Joint Precoding and Beam Hoping Design for Payload Power Minimization in GEO Satellite Communication Networks

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***Abstract*—This paper jointly designs the precoding and beam hoping for the GEO satellite communication systems to minimize the operating cost within a specific window time ...**

***Index Terms*—Hybrid precoding, mmWave, energy efficiency, MIMO, multi-user.**

I. Introduction

RECENTLY, SatCom has been considered as ....

A. Related Works

While ...

B. Research Contributions

We consider ...

Notations: $(\mathbf{X})^T$ and $(\mathbf{X})^H$ denote the transpose and conjugate transpose of the matrix $\mathbf{X}$, respectively; $\|\mathbf{x}\|_0$ and $\|\mathbf{x}\|$ denote the norm-0 and Euclidean norm of a vector $\mathbf{x}$, respectively.

II. System Model and Problem Formulation

A. Beam Hopping, Beam Clustering, and Precoding

Consider a forward link of a broadband multibeam satellite system with N beams serving M ground users within a window time of T time-slots. For service demand of users, the amount of data stored in satellite memory corresponding to M users, which can be represented by $\bar{Q}_1, ..., \bar{Q}_M$ (bits), should be delivered to M users not later than time-slots $\bar{T}_1, ..., \bar{T}_M$ (seconds), respectively. Due to the limit of power, the multibeam satellite can provide at most K beams in every time-lot. Denote $x_n[t]$ as a binary indicator variable where

$$x_n[t] = \begin{cases} 1, & \text{if beam } n \text{ is illuminated in time-slot } t, \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

In this system, each user can be served by a number of beams which called cluster. In addition, the user-centric clustering strategy is focused on in this work where a cluster of beams is selected per user for its transmission; hence, the different clusters due to different users might overlap. Let $\mathcal{N}$ be the set of all beams. Due to the channel nullification and the design demand, only a subset of $\mathcal{N}$ should be utilized for the transmission of a specific user. In particular, let $\mathcal{C}_m$ denote the set of beams which can be employed for serving user m if they are activated. Once a number of beams in this set are illuminated in a specific time-slot, we assume that all these beams will clustered to coordinately perform MISO transmission to user m. If beam n in $\mathcal{C}_m$ is illuminated in time-slot t, a digital precoding (DP) factor $w_{n,m}[t] \in \mathbb{C}$ is applied to the data symbol $s_m[t] \in \mathbb{C}$, intended for user m. Without loss of generality, we assume $\mathbb{E}_{s_m}\{|s_m|\} = 1$. Then, received signal at user m in time-clot t can be described as

$$z_m[t] = \sum_{j=1}^{M} \sum_{k \in \mathcal{C}_j} x_k[t] h_m^k[t]' w_{k,j}[t] s_m[t] + \eta_m[t], \tag{2}$$

where $h_j^k[t] \in \mathbb{C}$ is the channel coefficient from antenna of beam k to user j in time-slot t and $\eta_m[t] \in \mathbb{C}$ is an AWGN noise. The received signal in (2) yields the SINR at user m in time-slot t as

$$\Gamma_m[t] = \frac{\sum\limits_{n \in \mathcal{C}_m} x_n[t] \left| h_m^n[t]' w_{n,m}[t] \right|^2}{\sum\limits_{j \neq m} \sum\limits_{k \in \mathcal{C}_j} x_k[t] \left| h_m^k[t]' w_{k,j}[t] \right|^2 + \sigma_m^2}, \tag{3}$$

where σ_m^2 represents the noise power at user m.

B. DVB-S2X-standardized Discrete Rate

Following to DVB-S2X standard [1], we assume that the satellite system select one MODCOD scheme out of S candidates for the data transmission for each scheduled user during everything time slot. The MODCOD scheme can be varied over different time-slots. Once a MODCOD scheme is assigned for an user, the corresponding modulation and coding rate are applied to process the bit frame into sequence of symbols. To guarantee a predetermined block-error-rate (BLER) target for the transmission, ETSI technical report in [1]) has suggested different minimum SINR requirement for every MODCOD scheme.

