Robust Hybrid Beamforming for Satellite-Terrestrial Integrated Networks

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Outline

Introduction

- SATCOM Superiority
  1. Inherent large coverage
  2. High-speed broadband access
  3. Services in areas where terrestrial communication systems are infeasible
- **The goal of next generation communication system:**
  1. Seamless Connectivity
  2. Increasing demand for broadband satellite services
- **Problems:**
  1. Scarce spectrum resources
  2. Increasing data rate demands

Introduction

- **The deployment of high frequency band: Ka or mmWave**
  1. Huge available bandwidth.
  2. Antenna arrays with directional beam compensating propagation losses.
- **Promising Infrastructure: Satellite-Terrestrial Integrated Networks (STIN)**
  1. An supplement for drawbacks experienced by terrestrial/satellite systems.
  2. Use dynamic spectrum access technology to enhance the utilization of limited spectrum significantly.
  3. Design an integrated network to satisfy the demand for anytime, anywhere, and anyway service.

Introduction

- **Energy Efficiency and Security Requirements**
  1. Huge energy consumption of base stations and especially the radio access subsystems
  2. Important factor from both economic and ecological perspectives
  3. Security requirement brings new challenage
  4. By defining the ratio between the secrecy rate and the consumed power, the concept of secrecy energy efficiency (SEE) is introduced to balance the security and EE

Introduction

Our contributions:

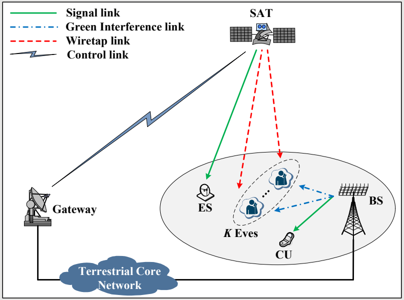
- We formulate a constrained optimization problem to maximize the SEE of the considered system while satisfying the SINR requirements of both the earth station and cellular user. Robustness is incorporated in the design by considering imperfect knowledge of the angles of departure for the downlink wiretap channels.
- We then propose a new iterative search algorithm based on the Charnes-Cooper approach to solve the optimization problem and obtain the desired hybrid BF weight vectors.

Outline

System Model

System Model of the considered STIN:

- The GEO satellite serves an earth station (ES) in the presence of K eavesdroppers (Eves), while the BS serves a cellular user (CU). It is assumed that the Eves, but not the ES, are under coverage of the cellular sub-network, and therefore receive interference from the BS.



System Model

Channel Model

Satellite downlink channel

Considering the effects of path loss, atmospheric attenuation and satellite antenna gain in satellite downlink channel, it can be written as

$$\mathbf{f} = \sqrt{C_L G_r}\mathbf{r} \odot \mathbf{b}^{\frac{1}{2}} \tag{1}$$

Terrestrial downlink channel

A typical mmWave channel with a predominant LoS propagation component and a sparse set of single-bounce NLoS components can be described as

$$\begin{aligned}\mathbf{h} = & \sqrt{g\left(\theta_0, \varphi_0\right)}\rho_0 \mathbf{a}_h\left(\theta_0, \varphi_0\right) \otimes \mathbf{a}_v\left(\theta_0\right) \\ & + \sqrt{\frac{1}{J}} \sum_{j=1}^{J} \sqrt{g\left(\theta_j, \varphi_j\right)}\rho_j \mathbf{a}_h\left(\theta_j, \varphi_j\right) \otimes \mathbf{a}_v\left(\theta_j\right).\end{aligned} \tag{2}$$

System Model

Channel Model

Steering vector

$\mathbf{a}_h\left(\theta,\varphi\right)$ and $\mathbf{a}_v\left(\theta\right)$ denote the horizontal and vertical array steering vectors (SVs) of the UPA, which are, respectively, given by

$$\begin{aligned}\mathbf{a}_h\left(\theta,\varphi\right) = \Big[&e^{-i\beta((N_1-1)/2)d_1\sin\theta\cos\varphi},\dots \\ &,e^{+i\beta((N_1-1)/2)d_1\sin\theta\cos\varphi}\Big]^T,\end{aligned} \tag{3a}$$

$$\mathbf{a}_v\left(\theta\right)=\Big[e^{-i\beta((N_2-1)/2)d_2\cos\theta},\dots,e^{+i\beta((N_2-1)/2)d_2\cos\theta}\Big]^T. \tag{3b}$$

