Letter

SLNR-based Secure Energy Efficient Beamforming in Multibeam Satellite Systems

Abstract—**Motivated by the fact that both security and energy efficiency are the fundamental requirements and design targets of future satellite communications, this letter investigates secure energy efficient beamforming in multibeam satellite systems, where the satellite user in each beam is surrounded by an eavesdropper attempting to intercept the confidential information. To simultaneously improve the transmission security and reduce power consumption, our design objective is to maximize the system secrecy energy efficiency (SEE) under the constraint of total transmit power budget. Different from the existing schemes with high complexity, we propose an alternating optimization scheme to address the SEE problem by decomposing the original nonconvex problem into subproblems. Specifically, we first utilize the signal-to-leakage-plus-noise ratio (SLNR) metric to obtain closed-form normalized beamforming weight vectors, while the successive convex approximation (SCA) method is used to efficiently solve the power allocation subproblem. Then, an iterative algorithm is proposed to obtain the suboptimal solutions. Finally, simulation results are provided to verify the superiority of the proposed scheme compared to the benchmark schemes.**

Index Terms—**Multibeam satellite systems, SEE, SLNR, alternating optimization.**

I. INTRODUCTION

THE upcoming sixth generation (6G) mobile networks will have to satisfy the seamless coverage and huge connectivity demands triggered by new applications, enriched multimedia content in ultra-dense regions and the massive diffusion of sensors in remote areas [1]-[2], which also bring tough challenges, such as the spectrum scarcity and uneconomic deployment of terrestrial infrastructures. Considering the natural characteristics of vast coverage area and efficient frequency reuse, the multibeam satellite (MS) system is regarded as a promising solution to accommodate both ultra-massive connections and low-cost service in rural regions [3].

Despite the above advantages, MS communications now faces severe security challenges due to the universal coverage and broadcast nature [4]. To address this issue, the physical layer security techniques have been applied to enhance the security of MS systems. Specifically, the authors in [5] investigated secrecy rate maximization problem with coordinated and uncoordinated eavesdropper (Eves). Except for communication security, the transmit power should be also taken into account in MS systems due to the limited onboard energy resource. The authors in [6] investigated the optimization of SEE, which is defined as the ratio of the secrecy rate to consumed power, in the satellite communications field for the first time.

Note that the aforementioned works focused on obtaining optimal solutions. Nevertheless, they inevitably bring high computational complexity and heavy hardware burden, even fail to achieve real-time on-board processing. Thus, researchers have tried to relax complexity by using zero-forcing (ZF) beamforming in [7], which utilized degree of spatial freedom to null out the multiuser interference. ZF beamforming requires the dimension condition that the number of transmit antennas is larger than that of total unintended users, and it also neglects the noise influence for the optimization object. To address the above issues, the concept of SLNR has been considered as a practical criterion for decoupling the coupled optimization problem and offering closed-form solutions [8].

To the best of our knowledge, so far the challenge of low-complexity SEE solutions has not been well investigated and the SLNR criterion has not been considered in MS systems. In this letter, we aim to propose an effective approach to maximize the SEE of MS system, while satisfying the satellite transmit power budget. Due to the coupled variables and nonconvex object, we propose a novel alternating optimization (AO) scheme wherein SLNR based criterion is applied to obtain the normalized beamforming weight vectors, while SCA approach is used to iteratively solve the power allocation problem. Unlike the high-complex SEE optimization of single user scenario considered in [6] and implied restriction of transmit antennas in [7], the proposed AO scheme obtains satisfying SEE performance with low computational complexity.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider the MS downlink transmission scenario, where the multibeam satellite transmits private signals to K users, each of which is surrounded with an Eve attempting to wiretap the signals to the targeted user. It is assumed that the satellite is equipped with L antenna feeds while each user and Eve is deployed with a single antenna. By considering the effects of rain attenuation, free space path loss and beam gains, the multibeam satellite downlink channel from the satellite to the k-th user can be modeled as [7]

