URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Non-Orthogonal Multicast and Unicast Beamforming for Multi-Beam Satellite Communications

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Abstract

We investigate the non-orthogonal multicast and unicast beamforming for multi-beam satellite communications and focus on the spectral efficiency and energy efficiency tradeoff. First of all, the approximate ergodic rate and semidefinite relaxation are adopted to simplify the problem formulation. Then, a nested iterative algorithm applying the majorization-minimization method and quadratic transformation is proposed. Numerical results illustrate the performance of the proposed algorithm.

1 Introduction

In 5G and beyond communications, joint multicast and unicast transmission has attracted some research concerns [1]. The conventional orthogonal multicast and unicast (O-MU) scheme, where the multicast and unicast signals are assigned to different time-frequency resources, is not efficient in spectrum utilization. Therefore, we investigate non-orthogonal multicast and unicast (NOMU) beamforming design where the multicast and unicast signals are transmitted using the same time-frequency resources. On the other hand, the improved spectral efficiency (SE) leads to an increase in energy consumption, which might lead to reduced energy efficiency (EE). However, EE is also an important performance indicator in satellite communications (SATCOM). Hence striking a tradeoff between SE and EE is crucial for beamforming design in SATCOM.

Inspired by the considerations mentioned above, we study the non-trivial SE and EE tradeoff for NOMU beamforming in multi-beam SATCOM. Aimed at jointly optimizing the system SE and EE, we apply the resource efficiency (RE) metric, defined as the weighted sum of SE and EE [2]. Besides, the expectation-based robust approach is considered since the long propagation delay in SATCOM makes the accurate channel state information (CSI) hard to obtain. Specifically, we aim to maximize the system RE under the total power and quality of service (QoS) constraints. The challenges lie in the expectation operations and the sum-of-ratios fractional programming. We first adopt the approximate ergodic rate, which admits a closed form. Then, the semidefinite relaxation (SDR) is applied to simplify the problem. Furthermore, a nested iterative algorithm applying the majorization-minimization (MM) method and quadratic transformation is proposed to simplify the non-convex problem. In addition, the eigenvalue decomposition is used to obtain the beamforming vectors. Simulation results verify the performance of the proposed algorithm for NOMU transmission in SATCOM.

2 System Model and Problem Formulation

Consider the downlink of the multi-beam SATCOM system, where the satellite simultaneously transmits unicast and multicast signals to multiple single-antenna users. There are N_{t} beams and a total of $K = N_{\mathrm{t}}$ multicast groups, i.e., one multicast group per beam. Let $\mathscr{K} = \{1,\ldots,K\}$ represent the set of indices for all groups. We denote the set of indices for users belonging to the kth multicast group as $\mathscr{U}_k$ where $k \in \mathscr{K}$. Every user only belongs to one multicast group, which can be mathematically represented as $\mathscr{U}_k \cap \mathscr{U}_\ell = \varnothing, \forall k,\ell \in \mathscr{K}$, $k \neq \ell$. The number of users in group k is denoted as N_k. The downlink transmit signal can be denoted as $s = \sum_{k=1}^{K} s_k^{\mathrm{m}} + \sum_{k=1}^{K}\sum_{i\in\mathscr{U}_k} s_{k,i}^{\mathrm{u}}$ where $s_k^{\mathrm{m}} \in \mathbb{C}$ and $s_{k,i}^{\mathrm{u}} \in \mathbb{C}$ represent the normalized multicasting information intended for all users in group k and unicasting information for user i belonging to group k, respectively.

