# Outage Constrained Robust Multigroup Multicast Beamforming for Multi-Beam Satellite Communication Systems

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***Abstract*—We investigate outage constrained robust multigroup multicast beamforming for multi-beam satellite communication systems with full frequency reuse. Based on a satellite downlink beam domain channel model with channel phase uncertainty taken into account, we first investigate robust multigroup multicast beamforming with the aim to maximize the worst-case outage signal-to-interference-plus-noise ratio under the outage and the per-beam power constraints. We then cast the outage constrained robust beamforming design into the convex optimization framework with some approximation techniques. Simulation results show that the proposed robust multigroup multicast beamformer can provide significant performance gains in terms of multicast rate and outage probability over the conventional approach.**

***Index Terms*—Multi-beam satellite communication systems, robust transmission, multigroup multicast beamforming, outage probability, channel state information (CSI).**

## I. Introduction

MULTI-BEAM satellite communication has received extensive research interest recently due to its potential to increase the satellite transmission rate and provide seamless connectivity in a wide coverage area [1]. Meanwhile, aggressive spectrum reuse among beams is desirable to achieve high transmission rates in multi-beam satellite communication systems [2], [3]. As a result, interference mitigation techniques become mandatory in multi-beam satellite systems with aggressive frequency reuse to reduce the inter-beam interference. Inter-beam interference mitigation can be performed at either the satellite side or the user side. In this letter, we focus on investigating linear beamforming performed at the satellite side as it can effectively manage the inter-beam interference with a relatively low complexity.

For beamforming design in multi-beam satellite communication systems, several practical issues should be taken into account. Firstly, one beamformer is applied to several users in the same frame to cope with the framing structure of the current satellite standards, e.g., DVB-S2 [4] and DVB-S2X [5], which leads the beamforming design in multi-beam satellite communication systems cast into a multigroup multicast beamforming optimization problem. In addition, the channel phase uncertainty due to, e.g., the long propagation delays in satellite communication systems [6] motivates a robust beamforming design. Moreover, the per-beam power constraints should be taken into account due to the limitation of on-board inter-beam power sharing.

Motivated by the above practical issues, we investigate robust multigroup multicast beamforming for multi-beam satellite communications in this letter. Most of the previous works on multigroup multicast precoding, see [7], usually assumed perfect channel state information at the transmitter (CSIT), which, however, is difficult to obtain in practical satellite communication systems. For the imperfect CSIT case, the expectation-based robust precoding designs were investigated in unicast [8] and multicast [9] multi-beam satellite transmissions, respectively. In addition, the outage constrained robust precoding designs were investigated in unicast [6] and single-group multicast [10] transmissions, respectively. Satellite relaying systems were investigated in [17] and [18].

In this letter, we investigate outage-based robust multigroup multicast beamforming for multi-beam satellite communication systems. Based on a satellite downlink beam domain channel model with the channel phase uncertainty taken into account, we first investigate outage constrained robust multigroup multicast beamforming subject to the per-beam power constraints. We further cast the outage constrained robust beamforming design into the convex optimization framework with some formulation. Simulation results demonstrate the performance gains of our proposed robust approach over the conventional approach.

## II. Satellite Channel Model

We consider a multi-beam satellite communication system with full frequency reuse, where $N_t$ beams are utilized to simultaneously serve $N_u$ single-antenna users. Consider the multigroup multicast transmission where the number of multicast clusters is $K = N_t$ and each user belongs to only one cluster [11]. We denote $\mathcal{K} = \{1, 2, \ldots, K\}$ as the total cluster set and $\mathcal{B} = \{1, 2, \ldots, N_t\}$ as the total beam set.

