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Filter Design for Full-Duplex Multiuser Systems Based on Single-Carrier Transmission in Frequency-Selective Channels

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SUMMARY In this paper, we consider interference suppression for a full-duplex (FD) multiuser system based on single-carrier transmission in frequency-selective channels where a FD base-station (BS) simultaneously communicates with half-duplex (HD) uplink and downlink mobile users. We propose a design method for time-domain filtering where the filters in the BS transmitter suppress inter-symbol interference (ISI) and downlink inter-user interference (IUI); those in the BS receiver, self-interference, ISI, and uplink IUI; and those in the downlink mobile users, co-channel interference (CCI) without the channel state information of the CCI channels. Simulation results indicate that the FD system based on the proposed method outperforms the conventional HD system and FD system based on multicarrier transmission.

key words: *full-duplex, multiuser systems, beamforming, inter-symbol interference, inter-user interference, self-interference, co-channel interference*

1. Introduction

In full-duplex (FD) transmission, terminals transmit and receive simultaneously on the same frequency band. FD is considered as a key technology for future wireless communication systems because of its higher spectral efficiency compared with traditional half-duplex (HD) transmission [1], [2]. However, improvement in FD transmission exhibits a limitation owing to the self-interference (SI) that is caused by its own transmission. In order to realize the benefit of FD transmission, a crucial task involves suppressing the SI in the digital-domain after propagation- and analog-domain cancellation [1], [3].

A potential application of FD transmission is multiuser multiple-input multiple-output (MU-MIMO) systems where a base-station (BS) with multiple antennas communicates with uplink mobile users (UMUs) and downlink mobile users (DMUs) [1], [2]. In the FD MU-MIMO system, it is essential to mitigate the SI that the BS operating in the FD mode is subject to. Furthermore, a major challenge for the FD MU-MIMO system is to mitigate the inter-user interference (IUI) that occurs between users in the same link and co-channel interference (CCI) that occurs between UMUs and DMUs.

Thus far, several studies have developed interference mitigation techniques for FD MU-MIMO systems [4]–[10]. Beamforming at the receiver and transmitter of the BS is a requisite to jointly suppress SI and IUI. Various designs for the BS beamforming are extensively studied and include sum rate maximization [4] and max-min fairness signal-to-interference-plus-noise ratio (SINR) maximization [5]. The transmit power allocation of UMUs [4]–[9] and user selection [8]–[10] are effective approaches to decrease the effect of IUI and CCI. Beamforming at DMUs and UMUs is also known as effective in suppressing CCI [6], [9].

In the aforementioned methods, the channels are assumed as frequency-nonselective. If we apply the above methods to wideband communications over frequency-selective channels suffering from the inter-symbol interference (ISI), then a common approach to avoid ISI involves adopting block transmissions such as orthogonal frequency division multiplexing (OFDM) using cyclic prefix (CP). However, the adoption of OFDM leads to the achievable rate loss due to the presence of CP and delay increase due to block processing. Additionally, it increases complexity due to the requirement of accurate time synchronization among users. Furthermore, the aforementioned methods require perfect channel state information (CSI). However, channel estimation is cumbersome especially for CCI channels between UMUs and DMUs.

In this paper, we consider interference suppression for a FD MU-MIMO system based on single-carrier transmission without CP in frequency-selective channels. We propose a design method for time-domain finite-impulse response (FIR) filters, which can be viewed as an extension of beamforming, to suppress ISI, IUI, SI, and CCI. In the proposed method, the filters in the BS transmitter are determined to suppress ISI and downlink IUI, and the filters in the BS receiver are subsequently determined to suppress ISI, uplink IUI, and SI. To suppress CCI, the filters in the DMUs are determined without the CSI of CCI channels by borrowing the idea of blind beamforming [11]. The advantage of the proposed method is that it enables to suppress interference including ISI by FIR filtering while avoiding the requirement of the CSI of CCI channels and disadvantages of OFDM.

Notation: $(\cdot)^T$, $(\cdot)^H$, and $(\cdot)^*$ denote the transpose, Hermitian transpose, and complex conjugate of a vector or matrix, respectively. $\mathbb{E}[\cdot]$ denotes expectation. $\otimes$ denotes the Kronecker product. $\mathbf{0}_{N\times M}$ denotes an $N \times M$ zero matrix, $\mathbf{1}_{N\times M}$ denotes $N \times M$ matrix in which all elements are equal to 1, and $\mathbf{I}_N$ denotes $N \times N$ identity matrix. $\mathcal{CN}(0, \sigma^2)$ denotes the zero mean circularly symmetric complex Gaussian distribution with variance σ^2. toeplitz$(\mathbf{A}, L)$ denotes

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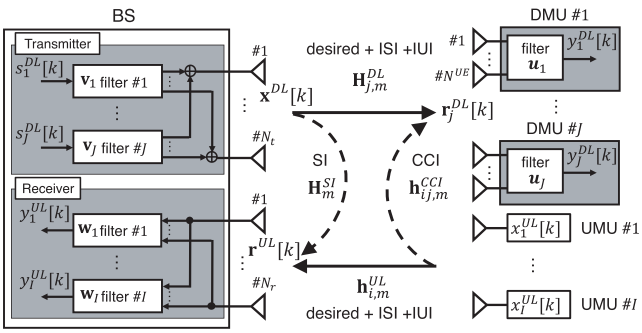

Fig. 1 Full-duplex multiuser system model.

the block-toeplitz matrix defined by toeplitz$(\mathbf{A}_{N\times M}, L) \triangleq [\mathbf{A}_0^T \cdots \mathbf{A}_{L-1}^T]^T$ where $\mathbf{A}_l \triangleq [\mathbf{0}_{N\times l}\ \mathbf{A}_{N\times M}\ \mathbf{0}_{N\times(L-1-l)}]$.

2. System Model

We consider a full-duplex multiuser system based on single-carrier transmission, as shown in Fig. 1. In the system, a BS operating in the FD mode communicates with I UMUs and J DMUs operating in the HD mode. We assume that all channels are time-invariant frequency-selective and cause severe ISI. The BS receives signals sent from UMUs that are corrupted by ISI and uplink IUI and receives the signal sent from its own transmitter that results in SI. Each DMU receives the signal sent from the BS that is corrupted by ISI and downlink IUI and also receives the signal sent from UMUs, and this results in CCI. To suppress the interference by spatiotemporal processing, the BS is equipped with N_r receive antennas and N_t transmit antennas and uses I FIR filters in the receiver and J FIR filters in the transmitter. Each mobile user has N^{UE} antennas. When a mobile user is in the reception mode, the user uses N^{UE} antennas for the reception as DMU and a FIR filter to suppress CCI. When a mobile user is in the transmission mode, the user uses a single antenna for the transmission as UMU.