$$\mathbf{h}_k = \sqrt{C_k}\mathbf{r}_k^{-\frac{1}{2}} \odot \mathbf{b}_k^{\frac{1}{2}} \odot e^{j\boldsymbol{\theta}_k} \tag{1}$$

where $C_k = (\lambda/4\pi d_k)^2$ denotes the free space loss, λ is the wavelength and d_k is the transmission distance between the satellite and k-th user. $\mathbf{r}_k \in \mathbb{C}^{L\times 1}$ and $\mathbf{b}_k \in \mathbb{C}^{L\times 1}$ denote the rain attenuation coefficient and beam gain. $\boldsymbol{\theta}_k \in \mathbb{C}^{L\times 1}$ is the phase vector with elements uniformly distributed among $[0, 2\pi)$.

The satellite transmits its normalized signal $x_k(t)$ towards the k-th user, which is mapped by the beamforming weight vector $\mathbf{w}_k$ before transmission. A nearby Eve, named k-th Eve, attempts to intercept the confidential signal to the k-th user. By defining $\mathbf{h}_k$ and $\mathbf{g}_k$ as the channels from the satellite to users and Eves,[1] respectively, the received signals at the k-th user and k-th Eve can be written as

$$\begin{aligned} y_k(t) &= \mathbf{h}_k^H \mathbf{w}_k x_k(t) + \sum_{i\neq k}^{K} \mathbf{h}_k^H \mathbf{w}_i x_k(t) + n_k(t), \\ y_{k,e}(t) &= \mathbf{g}_k^H \mathbf{w}_k x_k(t) + \sum_{i\neq k}^{K} \mathbf{g}_k^H \mathbf{w}_i x_k(t) + n_{k,e}(t) \end{aligned} \tag{2}$$

where $n_k(t)$ and $n_{k,e}(t)$ are the additive Gaussian white noise at the k-th user and k-th Eve.

Based on (2), the received SINRs at the k-th user and k-th Eve are given by, respectively

$$\begin{aligned} \gamma_k &= \frac{\left|\mathbf{h}_k^H \mathbf{w}_k\right|^2}{\sum\limits_{i\neq k}^{K}\left|\mathbf{h}_k^H \mathbf{w}_i\right|^2 + \sigma_k^2}, \\ \gamma_{k,e} &= \frac{\left|\mathbf{g}_k^H \mathbf{w}_k\right|^2}{\sum\limits_{i\neq k}^{K}\left|\mathbf{g}_k^H \mathbf{w}_i\right|^2 + \sigma_{k,e}^2}. \end{aligned} \tag{3}$$

Then, the secrecy rate at the k-th user can be written as

$$R_{s,k} = \log_2(1+\gamma_k) - \log_2(1+\gamma_{k,e}). \tag{4}$$

To achieve the trade-off between transmission security and transmit power, the objective is to maximize the system SEE under the total transmit power constraint. The optimization problem can be written as

$$\begin{aligned} &\max_{\mathbf{w}_k} \frac{\sum_{k=1}^{K} R_{s,k}}{\mu\sum_{k=1}^{K}\|\mathbf{w}_k\|^2 + P_c} \\ &\text{s.t.} \quad \sum_{k=1}^{K}\|\mathbf{w}_k\|^2 \le P_s \end{aligned} \tag{5}$$

where η_k denotes the weight factor of the priority for the k-th user and satisfies $\sum_{k=1}^{K}\eta_k = K$, $\mu \ge 1$ is the inverse of the amplifier efficiency at the satellite, P_c represents the static circuit power dissipated in all hardware blocks, P_s is the total transmit power budget at the satellite.

Obviously, the formulated problem (5) is challenging and intractable to solve due to its non-convex and fractional objective. In addition, the existing schemes for solving energy efficiency and SEE maximization typically adopted penalty function method [1] or difference of two-convex functions approximation method [6] to obtain beamforming metrics, which have high complexity and would further cause computational burden to the limited onboard load resource, especially for massive MIMO scenario. Thus, the next section develops an efficient and low-complexity scheme to solve (5).