Denote $\mathcal{U}_k$ as the $k$th multicast cluster. We focus on the signal model in the beam domain. The signal received by the $i$th user in cluster $\mathcal{U}_k$ can be expressed as

$$y_i = \mathbf{h}_i^H \mathbf{w}_k s_k + \sum_{\ell \neq k} \mathbf{h}_i^H \mathbf{w}_\ell s_\ell + n_i, \quad i \in \mathcal{U}_k, \tag{1}$$

where $\mathbf{h}_i \in \mathbb{C}^{N_t \times 1}$ is the downlink beam domain channel vector from the $N_t$ beams to the $i$th user, $\mathbf{w}_k \in \mathbb{C}^{N_t \times 1}$ is the beam domain precoder for cluster $\mathcal{U}_k$, $s_k$ is the signal intended for users in cluster $\mathcal{U}_k$ with unit power, and $n_i \sim \mathcal{CN}(0, N_0)$ is the additive noise. Note that the radiation power from the $n$th beam is given by $[\sum_{k=1}^K \mathbf{w}_k \mathbf{w}_k^H]_{n,n}$.

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The downlink channel vector between the satellite and the *i*th user in the beam domain can be modeled as [2], [8]

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

where $\odot$ denotes the Hadamard product, $\psi_i$ is the large scale fading coefficient, $\mathbf{b}_i$ denotes the far-field beam radiation pattern [12], $\mathbf{r}_i$ represents the rain attenuation with elements obeying the lognormal distribution [13], and $\boldsymbol{\theta}_i$ denotes the channel phase vector with elements independently and uniformly distributed between 0 and $2\pi$ [3].

For the *i*th user, the channel vector is estimated at instant $t_0$ and fed back to the gateway. Then the CSIT is used at instant $t_1$ after the propagation delays plus the processing delays [6], [14]. Due to the temporary invariance of amplitude, we model the channel phase at $t_1$ as follows

$$\boldsymbol{\theta}_i(t_1) = \boldsymbol{\theta}_i(t_0) + \mathbf{e}_i, \tag{3}$$

where $\mathbf{e}_i \sim \mathcal{N}(\mathbf{0}, \sigma_i^2\mathbf{I})$ is the channel phase error and $\sigma_i^2$ is the variance of the phase error vector [8], [14]. We denote the estimated channel at $t_0$ and the actual channel at $t_1$ by $\hat{\mathbf{h}}_i$ and $\mathbf{h}_i$, respectively. Then $\mathbf{h}_i$ can be modeled as [6]

$$\mathbf{h}_i = \hat{\mathbf{h}}_i \odot \mathbf{q}_i = \mathrm{diag}\ (\hat{\mathbf{h}}_i)\mathbf{q}_i, \tag{4}$$

where $\mathbf{q}_i \triangleq \exp\{\jmath\mathbf{e}_i\}$. Let $\mathbf{Q}_i \triangleq \mathbf{q}_i\mathbf{q}_i^H$, then the long term correlation matrix of $\mathbf{q}_i$ can be expressed as

$$\mathbf{A}_i = \mathbb{E}\{\mathbf{q}_i\mathbf{q}_i^H\} = \mathbb{E}\{\mathbf{Q}_i\}. \tag{5}$$

It is not difficult to obtain the elements of $\mathbf{A}_i$ as follows [9]

$$[\mathbf{A}_i]_{m,n} = \begin{cases} 1, & m = n, \\ \exp\{-\sigma_i^2\}, & \text{otherwise.} \end{cases} \tag{6}$$

## III. Robust Multigroup Multicast Beamforming

In this section, we investigate outage constrained robust multigroup multicast beamforming for frame-based satellite communication systems. From the signal model in (1), the signal-to-interference-plus-noise ratio (SINR) at the *i*th user in cluster $\mathcal{U}_k$ can be represented as [6]

$$\mathrm{SINR}_i \triangleq \frac{\mathbf{h}_i^H\mathbf{W}_k\mathbf{h}_i}{\sum_{\ell\neq k}\mathbf{h}_i^H\mathbf{W}_\ell\mathbf{h}_i + N_0}, \quad \forall i \in \mathcal{U}_k,\ k, \ell \in \mathcal{K}, \tag{7}$$

where $\mathbf{W}_k \triangleq \mathbf{w}_k\mathbf{w}_k^H$.