System Model

Signal Models

- The received signals at the CU, ES, and *k*-th Eve are, respectively, expressed as

$$\begin{aligned} y_c(t) &= \mathbf{h}_c^H \mathbf{P} \mathbf{v} x(t) + \mathbf{f}_c^H \mathbf{w} s(t) + n_c(t), \\ y_s(t) &= \mathbf{f}_s^H \mathbf{w} s(t) + n_s(t), \\ y_k(t) &= \mathbf{f}_k^H \mathbf{w} s(t) + \mathbf{h}_k^H \mathbf{P} \mathbf{v} x(t) + n_k(t) \end{aligned} \tag{4}$$

- Then, the SINR at the CU, ES, and *k*-th Eve are given by

$$\gamma_c = \frac{\left|\mathbf{h}_c^H \mathbf{P} \mathbf{v}\right|^2}{\left|\mathbf{f}_c^H \mathbf{w}\right|^2 + \sigma_c^2}, \gamma_s = \frac{\left|\mathbf{f}_s^H \mathbf{w}\right|^2}{\sigma_s^2}, \gamma_k = \frac{\left|\mathbf{f}_k^H \mathbf{w}\right|^2}{\left|\mathbf{h}_k^H \mathbf{P} \mathbf{v}\right|^2 + \sigma_k^2}. \tag{5}$$

System Model

- The achievable secrecy rate of the ES is given by

$$R_s = \left[\log_2 \left(1 + \gamma_s \right) - \max_{k \in \{1, \cdots, K\}} \log_2 \left(1 + \gamma_k \right) \right]^+ \tag{6}$$

- The total power consumption of the considered system is modeled as

$$P_{tot} = \eta_1 \|\mathbf{w}\|^2 + \eta_2 \|\mathbf{v}\|^2 + P_S + P_B \tag{7}$$

System Model

Problem formulation

- By assuming that the available cellular wiretap channel of the k-th Eves belongs to a given AoD uncertainty set Δ_k defined by $\theta_k \in \left[\theta_k^L, \theta_k^U\right]$ and $\varphi_k \in \left[\varphi_k^L, \varphi_k^U\right]$, the optimization problem can be formulated as

$$\max_{\mathbf{w},\mathbf{v},\mathbf{P}} \min_{\Delta_k} R_s/P_{tot} \tag{8a}$$

$$\text{s.t. } \gamma_c \geq \Gamma_c, \tag{8b}$$

$$\gamma_s \geq \Gamma_s, \tag{8c}$$

$$\left|[\mathbf{P}]_{i,j}\right|^2 = 1/N_b,\ i = 1, \cdots, N_b,\ j = 1, \cdots, N_r, \tag{8d}$$

$$\|\mathbf{v}\|_F^2 \leq P_b,\ \ \|\mathbf{w}\|_F^2 \leq P_s \tag{8e}$$

Outline

Robust BF Scheme

- By assuming that the elevation and azimuth AoD angles for the wiretap channel of the k-th Eve can only take uniformly spaced values within their respective range $\theta_k \in \left[\theta_k^L, \theta_k^U\right]$ and $\varphi_k \in \left[\varphi_k^L, \varphi_k^U\right]$, as given by

$$\begin{aligned} \theta_k^{(i)} &= \theta_k^L + i\Delta\theta, \quad i = 0, \cdots, M_1, \\ \varphi_k^{(j)} &= \varphi_k^L + j\Delta\varphi, \quad j = 0, \cdots, M_2 \end{aligned} \tag{9}$$

where $\Delta\theta = (\theta_k^U - \theta_k^L)/M_1$ and $\Delta\varphi = (\varphi_k^U - \varphi_k^L)/M_2$. Then, we define $\tilde{\mathbf{H}} = \sum_{i=0}^{M_1} \sum_{j=0}^{M_2} \mu_{i,j} \mathbf{H}^{(i,j)}$ and $\tilde{\mathbf{F}} = \sum_{i=0}^{M_1} \sum_{j=0}^{M_2} \mu_{i,j} \mathbf{F}^{(i,j)}$, where $\mathbf{H}^{(i,j)} = \mathbf{h}^{(i,j)} \left(\mathbf{h}^{(i,j)}\right)^H$, $\mathbf{F}^{(i,j)} = \mathbf{f}^{(i,j)} \left(\mathbf{f}^{(i,j)}\right)^H$, $\mu_{i,j} = \frac{1}{(M_1+1)(M_2+1)}$. By using these *averaged* channel matrices in problem (8) instead of the *imperfect* ones, the minimization over Δ_k can be removed.

