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Mitigation of the inter-node interference in multi-antenna full-duplex networks

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ABSTRACT

When multiple single-antenna half-duplex (HD) nodes communicate with a full-duplex (FD) base station equipped with multiple transmit and receive antennas, the uplink nodes would generate inter-node interference (INI) on the downlink nodes. We propose a base station assisted INI suppression scheme. The scheme is to design a proper amplify-and-forward matrix at the base station so that the sum achievable rate of the uplink and downlink is maximized. We derive the close-form expression of the amplify-and-forward matrix, which is the product of a parameter optimization and a zero-forcing beamforming (ZFBF) matrices. Finally, we investigate the performance of the proposed INI suppression scheme in a single cell.

1. Introduction

Half-duplex (HD) wireless communications have been regarded as a successful paradigm, whose resources are divided orthogonally in either time or frequency space [1]. In contrast, full-duplex (FD) wireless communications simultaneously enjoy transmitting and receiving on the same frequency resource, which have the potential to double the spectrum efficiency [2].In the past several decades, there has been no effective method to deal with the self-interference (SI). Recently, combing analog and digital SI cancelation techniques, such as spatial, radio frequency (RF) and digital SI suppression techniques, the SI can be attenuated to detect the intended signal [2,4,3].

The feasibility of FD operation open a new design world for wireless networks. There are two types of interference in this situation: SI and inter-node interference (INI) from the uplink nodes to the downlink nodes. Those two forms of interference differ in one important side: the SI signal is known at the base station, since the transmitter and receiver are co-located, but the INI signal is not known by the downlink nodes [5]. Thus, to manage the INI is more challenging. In this paper, we focus on INI suppression.

The simplest method avoids INI by pairing nodes that are completely hidden from each other [6]. However, this method is not fair. To reduce INI, Ramirez et al. give a joint power control and routing algorithm regarding overall SI and INI between neighboring nodes in FD wireless relay networks [7]. The authors [8] study INI issue that happens in multi-user scenarios and show that FD transceiver can be designed more robust against INI, which unavoidably occurs in cellular wireless communication. Shao et al. [9] give a partitioning scheme that the cellular system is divided into several partitions where the INI is considered as Gaussian noise at the mobile node receiver and the same frequency resource is allocated to the two nodes who are far enough from each other. This scheme is suitable for the larger cellular system.In [10], the authors study the joint problem of subcarrier and power allocation to maximize the sum achievable rate in FD orthogonal frequency division multiple access (OFDMA) networks. In [11] an INI coordination method based on geographical context information is investigated, which takes advantage of the signal attenuation from obstacles between mobile nodes such that the INI is minimized. To potentially mitigate co-time and co-frequency interference caused by other nodes, the opportunistic interference suppression (OIC) technique is exploited at user side and a joint mode selection, user scheduling, and channel assignment problem is formulated to maximize the system throughput [12]. The abovementioned INI management techniques are based on the resource allocation and the optimization operation is centralized at the base station. In [14] antenna directionality is used for interference mitigation in FD cellular networks. The performance of this type of INI suppression techniques dramatically degrades when the radius of the cellular becomes smaller [13].

Different from the resource allocation approach in the MAC and network, direct INI suppression methods in physical layer (PHY)

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are more preferable especially when the radius of the cellular becomes smaller. Intuitively, antenna selection can be implemented in the INI suppression if the uses are equipped with multiple antennas [16]. Bai et al. [15] first investigate the cancelation of INI making use of additional side-channel information and propose four schemes. To deal with the severe INI, Sahai et al. give an interference management (IA) approach to mitigate INI for multiple-antenna FD communication systems in terms of degrees of freedom (DoF) [17]. In [18], successive interference suppression (SIC) is used, which is based on the fact that the downlink node observes a medium access control (MAC) of two nodes and thus the downlink node has an opportunity to remove the INI. In their following work [19], superposition coding based INI suppression (SCIIC) is proposed referenced by the interference suppression approach used in the X-interference channel. In [20], a simple single-antenna base station assisted INI method is proposed for single-antenna terminals. The basic idea is that if the base station knows the channel state information (CSI), the base station can retransmit the weighted received uplink signal to the downlink user for the INI suppression. They show that the INI can be attenuated, as long as the power of the uplink, the downlink, and the interference channels is not zero.