First, we explain the downlink transmission. The BS transmitter broadcasts the signal processed by single-input multiple-output (SIMO) FIR filters to send data symbols to DMUs. We assume that $s_j^{DL}[k]$ is the data symbol of the jth DMU at time k with normalized power $\mathbb{E}[|s_j^{DL}[k]|^2] = 1$. The jth transmit SIMO FIR filter has an impulse response (IR) $\mathbf{v}_{j,m} \triangleq [v_{j,m,1} \cdots v_{j,m,N_t}]^T$ of length L^{DL}, and its output is expressed as $\mathbf{x}_j^{DL}[k] \triangleq [x_{j,1}^{DL}[k] \cdots x_{j,N_t}^{DL}[k]]^T = \sum_{m=0}^{L^{DL}-1} \mathbf{v}_{j,m}^* s_j^{DL}[k-m]$. The sum of the filter outputs is transmitted from N_t antennas at time k.

$$\mathbf{x}^{DL}[k] = \sum_{j=1}^{J} \mathbf{x}_j^{DL}[k] = \sum_{j=1}^{J} \sum_{m=0}^{L^{DL}-1} \mathbf{v}_{j,m}^* s_j^{DL}[k-m]. \tag{1}$$

The jth DMU receives the signal sent from the BS via a MIMO downlink channel where IR denotes $\mathbf{H}_{j,m}^{DL}$ of length $M^{DL\dagger}$. Additionally, the jth DMU receives the signal sent from the ith UMU through a SIMO CCI channel in which the IR is $\mathbf{h}_{ij,m}^{CCI} \triangleq [h_{ij,m,1}^{CCI} \cdots h_{ij,m,N^{UE}}^{CCI}]^T$ of length M^{CCI}. In digital baseband domain, the received signal at the jth DMU $\mathbf{r}_j^{DL}[k] \triangleq [r_{j,1}^{DL}[k] \cdots r_{j,N^{UE}}^{DL}[k]]^T$ at time k is expressed as

$$\mathbf{r}_j^{DL}[k] = \sum_{m=0}^{M^{DL}-1} \mathbf{H}_{j,m}^{DL} \mathbf{x}^{DL}[k-m] + \sum_{i=1}^{I} \sum_{m=0}^{M^{CCI}-1} \mathbf{h}_{ij,m}^{CCI} x_i^{UL}[k-m] + \mathbf{n}_j^{DL}[k] \tag{2}$$

where

$$\mathbf{H}_{j,m}^{DL} \triangleq \begin{bmatrix} h_{j,m,1,1}^{DL} & \cdots & h_{j,m,N_t,1}^{DL} \\ \vdots & \ddots & \vdots \\ h_{j,m,1,N^{UE}}^{DL} & \cdots & h_{j,m,N_t,N^{UE}}^{DL} \end{bmatrix},$$

$x_i^{UL}[k]$ denotes the transmit signal of the ith UMU, and $\mathbf{n}_j^{DL}[k] \triangleq [n_{j,1}^{DL}[k] \cdots n_{j,N^{UE}}^{DL}[k]]^T \sim \mathcal{CN}(0, (\sigma_j^{DL})^2 \mathbf{I}_{N^{UE}})$ denotes the additive white Gaussian noise (AWGN) at the jth DMU. In (2), the first term includes the desired data symbol, ISI, and IUI originating from the signals sent to $J-1$ DMUs and the second term denotes CCI from I UMUs. The aim of the FIR filters $\mathbf{v}_j$ in the BS transmitter is to jointly suppress the ISI and downlink IUI. To suppress CCI and obtain the estimate of the data symbol, the received signal is processed by a MISO FIR filter in which the IR is $\mathbf{u}_{j,m} \triangleq [u_{j,m,1} \cdots u_{j,m,N^{UE}}]^T$ of length L^{UE}. The filter output of the jth DMU at time k is expressed as

$$y_j^{DL}[k] = \sum_{m=0}^{L^{UE}-1} \mathbf{u}_{j,m}^H \mathbf{r}_j^{DL}[k-m]. \tag{3}$$

We then explain the uplink transmission. We assume that $s_i^{UL}[k]$ is the data symbol of the ith UMU at time k with $\mathbb{E}[|s_i^{UL}[k]|^2] = 1$. The ith UMU transmission power is limited to P_i^{UL}. Subsequently, the transmit signal of the ith UMU is expressed as

$$x_i^{UL}[k] = \sqrt{P_i^{UL}} s_i^{UL}[k]. \tag{4}$$

The BS receives the signal $x_i^{UL}[k]$ through a SIMO uplink channel in which the IR is $\mathbf{h}_{i,m}^{UL} \triangleq [h_{i,m,1}^{UL} \cdots h_{i,m,N_r}^{UL}]^T$ of length M^{UL}. Simultaneously, the BS receives the signal $\mathbf{x}^{DL}[k]$ sent from its own transmitter through a MIMO loop-back (SI) channel in which the IR is $\mathbf{H}_m^{SI}$ of length M^{SI}. The receive signal at the BS $\mathbf{r}^{UL}[k] \triangleq [r_1^{UL}[k] \cdots r_{N_r}^{UL}[k]]^T$ is expressed as

$$\mathbf{r}^{UL}[k] = \sum_{i=1}^{I} \sum_{m=0}^{M^{UL}-1} \mathbf{h}_{i,m}^{UL} x_i^{UL}[k-m] + \sum_{m=0}^{M^{SI}-1} \mathbf{H}_m^{SI} \mathbf{x}^{DL}[k-m] + \mathbf{n}^{UL}[k] \tag{5}$$

[†]For simplicity, we assume that the IR length of all downlink channels $\mathbf{H}_{j,m}^{DL}$ corresponds to M^{DL}. The same assumption is adopted for other types of channels and filters.

where

$$\mathbf{H}_m^{SI} \triangleq \begin{bmatrix} h_{m,1,1}^{SI} & \cdots & h_{m,N_t,1}^{SI} \\ \vdots & \ddots & \vdots \\ h_{m,1,N_r}^{SI} & \cdots & h_{m,N_t,N_r}^{SI} \end{bmatrix},$$

and $\mathbf{n}^{UL}[k] \sim \mathcal{CN}(0, (\sigma^{UL})^2\mathbf{I}_{N_r})$ is AWGN at the BS receiver. In (5), the first term includes the desired data symbol, ISI, and IUI originated from the signals sent from $I-1$ UMUs and the second term represents SI. The received signal is processed by a MISO FIR filter in which the IR is $\mathbf{w}_{i,m} \triangleq [w_{i,m,1} \cdots w_{i,m,N_r}]^T$ of length L^{UL}. The output of the ith FIR filter in the BS receiver is expressed as

$$y_i^{UL}[k] = \sum_{m=0}^{L^{UL}-1} \mathbf{w}_{i,m}^H \mathbf{r}^{UL}[k-m]. \tag{6}$$

The aim of the FIR filter $\mathbf{w}_i \triangleq [\mathbf{w}_{i,0}^T \cdots \mathbf{w}_{i,L^{UL}-1}^T]^T$ in the BS receiver is to jointly suppress the ISI, uplink IUI, and SI such that the ith UMU's data symbol can be extracted.

3. Filter Design Method

We describe the design of the FIR filters in the BS and DMUs. The difficulty of the filter design is that the filters are dependent on each other. Although the joint design of all the filters is optimum in terms of performance, it is a complicated task to solve. We propose a reasonable method to obtain a suboptimal performance, where each group of filters is sequentially determined. Specifically, we first determine the filters in the BS transmitter and then the filters in the BS receiver and filters of DMUs. In the following, we assume that the BS has the perfect CSI of downlink (BS to DMUs) channels, uplink (UMUs to BS) channels, and SI (BS to BS) channels, which should be estimated by using training symbols before data transmission. The BS and DMUs do not need the CSI of CCI (UMUs to DMUs) channels.