Let $\mathcal{S} = \{0, \bar{\gamma}_1, \bar{\gamma}_2, ..., \bar{\gamma}_S\}$, where $0 < \bar{\gamma}_1 < \bar{\gamma}_2 < ... < \bar{\gamma}_S$, be the set of zero and S minimum SINR requirement value corresponding to S MODCOD scheme for a specific predetermined BLER target in our design, e.g., an example can be found in Table 20a-b-c in [1] for BLER target of 10^{-5}. Then, we introduce the discrete variable $g_m[t] \in \mathcal{S}$, which $g_m[t] = \bar{\gamma}_s$ means MODCOD scheme s is selected for the transmission of user m in time-slot t and $g_m[t] = 0$ implies that no transmission for user m is process within time-lot t. Denote $\mathcal{R}_{\mathsf{DVB}} = \{0, R_1, ..., R_S\}$ the set of zero value and S data

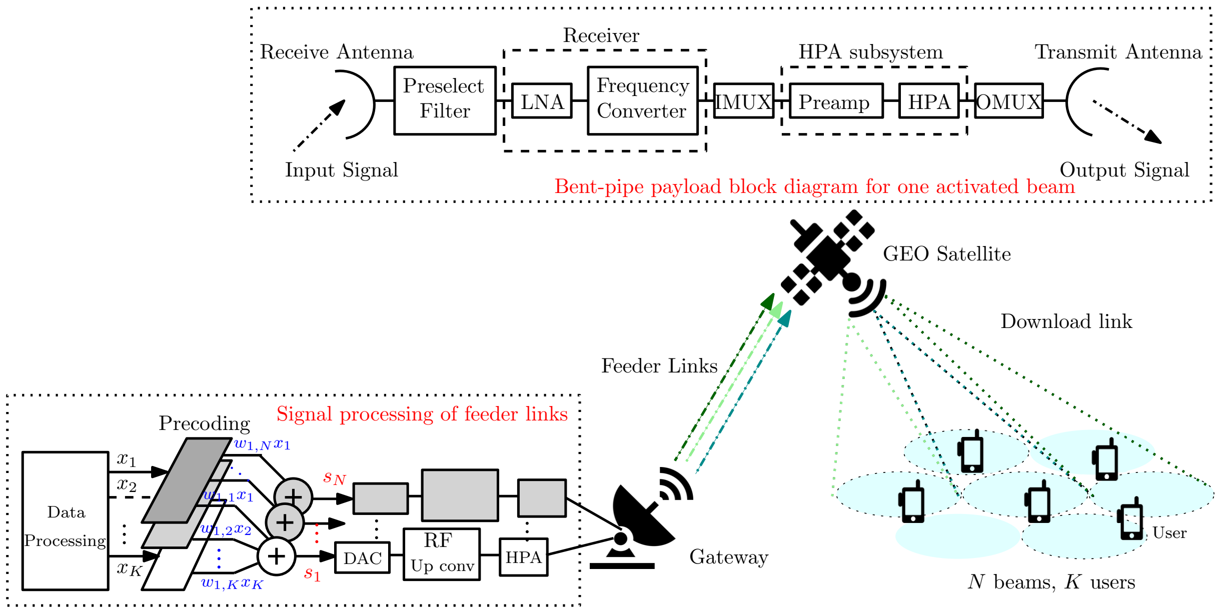

Fig. 1. Structure and Diagram of a bent-pipe multi-beam GEO satellite system.

rates corresponding to S MODCOD schemes. Let us present a mapping function $f_{\mathsf{DVB}}(x) : \mathcal{S} \mapsto \mathcal{R}_{\mathsf{DVB}}$ where

$$f_{\mathsf{DVB}}(0) = 0 \text{ and } f_{\mathsf{DVB}}(\bar{\gamma}_s) = R_s, \forall s. \quad (4)$$