Usually the performance of the resource allocation approach degrades significantly when the radius of the cell decreases. Thus, we mainly focus on the PHY INI suppression schemes which is expected to be a supplement to resource allocation approach. To best knowledge of the authors, most of the proposed PHY INI suppression schemes in the literatures cannot directly generalized for the situation where a multiple-antenna base station serves distributed multiple uplink and downlink nodes. In this paper, an INI suppression scheme is proposed for the INI suppression at the multiple-antenna base station while serving multiple uplink and downlink nodes. In this case, it needs to design an amplify-and-forward matrix at the base station, which is different from the single-antenna situation in [20]. Our contributions are summarized as follows: (1) we derive the close-form expression of the amplify-and-forward matrix, which is the multiplication of a parameter optimization and a zero-forcing beamforming (ZFBF) matrices (2), the parameter optimization matrix can be optimized for each downlink node; (3), for energy efficient fair, we investigate the performance of the proposed scheme compared to the INI no suppression case when the energy used for the INI suppression is used for the downlink node transmissions.

Notation. $\mathbf{E}$ denotes the expectation operation. $\mathcal{CN}\left(\mu,\delta^2\right)$ denotes complex Gaussian process with μ mean and δ^2 variance. $\mathbf{tr}, ^*, ^H, ^T, ^{-1}$, and † represent the trace operation, complex conjugate, conjugate transpose, transpose, inverse and pseudo-inverse of the matrix. $\boldsymbol{I}_n$ denotes the $n\times n$ identity matrix. $\boldsymbol{A}\succ\mathbf{0}$ denotes that $\boldsymbol{A}$ is a positive semidefinite matrix. $[\boldsymbol{A}]_{k,:}$ denotes the k row of matrix $\boldsymbol{A}$. $\mathbf{diag}\{a_1,a_2,\ldots,a_n\}$ denotes a diagonal matrix with diagonal elements $a_1,a_2,\ldots,a_n$. $\mathbb{C}$ denotes the complex domain.

2. System model

As shown in Fig. 1, the network is comprised of the downlink transmissions interfered by the uplink nodes and the interference-free uplink transmissions. The base station is equipped with M_r receive and M_t transmit antennas.Each uplink and downlink node is equipped with one antenna. Let N_r and N_t denote the numbers of the active uplink and downlink nodes on the same time and frequency. In general, the numbers of active uplink and downlink nodes N_r and N_t should satisfy $N_r\leqslant M_r$ and $N_t\leqslant M_t$.

We assume that the overall communication resource is separated into orthogonal blocks based on a certain orthogonalization scheme such as orthogonal frequency-division multiplexing (OFDM). Thus, signal model considered is built upon frequency-flat block-fading channels [22]. For simplify, the signal channel denotes a single sub-carrier in the rest of the paper. We assume that the propagation delay difference between the INI signal and the INI suppression signal transmitted by the base station is small compared to the frame length and can be neglected.[1]

The following equations give the signal relationship between the base station and the nodes

$$\tilde{\boldsymbol{r}}_{\boldsymbol{u}}[n]=\boldsymbol{G}_{rx}\boldsymbol{r}_u[n]$$

$$\boldsymbol{r}_u[n]=\boldsymbol{H}_u\boldsymbol{s}_u[n]+\boldsymbol{H}_R\hat{\boldsymbol{s}}_d[n]+\boldsymbol{n}_u[n],$$

$$\hat{\boldsymbol{s}}_d[n]=\boldsymbol{s}_{ic}[n]+\tilde{\boldsymbol{s}_d}[n]=\boldsymbol{G}_{ic}\boldsymbol{r}_u[n-\tau]+\boldsymbol{G}_{tx}\boldsymbol{s}_d[n],$$

$$\boldsymbol{r}_d[n]=\boldsymbol{H}_d\hat{\boldsymbol{s}}_d[n]+\boldsymbol{H}_i\boldsymbol{s}_u[n]+\boldsymbol{n}_d[n],$$