3.1 Filters in BS Transmitter

First, we design the FIR filters $\mathbf{v}_j$ in the BS transmitter. We assume that $s_j^{DL}[k-d_j^{DL}]$ is the desired data symbol in the received signal of the jth DMU, where $d_j^{DL} \in \{0, 1, \cdots, M^{DL}+L^{DL}-1\}$ denotes the predetermined delay. By substituting (1) into (2), after some algebra, we obtain the receive signal at the nth antenna of the jth DMU as

$$\begin{aligned} r_{j,n}^{DL}[k] &= \mathbf{v}_j^H \check{\mathbf{h}}_{j,n}^{DL} s_j^{DL}[k-d_j^{DL}] + \mathbf{v}_j^H \check{\mathbf{H}}_{j,n}^{DL} \check{\mathbf{s}}_j^{DL}[k] \\ &+ \sum_{\substack{l=1 \\ l\neq j}}^{J} \mathbf{v}_l^H \tilde{\mathbf{H}}_{j,n}^{DL} \tilde{\mathbf{s}}_l^{DL}[k] + \sum_{i=1}^{I} (\tilde{\mathbf{h}}_{ij,n}^{CCI})^T \mathbf{x}_i^{CCI}[k] \\ &+ n_{j,n}^{DL}[k] \end{aligned} \tag{7}$$

where

$$\mathbf{v}_j \triangleq \begin{bmatrix} \mathbf{v}_{j,0}^T & \cdots & \mathbf{v}_{j,L^{DL}-1}^T \end{bmatrix}^T,$$

$$\tilde{\mathbf{H}}_{j,n}^{DL} \triangleq \mathrm{toeplitz}(\check{\mathbf{H}}_{j,n}^{DL}, L^{DL}),$$

$$\check{\mathbf{H}}_{j,n}^{DL} \triangleq \begin{bmatrix} \tilde{\mathbf{h}}_{j,0,n}^{DL} & \cdots & \tilde{\mathbf{h}}_{j,M^{DL}-1,n}^{DL} \end{bmatrix},$$

$$\tilde{\mathbf{h}}_{j,m,n}^{DL} \triangleq \begin{bmatrix} h_{j,m,1,n}^{DL} & \cdots & h_{j,m,N_t,n}^{DL} \end{bmatrix}^T,$$

$$\tilde{\mathbf{h}}_{ij,n}^{CCI} \triangleq \begin{bmatrix} h_{ij,0,n}^{CCI} & \cdots & h_{ij,M^{CCI}-1,n}^{CCI} \end{bmatrix}^T,$$

$$\mathbf{x}_i^{CCI}[k] \triangleq \left[x_i^{UL}[k] \cdots x_i^{UL}[k-M^{CCI}+1]\right]^T,$$

$$\tilde{\mathbf{s}}_l^{DL}[k] \triangleq \left[s_l^{DL}[k] \cdots s_l^{DL}[k-M^{DL}-L^{DL}+2]\right]^T,$$

$\check{\mathbf{h}}_{j,n}^{DL}$ denotes the $d_j^{DL}+1$th column of $\tilde{\mathbf{H}}_{j,n}^{DL}$, $\check{\mathbf{H}}_{j,n}^{DL}$ denotes the remaining part of $\tilde{\mathbf{H}}_{j,n}^{DL}$, and $\check{\mathbf{s}}_j^{DL}[k]$ is obtained by removing $s_j^{DL}[k-d_j^{DL}]$ from $\tilde{\mathbf{s}}_j^{DL}[k]$. In (7), the first term denotes the desired component, the second term corresponds to ISI, the third term corresponds to downlink IUI, and the fourth term corresponds to CCI. The role of the filter $\mathbf{v}_i$ is to suppress ISI and IUI. Hence, we employ the null-space-projection, and the filter $\mathbf{v}_i$ then satisfies the following conditions:

$$\left(\check{\mathbf{H}}_{j,n}^{DL}\right)^H \mathbf{v}_j = \mathbf{0},\ \left(\tilde{\mathbf{H}}_{l,n}^{DL}\right)^H \mathbf{v}_j = \mathbf{0} \tag{8}$$

for $n = 1, \cdots, N^{UE}, l = 1, \cdots, j-1, j+1, \cdots, J$. To uniquely determine the filter $\mathbf{v}_j$, we select $\mathbf{v}_j$ which maximizes the signal-to-noise ratio $\tilde{\gamma}_j^{DL}$ of the received signal at the jth DMU's receiver where the signal component is defined by $q_j[k] \triangleq \sum_{n=1}^{N^{UE}} \mathbf{v}_j^H \check{\mathbf{h}}_{j,n}^{DL} s_j^{DL}[k-d_j^{DL}]$. Specifically, the FIR filter in the BS receiver is obtained by solving the following optimization problem:

$$\begin{aligned} &\max_{\mathbf{v}_j} \tilde{\gamma}_j^{DL} \triangleq \frac{E[|q_j[k]|^2]}{E[\|\mathbf{n}_j^{DL}\|^2]} = \frac{\mathbf{v}_j^H \mathbf{c}_j^{DL} (\mathbf{c}_j^{DL})^H \mathbf{v}_j}{N^{UE}(\sigma_j^{DL})^2} \\ &\text{s.t. } P_j^{BS} = P_{\max,j}^{BS},\ (\mathbf{H}_j^{INT})^H \mathbf{v}_j = \mathbf{0} \end{aligned} \tag{9}$$

where $P_j^{BS} \triangleq \mathbb{E}[\|\mathbf{x}_j^{DL}[k]\|^2] = \|\mathbf{v}_j\|^2$ denotes the power consumed to transmit $\mathbf{x}_j^{DL}[k]$, $\mathbf{c}_j^{DL} \triangleq \sum_{n=1}^{N^{UE}} \check{\mathbf{h}}_{j,n}^{DL}$, and

$$\mathbf{H}_j^{INT} \triangleq \left[\check{\mathbf{H}}_{j,1}^{DL} \cdots \check{\mathbf{H}}_{j,N^{UE}}^{DL} \tilde{\mathbf{H}}_{1,1}^{DL} \cdots \tilde{\mathbf{H}}_{j-1,N^{UE}}^{DL} \tilde{\mathbf{H}}_{j+1,1}^{DL} \cdots \tilde{\mathbf{H}}_{J,N^{UE}}^{DL}\right].$$

In (9), the first constraint limits the transmit power to the maximum transmission power $P_{\max,j}^{BS}$ that is allocated to $\mathbf{x}_j^{DL}[k]$. To satisfy the second constraint of the null-space-projection, we introduce an orthonormal projection matrix $\mathcal{K}_j^{DL}$ that satisfies $\mathbf{H}_j^{INT}\mathcal{K}_j^{DL} = \mathbf{0}$ and redefine the filter vector as $\mathbf{v}_j \triangleq \mathcal{K}_j^{DL}\tilde{\mathbf{v}}_j$. Subsequently, we can rewrite the problem in (9) as

$$\begin{aligned} &\max_{\tilde{\mathbf{v}}_j} \tilde{\mathbf{v}}_j^H (\mathcal{K}_j^{DL})^H \mathbf{c}_j^{DL} (\mathbf{c}_j^{DL})^H \mathcal{K}_j^{DL} \tilde{\mathbf{v}}_j \\ &\text{s.t. } \|\tilde{\mathbf{v}}_j\|^2 = P_{\max,j}^{BS}. \end{aligned} \tag{10}$$

The optimal solution is given by

$$\tilde{\mathbf{v}}_j^{opt} = \sqrt{P_{\max,j}^{BS}} \frac{(\mathcal{K}_j^{DL})^H \mathbf{c}_j^{DL}}{\|\mathbf{c}_j^{DL}\|^2},\ \mathbf{v}_j^{opt} = \mathcal{K}_j^{DL}\tilde{\mathbf{v}}_j^{opt}. \tag{11}$$

The projection matrix $\mathcal{K}_j^{DL}$ is obtained by the singular value decomposition of $\mathbf{H}_j^{INT} \in C^{N_t L^{DL} \times D_h}$, $D_h = JN^{UE}(M^{DL} + L^{DL} - 1) - N^{UE}$, and it exists if

$$N_t L^{DL} > D_h. \tag{12}$$

The condition can be satisfied when the BS includes a sufficient number of transmit antennas N_t and the IR length of the FIR filters L^{DL} in the BS transmitter is sufficiently long.

