Local CSI-Based Interference Cancellation in FD-Enabled Space-Earth Integrated Systems

Julius Ssimbwa†, Byungju Lim‡, Jung Min Suh†, and Young-Chai Ko†
†School of Electrical and Computer Engineering, Korea University, Seoul, Korea
‡Department of Electronic Engineering, Pukyong National University, Busan, Korea
(e-mail: kayjulio@korea.ac.kr, limbj@pknu.ac.kr, jmsuh904@korea.ac.kr, koyc@korea.ac.kr).

Abstract

This paper investigates an interference cancellation strategy based on local channel state information (CSI) for full-duplex (FD) based space-earth integrated networks (SEIN). In this context, we strive to maximize the network throughput while minimizing the interference such as self-interference (SI) and cross-tier interference, with reduced signaling overhead. An optimization problem is formulated to optimize the beamforming vectors of the base station (BS) and the satellite (SAT). To ensure no sharing CSI between BS and SAT, the problem is divided into two, namely the SAT and BS beamforming subproblems, which are separately solved using generalized iteration power (GPI) technique. The results show a significant improvement in system performance by the proposed scheme compared to the conventional schemes.

I. Introduction

Over the past decade, the rapid and ever-growing demand for seamless wireless connectivity has fueled the development of next-generation communication technologies such as 5G and beyond. Alongside this evolution, user expectations for low-latency, high-reliability, and ubiquitous access continue to push the boundaries of wireless network design. To address the limitations of terrestrial infrastructure particularly in remote, rural, and disaster-affected regions, non-terrestrial networks (NTNs) have emerged as a key enabler of future wireless systems [1]. To distinguish our work from the existing studies, we propose a network that incorporates a combination of three disruptive communication technologies, namely the space-earth integrated networks (SEIN), integrated access and backhaul (IAB), and full-duplex (FD) operation. Herein, we target enhanced global connectivity by jointly improving coverage, capacity, and spectral efficiency. We leverage the satellite network capability to provide service ubiquity via wireless backhaul connectivity to areas lacking sufficient terrestrial coverage. Furthermore, we apply FD operation to exploit its potential benefits associated with improving spectral efficiency and reducing latency.

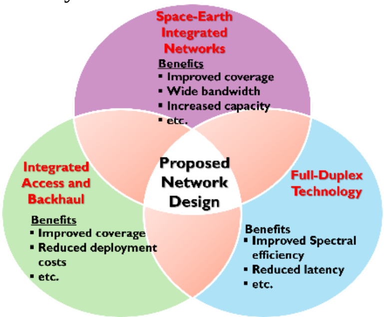


Fig. 1. Harnessing the synergy of three disruptive technologies.

Going forward, since such a network constitutes space and earth networks characterized by different design specifications despite sharing the same spectrum, it is susceptible to increased interference such as cross-tier interference. Moreover, the consequence of adopting the FD technique lies in the creation of self-interference. We tackle this network interference challenge using a distributed beamforming strategy without sharing channel state information (CSI) between SAT and BS as shown in the following sections.

II. Main part

The proposed system model is made up of a SAT equipped with N_s uniform planar array (UPA) antennas, B BSs each equipped with N_b^t transmit and N_b^r receive UPA antennas and K users each equipped with a single antenna. The BS simultaneously receives signals from SAT and transmits signals to users as shown in Fig.1. According to Fig.1, the overall network performance is compromised by undesirable interference such as self-interference (SI), intra-tier interference (ITI), and cross-tier interference (CRI).

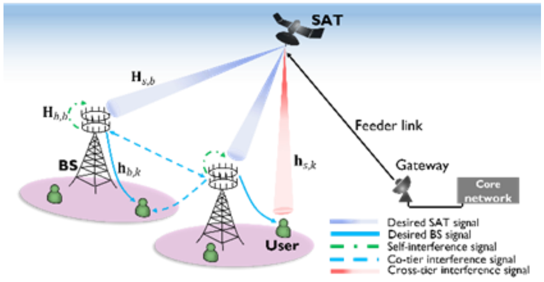


Fig. 2. Proposed system model of a FD-SEIN.