III. LOW-COMPLEXITY AO SCHEME

To solve the problem (5) with a low complexity, we propose a novel AO scheme to iteratively obtain the normalized beamforming weight vectors $\mathbf{v}_k$, and power allocation factors p_k, with $\mathbf{w}_k = \sqrt{p_k}\mathbf{v}_k$ and $\|\mathbf{v}_k\|^2 = 1$.

[1]Similar to [7], we here suppose that Eves are also satellite users, but unauthorized for the private signals, thus both legitimate and wiretap channel state information are available at the satellite.

A. Optimization on $\mathbf{v}_k$

Different from the traditional ZF beamforming [7], SLNR based beamforming approach takes the noise power into account, and decouple the complex coupling signal crossing problem to provide closed-form solutions. Here, we apply SLNR based beamforming to maximize the intended receiving signal power while suppressing the private signal leakage to both unintended users and Eves. Thus, we have

$$\begin{aligned}\mathrm{SLNR}_k &= \frac{\mathbf{w}_k^H\mathbf{h}_k\mathbf{h}_k^H\mathbf{w}_k}{\sum\limits_{i\neq k}^{K}\mathbf{w}_k^H\mathbf{h}_i\mathbf{h}_i^H\mathbf{w}_k+\mathbf{w}_k^H\mathbf{g}_k\mathbf{g}_k^H\mathbf{w}_k+\sigma_k^2}\\ &= \frac{\mathbf{v}_k^H\mathbf{h}_k\mathbf{h}_k^H\mathbf{v}_k}{\mathbf{v}_k^H\left(\sum\limits_{i\neq k}^{K}\mathbf{h}_i\mathbf{h}_i^H+\mathbf{g}_k\mathbf{g}_k^H+\frac{\sigma_k^2}{p_k}\mathbf{I}_N\right)\mathbf{v}_k}\end{aligned} \tag{6}$$

where $\mathbf{I}_N \in \mathbb{C}^{N\times N}$ is identity matrix. By using SLNR based beamforming, the optimization problem (5) can be relaxed into the following SLNR maximization problem for $\forall k$

$$\begin{aligned}&\max_{\mathbf{v}_k}\mathrm{SLNR}_k\\ &\text{s.t.}\quad \|\mathbf{v}_k\|^2=1.\end{aligned} \tag{7}$$

By using the concept of Rayleigh quotient, we can obtain

$$\mathbf{v}_k=\frac{\left(\sum\limits_{i\neq k}^{K}\mathbf{h}_i\mathbf{h}_i^H+\mathbf{g}_k\mathbf{g}_k^H+\frac{\sigma_k^2}{p_k}\mathbf{I}_N\right)^{-1}\mathbf{h}_k}{\left\|\left(\sum\limits_{i\neq k}^{K}\mathbf{h}_i\mathbf{h}_i^H+\mathbf{g}_k\mathbf{g}_k^H+\frac{\sigma_k^2}{p_k}\mathbf{I}_N\right)^{-1}\mathbf{h}_k\right\|}. \tag{8}$$

According to (8), the solution of $\mathbf{v}_k$ is closely related to the power allocation factor. However, the joint optimization of $\mathbf{v}_k$ and p_k is complex and difficult to resolve with respect to the problem (5). Thus, we prepare to iteratively use the closed-form (8) of $\mathbf{v}_k$ and optimize the power allocation factors.

B. Optimization on p_k

Since the optimization on $\mathbf{v}_k$ is solved by SLNR based beamforming, it take both the multibeam interference and security into consideration, which is not closely related to the SEE maximization problem. Thus, by substituting (8) into (5), introducing the auxiliary variable τ and defining $v_k = \left|\mathbf{h}_k^H\mathbf{v}_j\right|^2$, $v_{k,i} = \left|\mathbf{h}_k^H\mathbf{v}_i\right|^2$, $v_{e,k} = \left|\mathbf{g}_k^H\mathbf{v}_j\right|^2$ and $v_{e,k,i} = \left|\mathbf{g}_k^H\mathbf{v}_i\right|^2$, the problem (5) is formulated as