3.2 Filters in BS Receiver

Next, we design the FIR filters $\mathbf{w}_i$ in the BS receiver. We assume that $x_i^{UL}[k - d_i^{UL}]$ is the desired data symbol of the ith UMU, where $d_i^{UL} \in \{0, \cdots, M^{UL} + L^{UL} - 1\}$ denotes the predetermined delay. We substitute (5) into (6) and obtain the following after some mathematical manipulations

$$\begin{aligned} y_i^{UL}[k] &= \mathbf{w}_i^H \check{\mathbf{h}}_i^{UL} x_i^{UL}[k - d_i^{UL}] + \mathbf{w}_i^H \check{\mathbf{H}}_i^{UL} \check{\mathbf{x}}_i^{UL}[k] \\ &\quad + \mathbf{w}_i^H \sum_{\substack{l=1 \\ l \neq i}}^{I} \bar{\mathbf{H}}_l^{UL} \bar{\mathbf{x}}_l^{UL}[k] + \mathbf{w}_i^H \bar{\mathbf{H}}^{SI} \sum_{j=1}^{J} \bar{\mathbf{x}}_j^{SI}[k] \\ &\quad + \mathbf{w}_i^H \bar{\mathbf{n}}^{UL}[k] \end{aligned} \tag{13}$$

where

$$\begin{aligned} &\mathbf{w}_i \triangleq \left[\mathbf{w}_{i,0}^T \cdots \mathbf{w}_{i,L^{UL}-1}^T\right]^T, \\ &\bar{\mathbf{H}}_i^{UL} \triangleq \text{toeplitz}(\mathbf{H}_i^{UL}, L^{UL}), \\ &\mathbf{H}_i^{UL} \triangleq \left[\mathbf{h}_{i,0}^{UL} \cdots \mathbf{h}_{i,M^{UL}-1}^{UL}\right], \\ &\bar{\mathbf{H}}^{SI} \triangleq \text{toeplitz}(\mathbf{H}^{SI}, L^{UL}), \\ &\mathbf{H}^{SI} \triangleq \left[\mathbf{H}_0^{SI} \cdots \mathbf{H}_{M^{SI}-1}^{SI}\right], \\ &\bar{\mathbf{x}}_i^{UL} \triangleq \left[x_i^{UL}[k] \cdots x_i^{UL}[k - M^{UL} - L^{UL} + 2]\right]^T, \\ &\bar{\mathbf{x}}^{SI}[k] \triangleq \left[(\mathbf{x}^{DL}[k])^T \ \cdots \ (\mathbf{x}^{DL}[k - M^{SI} - L^{UL} + 2])^T\right]^T, \\ &\bar{\mathbf{n}}^{UL}[k] \triangleq \left[(\mathbf{n}_i^{UL}[k])^T \cdots (\mathbf{n}_i^{UL}[k - L^{UL} + 1])^T\right]^T, \end{aligned}$$

$\check{\mathbf{h}}_i^{UL}$ denotes $d_i^{UL} + 1$th column of $\bar{\mathbf{H}}_i^{UL}$, $\check{\mathbf{H}}_i^{UL}$ denotes the remaining part of $\bar{\mathbf{H}}_i^{UL}$, $\check{\mathbf{x}}_i^{UL}[k]$ that is obtained by removing $x_i^{UL}[k - d_i^{UL}]$ from $\bar{\mathbf{x}}_i^{UL}[k]$. In (13), the first term denotes the desired component, the second term corresponds to ISI, the third term corresponds to uplink IUI, and the fourth term corresponds to SI. The role of the filter $\mathbf{w}_i$ is to jointly suppress ISI, IUI, and SI. Hence, the filter $\mathbf{w}_i$ is determined such that the SINR γ_i^{UL} at the BS receiver corresponding to the ith UMU is maximized. From (13), the SINR maximization problem is expressed as

$$\max_{\mathbf{w}_i} \ \gamma_i^{UL} = \frac{\mathbf{w}_i^H \mathbf{Q}_{\text{des},i}^{UL} \mathbf{w}_i}{\mathbf{w}_i^H \mathbf{Q}_{\text{INT},i}^{UL} \mathbf{w}_i + (\sigma^{UL})^2 \mathbf{w}_i^H \mathbf{w}_i} \tag{14}$$

where $\mathbf{Q}_{\text{des},i}^{UL} \triangleq P_i^{UL} \check{\mathbf{h}}_i^{UL} (\check{\mathbf{h}}_i^{UL})^H$, $\mathbf{Q}_{\text{INT},i}^{UL} \triangleq \mathbf{Q}_{\text{ISI},i}^{UL} + \mathbf{Q}_{\text{IUI},i}^{UL} + \mathbf{Q}_{\text{SI},i}^{UL}$, $\mathbf{Q}_{\text{ISI},i}^{UL} \triangleq P_i^{UL} \check{\mathbf{H}}_i^{UL} (\check{\mathbf{H}}_i^{UL})^H$, $\mathbf{Q}_{\text{IUI},i}^{UL} \triangleq \sum_{\substack{l=1 \\ l \neq i}}^{I} P_l^{UL} \bar{\mathbf{H}}_l^{UL} (\bar{\mathbf{H}}_l^{UL})^H$, and $\mathbf{Q}_{\text{SI},i}^{UL} \triangleq \sum_{j=1}^{J} \bar{\mathbf{H}}^{SI} (\bar{\mathbf{V}}_j^{SI})^H \bar{\mathbf{V}}_j^{SI} (\bar{\mathbf{H}}^{SI})^H$, $\bar{\mathbf{V}}_j^{SI} \triangleq \text{toeplitz}(\mathbf{V}_j, M^{SI} + L^{UL} - 1)$. The optimal solution of (14) is obtained by solving the generalized eigenvalue problem associated with (14), and it is expressed as

$$\mathbf{w}_i^{opt} = \mathcal{P}_{\text{gmax}}\{\mathbf{Q}_{\text{des},i}^{UL}, \mathbf{Q}_{\text{INT},i}^{UL} + (\sigma^{UL})^2 \mathbf{I}_{N_r L_i^{UL}}\} \tag{15}$$

where $\mathcal{P}_{\text{gmax}}(\mathbf{A}, \mathbf{B})$ denotes the normalized generalized eigenvector associated with the maximum generalized eigenvalue of the matrix pair $(\mathbf{A}, \mathbf{B})$.

3.3 Filters in DMU Receiver

Finally, we design the FIR filters $\mathbf{u}_j$ in the DMU receiver. We assume that the filters $\mathbf{v}_j$ in the BS transmitter can suppress ISI and IUI that occur in the downlink. Subsequently, the received signal in (2) is as follows

$$\begin{aligned} \mathbf{r}_j^{DL}[k] &= \mathbf{H}_j^{DL} \hat{\mathbf{v}}_j^* s_j^{DL}[k - d_j^{DL}] + \sum_{i=1}^{I} \mathbf{H}_{ij}^{CCI} \mathbf{x}_i^{CCI}[k] \\ &\quad + \mathbf{n}_j^{DL}[k] \end{aligned} \tag{16}$$

where $\hat{\mathbf{v}}_j$ denotes the $d_j^{DL} + 1$th column of $\tilde{\mathbf{V}}_j \triangleq \text{toeplitz}(\mathbf{V}_j, M^{DL})$, $\mathbf{V}_j \triangleq [\mathbf{v}_{j,0} \cdots \mathbf{v}_{j,L^{DL}-1}]$,

$$\begin{aligned} &\mathbf{H}_j^{DL} \triangleq \left[\ \mathbf{H}_{j,0}^{DL} \quad \cdots \quad \mathbf{H}_{j,M^{DL}-1}^{DL}\ \right], \\ &\mathbf{H}_{ij}^{CCI} \triangleq \left[\ \mathbf{h}_{ij,0}^{CCI} \quad \cdots \quad \mathbf{h}_{ij,M^{CCI}-1}^{CCI}\ \right]. \end{aligned}$$