Then, the achievable rate of user m in time-slot t can be calculated based on this function as $R_m[t] = f_{\mathsf{DVB}}(g_m[t])$ which yields

$$Q_m[t] = \Delta_T \sum_{j=1}^{t} f_{\mathsf{DVB}}(g_m[j]), \quad (5)$$

where $Q_m[t]$ is the total amount of data transmitted for user m after time-slot t. In addition, the corresponding SINR requirement can be transferred into the following constraint,

$$\Gamma_m[t] \geq g_m[t]. \quad (6)$$

C. Payload Power Consumption

1) Transmission Power: Let $\mathcal{M}_n$ be the set of users that can be served by beam n, i.e., $\mathcal{M}_n = \{m | n \in \mathcal{C}_m\}$. Then, the transmission power of beam n in time-slot can be expressed as

$$P_n[t] = \sum_{m \in \mathcal{M}_n} w_{n,m}[t]' w_{n,m}[t]. \quad (7)$$

It can be observed that beam n is illuminated in time-slot t if its total transmission power corresponding to time-slot t is greater than zero, and vice versa, which can be expressed as

$$x_n[t] = \|P_n[t]\|_0 = \left\| \sum_{m \in \mathcal{M}_n} w_{n,m}[t]' w_{n,m}[t] \right\|_0 \quad (8)$$

2) Operating Power: Beam transmission process requires the operation of several hardware elements, such as, pre-select filter, low-noise amplifier, frequency converter, input/output multiplexers, pre-amplifier, and high-power amplifier, etc.. Hence, along with the transmission illuminating a beam may also cost a constant power which is the total amount of all power consumption due to the components. Denote this amount as ρ_{hw}, the illumination power of the satellite can be described as

$$P_{\mathsf{illu}} = \rho_{\mathsf{hw}} \sum_{t=1}^{T} \sum_{n=1}^{N} x_n[t] = \rho_{\mathsf{hw}} \|\mathbf{x}\|_0 , \quad (9)$$

where $\mathbf{x} = [x_1[1], ..., x_N[1], ..., x_1[T], ..., x_N[T]]^T$.

D. Problem Formulation

In this paper, we focus on optimizing the precoding design and beam hopping strategy to minimize the power consumption at the satellite while delivering information payload of all user within their required time duration. This problem can be stated as

$$\min_{\mathbf{W},\mathbf{x},\mathbf{g}} \; \rho_{\mathsf{hw}} \|\mathbf{x}\|_0 + \sum_{\forall(n,t)} P_n[t] = \sum_{\forall(n,t)} (P_n[t] + \rho_{\mathsf{hw}} \|P_n[t]\|_0) \quad (10a)$$

$$\text{s. t.} \quad P_n[t] \leq \bar{P}_{\mathrm{Tx}}^{\mathrm{GEO}}, \quad \forall(n,t), \quad (10b)$$

$$\Gamma_m[t] \geq g_m[t], \quad \forall(m,t), \quad (10c)$$

$$\sum_{\forall n} \|P_n[t]\|_0 \leq K_t, \quad \forall t, \quad (10d)$$

$$x_n[t] \in \{0, 1\}, \quad \forall(n,t), \quad (10e)$$

$$Q_m[\bar{T}_m] \geq \bar{Q}_m, \quad \forall m, \quad (10f)$$

$$g_m[t] \in \mathcal{S}, \quad \forall(m,t), \quad (10g)$$

where (10b) represents the constraint on transmit power of every satellite antenna in each time-slot while (10f) stands for the data transmission latency requirement of every user. Problem (10) is a complicated long-term optimization problem. The challenges for solving problem (10) not only come from the sparse norm-ℓ_0 term in the objective function and the coupling between binary and complex variables but also that the payload delivery depends on the resource allocation strategy in each time slot.