Robust BF Scheme

- By invoking the Charnes-Cooper approach and introducing auxiliary variables α and τ, (8) can be further transformed as

$$\max_{\mathbf{W},\mathbf{V},\mathbf{P}} \tau^{-1}\log_2\left(\frac{\sigma^2+\mathrm{Tr}\left(\mathbf{F}_s\mathbf{W}\right)}{\alpha}\right) \tag{10a}$$

$$\text{s.t.}\quad \eta_1\mathrm{Tr}\left(\mathbf{W}\right)+\eta_2\mathrm{Tr}\left(\mathbf{V}\right)+P_S+P_B=\tau, \tag{10b}$$

$$\frac{\mathrm{Tr}\left(\tilde{\mathbf{F}}_k\mathbf{W}\right)}{\mathrm{Tr}\left(\mathbf{P}^H\tilde{\mathbf{H}}_k\mathbf{P}\mathbf{V}\right)+\sigma^2}\le\alpha,\quad \forall k, \tag{10c}$$

$$\mathrm{Tr}\left(\mathbf{P}^H\mathbf{H}_c\mathbf{P}\mathbf{V}\right)-\Gamma_c\left(\mathrm{Tr}\left(\mathbf{F}_c\mathbf{W}\right)+\sigma^2\right)\ge 0, \tag{10d}$$

$$\mathrm{Tr}\left(\mathbf{F}_s\mathbf{W}\right)-\Gamma_s\sigma^2\ge 0, \tag{10e}$$

$$\left|[\mathbf{P}]_{i,j}\right|^2=1/N_b, i=1,\cdots,N_b, j=1,\cdots,N_r, \tag{10f}$$

$$\mathrm{Tr}\left(\mathbf{W}\right)\le P_s, \mathrm{Tr}\left(\mathbf{V}\right)\le P_b, \tag{10g}$$

$$\mathrm{rank}\left(\mathbf{W}\right)=1, \mathrm{rank}\left(\mathbf{V}\right)=1 \tag{10h}$$

where $a_k=\frac{\mathrm{Tr}\left(\mathbf{H}_{ir,k}\mathbf{W}_{k,1}\right)}{\sigma^2_{ir,k}}$.

Robust BF Scheme

Iteratively Solving $\mathbf{W}$

- The optimization problem for the digital beamforming weight vector can be expressed as

$$\max_{\mathbf{W},\mathbf{V},\tau,\alpha} \log_2\left(\frac{\sigma^2+\mathrm{Tr}\left(\mathbf{F}_s\mathbf{W}\right)}{\alpha}\right)\tau^{-1} \tag{11a}$$

$$\text{s.t.}\quad \eta_1\mathrm{Tr}\left(\mathbf{W}\right)+\eta_2\mathrm{Tr}\left(\mathbf{V}\right)+P_S+P_B=\tau, \tag{11b}$$

$$\frac{\mathrm{Tr}\left(\tilde{\mathbf{F}}_k\mathbf{W}\right)}{\mathrm{Tr}\left(\mathbf{P}^{(n)H}\tilde{\mathbf{H}}_k\mathbf{P}^{(n)}\mathbf{V}\right)+\sigma^2}\leq\alpha,\quad\forall k, \tag{11c}$$

$$\mathrm{Tr}\left(\mathbf{P}^{(n)H}\mathbf{H}_c\mathbf{P}^{(n)}\mathbf{V}\right)-\Gamma_c\left(\mathrm{Tr}\left(\mathbf{F}_c\mathbf{W}\right)+\sigma^2\right)\geq 0, \tag{11d}$$

$$\mathrm{Tr}\left(\mathbf{F}_s\mathbf{W}\right)-\Gamma_s\sigma^2\geq 0, \tag{11e}$$

$$\mathrm{Tr}\left(\mathbf{W}\right)\leq P_s,\mathrm{Tr}\left(\mathbf{V}\right)\leq P_b, \tag{11f}$$

$$\mathrm{rank}\left(\mathbf{W}\right)=1,\mathrm{rank}\left(\mathbf{V}\right)=1 \tag{11g}$$