The receiving signal of user i in group k can be denoted as

$$\begin{aligned} y_{k,i} = &\overbrace{\mathbf{h}_i^H \mathbf{w}_k^{\mathrm{m}} s_k^{\mathrm{m}}}^{\text{desired multicast signal}} + \overbrace{\mathbf{h}_i^H \mathbf{w}_{k,i}^{\mathrm{u}} s_{k,i}^{\mathrm{u}}}^{\text{desired unicast signal}} \\ &+ \overbrace{\sum_{\ell\neq k} \mathbf{h}_i^H \mathbf{w}_\ell^{\mathrm{m}} s_\ell^{\mathrm{m}}}^{\text{inter-group interference}} + \overbrace{\sum_{\ell=1}^{K} \sum_{\substack{j\in\mathscr{U}_\ell,\\ (\ell,j)\neq(k,i)}} \mathbf{h}_i^H \mathbf{w}_{\ell,j}^{\mathrm{u}} s_{\ell,j}^{\mathrm{u}}}^{\text{inter-user interference}} + n_i, \end{aligned} \tag{1}$$

where $\mathbf{h}_i \in \mathbb{C}^{N_{\mathrm{t}}\times 1}$ denotes the channel vector in the beam domain from the satellite to user i, $\mathbf{w}_k^{\mathrm{m}} \in \mathbb{C}^{N_{\mathrm{t}}\times 1}$ and $\mathbf{w}_{k,i}^{\mathrm{u}} \in \mathbb{C}^{N_{\mathrm{t}}\times 1}$ are the multicast and unicast beamforming vectors for group k and user i in group k, respectively, and n_i is the additive white Gaussian noise with variance N_0.

The downlink channel vector $\mathbf{h}_i$ in (1) is modeled as [3]

$$\mathbf{h}_i = \sqrt{\psi_i}\mathbf{b}_i^{\frac{1}{2}} \odot \mathbf{r}_i^{\frac{1}{2}} \odot \exp\{\imath \boldsymbol{\theta}_i\}, \tag{2}$$

where ψ_i denotes the scale parameter, $\mathbf{b}_i$ is the far-field beam gain vector, $\mathbf{r}_i$ represents the rain fading coefficient vector, and $\boldsymbol{\theta}_i = [\theta_{i,1}, \theta_{i,2}, \ldots, \theta_{i,N_{\mathrm{t}}}]^T$ is the channel phase whose elements are independently and uniformly distributed between 0 and 2π [4]. Note that the channel amplitude is determined by some constant coefficients over the coherence time interval, and then can be considered time-invariant. However, the channel phase consists of a series of time-varying components such as the tropospheric fading and different local oscillators onboard the satellite, and then is considered to be time-variant.

The channel phase uncertainty is studied in the following. The user i estimates the channel vector at time t_0 and then feeds back to the satellite. After the long propagation and processing delays, the estimated CSI is used at time t_1. Therefore, the channel phase model of user i at time t_1 is denoted as $\boldsymbol{\theta}_i(t_1) = \boldsymbol{\theta}_i(t_0) + \mathbf{e}_i$, where $\mathbf{e}_i = [e_{i,1}, e_{i,2}, \dots e_{i,N_\mathrm{t}}]^T$ is the channel phase error with the distribution of $\mathbf{e}_i \sim \mathcal{N}(\mathbf{0}, \sigma_i^2 \mathbf{I})$. The estimated channel at time t_0 and the actual channel at time t_1 are indicated as $\hat{\mathbf{h}}_i$ and $\mathbf{h}_i$, respectively. Then, the actual channel can be modeled as $\mathbf{h}_i = \hat{\mathbf{h}}_i \odot \mathbf{q}_i = \mathrm{diag}(\hat{\mathbf{h}}_i)\mathbf{q}_i$, where $\mathbf{q}_i \triangleq \exp\{\iota \mathbf{e}_i\}$ [5]. The correlation matrix of $\mathbf{q}_i$ is denoted as $\mathbf{A}_i = \mathbb{E}\{\mathbf{q}_i \mathbf{q}_i^H\}$, whose elements can be easily obtained [6]. Note that the values of matrix $\mathbf{A}_i$ are relatively fixed compared with the channel phase error, which is a random variable.