III. Two-Level Optimization Approach

Problem (10) can be decomposed into two-level problems. The lower-level problem (LLP) aims to optimize the beam hopping and precoding design for given $\mathbf{g}$ which is equivalent to the fixed MODCOD scheme selection. The output of the LLP can be considered as the function of $\mathbf{g}$ based on which the upper-level problem (ULP) is formulated to minimize this function over the feasible space of $\mathbf{g}$. In particular, for given $\mathbf{g}$, problem (10) can be further decomposed into T LLP corresponding to T time slots as

$$\left(\mathcal{P}_t^{\mathsf{LLP}}\right) \quad \min_{\mathbf{W},\mathbf{x}} \quad \sum_{\forall(n,t)} (P_n[t] + \rho_{\mathsf{hw}} \|P_n[t]\|_0)$$
$$\text{s.t.} \quad \text{constraints (10b), (10c), (10d), (10e)} \quad (11)$$

Let $F(\mathbf{g})$ be the optimal objective value of problem (11) if it is feasible. Then, optimizing the remaining variable $\mathbf{g}$ can be fulfilled by considering the following problem

$$\left(\mathcal{P}^{\mathsf{ULP}}\right) \ \min_{\mathbf{g}} F(\mathbf{g}) \text{ s.t. constraints (10f) and (10g).} \quad (12)$$

Afterward, merging the optimal $\mathbf{g}^*$ obtained by solving ULP with the solution of LLP $\mathbf{W}^*, \mathbf{x}^*$ corresponding to $\mathbf{g}^*$ returns the optimal solution of problem (10).

A. Sparse-Precoding Design

In this section, we consider LLP $\left(\mathcal{P}_t^{\mathsf{LLP}}\right)$. As can be observed, it is NP-hard due to the the ℓ_0-norm terms in both objective function and constraint (10d) as well as the mixed integer coupling between $\mathbf{x}$ and $\mathbf{W}$ in constraint (10c). Hence, finding its globally optimal solution is prohibitively complex. In this case, an efficient (probably sub-optimal) solution is more sought instead. In what follows, we will provide such an efficient solution which employs the re-weighted ℓ_1-norm minimization method, originally proposed to enhance the data acquisition in compressed sensing. The method tends to utilize special weights on the sparsity related elements, which is updated iteratively in order to relax the ℓ_0-norm terms ℓ_1-norm form as closed as possible. Employing this method, $\|P_n[t]\|_0$ can approximate to

$$\|P_n[t]\|_0 \approx \psi_n[t]^{(k)} P_n[t], \quad (13)$$

where $\psi_n[t]^{(k)}$ is the ℓ_1-norm relaxing weight. Following the well-known way proposed in [2], one can determine $\psi_n[t]^{(k)}$ based on the value of $P_n[t]$ in the iteration k, i.e., $P_n[t]^{(k)}$, as

$$\psi_n[t]^{(k)} = \left(\frac{1}{(P_n[t]^{(k)})^2 + \varepsilon}\right)^{1/2}, \quad (14)$$

where $\varepsilon \ll 1$. By properly choosing and updating $\{\psi_n[t]^{(k)}\}$'s iteratively and exploiting the relationship among $x_n[t]$'s, $P_n[t]$'s, and $w_{n,m}[t]$'s given in (8), problem $\left(\mathcal{P}_t^{\mathsf{LLP}}\right)$ can be approximated to the following.

$$\min_{\mathbf{W}} \sum_{\forall n} \left(1 + \rho_{\mathsf{hw}} \psi_n[t]^{(k)}\right) \sum_{m \in \mathcal{M}_n} w_{n,m}[t]' w_{n,m}[t] \quad (15a)$$
$$\text{s. t.} \sum_{m \in \mathcal{M}_n} w_{n,m}[t]' w_{n,m}[t] \le \bar{P}_{\text{Tx}}^{\text{GEO}}, \quad \forall n \quad (15b)$$
$$\Gamma_m[t] \ge g_m[t], \quad \forall m, \quad (15c)$$
$$\sum_{\forall n} \psi_n[t]^{(k)} \sum_{m \in \mathcal{M}_n} w_{n,m}[t]' w_{n,m}[t] \le K_t, \quad (15d)$$

This problem is a traditional power minimization precoding design problem which can be solved effectively by employing the Semi-Definite Programming transformation as presented Appendix A.

B. Bilevel Optimization

IV. DRL-based Solution Approach

Moreover, jointly optimizing problem (10) for all T time-lots at one time is very challenging since the channel state of information (CSI) collected at the first time-slot might be updated if T is too large.