We substitute (16) into (3) to obtain the output of the filter $\mathbf{u}_j$ as

$$\begin{aligned} y_j^{DL}[k] &= \mathbf{u}_j^H \bar{\mathbf{r}}_j^{DL}[k] \\ &= \mathbf{u}_j^H \left\{\mathbf{I}_{L^{UE}} \otimes \left(\mathbf{H}_j^{DL} \hat{\mathbf{v}}_j^*\right)\right\} \bar{\mathbf{s}}_j^{DL}[k] \\ &\quad + \mathbf{u}_j^H \sum_{i=1}^{I} \bar{\mathbf{H}}_{ij}^{CCI} \bar{\mathbf{x}}_i^{CCI}[k] + \mathbf{u}_j^H \bar{\mathbf{n}}_j^{DL}[k] \end{aligned} \tag{17}$$

where

$$\begin{aligned} &\mathbf{u}_j \triangleq [\mathbf{u}_{j,0}^T \cdots \mathbf{u}_{j,L^{UE}-1}^T]^T, \\ &\bar{\mathbf{r}}_j^{DL}[k] \triangleq [(\mathbf{r}_j^{DL}[k])^T \ \cdots \ (\mathbf{r}_j^{DL}[k - L^{UE} + 1])^T]^T \\ &\bar{\mathbf{H}}_{ij}^{CCI} \triangleq \text{toeplitz}(\mathbf{H}_{ij}^{CCI}, L^{UE}), \\ &\bar{\mathbf{s}}_j^{DL}[k] \triangleq [s_j^{DL}[k - d_j^{DL}] \ \cdots \ s_j^{DL}[k - d_j^{DL} - L^{UE} + 1]]^T, \\ &\bar{\mathbf{x}}_i^{CCI}[k] \triangleq [x_i^{UL}[k] \ \cdots \ x_i^{UL}[k - M^{CCI} - L^{UE} + 2]]^T, \\ &\bar{\mathbf{n}}_j^{DL}[k] \triangleq [(\mathbf{n}_j^{DL}[k])^T \cdots (\mathbf{n}_j^{DL}[k - L^{UE} + 1])^T]^T, \end{aligned}$$

In (17), the first term contains the desired component and ISI, and the second term includes the CCI. We consider two filter design methods to suppress ISI and CCI by the filter $\mathbf{u}_j$. The advantage is that they do not require the CSI of the CCI channels $\mathbf{h}_{ij,m}^{CCI}$ in contrast to common filter design methods such as the minimum mean-squared-error (MMSE) filtering.

In the first method based on the minimum variance distortionless response (MVDR) principle [11], the filter $\mathbf{u}_j$ is obtained by minimizing the variance of the filter output $y_j^{DL}[k]$ under the constraint in which the response to the desired component is undistorted. We assume that $s_j^{DL}[k -$

$d_j^{DL}-\rho_j]$ is the desired data symbol in the filter output of the jth DMU where $\rho_j \in \{1,2,\cdots,M_j^{DL}+L_j^{DL}+L_j^{UL}-d_j^{DL}-3\}$ denotes the predetermined delay. In the first term of (17), the desired component is represented as $\mathbf{u}_j^H\tilde{\mathbf{c}}_j^{DL}s_j^{DL}[k-d_j^{DL}-\rho_j]$ where

$$\tilde{\mathbf{c}}_j^{DL} = \left[\mathbf{0}_{1\times N_j^{UE}(\rho_j-1)}\ (\mathbf{H}_j^{DL}\hat{\mathbf{v}}_j^*)^T\ \mathbf{0}_{1\times N_j^{UE}(L^{UE}-\rho_j)}\right]^T. \tag{18}$$

The filter $\mathbf{u}_j$ based on the MVDR principle is obtained by solving the following optimization problem:

$$\min_{\mathbf{u}_j}\mathbb{E}[|y_j^{DL}[k]|^2] = \mathbf{u}_j^H\mathcal{R}_j^{DL}\mathbf{u}_j \quad \text{s.t.}\ \ \mathbf{u}_j^H\tilde{\mathbf{c}}_j^{DL} = 1 \tag{19}$$

where $\mathcal{R}_j^{DL} \triangleq \mathbb{E}[\bar{\mathbf{r}}_j^{DL}[k](\bar{\mathbf{r}}_j^{DL}[k])^H]$. In practical situations, $\mathcal{R}_j^{DL}$ is obtained via the time-average of $\bar{\mathbf{r}}_j^{DL}[k](\bar{\mathbf{r}}_j^{DL}[k])^H$. The problem (19) can be solved by using a Lagrange multiplier as

$$\min_{\mathbf{u}_j}\mathcal{L}_j(\mathbf{u}_j,\lambda_j) = \mathbf{u}_j^H\mathcal{R}_j^{DL}\mathbf{u}_j - \lambda_j(\mathbf{u}_j^H\tilde{\mathbf{c}}_j^{DL}-1). \tag{20}$$

The optimal solution of (20) is given by [11]

$$\mathbf{u}_j = \{(\tilde{\mathbf{c}}_j^{DL})^H(\mathcal{R}_j^{DL})^{-1}\tilde{\mathbf{c}}_j^{DL}\}^{-1}(\mathcal{R}_j^{DL})^{-1}\tilde{\mathbf{c}}_j^{DL}. \tag{21}$$

Note that the MVDR design (21) requires the desired signal component vector $\tilde{\mathbf{c}}_j^{DL}$ that includes the filter $\mathbf{v}_j$ in the BS transmitter. Hence, the BS should transmit the information of $\mathbf{v}_j$ to the jth DMU.

In the second method based on the generalized sidelobe canceller (GSC) principle [11], the desired signal component vector $\tilde{\mathbf{c}}_j^{DL}$ is blindly estimated without the transmission of $\mathbf{v}_j$ from the BS. We introduce a parameter vector $\hat{\mathbf{c}}_j^{DL}$ to parameterize $\tilde{\mathbf{c}}_j^{DL}$ as

$$\mathbf{E}_j\hat{\mathbf{c}}_j^{DL} = \tilde{\mathbf{c}}_j^{DL} \tag{22}$$

where

$$\mathbf{E}_j = \begin{bmatrix}\mathbf{0}_{N^{UE}(\rho_j-1)\times N^{UE}}\\ \mathbf{I}_{N^{UE}\times N^{UE}}\\ \mathbf{0}_{N^{UE}(L^{UE}-\rho_j)\times N^{UE}}\end{bmatrix}.$$

Given the parameter vector $\hat{\mathbf{c}}_j^{DL}$, we solve the following optimization problem with multiple constraints to derive the filter $\mathbf{u}_j$ by the GSC principle

$$\min_{\mathbf{u}_j}\mathbf{u}_j^H\mathcal{R}_j^{DL}\mathbf{u}_j \quad \text{s.t.}\ \ \mathbf{E}_j^H\mathbf{u}_j = \hat{\mathbf{c}}_j^{DL}. \tag{23}$$

The optimal solution of (23) is given by [11]

$$\mathbf{u}_j = (\mathcal{R}_j^{DL})^{-1}\mathbf{E}_j\{\mathbf{E}_j^H(\mathcal{R}_j^{DL})^{-1}\mathbf{E}_j\}^{-1}\hat{\mathbf{c}}_j^{DL}. \tag{24}$$

Subsequently, the minimum variance of the filter output is given by $\mathbf{u}_j^H\mathcal{R}_j^{DL}\mathbf{u}_j = (\hat{\mathbf{c}}_j^{DL})^H\{\mathbf{E}_j^H(\mathcal{R}_j^{DL})^{-1}\mathbf{E}_j\}^{-1}\hat{\mathbf{c}}_j^{DL}$. We determine the parameter vector $\hat{\mathbf{c}}_j^{DL}$ such that the minimum variance is maximized.

$$\hat{\mathbf{c}}_j^{DL} = \arg\max_{\hat{\mathbf{c}}_j^{DL}}\frac{(\hat{\mathbf{c}}_j^{DL})^H\{\mathbf{E}_j^H(\mathcal{R}_j^{DL})^{-1}\mathbf{E}_j\}^{-1}\hat{\mathbf{c}}_j^{DL}}{(\hat{\mathbf{c}}_j^{DL})^H\hat{\mathbf{c}}_j^{DL}}. \tag{25}$$

The solution to (25) is obtained by solving the eigenvalue problem, and it is expressed as

$$\hat{\mathbf{c}}_j^{DL} = \mathcal{P}_{\max}\{\{\mathbf{E}_j^H(\mathcal{R}_j^{DL})^{-1}\mathbf{E}_j\}^{-1}\} \tag{26}$$

where $\mathcal{P}_{\max}(\mathbf{A})$ denotes the normalized eigenvector associated with the maximum eigenvalue of the matrix $\mathbf{A}$. We substitute (26) into (24) and obtain the optimal filter $\mathbf{u}_j$.