Note that for the imperfect CSI case, it is difficult to design a beamformer to guarantee a target SINR all the time due to the channel uncertainty. Thus, we are interested in the robust beamforming design and we aim to maximize the worst-case outage SINR of all users in a high probability, which can be formulated as the following problem

$$\begin{aligned} \mathcal{F}: \max_{\{\mathbf{W}_k\}_{k=1}^K} \quad & \min_i \ \gamma_i \\ \text{s.t.} \quad & p_i \triangleq \Pr\{\mathrm{SINR}_i \geq \gamma_i\} \geq \alpha_i, \\ & \left[\sum_{k=1}^K \mathbf{W}_k\right]_{n,n} \leq P_n,\ \forall n \in \mathcal{B}, \\ & \mathbf{W}_k \succeq \mathbf{0},\ \mathrm{rank}(\mathbf{W}_k) = 1, \forall k \in \mathcal{K}, \end{aligned} \tag{8}$$

where $\alpha_i$ is the non-outage probability threshold for user *i* and $P_n$ is the power budget of the *n*th beam. We focus on the case where $\alpha_i > 0.5$, which is of more practical interest [6].

The outage constrained robust multigroup multicast beamforming design formulated in (8) takes several practical issues in multi-beam satellite communication systems into account. Firstly, the multigroup multicast beamforming formulation naturally embraces the framing structure of the existing satellite communication standards [4], [5]. The per-beam power constraints are also taken into account in the problem formulation. In addition, a feasible solution to the problem $\mathcal{F}$ can guarantee the quality of service of all users under the channel uncertainty, which is practically meaningful for satellite communications.

The problem $\mathcal{F}$ is in general difficult to handle. We first decompose the problem $\mathcal{F}$ into a sequence of outage constrained power minimization problem. In particular, for the predetermined SINR thresholds $\{\gamma_i\}_i$, the outage constrained power minimization robust multigroup multicast beamforming design can be formulated as follows

$$\begin{aligned} \mathcal{Q}: \min_{\{\mathbf{W}_k\}_{k=1}^K} \quad & r \\ \text{s.t.} \quad & p_i \triangleq \Pr\{\mathrm{SINR}_i \geq \gamma_i\} \geq \alpha_i, \\ & \frac{1}{P_n}\left[\sum_{k=1}^K \mathbf{W}_k\right]_{n,n} \leq r, \quad \forall n \in \mathcal{B},, \\ & \mathbf{W}_k \succeq \mathbf{0},\ \mathrm{rank}(\mathbf{W}_k) = 1, \quad \forall k \in \mathcal{K}. \end{aligned} \tag{9}$$

Note that the feasible set of the problem $\mathcal{Q}$ will decrease as $\min_i\{\gamma_i\}$ increases. Then, the optimum objective value of $\mathcal{Q}$ is monotonically non-decreasing in $\min_i\{\gamma_i\}$. Thus, using a classic bisection search approach [15], the problem $\mathcal{F}$ can be solved via iteratively solving the problem $\mathcal{Q}$ with different SINR thresholds $\{\gamma_i\}_i$. In the following, we will focus on the outage constrained power minimization robust beamforming design problem $\mathcal{Q}$.

We first investigate the expression of the non-outage probability $p_i = \Pr\{\mathrm{SINR}_i \geq \gamma_i\}$. Define some auxiliary variables $\mathbf{Z}_k \triangleq \mathbf{W}_k - \gamma_i\sum_{\ell\neq k}\mathbf{W}_\ell$, and $\mathbf{R}_i \triangleq \mathbf{h}_i\mathbf{h}_i^H = \mathrm{diag}(\hat{\mathbf{h}}_i)\mathbf{Q}_i\mathrm{diag}(\hat{\mathbf{h}}_i^H)$, then the non-outage probability $p_i$ in (9) can be expressed as

$$\begin{aligned} p_i &= \Pr\left\{\mathrm{Tr}(\mathbf{R}_i\mathbf{W}_k) \geq \gamma_i\sum_{\ell\neq k}\mathrm{Tr}(\mathbf{R}_i\mathbf{W}_\ell) + \gamma_i N_0\right\} \\ &= \Pr\{\mathrm{Tr}(\mathbf{R}_i\mathbf{Z}_k) \geq \gamma_i N_0\}. \end{aligned} \tag{10}$$

