in terms of resource management because of the demand and channel variations over time. Nowadays, operators invest in advanced payload technologies with reconfiguration capability to properly manage the satellite resources according to the user demands [2], [3]. This emerging technology opens a door for a substantially higher efficiency of resource utilization [4]. Furthermore, precoding techniques should be applied to flexible payloads to mitigate the interference signals from aggressive frequency reuse [5]. Hence, we can obtain high spectral efficiency.

In the above context, the performance of linear precoding for satellite communication systems has been studied in [6]. Furthermore, precoding design with respect to user fairness has been considered in [7]. Similarly, precoding optimization by taking into account sum-rate capacity with the concept of frame-based precoding has been studied in [8]. In [9]-[11], energy-efficient precoding optimization for satellite communication has been investigated to minimize the total transmit power while preserving the quality of service. In [12], a comparison has been performed among full-precoding, without precoding, and partial precoding. However, the above methods focus on a single-carrier operation that utilizes the total bandwidth of the system.

In this paper, we consider a resource-efficient multi-carrier operation with precoding optimization to increase the energy efficiency, spectral efficiency, bandwidth utilization, and demand matching of the system. While joint carrier and power allocation have been addressed in the literature (e.g. [13]-[17]), the focus of this paper is to study the synergy between carrier allocation and precoding. The contribution of this paper as follows:

- Firstly, we formulate a multi-objective function for interference and resource-limited geostationary (GEO) satellite systems to jointly design the carrier allocation and precoding matrix.
- Secondly, we propose an optimization problem to minimize the number of carrier allocations and the power consumption while matching the user demand.
- Finally, we compare the performance of the proposed method with the existing benchmark schemes through extensive numerical results. We observe that the proposed method provides high demand satisfaction with lower power consumption and less number of carriers than the benchmark schemes.

The remainder of this paper is organized as follows. Section 2 covers the system model and the problem formulation. Section 3 describes the proposed solution to the problem. Finally, the simulation results and conclusion are presented in Section 4 and Section 5, respectively.

Notation: The boldface of lower case letters represents a vector. The symbol $\lceil . \rceil$ represents the ceiling function. Furthermore, the second norm of a vector and conjugate transpose of a vector are represented by $\|.\|_2$ and $[.]^H$, respectively.

2. System Model and Problem Formulation

We consider a downlink GEO satellite which comprises N overlapping beams and K carriers with sub-carrier bandwidth $B_{\text{sc}} = \frac{B_{\text{total}}}{K}$, where B_{total} is the total bandwidth of the system. We defined the set of carriers as $\mathcal{K} = \{1,2,\dots,K\}$. Furthermore, we assume a single user per beam to represent the total demand per beam. We denote the channel vector from the satellite ith beam over the kth carrier as $\mathbf{h}_{i,k} \in \mathbb{C}^{N\times 1}$. The corresponding precoding vector is defined as $\mathbf{w}_{i,k} \in \mathbb{C}^{N\times 1}$. Then, the signal-to-interference-plus-noise ratio (SINR) experienced by the ith user is given by

$$\gamma_{i,k} = \frac{|\mathbf{h}_{i,k}^H \mathbf{w}_{i,k}|^2}{\sum_{j=1,j\neq i}^{N} |\mathbf{h}_{i,k}^H \mathbf{w}_{j,k}|^2 + N_0 B_{\text{sc}}} \qquad (1)$$

where N_0 is the noise spectral density. Hence, the offered capacity to user i is

$$C_i = \sum_{k=1}^{K} x_{i,k} B_{\text{sc}} \log_2(1+\gamma_{i,k}). \qquad (2)$$