Subsequently, we examine the performance of our proposed system by analyzing the sum-rate of the network under BS and SAT power allocation constraints. Unlike the conventional form of computing spectral efficiency using the signal-to-interference-plus-noise ratio (SINR), we derive the rates using the signal-to-interference-plus-leakage-plus-noise ratio (SILNR). In this setting, we can reduce overhead signaling by ensuring no CSI sharing between SAT and BS. Therefore, the SILNR of the k-th user can be stated as

$$\mathrm{SILNR}_{b,k} = \frac{\left|\mathbf{h}_{b,k}^H \mathbf{w}_{b,k}\right|^2}{\sum_{\substack{l\in K,\\ l\neq k}}\left|\mathbf{h}_{b,k}^H \mathbf{w}_{b,l}\right|^2 + \sum_{b\in B}\left|\mathbf{h}_{s,k}^H \mathbf{v}_{s,b}\right|^2 \frac{P_s}{P_b} + \sum_{\substack{a\in K,\\ a\neq k}}\left|\mathbf{h}_{b,a}^H \mathbf{w}_{b,k}\right|^2 + \bar{\sigma}_{b,k}^2}, \quad (1)$$

with $\bar{\sigma}_{b,k}^2 = \mathbb{E}\left[\sum_{\substack{i\in B\\ i\neq b}}\sum_{\substack{a\in K,\\ a\neq k}}\left|\mathbf{h}_{i,k}^H \mathbf{w}_{i,a}\right|^2\right] + \frac{\sigma^2}{P_b}$, where $\mathbf{w}_{b,k}$ and $\mathbf{v}_{s,b}$ are transmit beamforming vectors and $x_{b,k}$ and $x_{s,b}$ are transmit symbols, while P_s and P_b are transmit powers for BS and SAT, respectively. In (1), the third term in the denominator represents the leakage power, which is signal power that radiated towards other users in other cells as the b-th BS transmits to its k-th user. Furthermore, due to the no CSI sharing rule, the co-tier interference term is treated as noise by taking its expectation and adding it to the noise power σ^2 as defined in the term $\bar{\sigma}_{b,k}^2$. Similarly, the SILNR of the b-th BS can be written as

$$\mathrm{SILNR}_{s,b} = \frac{\left|\tilde{\mathbf{h}}_{s,b}^H \mathbf{v}_{s,b}\right|^2}{\sum_{\substack{j\in B,\\ j\neq b}}\left|\tilde{\mathbf{h}}_{s,b}^H \mathbf{v}_{s,j}\right|^2 + \sum_{k\in K}\left|\tilde{\mathbf{h}}_{b,b}^H \mathbf{w}_{b,k}\right|^2 \frac{P_b}{P_s} + \sum_{\substack{j\in B\\ j\neq b}}\left|\tilde{\mathbf{h}}_{s,j}^H \mathbf{v}_{s,b}\right|^2 + \bar{\sigma}_{s,b}^2}, \quad (2)$$

with $\bar{\sigma}_{s,b}^2 = \mathbb{E}\left[\sum_{\substack{j\in B\\ j\neq b}}\left|\tilde{\mathbf{h}}_{j,b}^H \mathbf{w}_{j,k}\right|^2\right]\frac{P_b}{P_s} + \frac{\sigma^2}{P_s}$, $\tilde{\mathbf{h}}_{s,b} = \mathbf{f}_b^H \mathbf{H}_{s,b}$, and $\tilde{\mathbf{h}}_{b,b} = \mathbf{f}_b^H \mathbf{H}_{b,b}$, where $\mathbf{f}_b^H$ is the receive beamforming vector at b-th BS. Further still the third term in the denominator of (2) indicates the leakage power directed towards other BSs as SAT transmits to the b-th BS. The co-tier interference is treated in a similar way to (1). We then formulate an optimization problem to optimize BS and SAT beamforming while maximizing the sum-rate of users, subject to SAT and BS power constraints C1 and C2 as follows.

$$\begin{aligned}
(\mathrm{P1}):\ &\max_{\mathbf{v},\mathbf{w}} \sum_{b\in B} \min\left\{\log_2\left(1+\mathrm{SILNR}_{s,b}\right), \sum_{k\in K}\log_2\left(1+\mathrm{SILNR}_{b,k}\right)\right\} \\
&\text{s.t. C1: } \sum_{b\in B}\left\|\mathbf{v}_{s,b}\right\|_2^2 \le 1;\ \forall b\epsilon B \\
&\qquad \text{C2: } \sum_{k\in K}\left\|\mathbf{w}_{b,k}\right\|_2^2 \le 1;\ \forall k\epsilon K
\end{aligned} \quad (3)$$

Due to the nonconvexity of (P1), we make the problem more tractable by transforming the rates into the Rayleigh quotient form and apply the LogSumExp approximation to smoothen the objective function [2]. To this end, our problem is convex and solvable. Bearing in mind that we seek to design the SAT and BS beamforming vectors without sharing CSI, we implement a distributed beamforming strategy by dividing the resulting problem into subproblems (P2) and (P3) and use them to solve the SAT beamforming and BS beamforming, respectively.