Define $x_i \triangleq \mathrm{Tr}(\mathbf{R}_i\mathbf{Z}_k)$ and $x_i$ can be rewritten as

$$x_i = \mathrm{Tr}\Big(\mathrm{diag}(\hat{\mathbf{h}}_i)\mathbf{Q}_i\mathrm{diag}(\hat{\mathbf{h}}_i^H)\mathbf{Z}_k\Big) = \mathrm{Tr}(\mathbf{C}_k\mathbf{Q}_i), \tag{11}$$

where $\mathbf{C}_k = \mathrm{diag}(\hat{\mathbf{h}}_i)\mathbf{Z}_k\mathrm{diag}(\hat{\mathbf{h}}_i^H)$. We can observe from (11) that $x_i$ is real-valued and is the sum of statistically independent random variables. Thus, $x_i$ can be approximated by a real-valued Gaussian distribution when $N_t$ is sufficiently large from the central limit theorem. The mean and variance of the real valued random variable $x_i$ can be obtained as follows

$$\mu_i = \mathbb{E}\{x_i\} = \mathrm{Tr}(\mathbf{C}_k\mathbb{E}\{\mathbf{Q}_i\}) = \mathrm{Tr}(\mathbf{C}_k\mathbf{A}_i), \tag{12}$$

$$\begin{aligned} v_i^2 &= \mathbb{E}\{(\mathrm{Tr}(\mathbf{C}_k\mathbf{Q}_i))^2\} - \mu_i^2 \\ &= \mathrm{vec}^H(\mathbf{C}_k^H)\mathbb{E}\{\mathrm{vec}(\mathbf{Q}_i)\mathrm{vec}^H(\mathbf{Q}_i)\}\mathrm{vec}(\mathbf{C}_k^H) - \mu_i^2 \\ &= \mathrm{vec}^H(\mathbf{C}_k^H)\mathbb{E}\{(\mathbf{q}_i^* \otimes \mathbf{q}_i)(\mathbf{q}_i^* \otimes \mathbf{q}_i)^H\}\mathrm{vec}(\mathbf{C}_k^H) - \mu_i^2 \\ &= \mathrm{vec}^H(\mathbf{C}_k^H)\mathbb{E}\{\mathbf{Q}_i^T \otimes \mathbf{Q}_i\}\mathrm{vec}(\mathbf{C}_k^H) - \mu_i^2, \end{aligned} \tag{13}$$

where $\mathrm{vec}(\cdot)$ denotes the vectorization operation and $\otimes$ denotes the Kronecker product.

Define $\mathbf{G}_i \triangleq \mathbb{E}\{\mathbf{Q}_i^T \otimes \mathbf{Q}_i\}$, it is not difficult to show that the (*m, n*)th element of $\mathbf{G}_i$ with $m = (m_1 - 1)K + m_2$ and $n = (n_1 - 1)K + n_2$ is given by

$$[\mathbf{G}_i]_{m,n} = \begin{cases} 1, & m_1 = n_1 \text{ and } m_2 = n_2 \\ \exp\{-2\sigma_i^2\}, & m_1 \neq n_1 \text{ and } m_2 \neq n_2 \\ \exp\{-\sigma_i^2\}, & \text{otherwise.} \end{cases}$$

With the above derivations, we can then obtain the expression of the non-outage probability $p_i = \Pr\{x_i \geq \gamma_i N_0\}$ as follows

$$p_i = \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{\mu_i - \gamma_i N_0}{\sqrt{2}v_i}\right), \quad \text{for} \quad \gamma_i N_0 \leq \mu_i, \quad (14)$$

where $\mathrm{erf}(\cdot)$ is the Gaussian error function. Note that in the evaluation of the non-outage probability, we only focus on the case where $p_i > 0.5$, which is of interest for practical satellite communication links.