where $x_{i,k} \in \{0,1\}$ is a binary carrier allocation variable, i.e. $x_{i,k} = 1$ indicates the kth carrier is allocated to ith beam. Finding the values of $x_{i,k}, \forall_{i,k}$ is a combinatrial problem which typically requires computationally expensive full search. Hence, to reduce the computational complexity, we consider a lower bound of (2) by assuming a flat fading channel[1] as $C_i = K_i \min_k\{B_{\text{sc}}\log_2(1+\gamma_{i,k})\}$, with $K_i \in \mathcal{K}$, where K_i refers to the number of carriers required by the user in beam i. With this assumption, we can formulate the optimization problem to design $\mathbf{w}_{i,k}$ and determine the value of K_i so that the system offered capacity C_i can be matched with the user demand D_i. The optimization problem is formulated as follows

$$\begin{aligned}
\underset{\substack{K_i,\\ \mathbf{w}_{i,k},\forall_{i,k}}}{\text{minimize}} \quad & C_{\text{unmet}} + \frac{1}{K}\sum_{i=1}^{N} K_i + \frac{1}{P_{\text{total}}}\sum_{i=1}^{N}\sum_{i=1}^{K} \| \mathbf{w}_{i,k} \|_2^2 \\
\text{s.t.} \quad & V1: \gamma_{i,k} \geq \gamma^{\min}, \forall_{i,k}, \\
& V2: \sum_{i=1}^{N}\sum_{i=1}^{K} \| \mathbf{w}_{i,k} \|_2^2 \leq P_{\text{total}}, \qquad (3) \\
& V3: \sum_{i=1}^{K} \| \mathbf{w}_{i,k} \|_2^2 \leq P_{\max}, \forall_i, \\
& V4: K_i \in \mathcal{K}, \forall_i
\end{aligned}$$

where the normalized unmet system capacity C_{unmet} is given by

$$C_{\text{unmet}} = \sum_{i=1}^{N} \max(1 - C_i/D_i, 0). \qquad (4)$$

Remarks:

- $V1$ constraint specifies the minimum system SINR requirement $\gamma^{\min}$.
- $V2$ limits the overall transmit power from exceeding the system available total power P_{total}.
- $V3$ assures the transmit power per beam does not exceed the maximum power per beam $P_{\max}$.
- Finally, $V4$ is a set constraint for the number of carrier allocation K_i.

3 Proposed Solution

First, we equivalently replace the unmet system capacity by introducing upper bound slack variable s_i for $s_i \geq 0$ and $s_i \geq 1 - C_i/D_i$. Second, we replace the function $\min_k\{B_{\text{sc}}\log_2(1+\gamma_{i,k})\}$ by lower bound slack variable ϕ_i with $C_i = K_i\phi_i$ for $\phi_i \leq B_{\text{sc}}\log_2(1+\gamma_{i,k})$ and $\phi \geq 0$. Finally, we decouple the $\gamma_{i,k}$ from the $\log_2(1+\gamma_{i,k})$ by replacing it with a lower bond slack variable $\Gamma_{i,k}$ for $\Gamma_{i,k} \leq \gamma_{i,k}$ and $\Gamma_{i,k} \geq \gamma^{\min}$. Then, the equivalent re-formulation problem of (3) is given by

$$\begin{aligned}
\underset{\substack{K_i,s_i,\\ \mathbf{w}_{i,k},\forall_{i,k}}}{\text{minimize}} \quad & \sum_{i=1}^{N} s_i + \frac{1}{K}\sum_{i=1}^{N} K_i + \frac{1}{P_{\text{total}}}\sum_{i=1}^{N}\sum_{i=1}^{K} \| \mathrm{w}_{i,k} \|_2^2 \\
\text{s.t.} \quad & V1: \Gamma_{i,k} \geq \gamma^{\min}, \forall_{i,k}, \\
& V2, V3, V4, \\
& V5: 1 - \frac{K_i\phi_i}{D_i} \leq s_i, \forall_i, \qquad (5) \\
& V6: \phi_i - B_{sc}\log_2\left(1+\Gamma_{i,k}\right) \leq 0, \forall_{i,k}, \\
& V7: \Gamma_{i,k} \leq \gamma_{i,k}, \forall_{i,k}, \\
& V8: s_i \geq 0, \forall_i, \\
& V9: \phi_i \geq 0, \forall_i.
\end{aligned}$$