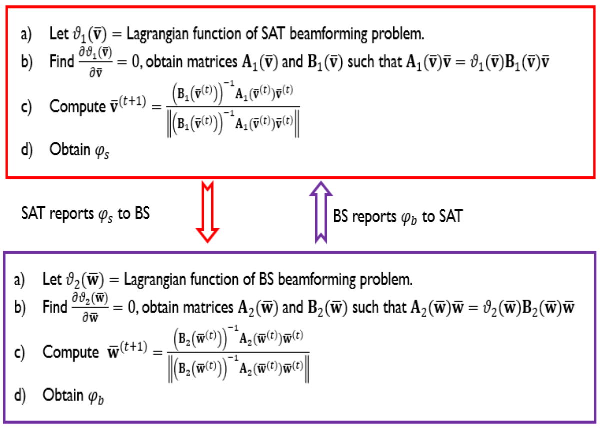
$$\text{P2:} \max_{\bar{\mathbf{v}}} \sum_{b\in B} -\alpha \ln\left[\left(\frac{\bar{\mathbf{v}}^H\left(\mathbf{A}_b+\mathbf{Y}_{s,b}(\bar{\mathbf{v}})^{\frac{J_b}{B}}\right)\bar{\mathbf{v}}}{\bar{\mathbf{v}}^H\left(\mathbf{B}_b+\mathbf{Y}_{s,b}(\bar{\mathbf{v}})^{\frac{J_b}{B}}\right)\bar{\mathbf{v}}}\right)^{\beta}+\varphi_b\right];\ \text{s.t}\ \hat{\text{C}}1$$

$$\text{P3:} \max_{\bar{\mathbf{w}}} \sum_{b\in B} -\alpha \ln\left[\varphi_s+\left(\frac{\bar{\mathbf{w}}^H(\mathbf{A}_k+\mathbf{F}_{b,k}(\bar{\mathbf{w}})^{\frac{K_a}{K}})\bar{\mathbf{w}}}{\bar{\mathbf{w}}^H(\mathbf{B}_k+\mathbf{F}_{b,k}(\bar{\mathbf{w}})^{\frac{K_a}{K}})\bar{\mathbf{w}}}\right)^{\beta}\right];\ \text{s.t}\ \hat{\text{C}}2 \quad (4)$$

with $\varphi_s=(\bar{\mathbf{v}}^H(\mathbf{A}_b+\mathbf{Y}_{s,b}(\bar{\mathbf{v}})^{\frac{J_b}{B}})\bar{\mathbf{v}}/\bar{\mathbf{v}}^H(\mathbf{B}_b+\mathbf{Y}_{s,b}(\bar{\mathbf{v}})^{\frac{J_b}{B}})\bar{\mathbf{v}})^{\beta}$ and $\varphi_b=(\bar{\mathbf{w}}^H(\mathbf{A}_k+\mathbf{F}_{b,k}(\bar{\mathbf{w}})^{\frac{K_a}{K}})\bar{\mathbf{w}}/\bar{\mathbf{w}}^H(\mathbf{B}_k+\mathbf{F}_{b,k}(\bar{\mathbf{w}})^{\frac{K_a}{K}})\bar{\mathbf{w}})^{\beta}$, where $\bar{\mathbf{v}}=[\mathbf{v}_{s,1}^H,\mathbf{v}_{s,2}^H,\dots,\mathbf{v}_{s,B}^H]^H$ and $\bar{\mathbf{w}}=[\mathbf{w}_{b,1}^H,\mathbf{w}_{b,2}^H,\dots,\mathbf{w}_{b,K}^H]^H$ are network-wide beamforming vectors, $\mathbf{A}_{(\cdot)}$ and $\mathbf{B}_{(\cdot)}$ are positive semi-definite block diagonal matrices, $\mathbf{Y}_{s,b}$ is the geometric mean of the interference leakage to other BSs served by SAT, $\mathbf{F}_{b,k}$ is the geometric mean of the interference leakage to users served by other BSs, J_b is the number of other BSs served by SAT, and K_a is the number of other users served by other BSs. Furthermore, $\beta=-1/\alpha\ln 2$, where α is a smoothing function while $\hat{\text{C}}1$: $\|\bar{\mathbf{v}}\|_2^2=1$ and $\hat{\text{C}}2$: $\|\bar{\mathbf{w}}\|_2^2=1$, are relaxations of C1 and C2, respectively.