Robust BF Scheme

Iteratively Solving $\mathbf{P}$

- The optimization problem of the analog precoder can then be written as follows

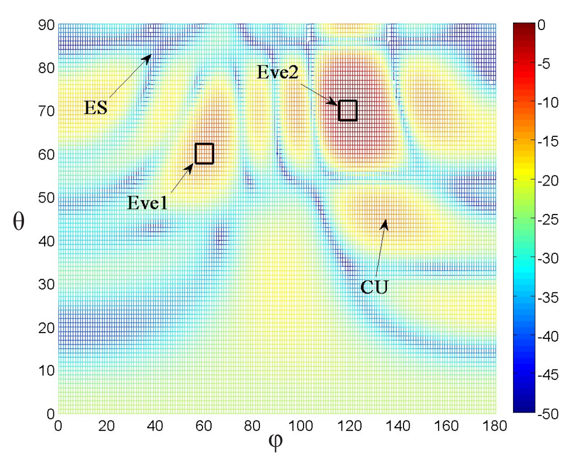
$$\begin{aligned}
\max_{\hat{\mathbf{P}}} \ & t \\
\text{s.t.} \ & \mathrm{Tr}\left(\hat{\mathbf{V}}^{(n)H}\tilde{\mathbf{H}}_k\hat{\mathbf{V}}^{(n)}\hat{\mathbf{P}}\right)+\sigma^2 \geq t\mathrm{Tr}\left(\tilde{\mathbf{F}}_k\mathbf{W}^{(n)}\right), \quad \forall k, \\
& \mathrm{Tr}\left(\hat{\mathbf{V}}^{(n)H}\tilde{\mathbf{H}}_c\hat{\mathbf{V}}^{(n)}\hat{\mathbf{P}}\right) \geq \Gamma_c\left(\mathrm{Tr}\left(\mathbf{F}_c\mathbf{W}^{(n)}\right)+\sigma^2\right), \\
& \mathrm{diag}\left[\hat{\mathbf{P}}\right]_q = \left[\mathbf{q}\mathbf{q}^H\right]_q, \quad q=1,\cdots,N_bN_r, \\
& \mathrm{rank}\left(\hat{\mathbf{P}}\right)=1
\end{aligned} \tag{12}$$

where $\hat{\mathbf{P}}=\mathbf{p}\mathbf{p}^H$, $\mathbf{q}=\mathrm{vec}\left(\Phi\right)$, $\mathbf{p}=\mathrm{vec}\left(\mathbf{P}\right)\in\mathbb{C}^{N_bN_r\times 1}$, $\hat{\mathbf{V}}^{(n)}=\mathrm{block}-\mathrm{diag}(\mathbf{v}^{(n)T},\cdots,\mathbf{v}^{(n)T})\in\mathbb{C}^{N_b\times N_bN_r}$, $\Phi=\mathbf{1}_{N_b\times N_r}/N_b$

Outline

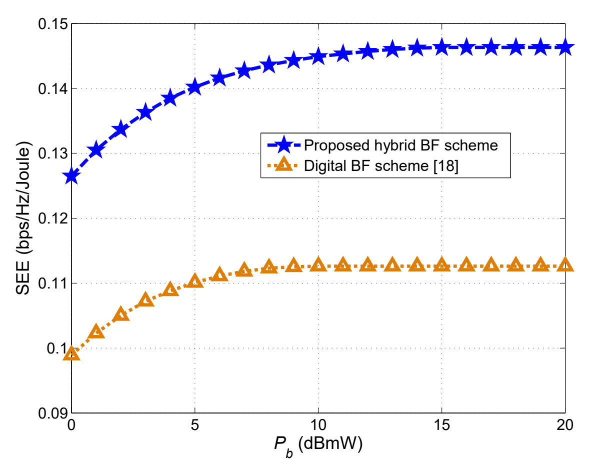
Simulations

3D beampattern of $\mathbf{Pv}$:



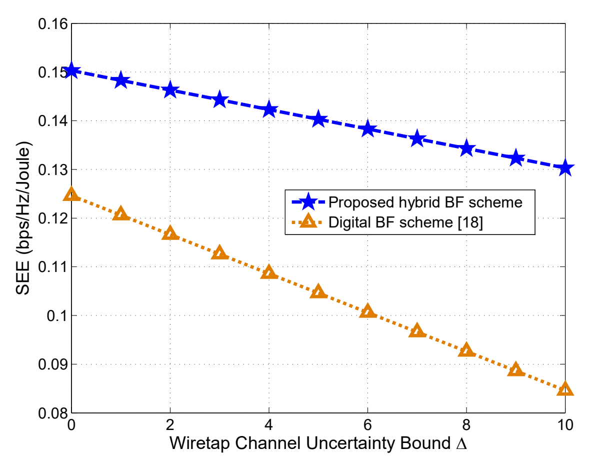
Simulations

SEE versus P_b:



Simulations

SEE versus Δ:



Outline

Conclusion

- We have proposed a hybrid BF scheme to achieve SEE maximization in STIN. To solve the original non-convex problem, we first used a discretization method to transform the constraints on the imperfect channel AoD into solvable ones.
- Then, an iterative BF algorithm based on the Charnes-Cooper method was conceived to solve the problem and obtain the digital and analog BF weight vectors.
- Finally, numerical results were given to demonstrate the superiority and effectiveness of the proposed hybrid BF scheme in comparison with an existing method.

Thank You!

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