3.1 Problem convexification

Unfortunately, the integer constraint $V4$, the product part of $V5$, and the fractional part $\gamma_{i,k}$ of $V7$ are still non-convex. To convexify the problem, first, we relax the constraint $V4$ to be continuous between 1 and K, i.e $1 \leq K_i \leq K$. Then, we re-arrange the constraints $V5$ and $V7$ in the form of the Difference Convex (DC) program [18]. The DC program can be tackled using the Successive Convex Approximation (SCA) method to iteratively solve the problem [19]. The DC form of $V5$ and $V7$ is provided as follows:

$$\tilde{V}5: 1 - s_i + \frac{(K_i-\phi_i)^2}{4D_i} - \frac{(K_i+\phi_i)^2}{4D_i} \leq 0, \forall_i, \qquad (6)$$

$$\tilde{V}7: \sum_{j=1,j\neq i}^{N} |\mathbf{h}_{i,k}^H \mathbf{w}_{j,k}|^2 + N_0 B_{\text{sc}} - \frac{|\mathbf{h}_{i,k}^H \mathbf{w}_{i,k}|^2}{\Gamma_{i,k}} \leq 0, \forall_{i,k}.$$

[1] In GEO satellites, the channel across different carriers does not fluctuate much. Such that this assumption is justified.

where $1 - s_i + \frac{(K_i-\phi_i)^2}{4D_i}$, $\frac{(K_i+\phi_i)^2}{4D_i}$, and $\sum_{j=1,j\neq i}^{N} |\mathbf{h}_{i,k}^H \mathbf{w}_{j,k}|^2 + N_0 B_{\mathrm{sc}}$, $\frac{|\mathbf{h}_{i,k}^H \mathbf{w}_{i,k}|^2}{\Gamma_{i,k}}$ are the respective convex functions. The SCA algorithm can be applied to solve the DC program by approximating the concave part of $\tilde{V}5$ and $\tilde{V}7$. The first-order approximation of $\tilde{V}5$ and $\tilde{V}7$ is given by

$$\hat{V}5: 1 - s_i + \frac{(K_i-\phi_i)^2}{4D_i} + f_1(K_i,\phi_i) \leq 0, \forall_i, \qquad (7)$$

$$\hat{V}7: \sum_{j=1,j\neq i}^{N} |\mathbf{h}_{i,k}^H \mathbf{w}_{j,k}|^2 + N_0 B_{\mathrm{sc}} + f_2(\mathbf{w}_{i,k},\Gamma_{i,k}) \leq 0, \forall_{i,k},$$

$$f_1(K_i,\phi_i) = -\frac{(K_i^{(l)}+\phi_i^{(l)})^2}{4D_i} - \frac{(K_i^{(l)}+\phi_i^{(l)})(K_i+\phi_i-K_i^{(l)}-\phi_i^{(l)})}{2D_i} \qquad (8)$$

$$f_2(\mathbf{w}_{i,k},\Gamma) = -\frac{|\mathbf{h}_{i,k}^H \mathbf{w}_{i,k}^{(v)}|^2}{\Gamma_{i,k}^{(v)}} + \frac{|\mathbf{h}_{i,k}^H \mathbf{w}_{i,k}^{(v)}|^2}{(\Gamma_{i,k}^{(v)})^2}\left(\Gamma_{i,k} - \Gamma_{i,k}^{(v)}\right) - \frac{2\Re\{(\mathbf{w}_{i,k}^{(v)})^H \mathbf{h}_{i,k}\mathbf{h}_{i,k}^H(\mathbf{w}_{i,k}-\mathbf{w}_{i,k}^{(v)})\}}{\Gamma_{i,k}^{(v)}}. \qquad (9)$$