$$\max_{p_k,\tau}\tau \tag{9a}$$

$$\text{s.t.}\quad \sum_{k=1}^{K}\eta_k\ln\frac{1+\frac{v_kp_k+\sigma_k^2}{\sum\limits_{i\neq k}^{K}v_{k,i}p_i+\sigma_k^2}}{1+\frac{v_{e,k}p_k+\sigma_{k,e}^2}{\sum\limits_{i\neq k}^{K}v_{e,k,i}p_i+\sigma_{k,e}^2}}\geq\tau\left(\mu\sum_{k=1}^{K}p_k+P_c\right), \tag{9b}$$

$$\sum_{k=1}^{K}p_k\leq P_s,\ p_k\geq 0,\ \forall k. \tag{9c}$$

It can be observed that the problem (9) is still nonconvex due to its constraints. Next, the SCA approach is applied to transform the nonconvex constraints into second-order cone (SOC) and linear matrix inequality (LMI) forms. By introducing auxiliary variable τ and $\{a_k, b_k, c_k\}$, the constraint (10b) can be converted to

$$\ln(1+a_k)-\ln(1+b_k)\geq c_k, \tag{10a}$$

$$\sum_{k=1}^{K}\eta_kc_k\geq\tau\left(\mu\sum_{k=1}^{K}p_k+P_c\right), \tag{10b}$$

$$v_kp_k+\sigma_k^2\geq\left(\sum_{i\neq k}^{K}v_{k,i}p_i+\sigma_k^2\right)a_k, \tag{10c}$$

$$v_{e,k}p_k+\sigma_{k,e}^2\leq\left(\sum_{i\neq k}^{K}v_{e,k,i}p_i+\sigma_{k,e}^2\right)b_k. \tag{10d}$$

Similarly, we introduce auxiliary variable f into the constraint (10b)-(10d), which can be transformed as

$$\sum_{k=1}^{K}\eta_kc_k\geq f^2, \tag{11a}$$

$$\frac{f^2}{\tau}\geq\mu\sum_{k=1}^{K}p_k+P_c,\ \frac{v_kp_k+\sigma_k^2}{a_k}\geq\sum_{i\neq k}^{K}v_{k,i}p_i+\sigma_k^2, \tag{11b}$$

$$\frac{v_{e,k}p_k+\sigma_{k,e}^2}{b_k}\leq\sum_{i\neq k}^{K}v_{e,k,i}p_i+\sigma_{k,e}^2 \tag{11c}$$

where (11a) can be converted to the following SOC forms

$$\frac{\sum_{k=1}^{K}\eta_kc_k+1}{2}\geq\left\|\left[\left(\sum_{k=1}^{K}\eta_kc_k-1\right)/2,f\right]^T\right\|_2. \tag{12}$$

By using first order Taylor expansion into the constraints (11b) and (11c), they can be reformulated as

$$\begin{aligned}&\frac{2f^{(n)}}{\tau^{(n)}}f-\frac{\left(f^{(n)}\right)^2}{\left(\tau^{(n)}\right)^2}\tau\geq\mu\sum_{k=1}^{K}p_k+P_c,\\ &\frac{v_kp_k}{a_k^{(n)}}-\frac{v_kp_k^{(n)}a_k}{\left(a_k^{(n)}\right)^2}+\frac{v_kp_k^{(n)}+\sigma_k^2}{a_k^{(n)}}\geq\sum_{i\neq k}^{K}v_{k,i}p_i+\sigma_k^2,\\ &\frac{v_{e,k}p_k}{b_k^{(n)}}-\frac{v_{e,k}p_k^{(n)}b_k}{\left(b_k^{(n)}\right)^2}+\frac{v_{e,k}p_k^{(n)}+\sigma_{k,e}^2}{b_k^{(n)}}\leq\sum_{i\neq k}^{K}v_{e,k,i}p_i+\sigma_{k,e}^2.\end{aligned} \tag{13}$$

For (10a), by introducing auxiliary variables q_k and using first-order Taylor series expansion, we have

$$\begin{aligned}&1+a_k\geq e^{q_k},\\ &q_k-\ln\left(1+b_k^{(n)}\right)-\frac{b_k-b_k^{(n)}}{1+b_k^{(n)}}\geq c_k.\end{aligned} \tag{14}$$

Thus, the original power allocation problem can be transformed as the following iterative problem

$$\begin{aligned}&\max_{p_k,\tau}\tau\\ &\text{s.t.}\quad (9c),(12),(13),(14).\end{aligned} \tag{15}$$

Finally, the solutions of $\mathbf{w}_k$ can be obtained by iteratively solving (8) and (15).