Successive interference cancellation (SIC) is used at the users, i.e., each user successively decodes its desired signals and other signals are regarded as interference at the same time [1]. Due to the higher priority of the multicast signal in this work, we suppose that each user decodes the multicast signal first, which is subtracted from the received signal, and then decodes the unicast signal. Hence, the multicast SINR and unicast SINR of user i in group k can be indicated as

$$\mathrm{SINR}_{k,i}^{\mathrm{m}} \triangleq \frac{\left|(\mathbf{w}_k^{\mathrm{m}})^H \mathbf{h}_i\right|^2}{\sum_{\ell \neq k} \left|(\mathbf{w}_\ell^{\mathrm{m}})^H \mathbf{h}_i\right|^2 + \sum_{\ell=1}^K \sum_{j \in \mathscr{U}_\ell} \left|(\mathbf{w}_{\ell,j}^{\mathrm{u}})^H \mathbf{h}_i\right|^2 + N_0}, \quad (3)$$

and

$$\mathrm{SINR}_{k,i}^{\mathrm{u}} \triangleq \frac{\left|(\mathbf{w}_{k,i}^{\mathrm{u}})^H \mathbf{h}_i\right|^2}{\sum_{\ell \neq k} \left|(\mathbf{w}_\ell^{\mathrm{m}})^H \mathbf{h}_i\right|^2 + \sum_{\ell=1}^K \sum_{\substack{j \in \mathscr{U}_\ell, \\ (\ell,j) \neq (k,i)}} \left|(\mathbf{w}_{\ell,j}^{\mathrm{u}})^H \mathbf{h}_i\right|^2 + N_0}. \quad (4)$$

We consider the expectation-based robust beamforming design due to the infeasibility to get the accurate channel vector. The ergodic multicast and unicast rates of user i in group k are given by $R_{k,i}^{\mathrm{m}} \triangleq \mathbb{E}\left\{\log_2\left(1 + \mathrm{SINR}_{k,i}^{\mathrm{m}}\right)\right\}$ and $R_{k,i}^{\mathrm{u}} \triangleq \mathbb{E}\left\{\log_2\left(1 + \mathrm{SINR}_{k,i}^{\mathrm{u}}\right)\right\}$, respectively. Then, the achievable multicast rate of group k is indicated as $R_k^{\mathrm{m}} \triangleq \min_{i \in \mathscr{U}_k} R_{k,i}^{\mathrm{m}}$.

The system SE is defined as the weighted sum of unicast rate for all users and multicast rate for all groups as follows

$$\mathrm{SE} \triangleq \eta \sum_{k=1}^K R_k^{\mathrm{m}} + (1-\eta) \sum_{k=1}^K \sum_{i \in \mathscr{U}_k} R_{k,i}^{\mathrm{u}} \quad (\mathrm{bits/s/Hz}), \quad (5)$$