where $\boldsymbol{s}_u\in\mathbb{C}^{N_r\times1}$ and $\boldsymbol{s}_d\in\mathbb{C}^{N_t\times1}$ denote the uplink and the downlink signals respectively, $\boldsymbol{r}_u\in\mathbb{C}^{M_r\times1}$ and $\boldsymbol{r}_d\in\mathbb{C}^{N_t\times1}$ represents the receive signals at the base station and the downlink nodes respectively, $\tilde{\boldsymbol{r}}_{\boldsymbol{u}}\in\mathbb{C}^{N_r\times1}, \tilde{\boldsymbol{s}_d}\in\mathbb{C}^{M_t\times1}$, $\boldsymbol{s}_{ic}\in\mathbb{C}^{M_t\times1}$, and $\hat{\boldsymbol{s}}_d\in\mathbb{C}^{M_t\times1}$ denote the decoded, the precoded, the INI suppression, and the transmit signals at the base station respectively, $\boldsymbol{G}_{rx}\in\mathbb{C}^{N_r\times M_r}, \boldsymbol{G}_{tx}\in\mathbb{C}^{M_t\times N_t}$, and $\boldsymbol{G}_{ic}\in\mathbb{C}^{M_t\times M_r}$ denote the decoder, the precoder, and the INI suppression matrices, $\boldsymbol{n}_u\in\mathcal{CN}\left(\mathbf{0},\sigma_n^2\boldsymbol{I}_{M_r}\right)$ and $\boldsymbol{n}_d\in\mathcal{CN}\left(\mathbf{0},\sigma_n^2\boldsymbol{I}_{N_t}\right)$ denote the additive Gaussian noises at the base station and the downlink nodes respectively. $\boldsymbol{H}_u\in\mathbb{C}^{M_r\times N_r}, \boldsymbol{H}_d\in\mathbb{C}^{N_t\times M_t}, \boldsymbol{H}_R\in\mathbb{C}^{M_r\times M_t}$,and $\boldsymbol{H}_i\in\mathbb{C}^{N_t\times N_r}$ denote the uplink, the downlink, the BS self-interference and the interference channel matrices. We assume $\mathbf{E}\left[[s_u]_i\right]\leqslant P_u, i=1,\ldots,N_r$, $\mathbf{E}\left[[s_d]_i\right]\leqslant P_u, i=1,\ldots,N_t$.

The transmitted signal at the base station can be obtained recursively as

$$\begin{aligned}\hat{\mathbf{s}}_d[n]&=\mathbf{G}_{ic}\mathbf{H}_u\mathbf{s}_u[n-\tau]+\mathbf{G}_{ic}\mathbf{H}_R\hat{\mathbf{s}}_d[n-\tau]+\mathbf{G}_{ic}\mathbf{n}_u[n-\tau]+\mathbf{G}_{tx}\mathbf{s}_d[n]\\&=\sum_{j=0}^{\infty}(\mathbf{G}_{ic}\mathbf{H}_u)^j(\mathbf{G}_{ic}\mathbf{s}_u[n-j\tau-\tau]+\mathbf{G}_{ic}\mathbf{n}_u[n-j\tau-\tau]+\mathbf{G}_{tx}\mathbf{s}_d[n-j\tau]).\end{aligned} \quad (1)$$

Note that, base station would transmit the weighted received uplink signal as soon as it received. Furthermore, our system model is similar to FD relay model in [21]. As depicted in [21], if the residual SI signal is taken into account, the base station would retransmit the residual SI signal in turn, which make the optimization problems difficult and, thus it is hard to get the close-form solutions. To simplify the signal model and make the optimization problems more tractable, we assume that the SI at the FD base station can be perfectly suppressed.[2]

Thus, the signal relationship between the base station and the nodes becomes

$$\begin{aligned}&\tilde{\boldsymbol{r}}_u=\boldsymbol{G}_{rx}\boldsymbol{r}_u=\boldsymbol{G}_{rx}(\boldsymbol{H}_u\boldsymbol{s}_u+\boldsymbol{n}_u),\\&\hat{\boldsymbol{s}}_d=\boldsymbol{s}_{ic}+\tilde{\boldsymbol{s}_d}=\boldsymbol{G}_{ic}\boldsymbol{r}_u+\boldsymbol{G}_{tx}\boldsymbol{s}_d,\\&\boldsymbol{r}_d=\boldsymbol{H}_d\hat{\boldsymbol{s}}_d+\boldsymbol{H}_i\boldsymbol{s}_u+\boldsymbol{n}_d,\end{aligned}$$

Thus, the received signals at the downlink nodes can be expressed as

$$\boldsymbol{r}_d=\boldsymbol{H}_d\boldsymbol{G}_{tx}\boldsymbol{s}_d+(\boldsymbol{H}_d\boldsymbol{G}_{ic}\boldsymbol{H}_u+\boldsymbol{H}_i)\boldsymbol{s}_u+\boldsymbol{H}_d\boldsymbol{G}_{ic}\boldsymbol{n}_u+\boldsymbol{n}_d.$$

[1] For example, if a 100 μs OFDM frame is adopted and the propagation delay difference is 100 ns, the INI can be attenuated about 30 dB.

[2] In this case, the results in this paper can be considered as the upper bound of the proposed scheme.