4. Simulation Results

We show simulation results to evaluate the performance of the FD system using the proposed method. Unless otherwise stated, we used simulation parameters in Table 1. We set $P_{\max,j}^{BS} = P_{\max}^{BS}/J$ where $P_{\max}^{BS}$ denotes the total BS transmission power. Users are randomly generated and placed uniformly within a cell of radius 100 m. We modeled the coefficients of IR of channels with a uniform power delay profile as complex Gaussian random variables with zero-mean and variance β. The variance β is given by $\beta = 10^{-PL/10}$ for the downlink/uplink/CCI channels where the path loss PL is given by $PL_{\text{LOS}} = 103.8+20.9\log_{10}R$ dB for line-of-sight (LOS) or $PL_{\text{NLOS}} = 145.4+37.5\log_{10}R$ dB for non LOS (NLOS) [13] where R km denotes the distance between a transmitter and receiver and is given by $\beta = 10^{-(\sigma^{SI})^2/10}$ for the SI channels with path loss $(\sigma^{SI})^2$. LOS situations occur based on the probability $P_{\text{LOS}} = 0.5 - \min\left(0.5, 5\exp\left(\frac{-0.156}{R}\right)\right)+\min\left(0.5, 5\exp\left(\frac{-R}{0.03}\right)\right)$ [13]. We ran $T = 1000$ simulation trials where each trail included different channel realizations. The performance measure denotes the sum rate defined by $R^{UL} = \sum_{i=1}^{I}\log_2(1+\gamma_i^{UL})$ for FD uplink and $R^{DL} = \sum_{j=1}^{J}\log_2(1+\gamma_j^{DL})$ for FD downlink where SINR was obtained by averaging over T trials, and SINR of each trial is γ_i^{UL} in (14) for FD uplink and

$$\gamma_j^{DL} \triangleq \frac{\mathbf{u}_j^H\mathbf{Q}_{\text{des},j}^{DL}\mathbf{u}_j}{\mathbf{u}_j^H\mathbf{Q}_{\text{INT},j}^{DL}\mathbf{u}_j + (\sigma_j^{DL})^2\mathbf{u}_j^H\mathbf{u}_j} \tag{27}$$

for FD downlink †. Similarly, the sum rate is defined by

† $\mathbf{Q}_{\text{des},j}^{DL} \triangleq \tilde{\mathbf{c}}_j^{DL}(\tilde{\mathbf{c}}_j^{DL})^H$, $\mathbf{Q}_{\text{INT},j}^{DL} \triangleq \mathbf{Q}_{\text{ISI},j}^{DL}+\mathbf{Q}_{\text{IUI},j}^{DL}+\mathbf{Q}_{\text{CCI},j}^{DL}$, $\mathbf{Q}_{\text{ISI},j}^{DL} \triangleq \bar{\mathbf{H}}_j^{DL}\check{\mathbf{V}}_j^*\check{\mathbf{V}}_j^T(\bar{\mathbf{H}}_j^{DL})^H$, $\mathbf{Q}_{\text{IUI},j}^{DL} \triangleq \sum_{l=1,l\neq j}^{J}\bar{\mathbf{H}}_j^{DL}\bar{\mathbf{V}}_l^*\bar{\mathbf{V}}_l^T(\bar{\mathbf{H}}_j^{DL})^H$, $\mathbf{Q}_{\text{CCI},j}^{DL} \triangleq \sum_{i=1}^{I}P_i^{UL}\bar{\mathbf{H}}_{ij}^{CCI}(\bar{\mathbf{H}}_{ij}^{CCI})^H$, $\bar{\mathbf{V}}_j \triangleq \text{toeplitz}(\mathbf{V}_j, M^{DL}+L^{UE}-1)$, $\bar{\mathbf{H}}_j^{DL} \triangleq$

Table 1 Simulation parameters.

IR length of up/downlink channels: M^{UL}, M^{DL}	5
IR length of SI channels: M^{SI}	2
IR length of CCI channels: M^{CCI}	4
IR length of filters in BS: L^{DL}, L^{UL}	20
IR length of filters in DMU: L^{UE}	10
Path loss of SI channel: $(\sigma^{SI})^2$	−80 dB
UMU transmission power: P_i^{UL}	20 dBm
Number of DMU antennas: N^{UE}	5
Uplink receiver noise power: $(\sigma^{UL})^2$	−88 dBm
Downlink receiver noise power: $(\sigma_j^{DL})^2$	−91 dBm
Delay of the filters in BS Tx: d_j^{DL}	15
Delay of the filters in BS Rx: d_i^{UL}	4
Delay of the filters of DMUs: ρ_j	6

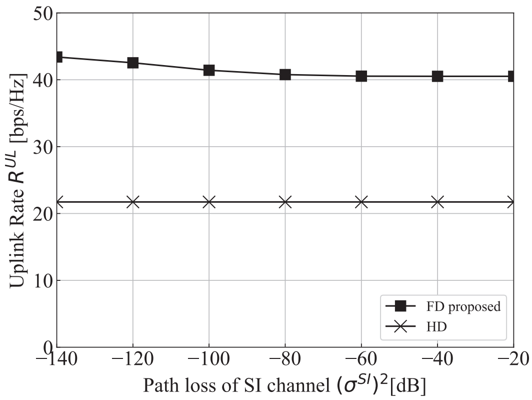

Fig. 2 Effect of path loss of SI channel to uplink rate.

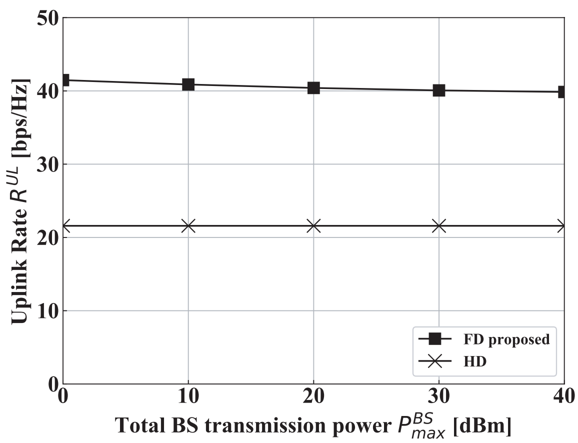

Fig. 3 Effect of BS transmit power on uplink rate.

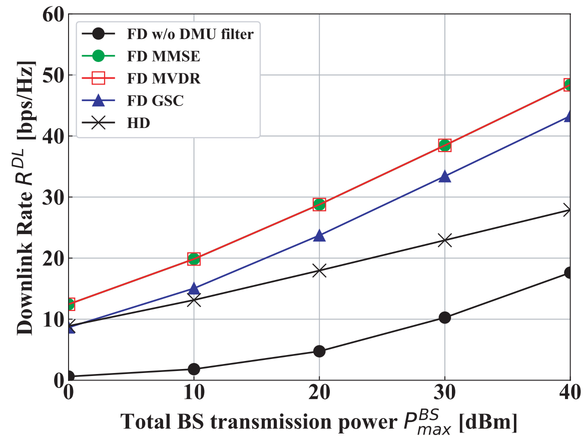

Fig. 4 Effect of BS transmit power on the downlink rate.