where $\eta \in [0,1]$ denotes a weighting factor. Considering the limitations of energy consumption in satellite communications, the EE has become a key performance metric in the design of transmission schemes, which is defined as the ratio of the sum rate, i.e., SE, to the total power consumption. Then the system EE can be denoted as $\mathrm{EE} \triangleq B\frac{\mathrm{SE}}{P_{\mathrm{tot}}}$ (bits/Joule)ïijŇ where B is the system bandwidth, and $P_{\mathrm{tot}} \triangleq \xi\left(\sum_{k=1}^K \|\mathbf{w}_k^{\mathrm{m}}\|_2^2 + \sum_{k=1}^K \sum_{i \in \mathscr{U}_k} \|\mathbf{w}_{k,i}^{\mathrm{u}}\|_2^2\right) + \sum_{k=1}^K N_k\left(P_{\mathrm{c,UE}} + P_{0,\mathrm{UE}}\right) + N_\mathrm{t} P_{\mathrm{c,SAT}} + P_{0,\mathrm{SAT}}$ is the total power consumption at the transmitter. In the power consumption model, $\xi \geq 1$ is a constant denoting the power amplifier inefficiency, $P_{\mathrm{c,UE}}$ and $P_{\mathrm{c,SAT}}$ denote the constant circuit power consumption per antenna at terrestrial user and satellite, respectively, $P_{0,\mathrm{UE}}$ and $P_{0,\mathrm{SAT}}$ represent the basic power consumed at each user and the satellite, respectively, which are independent of the number of antennas. We denote the constant circuit power as $P_{\mathrm{con}} = \sum_{k=1}^K N_k\left(P_{\mathrm{c,UE}} + P_{0,\mathrm{UE}}\right) + N_\mathrm{t} P_{\mathrm{c,SAT}} + P_{0,\mathrm{SAT}}$ for brevity. Since the power consumption at the satellite is restricted, we have the transmit power constraint $\sum_{k=1}^K \|\mathbf{w}_k^{\mathrm{m}}\|_2^2 + \sum_{k=1}^K \sum_{i \in \mathscr{U}_k} \|\mathbf{w}_{k,i}^{\mathrm{u}}\|_2^2 \leq P_{\max}$, where $P_{\max}$ denotes the transmit power threshold.

In this work, we aim to achieve the SE and EE optimization jointly by adopting the RE metric [2], which is defined as the weighted sum of the EE and SE given by

$$\mathrm{RE} = \mathrm{EE} + \beta \frac{B}{P_{\mathrm{sum}}} \mathrm{SE} \quad (\mathrm{bits/Joule}), \quad (6)$$

where β is a weighting factor, B/P_{sum} is used to unify the units of two items in (6), and $P_{\mathrm{sum}} = \xi P_{\max} + P_{\mathrm{con}}$ denotes the power threshold at the satellite. It can be observed that the SE-EE tradeoff can be achieved by varying β.

Our target is to maximize the system RE under the QoS and the total power constraints, which can be formulated as

$$\begin{aligned} \mathscr{R}_1: \quad & \max_{\mathbf{w}} \quad \mathrm{RE} \\ & \text{s.t.} \quad \sum_{k=1}^K \|\mathbf{w}_k^{\mathrm{m}}\|_2^2 + \sum_{k=1}^K \sum_{i \in \mathscr{U}_k} \|\mathbf{w}_{k,i}^{\mathrm{u}}\|_2^2 \leq P_{\max}, \\ & \qquad \mathbb{E}\left\{\mathrm{SINR}_{k,i}^{\mathrm{m}}\right\} \geq \gamma_{k,i}^{\mathrm{m}}, \forall i \in \mathscr{U}_k, k \in \mathscr{K}, \\ & \qquad \mathbb{E}\left\{\mathrm{SINR}_{k,i}^{\mathrm{u}}\right\} \geq \gamma_{k,i}^{\mathrm{u}}, \forall i \in \mathscr{U}_k, k \in \mathscr{K}, \end{aligned} \quad (7)$$

where $\mathbf{w} \triangleq \left\{\mathbf{w}_k^{\mathrm{m}}, \{\mathbf{w}_{k,i}^{\mathrm{u}}\}_{i \in \mathscr{U}_k}\right\}_{k=1}^K$, $\gamma_{k,i}^{\mathrm{m}}$ and $\gamma_{k,i}^{\mathrm{u}}$ represent the target ergodic multicast and unicast SINRs of user i in group k, respectively. Via changing β, we can get different SE-EE Pareto optimal solutions which constitute the SE-EE tradeoff curve.