where $f_1(K_i,\phi_i)$ is shown (8), and $f_2(\mathbf{w}_{i,k},\Gamma_{i,k})$ is shown (9) are the first-order approximation of $-\frac{(K_i+\phi_i)^2}{4D_i}$ and $-\frac{|\mathbf{h}_{i,k}^H \mathbf{w}_{i,k}|^2}{\Gamma_{i,k}}$, respectively. From (8), the $K_i^{(l)}$ and $\phi_i^{(l)}$ are the previous values of K_i and ϕ_i, respectively, used in the lth iteration of SCA algorithm. Similarly, From (9), the $\Gamma_{i,k}^{(l)}$ and $\mathbf{w}_{i,k}^{(l)}$ are the previous value of $\Gamma_{i,k}$ and $\mathbf{w}_{i,k}$, respectively, used in the lth iteration of the SCA algorithm. Finally, the problem of (5) becomes

$$\underset{\substack{K_i,s_i,\\ \mathbf{w}_{i,k},\forall_{i,k}}}{\text{minimize}} \quad \sum_{i=1}^{N} s_i + \frac{1}{K}\sum_{i=1}^{N} K_i + \frac{1}{P_{\mathrm{total}}}\sum_{i=1}^{N}\sum_{i=1}^{K} \| \mathbf{w}_{i,k} \|_2^2$$
$$\text{s.t.} \quad V1, V2, V3, V4, \hat{V}5, V6, \hat{V}7, V8, V9 \qquad (10)$$

The SCA algorithm to solve (10) is shown in Algorithm 1. First, we initialize the variables $\phi_i^{(l)}$, $\Gamma_{i,k}^{(l)}$, and $\mathbf{w}_{i,k}^{(l)}$ to a feasible point. By assuming $s_i = 0$, we initialize $K_i^{(l)} = 1$ and $\phi^{(l)} = 1$. Further, $\mathbf{w}_{i,k}^{(l)}$ is initialized using MMSE precoder assuming the sub-carrier bandwidth B_{sc} and the total transmit power per carrier $\frac{P_{\mathrm{total}}}{K}$. Accordingly, $\Gamma_{i,k}^{(l)}$ is initialized using (1). Subsequently, the algorithm solves (10) for the next iteration to obtain a new point of ϕ_i, $\Gamma_{i,k}$, and $\mathbf{w}_{i,k}$. Consequently, the value of $\phi_i^{(l)}$, $\Gamma_{i,k}^{(l)}$, and $\mathbf{w}_{i,k}^{(l)}$ are updated by the new value of ϕ_i, $\Gamma_{i,k}$, and $\mathbf{w}_{i,k}$, respectively. The algorithm updates these variables until the error difference between $\Gamma_{i,k}^{(l+1)}$ and $\Gamma_{i,k}^{(l)}$ becomes very small (10^{-4} in this work). Finally, we obtain the required number of carrier K_i and precoding matrix $\mathbf{w}_{i,k}$. Note that the solution K_i may have decimal values. Hence, K_i is approximated to $\widetilde{K}_i = \lceil K_i - \zeta \rceil$, where the variable $\zeta \in \mathbb{R}$ is chosen in order to maximize the system performance (4). Furthermore, the carrier $x_{i,k}$ is obtained from $\widetilde{K}_i$ using Contiguous Carrier Assignment (CCA) [16].

Algorithm 1: Joint Carrier Allocation and Precoding Optimization

Input: feasible point ;
$\Gamma_{i,k}^{(l)} = \frac{|\mathbf{h}_{i,k}^H \mathbf{w}_{i,k}^{(l)}|^2}{\sum_{j=1,j\neq i}^{N} |\mathbf{h}_{i,k}^H \mathbf{w}_{j,k}^{(l)}|^2 + N_0 B_{\mathrm{sc}}}$;
$v \leftarrow 0$;
repeat
    $l \leftarrow l + 1$;
    Solve (10) to obtain $\Gamma_{i,k}$, $\mathbf{w}_{i,k}$, K_i, and ϕ_i ;
    Update $\Gamma_{i,k}^{(l)} = \Gamma_{i,k}$, $\mathbf{w}_{i,k}^{(l)} = \mathbf{w}_{i,k}$, $K_i^{(l)} = K_i$, and $\phi_i^{(l)} = \phi_i$;
until $\{\sum_{i=1}^{N}\sum_{k=1}^{K} \left|\Gamma_{i,k}^{(l+1)} - \Gamma_{i,k}^{(l)}\right| \leq 10^{-4}\}$;
Output: $\widetilde{K}_i = \lceil K_i - \zeta \rceil$;
Output: $\mathbf{w}_{i,k}, \forall_{i,k}$;