$\bar{R}^{UL} = \frac{1}{2}\sum_{i=1}^{I}\log_2(1+\bar{\gamma}_i^{UL})$ for HD uplink and $\bar{R}^{DL} = \frac{1}{2}\sum_{j=1}^{J}\log_2(1+\bar{\gamma}_j^{DL})$ for HD downlink where SINR of each trial $\bar{\gamma}_i^{UL}$ is the same form as γ_i^{UL} in (14) but with $\mathbf{Q}_{\mathrm{SI},i}^{UL} = \mathbf{0}$ and $\bar{\gamma}_j^{DL}$ is the same form as γ_j^{DL} in (27) but with $\mathbf{Q}_{\mathrm{CCI},j}^{DL} = \mathbf{0}$. To evaluate the achievable performance, we assume that the channel estimation is perfect and $\mathcal{R}_j^{DL}$ is ideally obtained. We compare the proposed FD system with the HD system equipped with filters designed by solving (9), (14), and (19) under no SI and CCI conditions.

Figure 2 shows the effect of the path loss of the SI channel $(\sigma^{SI})^2$ to the uplink rate where we set $N_t = N_r = 20, I = J = 3$, $P_{\max}^{BS} = 30$ dBm. As shown in the figure, although the rate of the proposed FD system slightly decreases when $(\sigma^{SI})^2$ increases, it is almost twice the rate of the HD system. The result implies that the filters $\mathbf{w}_i$ in the BS receiver effectively suppress SI.

In Fig. 3, the effect of the total BS transmission power $P_{\max}^{BS}$ on the uplink rate is shown where we set $N_t = N_r = 20, I = J = 3$. As shown in the figure, the rate of the proposed FD system exceeds that of the HD system regardless of $P_{\max}^{BS}$. The rate of the proposed FD system slightly decreases as $P_{\max}^{BS}$ increases because the influence of SI becomes large as $P_{\max}^{BS}$ increases.

In Fig. 4, we show the downlink rate of the proposed FD system using the filters $\mathbf{u}_j$ of DMUs designed by the MVDR principle (21) and GSC principle (24) as a function of the total BS transmission power $P_{\max}^{BS}$, where we set $N_t = N_r = 20, I = J = 3$. For comparison purposes, we also show the results when the filters $\mathbf{u}_j$ designed by the MMSE principle with perfect CSI of the CCI channels are used and when the filters are not used, i.e., $\mathbf{u}_j = \mathbf{1}_{N^{UE}\times 1}$. We can observe that the rate of the proposed FD system with the MVDR filters is the same as that with the MMSE filters. This result shows that the MVDR filters can suppress CCI without the CSI of the CCI channels. Although the performance of the proposed FD system with the GSC filters is slightly worse that that with the MVDR filters, it is still higher than that of the FD system without the filters. This result implies that the filters $\mathbf{u}_j$ of DMUs is effective to suppress CCI. Moreover, it is clear that the rate of the proposed FD system exceeds that of the HD system. The result implies that the filters $\mathbf{v}_j$ in the BS transmitter successfully suppress ISI and IUI.

Figure 5 shows the effect of the number of DMUs J on the uplink rate, where we set $N_t = 32, N_r = 20, I = 3$, $P_{max}^{BS} = 30$ dBm. Evidently, the uplink rate of the proposed FD system is better than that of the HD system. The rate of the proposed FD system decreases when J increases. This is because the number of interfering signals consisting of SI, which corresponds to the fourth term in (13), that should be suppressed by filter $\mathbf{w}_i$ increases when J increases, and the filters are then unable to sufficiently suppress SI when the number of receive antennas N_r is limited.

Figure 6 shows the effect of the number of DMUs J on the downlink rate. The rates of the proposed FD systems exceed that of the HD system and that of the case without the filters of DMUs. When J increases, the downlink rates does not linearly increase with J because DMUs are more likely to be affected by the CCI from UMUs.

Figure 7 shows the effect of the number of UMUs I on the uplink rate where we set $N_t = N_r = 20, J = 3$,

toeplitz$(\mathbf{H}_j^{DL}, L^{UE})$, $\check{\mathbf{v}}_j$ denotes the $d_j^{DL}+\rho_j+1$th column of $\bar{\mathbf{V}}_j$, and $\check{\mathbf{V}}_j$ denotes the remaining part of $\bar{\mathbf{V}}_j$.

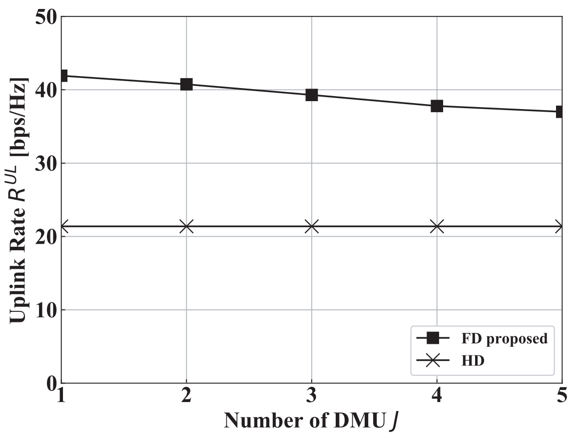

Fig. 5 Effect of the number of DMUs on uplink rate.

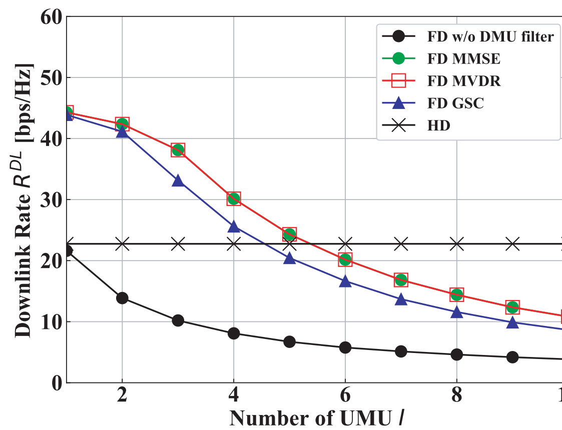

Fig. 8 Effect of the number of UMUs on downlink rate.

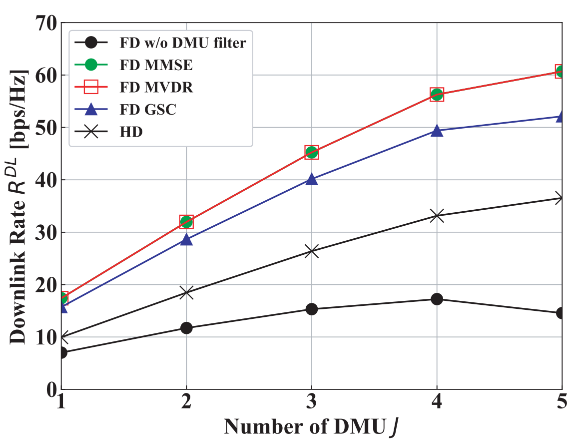

Fig. 6 Effect of the number of DMUs on downlink rate.