3 Robust Resource Efficiency Maximization

In this section, we investigate the RE maximization in NOMU satellite system. Note that the constant coefficient B in the objective function of problem $\mathscr{R}_1$ can be omitted in the following derivation procedure without loss of generality. Since the ergodic rates and SINRs do not admit closed-form expressions, we first invoke an approximate function $\overline{R}_{k,i}^{\mathrm{m}}$ of the ergodic multicast rate as follows [7]

$$R_{k,i}^{\mathrm{m}} \approx \overline{R}_{k,i}^{\mathrm{m}} \triangleq \log_2 \left(1 + \frac{\mathbb{E}\left\{\left|(\mathbf{w}_k^{\mathrm{m}})^H \mathbf{h}_i\right|^2\right\}}{\mathbb{E}\left\{\sum_{\ell \neq k} \left|(\mathbf{w}_\ell^{\mathrm{m}})^H \mathbf{h}_i\right|^2 + \sum_{\ell=1}^{K} \sum_{j \in \mathscr{U}_\ell} \left|(\mathbf{w}_{\ell,j}^{\mathrm{u}})^H \mathbf{h}_i\right|^2 + N_0\right\}}\right). \tag{8}$$

The approximated function $\overline{R}_{k,i}^{\mathrm{u}}$ of the ergodic unicast rate and SINR can be acquired in a similar manner.

To make problem $\mathscr{R}_1$ more tractable, we adopt the SDR approach and then transform the optimization variables $\mathbf{w}_{k,i}^{\mathrm{u}}$ and $\mathbf{w}_k^{\mathrm{m}}$ into $\mathbf{W}_{k,i}^{\mathrm{u}} \triangleq \mathbf{w}_{k,i}^{\mathrm{u}}(\mathbf{w}_{k,i}^{\mathrm{u}})^H$ and $\mathbf{W}_k^{\mathrm{m}} \triangleq \mathbf{w}_k^{\mathrm{m}}(\mathbf{w}_k^{\mathrm{m}})^H$, respectively. Then the approximate multicast rate in (8) can be rewritten as $\overline{R}_{k,i}^{\mathrm{m}} = \log_2\left(1 + \frac{\mathrm{Tr}(\mathbf{X}_i \mathbf{W}_k^{\mathrm{m}})}{\sum_{\ell \neq k} \mathrm{Tr}(\mathbf{X}_i \mathbf{W}_\ell^{\mathrm{m}}) + \sum_{\ell=1}^{K} \sum_{j \in \mathscr{U}_\ell} \mathrm{Tr}(\mathbf{X}_i \mathbf{W}_{\ell,j}^{\mathrm{u}}) + N_0}\right)$, where $\mathbf{X}_i = \mathbb{E}\{\mathbf{h}_i \mathbf{h}_i^H\} = \mathrm{diag}(\hat{\mathbf{h}}_i)\mathbb{E}\{\mathbf{q}_i \mathbf{q}_i^H\}\mathrm{diag}(\hat{\mathbf{h}}_i^H) = \mathrm{diag}(\hat{\mathbf{h}}_i)\mathbf{A}_i \mathrm{diag}(\hat{\mathbf{h}}_i^H)$ denotes the long term channel correlation matrix. Introducing some auxiliary variables $\{t_k\}_{k=1}^{K}$, where t_k is the lower bound of $R_{k,i}^{\mathrm{m}}$ for all $i \in \mathscr{U}_k$, and denoting $\mathbf{W} \triangleq \left\{\mathbf{W}_k^{\mathrm{m}}, \{\mathbf{W}_{k,i}^{\mathrm{u}}\}_{i \in \mathscr{U}_k}\right\}_{k=1}^{K}$ to make the notation more concise, problem $\mathscr{R}_1$ can be recast as

$$\mathscr{R}_2: \max_{\mathbf{W}, \{t_k\}_{k=1}^{K}} \left(\frac{1}{P_{\mathrm{tot}}(\mathbf{W})} + \frac{\beta}{P_{\mathrm{sum}}}\right)\left(\eta \sum_{k=1}^{K} t_k + (1-\eta) \sum_{k=1}^{K} \sum_{i \in \mathscr{U}_k} \log_2 \frac{g_k^{\mathrm{m}}(\mathbf{W})}{g_{k,i}^{\mathrm{u}}(\mathbf{W})}\right) \tag{9a}$$