Idea: If $\mathbf{g}$ are fixed, problem (10) becomes LLP $\left(\mathcal{P}_t^{\mathsf{LLP}}\right)$ which can be solved effectively for each time-slot separately. Then, we can use DQN to find the solution for $\mathbf{g}$.

V. Simulation Results

A. Channel Model and Data Generation

1) Channel Model: In this simulation, we assume that the downlink channel coefficient from antenna of beam n to user m, $h_m^n[t]$, which varies over the time-slots, can be modeled using Rician channel model as,

$$h_m^n[t] = e^{-j\left(\frac{2\pi d(\theta_m^{\mathsf{la}},\theta_m^{\mathsf{lo}})}{\lambda} + \phi_m^n[t]\right)} \left[G_m^{\mathsf{gu}} / P_{\mathsf{loss}}\left(\theta_m^{\mathsf{la}}, \theta_m^{\mathsf{lo}}\right)\right]^{1/2} \times \left[\sqrt{\frac{L}{L+1}} b_n^{\mathsf{pa}}\left(\theta_m^{\mathsf{la}}, \theta_m^{\mathsf{lo}}\right) + \sqrt{\frac{1}{L+1}} \alpha_m^n[t]\right], \quad (16)$$

where G_m^{gu} is the antenna receiving gain of user m; $P_{\mathsf{loss}}\left(\theta_m^{\mathsf{la}}, \theta_m^{\mathsf{lo}}\right)$ denote the path-loss from satellite to user m which is estimated based on its latitude and longitude, i.e., θ_m^{la} θ_m^{lo}, respectively; $b_n^{\mathsf{pa}}\left(\theta_m^{\mathsf{la}}, \theta_m^{\mathsf{lo}}\right)$ represents the pattern coefficient of beam n which includes the amplitude and phase corresponding to the location of user m; $\alpha_m^n[t]$ is the small NLoS fading; L denotes Rician factor that is the power ratio of the direct path (beam pattern coefficient) and the scattered wave; $d(\theta_m^{\mathsf{la}}, \theta_m^{\mathsf{lo}})$ is the distance between satellite and user m; λ is the wave length, and $\phi_m^n[t]$ stands for the phase noise. Here, the path-loss is calculated as

$$P_{\mathsf{loss}}\left(\theta_m^{\mathsf{la}}, \theta_m^{\mathsf{lo}}\right) = \left[\frac{\lambda}{4\pi d(\theta_m^{\mathsf{la}}, \theta_m^{\mathsf{lo}})}\right]^2. \quad (17)$$

And, $\phi_m^n[t]$ is model as the summation of the phase noises at satellite and at the user m as

$$\phi_m^n[t] = \phi^{\mathsf{GEO}}[t] + \phi_m^{\mathsf{gu}}[t]. \quad (18)$$

Here, phase noise is one of the imperfections from the hardware components, e.g., oscillators. Then, one assumes that $\phi^{\mathsf{GEO}}[t]$ is the same for all beams while $\phi_m^{\mathsf{gu}}[t]$'s vary independently.

2) Channel Data Generation: To generate the channel data for one realization, we first random the location of users, then typically model the phase noise samples using a random-walk process as

$$\phi^{\mathsf{GEO}}[t+1] = \phi^{\mathsf{GEO}}[t] + \delta^{\mathsf{GEO}}[t] \mod (2\pi), \quad (19)$$
$$\phi_m^{\mathsf{gu}}[t+1] = \phi_m^{\mathsf{gu}}[t] + \delta_m^{\mathsf{gu}}[t] \mod (2\pi), \quad (20)$$

where $\phi^{\mathsf{GEO}}[0]$, $\phi_m^{\mathsf{gu}}[0]$'s, $\delta^{\mathsf{GEO}}[t]$, and $\delta_m^{\mathsf{gu}}[t]$'s are all zero-mean random samples but with difference variances. We further assume $\alpha_m^n[0]$ as semi-static frequency-flat and uncorrelated complex Gaussian random variables with zero mean and unit variance. Then, a random-walk process is employed again to generate $\alpha_m^n[t]$ as

$$\alpha_m^n[t+1] = \alpha_m^n[t] + \xi_m^n[t], \quad (21)$$

where $\xi_m^n[t]$'s are also zero-mean random samples. Note that, $\phi^{\mathsf{GEO}}[0]$, $\phi_m^{\mathsf{gu}}[0]$'s, and $\alpha_m^n[0]$'s are generated independently over different realizations.