From (12), (13) and (14), the outage constraint $p_i \geq \alpha_i$ can be rewritten as

$$\left\|\mathbf{G}_i^{\frac{1}{2}}\mathrm{vec}(\mathbf{C}_k^H)\right\|_2^2 \leq \frac{1}{b_i^2}\left(\sqrt{b_i^2+1}\mathrm{Tr}(\mathbf{C}_k\mathbf{A}_i) - \frac{a_i}{\sqrt{b_i^2+1}}\right)^2 + \frac{a_i^2}{b_i^2+1}, \quad (15)$$

where $a_i = \gamma_i N_0$ and $b_i = \sqrt{2}\mathrm{erf}^{-1}(2\alpha_i - 1)$. Note that (15) can be transformed into a convex constraint when we drop the term $a_i^2/(b_i^2+1)$. Then problem $\mathcal{Q}$ can be reformulated as

$$\begin{aligned} \mathcal{Q}_s:\ &\min_{\{\mathbf{W}_k\}_{k=1}^K}\ r \\ &\text{s.t.}\ \left\|\mathbf{G}_i^{\frac{1}{2}}\mathrm{vec}(\mathbf{C}_k^H)\right\|_2 \leq \frac{1}{b_i}\left(\sqrt{b_i^2+1}\mathrm{Tr}(\mathbf{C}_k\mathbf{A}_i) - \frac{a_i}{\sqrt{b_i^2+1}}\right), \\ &\frac{1}{P_n}[\sum_{k=1}^K \mathbf{W}_k]_{n,n} \leq r,\ \forall n \in \mathcal{B}, \\ &\mathbf{W}_k \succeq \mathbf{0},\ \mathrm{rank}(\mathbf{W}_k) = 1,\ \forall k \in \mathcal{K}. \end{aligned} \quad (16)$$

As the term $a_i^2/(b_i^2+1) > 0$, then the feasible set of the transformed problem $\mathcal{Q}_s$ is a subset of the beamformer set that satisfies (15).

Using a semidefinite relaxation technique [16], we relax the non-convex rank-one constraint, and then the problem $\mathcal{Q}_s$ can be rewritten as follows

$$\begin{aligned} \mathcal{Q}_f:\ &\min_{\{\mathbf{W}_k\}_{k=1}^K}\ r \\ &\text{s.t.}\ \left\|\mathbf{G}_i^{\frac{1}{2}}\mathrm{vec}(\mathbf{C}_k^H)\right\|_2 \leq \frac{1}{b_i}\left(\sqrt{b_i^2+1}\mathrm{Tr}(\mathbf{C}_k\mathbf{A}_i) - \frac{a_i}{\sqrt{b_i^2+1}}\right), \\ &\frac{1}{P_n}[\sum_{k=1}^K \mathbf{W}_k]_{n,n} \leq r,\ \forall n \in \mathcal{B}, \\ &\mathbf{W}_k \succeq \mathbf{0},\ \forall k \in \mathcal{K}. \end{aligned} \quad (17)$$

TABLE I
SIMULATION SETUP PARAMETERS

| Parameter | Value |
|---|---|
| Hexagonal beam length | 250 (km) |
| Frequency band | $f = 20$ (GHz) |
| Boltzmann's constant | $\kappa = 1.38 \times 10^{-23}$ (J/m) |
| Noise bandwidth | $B = 50$ (MHz) |
| Satellite antenna gain | $G_T^j = 38$ (dBi) |
| Receiver gain to noise temperature | $G_{r,i}/T = 15$ (dB/K) |
| 3 dB angle | $\theta_{3dB} = 0.4°$ |
| Per beam power constraint | $P_n = 200$ (W) |
| Rain fading mean | $-2.6$ (dB) |
| Rain fading variance | 1.63 (dB) |

Problem $\mathcal{Q}_f$ is a convex optimization problem with a linear objective and second-order cone and semi-definite programming constraints and thus can be efficiently solved [15]. We observe from extensive simulation that the problem $\mathcal{Q}_f$ formulated in (17) yields rank-one solutions in most of the cases. For other cases, classic randomization approaches [16] can be adopted to address the rank issue.

## IV. SIMULATION RESULTS

We present simulation results to illustrate the performance of the proposed outage constrained robust multigroup multicast beamforming for frame-based multi-beam satellite communication systems. Conventional approach which adopts the outdated CSI directly as the true CSI is also considered for performance comparison [6]. The simulation results are based on $10^6$ channel realizations.

The simulation setup is presented as follows. We adopt the channel model presented in Section II, and detailed parameter values are listed in Table I. Assume that the channel phase error variances for different users are identical and given by $\sigma_i^2 = \sigma^2$. The non-outage probability and SINR thresholds for all users are set to be equal, i.e., $\alpha_i = \alpha$, $\gamma_i = \gamma_{\mathrm{th}}$. Assume that there are 7 beams covering the target area in which a total of 35 users are uniformly distributed.