$$\text{s.t. } \log_2 \frac{f_{k,i}(\mathbf{W})}{g_k^{\mathrm{m}}(\mathbf{W})} \geq t_k, \ \forall i \in \mathscr{U}_k, \ k \in \mathscr{K}, \tag{9b}$$

$$\sum_{k=1}^{K} \mathrm{Tr}(\mathbf{W}_k^{\mathrm{m}}) + \sum_{k=1}^{K} \sum_{i \in \mathscr{U}_k} \mathrm{Tr}\left(\mathbf{W}_{k,i}^{\mathrm{u}}\right) \leq P_{\max}, \tag{9c}$$

$$\mathrm{Tr}(\mathbf{X}_i \mathbf{W}_k^{\mathrm{m}}) \geq \gamma_{k,i}^{\mathrm{m}} g_k^{\mathrm{m}}(\mathbf{W}), \forall i \in \mathscr{U}_k, k \in \mathscr{K}, \tag{9d}$$

$$\mathrm{Tr}(\mathbf{X}_i \mathbf{W}_{k,i}^{\mathrm{u}}) \geq \gamma_{k,i}^{\mathrm{u}} g_{k,i}^{\mathrm{u}}(\mathbf{W}), \forall i \in \mathscr{U}_k, k \in \mathscr{K}, \tag{9e}$$

$$\mathbf{W}_k^{\mathrm{m}} \succeq \mathbf{0}, \ \forall k \in \mathscr{K}, \tag{9f}$$

$$\mathbf{W}_{k,i}^{\mathrm{u}} \succeq \mathbf{0}, \ \forall i \in \mathscr{U}_k, k \in \mathscr{K}, \tag{9g}$$

where

$$P_{\mathrm{tot}}(\mathbf{W}) = \xi \left(\sum_{k=1}^{K} \mathrm{Tr}(\mathbf{W}_k^{\mathrm{m}}) + \sum_{k=1}^{K} \sum_{i \in \mathscr{U}_k} \mathrm{Tr}\left(\mathbf{W}_{k,i}^{\mathrm{u}}\right)\right) + P_{\mathrm{con}},$$

$$g_k^{\mathrm{m}}(\mathbf{W}) = \sum_{\ell \neq k} \mathrm{Tr}(\mathbf{X}_i \mathbf{W}_\ell^{\mathrm{m}}) + \sum_{\ell=1}^{K} \sum_{j \in \mathscr{U}_\ell} \mathrm{Tr}(\mathbf{X}_i \mathbf{W}_{\ell,j}^{\mathrm{u}}) + N_0,$$

$$g_{k,i}^{\mathrm{u}}(\mathbf{W}) = \sum_{\ell \neq k} \mathrm{Tr}(\mathbf{X}_i \mathbf{W}_\ell^{\mathrm{m}}) + \sum_{\ell=1}^{K} \sum_{\substack{j \in \mathscr{U}_\ell, \\ (\ell,j) \neq (k,i)}} \mathrm{Tr}(\mathbf{X}_i \mathbf{W}_{\ell,j}^{\mathrm{u}}) + N_0,$$

$$f_{k,i}(\mathbf{W}) = \sum_{k=1}^{K} \mathrm{Tr}(\mathbf{X}_i \mathbf{W}_k^{\mathrm{m}}) + \sum_{\ell=1}^{K} \sum_{j \in \mathscr{U}_\ell} \mathrm{Tr}(\mathbf{X}_i \mathbf{W}_{\ell,j}^{\mathrm{u}}) + N_0. \tag{10}$$

Note that the non-convex constraints $\mathrm{rank}(\mathbf{W}_k^{\mathrm{m}}) = 1$ and $\mathrm{rank}(\mathbf{W}_{k,i}^{\mathrm{u}}) = 1$ are relaxed in problem $\mathscr{R}_2$.