B. Numerical Results

VI. Conclusion

Appendix A
SDP-based Solution

Let $\mathbf{w}_m[t] = \left[w_{n,m}[t]\big|_{n\in\mathcal{C}_m} \right]$ be the precoding vector designed for the signal of user m transmitted from all beams in $\mathcal{C}_m$. Here, if beam n is inactivated in time-slot t, the corresponding precoding factor $w_{n,m}[t]$ must be zero. We further define $\mathbf{W}_m[t] = \mathbf{w}_m[t]\mathbf{w}_m[t]^H \in \mathbb{C}^{|\mathcal{C}_m|\times|\mathcal{C}_m|}$, for all m. Then, $\mathbf{W}_m[t]$ is positive semi-definite ($\mathbf{W}_m[t] \succeq 0$) and has rank one because it is generated from vector $\mathbf{w}_m[t]$. Then, problem (15) can be rewritten in the SDP form as

$$\min_{\mathbf{W}_m[t]'s} \sum_{\forall n} \sum_{m\in\mathcal{M}_n} \left(1+\rho_{\mathsf{hw}}\psi_n[t]^{(k)}\right) \mathrm{Tr}\left(\mathbf{E}_{n,m}\mathbf{W}_m[t]\right) \quad (22a)$$
$$\text{s. t.} \quad \sum_{m\in\mathcal{M}_n} \mathrm{Tr}\left(\mathbf{E}_{n,m}\mathbf{W}_m[t]\right) \le \bar{P}_{\mathrm{Tx}}^{\mathrm{GEO}}, \forall n \quad (22b)$$
$$\mathrm{Tr}(\mathbf{H}_{m,m}\mathbf{W}_m[t]) - g_m[t] \sum_{j\neq m} \mathrm{Tr}(\mathbf{H}_{j,m}\mathbf{W}_j[t]) \ge g_m[t]\sigma_m^2, \forall m, \quad (22c)$$
$$\sum_{\forall n} \psi_n[t]^{(k)} \sum_{m\in\mathcal{M}_n} \mathrm{Tr}\left(\mathbf{E}_{n,m}\mathbf{W}_m[t]\right) \le K_t, , \quad (22d)$$
$$\mathbf{W}_m[t] \succeq 0, \mathrm{rank}(\mathbf{W}_m[t]) = 1, \ \forall m, \quad (22e)$$

where $\mathbf{E}_{n,m} = \mathsf{diag}[0,..,1,...,0] \in \mathbb{R}^{|\mathcal{C}_m|\times|\mathcal{C}_m|}$ is a diagonal matrix in which the element corresponding to beam n on the diagonal of $\mathbf{E}_{n,m}$ equals to one. This transformation reveals a special structure of the precoding design problem. If the rank-one constraint in (22e) is removed, problem (22) with remaining constraints is convex, which can be therefore solved easily by using standard tools such as CVX solver [4]. As given in *Theorem 3.1* of [5] and *Lemma 2* of [6], if problem (22) is feasible, then it has at least one solution, where $\mathrm{rank}(\mathbf{W}_m[t]) = 1, \forall u$. If the optimum solution is unique $\mathbf{w}_m[t]$ can be calculated as the eigenvector of $\mathbf{W}_m[t]$. Nevertheless, if the algorithm does produce one of such solutions where $\mathbf{W}_m[t]$ does not have rank one, we can still obtain rank-one optimum solution from that solution by using the method described in *Lemma 5* of [6], or by applying the solution method for solving the rank constrained problem presented in *Algorithm 2* of [7], or by utilizing the best rank-one approximation based on the largest eigenvalue and the corresponding eigenvector as discussed in Section II of [8].

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