Problems (P2) and (P3) are solved by finding a solution that satisfies the 1st-order necessary Karush-Kuhn-Tucker (KKT) condition. Next, we apply the generalized power iteration (GPI) technique in which the eigenvector corresponding to the maximum eigenvalue is obtained [3]. The procedure of the proposed scheme is summarized in the algorithm below, where the SAT and BS beamforming vectors are obtained alternately via t-iterations until convergence.

Algorithm 1: Distributed SAT-BS Beamforming



In our MATLAB-based simulations, we consider 1 low-earth orbit (LEO) SAT equipped with $N_s=9$ and $P_s=$ 50W, and 2 BSs, each serving 4 users randomly distributed in a region of 1km. It is worth noting that the rest of the assumptions, parameters and channel modeling criteria, are adopted from [4] and [5] for the SI channel and the rest of the channels. We compare the proposed scheme (GPI) with schemes: zero-forcing (ZF) and weighted minimum mean square error (WMMSE), as shown in the sequel.

Fig. 3 shows that as the sum rate increases as the BS transmit power is increased. This is greatly attributed to the improved signal-to-noise ratio (SNR). Moreover, it is shown that the proposed scheme outperforms the benchmark schemes owing to its superiority in ensuring appropriate power allocation and enhanced beamforming, which lead to improved received signal strength with minimized interference. On the other hand, Fig. 4 illustrates the impact of varying the number of BS transmit antennas on the sum rate. The sum rate improves with the increase in the number of BS transmit antennas. Moreover, the benchmark schemes continue to underperform relative to the proposed scheme due to enhanced beamforming gain and interference suppression capability.

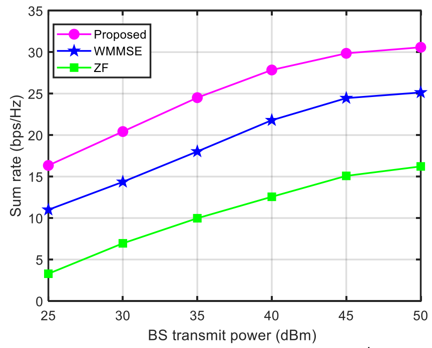


Fig. 3. Sum rate versus BS transmit power with N_b^t=16, and N_b^r= 9.

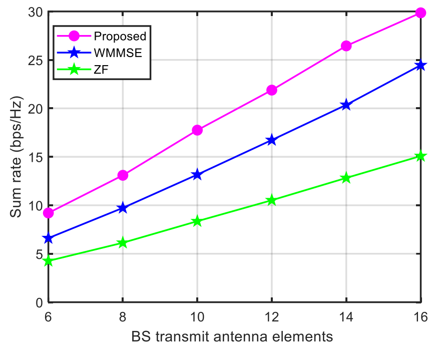


Fig. 4. Sum rate versus the number of BS transmit antenna elements with P_s =45 dBm and N_b^r=9.

III. Conclusion

In this article, we have proposed an interference cancellation strategy without CSI sharing in an FD-enabled SEIN. We have solved an optimization problem to maximize network throughput while minimizing the interference. Simulation results show the potential capability of the proposed scheme to improve spectral efficiency. This improvement in performance is attributed to the low-complex and high-performance features of the GPI-scheme. The challenge with using GPI lies in the conditioning of the matrices since any small system perturbations can lead to errors when matrices are ill-conditioned matrices. Moreover, more matrix inversions will be necessary, which can lead to delayed convergences and high complexity. In our future work, we hope to employ distributed learning techniques to combat interference in an FD-enabled SEIN.

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