Next, we apply the MM algorithm to tackle the nonconvex functions in (9a) and (9b). Then, the quadratic transformation method is adopted to transform the sum-of-ratios fractional programming into a series of concave problems [8]. After applying the nested algorithm, the objective function (9a) can be equivalent to

$$\eta \sum_{k=1}^{K} \left(2x_{k,(\tau)}\sqrt{t_k} - x_{k,(\tau)}^2 P_{\mathrm{tot}}(\mathbf{W})\right) + (1-\eta) \sum_{k=1}^{K} \sum_{i \in \mathscr{U}_k} \left(2y_{k,i,(\tau)}\sqrt{G_{k,i}(\mathbf{W})} - y_{k,i,(\tau)}^2 P_{\mathrm{tot}}(\mathbf{W})\right) + \frac{\beta}{P_{\mathrm{sum}}}\left(\eta \sum_{k=1}^{K} t_k + (1-\eta) \sum_{k=1}^{K} \sum_{i \in \mathscr{U}_k} G_{k,i}(\mathbf{W})\right), \tag{11}$$

where

$$G_{k,i}(\mathbf{W}) = \log_2(g_k^{\mathrm{m}}(\mathbf{W})) - \left(\log_2\left(g_{k,i}^{\mathrm{u}}\left(\mathbf{W}^{(\lambda)}\right)\right) + \mathrm{Tr}\left(\frac{\mathbf{X}_i}{g_{k,i}^{\mathrm{u}}\left(\mathbf{W}^{(\lambda)}\right)\ln 2}\left(\sum_{\ell \neq k}\left(\mathbf{W}_\ell^{\mathrm{m}} - \mathbf{W}_\ell^{\mathrm{m},(\lambda)}\right) + \sum_{\ell=1}^{K} \sum_{\substack{j \in \mathscr{U}_\ell, \\ (\ell,j) \neq (k,i)}} \left(\mathbf{W}_{\ell,j}^{\mathrm{u}} - \mathbf{W}_{\ell,j}^{\mathrm{u},(\lambda)}\right)\right)\right)\right), \tag{12}$$

$\mathbf{W}^{(\lambda)} \triangleq \left\{\mathbf{W}_k^{\mathrm{m},(\lambda)}, \{\mathbf{W}_{k,i}^{\mathrm{u},(\lambda)}\}_{i \in \mathscr{U}_k}\right\}_{k=1}^{K}$, and λ is the outer MM iteration index. Moreover, $\left\{x_{k,(\tau)}\right\}_{k=1}^{K}$ and $\left\{\{y_{k,i,(\tau)}\}_{i \in \mathscr{U}_k}\right\}_{k=1}^{K}$ are the auxiliary variables which we iteratively update to optimize the original variables $\mathbf{W}$ and $\{t_k\}_{k=1}^{K}$. For fixed $\mathbf{W}_{(\tau)}$ and $t_{k,(\tau)}$, the optimal $x_{k,(\tau)}$ and $y_{k,i,(\tau)}$ can be found in closed forms as $x_{k,(\tau)} = \frac{\sqrt{t_{k,(\tau)}}}{P_{\mathrm{tot}}(\mathbf{W}_{(\tau)})}$ and $y_{k,i,(\tau)} = \frac{\sqrt{G_{k,i}(\mathbf{W}_{(\tau)})}}{P_{\mathrm{tot}}\left(\mathbf{W}_{(\tau)}\right)}$, respectively, where $\mathbf{W}_{(\tau)} \triangleq \left\{\mathbf{W}_{k,(\tau)}^{\mathrm{m}}, \{\mathbf{W}_{k,i,(\tau)}^{\mathrm{u}}\}_{i \in \mathscr{U}_k}\right\}_{k=1}^{K}$, and τ denotes the inner iteration index. Finally, the eigenvalue decomposition is invoked to acquire the corresponding multicast beamformers $\mathbf{w}_k^{\mathrm{m}*}$ and unicast beamformers $\mathbf{w}_{k,i}^{\mathrm{u}}{}^*$ from the solutions $\mathbf{W}_k^{\mathrm{m}*}$ and $\mathbf{W}_{k,i}^{\mathrm{u}}{}^*$, respectively.