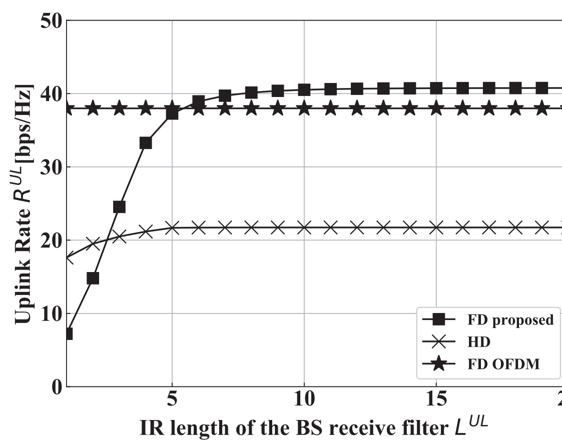

Fig. 9 Uplink rate relative to the IR length of the BS receive filter.

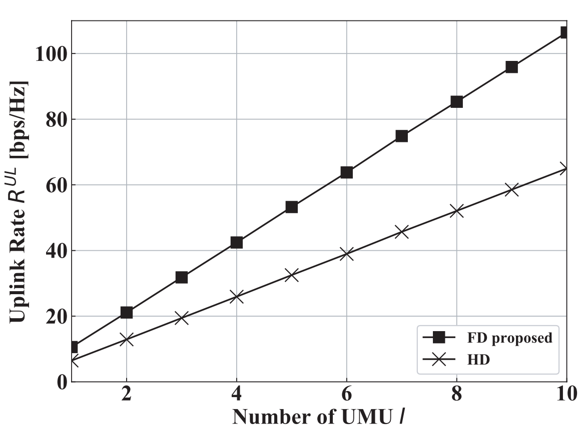

Fig. 7 Effect of the number of UMUs on uplink rate.

P_{max}^{BS} = 30 dBm. The rate of the proposed FD system increases linearly with I due to the successful suppression by the filters $\mathbf{w}_i$.

Figure 8 shows the effect of the number of UMUs I on the downlink rate. When I increases, the rates of the FD system decrease because the effect of CCI increases. Specifically, when $I \geq 5$, the rates of the proposed FD system are worse than that of the HD system. We can overcome the degradation by increasing the number of receive antennas of DMUs N^{UE}. However, increasing the number of antennas is impractical for small mobile devices. Subsequently, other complementary techniques, such as power allocation and user selection, should be used.

Finally, we compare the proposed FD system based on single-carrier transmission with the FD system based on OFDM using BS beamformers designed by solving (9) and (14) in the frequency domain. Figure 9 shows the uplink rate as a function of the IR length of the filters in the BS receiver L^{UL}, where we set $N_t = N_r = 20, J = 3, P_{max}^{BS} = 30$ dBm, number of subcarriers $N_s = 64$, and length of CP $N_s/8$. When L^{UL} becomes long, the rate of the proposed FD system increases. When L^{UL} is sufficiently long, the rate of the proposed FD system exceeds that of the FD-OFDM because the FD-OFDM suffers from rate loss due to CP.

If the channels change after the filters are determined, the filters do not work and have to be redesigned based on the updated channel estimation. To combat the channel variation, alternative approaches such as adaptive filtering [14] and robust filter designs [15] are worth considering.

5. Conclusion

In this paper, we proposed a filter design method to suppress interference in a FD multiuser system based on single-carrier transmission in frequency-selective channels. The employment of time-domain FIR filtering to jointly suppress ISI, IUI, SI, and CCI avoids the requirement of the CSI of the CCI channels and adoption of OFDM. Simulation results indicated that the FD system using the proposed method is superior to the HD system and FD system using OFDM.

Although the simplicity of the UMUs with a single transmit antenna is advantageous, it limits the performance. In more general cases where UMSs use multiple antennas, the uplink performance would be improved due to the spatial diversity, but the downlink performance would be degraded due to the increase of CCI. To overcome this problem, it is worth studying the combination of the proposed method and other techniques such as power allocation and user selection. Further studies should focus on the effect of the imperfect CSI and correlation matrix $\mathcal{R}_j^{DL}$. Additionally, the optimum joint design of all filters is a challenging topic for future research. The proposed method's performance is degraded by several non-idealities introduced by the limited resolution in analog-to-digital conversion and the effect of power saturation on analog circuits [16]. From a practical point of view, these effects are worthy of investigation.

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References

[1] A. Sabharwal, P. Schniter, D. Guo, D.W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," IEEE J. Sel. Areas Commun., vol.32, no.9, pp.1637–1652, Sept. 2014.
[2] V.W.S. Wong, R. Schober, D.W.K. Ng, and L.-C. Wang, eds., Key Technologies for 5G Wireless Systems, Cambridge Univ. Press, Cambridge, U.K., 2017.
[3] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," Proc. SIGCOMM, pp.375–386, Aug. 2013.
[4] D. Nguyen, L.-N. Tran, P. Pirinen, and M. Latva-aho, "On the spectral efficiency of full-duplex small cell wireless systems," IEEE Trans. Wireless Commun., vol.13, no.9, pp.4896–4910, Sept. 2014.
[5] T.-H. Chang, Y.-F. Liu, and S.-C. Lin, "Max-min-fairness linear transceiver design for full-duplex multiuser systems," Proc. IEEE SPAWC, pp.1–4, July 2017.
[6] A.C. Cirik, L. Zhou, and T. Ratnarajah, "Linear transceiver design with per-antenna power constraints in full-duplex multi-user MIMO systems," IEEE Wireless Commun. Lett., vol.5, no.4, pp.412–415, Aug. 2016.
[7] M.T. Kabir, M.R.A. Khandaker, and C. Masouros, "Interference exploitation in full-duplex communications: Trading interference power for both uplink and downlink power savings," IEEE Trans. Wireless Commun., vol.17, no.12, pp.8314–8329, Dec. 2018.
[8] V.-D. Nguyen, H.V. Nguyen, C.T. Nguyen, and O.-S. Shin, "Spectral efficiency of full-duplex multiuser system: Beamforming design, user grouping, and time allocation," IEEE Access, vol.5, pp.5785–5797, March 2017.
[9] M.-W. Un, W.-K. Ma, and P.C. Ching, "Joint transmit beamforming optimization and uplink/downlink user selection in a full-duplex multi-user MIMO system," Proc. IEEE ICASSP, pp.3639–3643, March 2017.
[10] M. Ahn, H. Kong, H.M. Shin, and I. Lee, "A low complexity user selection algorithm for full-duplex MU-MISO systems," IEEE Trans. Wireless Commun., vol.15, no.11, pp.7899–7907, Nov. 2016.
[11] M.K. Tsatsanis and Z. Xu, "Constrained optimization methods for direct blind equalization," IEEE J. Sel. Areas Commun., vol.17, no.3, pp.424–423, March 1999.
[12] H. Chen, A.B. Gershman, and S. Shahbazpanahi, "Filter-and-forward distributed beamforming in relay networks with frequency selective fading," IEEE Trans. Signal Process., vol.58, no.3, pp.1251–1262, March 2010.
[13] "3GPP TR36.828, Evolved Universal Terrestrial Radio Access (E- UTRA); Further enhancements to LTE Time Division Duplex (TDD) for Downlink-Uplink (DL-UL) interference management and traffic adaptation," 2012.
[14] A. Ambede, R.P. Sirigina, and A.S. Madhukumar, "Adaptive filter based blind AS self-interference cancellation in full-duplex MIMO transceivers," Proc. 2018 IEEE WCNC, April 2018.
[15] A.C. Cirik, S. Biswas, S. Vuppala, and T. Ratnarajah, "Robust transceiver design for full duplex multiuser MIMO systems," IEEE Wireless Commun. Lett., vol.5, no.3, pp.260–263, June 2016.
[16] D. Korpi, T. Riihonen, V. Syrjala, L. Antilla, M. Valkama, and R. Wichman, "Full-duplex transceiver system calculations: Analysis of ADC and linearity challenges," IEEE Trans. Wireless Commun., vol.13, no.7, pp.3821–3836, July 2014.

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