3 Simulation Results

In this section, we evaluate the performance of the proposed Joint Carrier allocation and Precoding Optimization (JCPO) method through simulations. Table 1 refers to the simulation parameters. Furthermore, all the simulation results are obtained by averaging from $M = 100$ Monte Carlo runs. For each run, a user location is selected from uniform distribution within the considered beam coverage.

Table 1 System Parameters

Parameter	Value
Satellite Orbit	13°E
Satellite Beam Pattern	Provided by ESA
Number of beams (N)	20
System bandwidth (B_{total})	500 MHz
Number of carrier (K)	8
Minimum SINR ($\gamma^{\min}$)	−2.2 dB
Noise power density (N_0)	−204 dBW/Hz
Max. beam gain ($G_i[j]$)	51.8 dBi
User antenna gain (G_R)	39.8 dBi
Total available transmit power (P_{total})	500 W
Maximum power per beam ($P_{\max}$)	100 W
Auxiliary variable (ζ)	0.1

We considered the following benchmarks schemes [12]:

- 1-Color full bandwidth with precoding scheme (1-Color with precoding):

$$C_i = B_{\mathrm{total}} R_i \qquad (11)$$

with

$$R_i = \log_2\left(1 + \frac{|\mathbf{h}_i^H \mathbf{w}_i|^2}{\sum_{j=1,j\neq i}^{N} |\mathbf{h}_i^H \mathbf{w}_j|^2 + N_0 B_{\mathrm{total}}}\right),$$

where $\mathbf{h}_i \in \mathbb{C}^{N\times 1}$ is the ith channel vector, and $\mathbf{w}_i \in \mathbb{C}^{N\times 1}$ is the ith MMSE precoding vector.

- 4-Color scheme without precoding (4-Color w/o precoding)

$$C_i = B_c R_i \qquad (12)$$

with

$$R_i = \log_2\left(1 + \frac{|h_{i,i}|^2 x_{k,i} p_i}{\sum_{j=1,j\neq i}^{N} |h_{i,j}|^2 x_{k,j} p_j + N_0 B_c}\right)$$

where $B_c = \frac{B_{\text{total}}}{4}$ is the bandwidth chunk per color, $p[i] = \frac{P_{\text{total}}}{N}$ is the ith transmitted power and $x_k[i] \in \{0,1\}$, $k = 1,2,3,4$ with $x_k[i] = 1$ indicates that the kth color is assigned to the ith beam.

The performance of the proposed method is evaluated with respect to:

- Average Unmet System Capacity (AUSC):

$$\frac{1}{NM}\sum_{m=1}^{M}\sum_{n=1}^{N} \max(D_i - C_i[m], 0), \qquad (13)$$

where $C_i[m]$ is offered capacity to beam i at mth Monte Carlo run.

- Average Bandwidth Utilization (ABU):

$$\frac{1}{M}\sum_{m=1}^{M} B_{\text{sc}} \max\{\widetilde{K}_i[m], \forall_i\}, \qquad (14)$$

where $\widetilde{K}_i[m]$ is the number of carriers allocated to ith beam at mth Monte Carlo run.

- Average Used Carriers (AUC):

$$\frac{1}{M}\sum_{m=1}^{M} \max\{\widetilde{K}_i[m], \forall_i\}, \qquad (15)$$

- Average Power Consumption (APC):

$$\frac{1}{M}\sum_{m=1}^{M}\sum_{i=1}^{N} \| \mathbf{w}_{i,k}[m] x_{i,k}[m] \|_2^2, \qquad (16)$$

where $\mathbf{w}_{i,k}[m]$ and $x_{i,k}[m]$ are the transmit power and the kth carrier allocation for beam i at mth Monte Carlo run.