We first evaluate the achievable sum multicast rate given by

$$R_{\mathrm{sum}} = \sum_{k=1}^K N_k \cdot r_k, \quad (18)$$

where $N_k$ is the number of users in cluster *k*, and $r_k$ is the multicast rate in cluster *k* given by

$$r_k = \mathbb{E}\left\{\log_2(1 + \min_{i \in \mathcal{U}_k} \mathrm{SINR}_i)\right\}. \quad (19)$$

We can observe from Fig. 1 that the proposed outage constrained robust approach shows multicast rate performance gains over the conventional approach. In addition, the performance gain becomes larger as the non-outage probability threshold $\alpha$ increases or the SINR threshold $\gamma_{\mathrm{th}}$

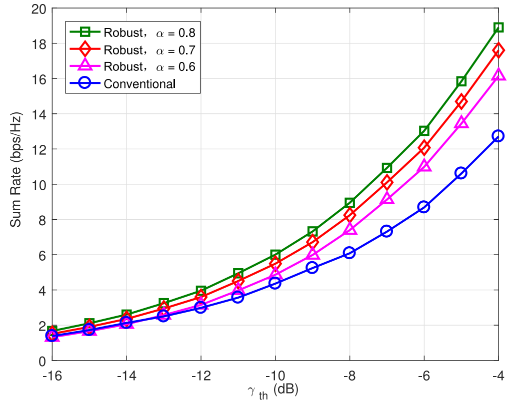


Fig. 1. Comparison of the achievable sum multicast rate between the proposed robust and conventional beamforming approaches. Results are shown versus the SINR threshold $\gamma_{\text{th}}$ for different values of non-outage probability threshold $\alpha$ with $\sigma^2 = 30°$.

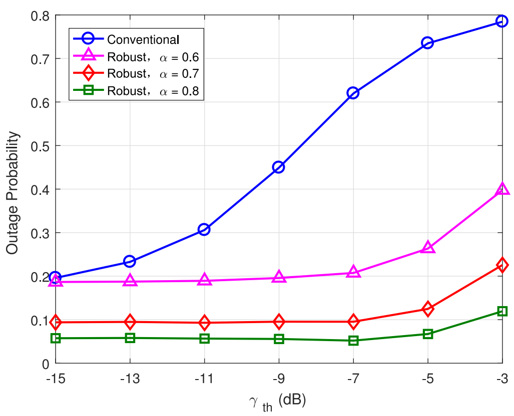


Fig. 2. Comparison of the outage probability between the proposed robust and conventional beamforming approaches. Results are shown versus the SINR threshold $\gamma_{\text{th}}$ for different values of non-outage probability threshold $\alpha$ with $\sigma^2 = 30°$.

increases. For the case with $\alpha = 0.8$ and $\gamma_{\text{th}} = -4$ dB, the proposed robust approach can provide approximately 46% multicast rate gain over the conventional approach.

In Fig. 2, the outage performance of the proposed robust and conventional approaches are depicted. We can observe that the proposed robust approach can provide significant reduction in outage probability than the conventional beamforming approach.[1] In particular, for the case with $\alpha = 0.8$ and $\gamma_{\text{th}} = -3$ dB, the proposed robust approach can provide approximately 65% outage performance gain over the conventional approach.

## V. Conclusion

In this letter, we have investigated outage constrained robust multigroup multicast beamforming for multi-beam satellite communication systems. With the channel phase uncertainty taken into account, we formulated a robust beamformer design with the aim to maximize the worst-case outage SINR of all users subject to the outage and the per-beam power constraints. We then reformulated the outage SINR maximization robust beamforming problem into a convex optimization problem. Simulation results demonstrated that the proposed outage constrained robust beamforming approach can provide significant performance gains in multicast rate and outage probability over the conventional approach.

[1] Note that for larger values of $\gamma_{\text{th}}$, infeasibility might arise in the considered problem due to, e.g., the channel uncertainty. For these scenarios, joint design of beamforming and admission control should be considered.

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