4 Numerical Results

Numerical results are presented in this section to illustrate the performance of the proposed algorithm. The channel

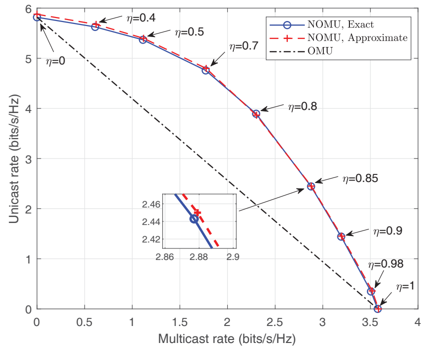

Figure 1. Comparison between the exact and approximate ergodic multicast-unicast rate region with NOMU and O-MU transmission ($P_{\max} = 52$ dBm, $\beta = 0.5$).

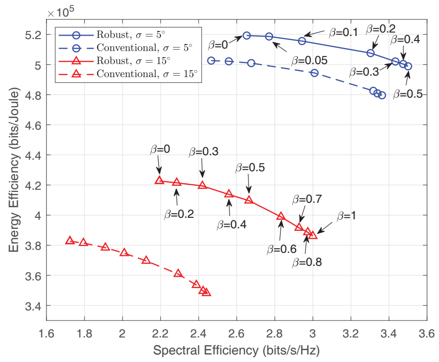

Figure 2. Comparison of SE-EE tradeoff curve between the robust and conventional approach ($P_{\max} = 52$ dBm, $\eta = 0.8$).

model and relevant parameters are the same as [6]. Assume that the variances of the channel phase errors are identical for all users, i.e., $\sigma_i^2 = \sigma^2$. Without loss of generality, the multicast and unicast SINR constraints are set to be identical, i.e., $\gamma_{k,i}^{\mathrm{m}} = \gamma_{k,i}^{\mathrm{u}} = \gamma_{\mathrm{th}} = 0.1, \forall i \in \mathscr{U}_k, \forall k \in \mathscr{K}$. The number of users in group $\mathscr{U}_k$ is set to $N_k = 5, \forall k$, and that of beams is set to $N_{\mathrm{t}} = 7$. The power amplifier inefficiency is set to $\xi = 2$. The power parameters in the power consumption model are set as $P_{\mathrm{c,UE}} = 23$ dBm, $P_{0,\mathrm{UE}} = 23$ dBm, $P_{\mathrm{c,SAT}} = 30$ dBm, and $P_{0,\mathrm{SAT}} = 40$ dBm.

The exact and approximate ergodic multicast-unicast rate region with NOMU and OMU transmission is compared in Fig. 1. We can observe that the gap between the exact and approximate rate is negligible, which illustrates the tightness of the adopted approximate function. In addition, compared with conventional OMU transmission, NOMU transmission has an apparent performance gain.

The comparison of the SE-EE tradeoff curve between the robust and conventional approach is depicted in Fig. 2. The estimated channel is used as the actual channel in the conventional approach which does not consider the channel phase error. The numerical results demonstrate that the proposed robust approach has a performance gain over the conventional one. And the gain increases as the phase error increases. Moreover, it can be observed that the balance between SE and EE can be obtained by adjusting β with the proposed algorithm.

5 Conclusion

In this work, we studied the robust RE optimization for NOMU beamforming in SATCOM with the total power and QoS constraints. We first adopted the approximate ergodic rate expressions and SDR method. Then the MM method and quadratic transformation were invoked to deal with the sum-of-ratios fractional programming and non-convex constraints. We indicated the performance gain of the NOMU transmission over the conventional baseline.

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