Fig. 1 shows the unmet system capacity of all schemes. We observe the JCPO have zero unmet system capacity for demand below 1 Gbps, whereas for 1-color with precoding and 4-color w/o precoding have zero unmet system capacity for a demand below 0.8 Gbps and 0.5 Gbps, respectively. Furthermore, the unmet system capacity of JCPO for demand above 1 Gbps is less than the benchmark schemes. Hence, the overall unmet system capacity of the proposed scheme is less than the benchmark schemes. This lower unmet system capacity results because the proposed method jointly optimizes the carrier allocation and precoder matrix according to the demand. In contrast, no optimization according to the demand is employed in the benchmark schemes, resulting in high unmet system capacity.

Fig. 2 shows the bandwidth utilization of the JCPO and the benchmark schemes. The JCPO has better bandwidth utilization for demand below 1.1 Gbps, while the benchmark schemes utilize the system's total bandwidth. Furthermore, we observe less bandwidth is required for low demand, and the bandwidth allocation increases as the demand increase. Hence, the JCPO allocates bandwidth according to the demand.

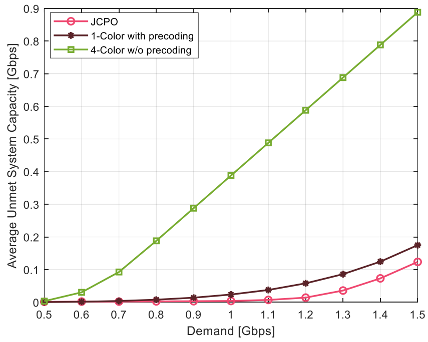

Fig. 1. Average Unmet system Capacity

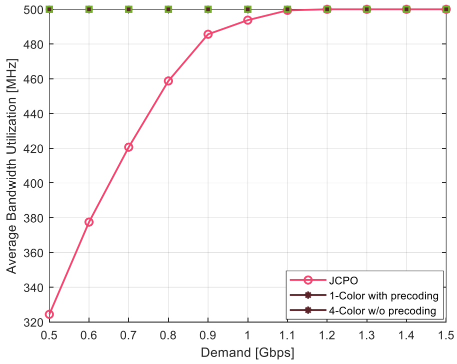

Fig. 2. Average Bandwidth Utilization

Table 2 shows the number of carriers used on average versus a demand. We observe that for lower demand, less number of carriers is allocated. For example, to satisfy 0.5 Gbps demand, 65% of the total number of carriers is required. However, as the demand increases, the number of utilized carriers increases.

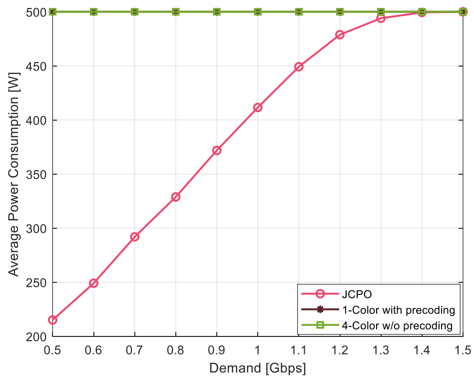

Fig. 3. Average Power Consumption

Fig. 3 shows the power allocation of all schemes. Similar to Fig. 2, the overall power consumption of the proposed method is less than the benchmark schemes. Additionally, the JCPO allocates less power for lower demand, and the power consumption increases as the demand increases. In contrast, the benchmark schemes consumes the system's total power irrespective of the user demand.

Table 2 Number of Carriers Versus Demand

Demand [Gbps]	0.5	0.6	0.7	0.8	0.9	1	1.1
AUC[In Percent]	65	75	84	91	97	99	100

4 Conclusion

This paper proposes a joint carrier allocation and precoding optimization for an interference-limited GEO satellite system. The nature of the multi-objective optimization problem is non-convex. Hence, we apply convex relaxation and successive convex approximation to solve the problem iteratively. The proposed method outperforms the benchmark schemes in terms of demand satisfaction and resource utilization.

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