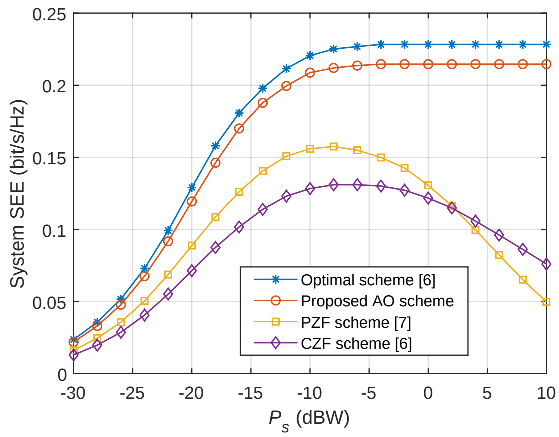

Fig. 1: System SEE versus P_s

IV. NUMERICAL RESULTS

We consider an MS system with $K = 3$ users and K Eves. Parameters are set as follows: $f_c = 18$ GHz, $B = 50$ MHz, $L = 7$, $\eta_k = 1$, $\mu = 1$, static circuit power $P_c = -20$ dBW. The complete ZF (CZF) and optimal schemes in [7], and the partial ZF (PZF) scheme in [6] are adopted for benchmarks. Here, by jointly considering the involved optimization problem, the size of input data, and the types of constraints, the complexity of the optimal scheme in [6] and the proposed AO scheme are, respectively, obtained as [2]

$$\begin{aligned} &O\left(\sqrt{K\left(L+4\right)+5}\cdot n_1\cdot\left[\left(4K+5\right)\left(1+n_1\right)\right.\right.\\ &\qquad\qquad\left.\left.+KL^2\left(L+1+n_1\right)+n_1^2\right]\right),\\ &O\left(\sqrt{5K+2}\cdot n_2\cdot\left[\left(4K+2\right)\left(1+n_2\right)+K+1+n_2^2\right]\right) \end{aligned} \tag{17}$$

where $n_1 = O\left(KL^2 + 4K + 5\right)$ and $n_2 = O\left(5K + 2\right)$.

Figure 1 depicts the achieved system SEE versus the transmit power budget. It can be seen that the system SEE is not monotonic with the transmit power, but instead admits a finite maximal value for the optimal and AO schemes. The reason is that the sum secrecy rate would linearly increase with the transmit power after reaching -5 dBW. The SEE of CZF and PZF schemes would degrade after reaching -8 dBW and -4 dBW, because both the schemes only optimize the nulling based beamforming with the maximal power, thus the growth rate of secrecy rate is lower than the transmit power when reach the turning points. When $P_s = -4$ dBW, the SEE of the proposed AO scheme is 43% and 65% more than those of the PZF and CZF schemes. The proposed scheme only degrade the SEE slightly with significantly reduced complexity compared to [6]. The above observations prove that the proposed scheme not only achieve satisfactory SEE, but also lower the on-board computing burden.

V. CONCLUSION

This letter has developed a low-complexity optimization framework in terms of SEE beamforming for MS systems, by maximizing the system SEE under the transmit power constraint, which was formulated as a nonconvex and intractable problem. Compared to the optimal scheme with high complexity and the ZF-based suboptimal scheme with limited performance gain, we proposed a novel AO scheme by using the SLNR criterion and SCA method to iteratively obtain closed-form beamforming weight and power allocation factors. Finally, simulation results validated the effectiveness of our proposed scheme.

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