Joint Tx/Rx Signal Processing for Distributed Antenna MU-MIMO Downlink

Shinya Kumagai[†] Yuta Seki[‡] and Fumiyuki Adachi[†,‡]
†Dept. of Communications Engineering, Graduate School of Engineering, Tohoku University
6-6-05, Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579, Japan
‡Research Organization of Electrical Communication, Tohoku University
2-1-1, Katahira, Aoba-ku, Sendai, Miyagi, 980-8577, Japan
{kumagai, seki}@mobile.ecei.tohoku.ac.jp, adachi@ecei.tohoku.ac.jp

***Abstract*—An introduction of multi-user multiple-input multiple-output (MU-MIMO) to distributed antenna-based small-cell networks is considered a promising approach toward 5G mobile networks to enhance the sum throughput. However, the inter-symbol interference (ISI) caused by the channel frequency-selectivity, the inter-antenna interference (IAI), and the inter-user interference (IUI) degrade the MU-MIMO downlink throughput. This paper proposes two joint transmit-and-receive (Tx/Rx) filtering schemes (called BD-SVD and MMSE-SVD) for MU-MIMO downlinks using single-carrier (SC) transmission and orthogonal frequency-division multiplexing (OFDM) transmission. In BD-SVD, IUI is removed by block diagonalization (BD) at the transmitter side, and then, the equivalent channel after BD is transformed into IAI-free eigenmodes using singular value decomposition (SVD). On the other hand, in MMSE-SVD, BD is not used and the channel is directly transformed into eigenmodes. IUI and IAI are suppressed by a minimum mean square error (MMSE)-based precoding at the transmitter assuming that each receiver does eigenmode reception. Furthermore, in the case of SC downlink, ISI is suppressed by applying MMSE-based Tx power allocation (PA) and Rx frequency-domain equalization (FDE) to each eigenmode. Numerical results show that BD-SVD and MMSE-SVD achieve a higher sum throughput than conventional MMSE precoding.**

Keywords*—distributed antenna; MU-MIMO; downlink; joint transmit and receive signal processing

I. INTRODUCTION

Distributed antenna-based small-cell network (or distributed antenna network) [1, 2] can improve both the spectrum and energy efficiencies simultaneously and is considered as a strong candidate for the fifth generation (5G) mobile networks. A number of distributed antennas are deployed in each macro-cell and they are connected to baseband unit (BBU) via optical links. An introduction of multi-user multiple-input multiple-output (MU-MIMO) transmission [3] to the distributed antenna-based small-cell network is a promising approach towards 5G to significantly increase the sum throughput [4].However, the MU-MIMO downlink throughput may degrade due to the inter-symbol interference (ISI) caused by the channel frequency-selectivity, the inter-antenna interference (IAI), and the inter-user interference (IUI). ISI is a serious problem for single-carrier (SC) transmission while IAI and IUI are a common problem for both SC and orthogonal frequency-division multiplexing (OFDM) transmissions. Minimum mean square error (MMSE)-based precoding [5] has been widely studied since it is computationally efficient, but its achievable transmission performance improvement is limited due to the presence of residual ISI, IAI, and IUI.

Recently, for SC-MU-MIMO uplink, we proposed a joint transmit-and-receive (Tx/Rx) MMSE filtering [6]. MIMO channel between each user terminal (UE) and BBU is transformed into eigenmodes (i.e., orthogonal channels), to each of which MMSE-based Tx frequency-domain power allocation (PA) and Rx frequency-domain equalization (FDE) are applied in order to suppress IAI and ISI significantly. IUI is suppressed by BBU's Rx filtering. As a consequence, joint Tx/Rx MMSE filtering achieves a higher sum throughput than the conventional Rx MMSE filtering.

In this paper, for SC and OFDM-MU-MIMO downlinks in distributed antenna-based small-cell networks, we propose two joint Tx/Rx filtering schemes (called BD-SVD and MMSE-SVD). In BD-SVD, IUI is removed by block diagonalization (BD) [7] at BBU, and then, the equivalent channel after BD is transformed into eigenmodes using singular value decomposition (SVD). On the other hand, in MMSE-SVD, BD is not used and the channel is directly transformed into eigenmodes. IUI and IAI are suppressed by a MMSE-based precoding at BBU assuming that each UE does eigenmode reception. Furthermore, in the case of SC transmission, ISI is suppressed by applying MMSE-based Tx PA and Rx FDE to each eigenmode. Numerical results show that BD-SVD and MMSE-SVD achieve a higher sum throughput than the conventional MMSE precoding.

The remainder of this paper is organized as follows. Sect. II presents the distributed antenna-based small-cell network model and the SC and OFDM-MU-MIMO downlink signal representations. Sect. III derives the optimal Tx/Rx filter matrices for BD-SVD and MMSE-SVD. Sect. IV shows the numerical results, and Sect. V gives the concluding remarks.

Notations: E[.], $[.]^T$, $[.]^H$, tr[.], and diag[.] denote the ensemble average operation, the transpose operation, the Hermitian transpose operation, the trace operation, and diagonal matrix, respectively. $\delta(x)$ and $(x)^+$ denotes the delta function and max(0, x), respectively. $\mathbf{I}_N$ is the $N \times N$ identity matrix.

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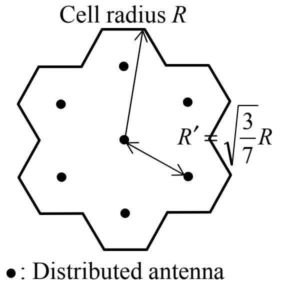


Fig. 1. Network model.

II. SYSTEM MODEL

This section presents the distributed antenna-based small-cell network and channel models assumed in this paper, and shows the SC and OFDM-MU-MIMO downlink signal representations.

A. Network Model

In the distributed antenna-based small-cell network, $N_{\rm total}$ antennas are uniformly distributed within the macro-cell with a radius of R, and each antenna covers the small-cell with a radius of R'. Fig. 1 shows the network model [6] assumed in this paper with $N_{\rm total}$=7 as an example. $N_{\rm total}$=7 antennas are distributed within the macro-cell and each antenna covers the small-cell with a radius of $R' = R/\sqrt{7}$ .In this paper, the single macro cell is considered in which all of $N_{\rm total}$ antennas are used for transmission (i.e. the number of transmit antennas, $N_{\rm t}$=$N_{\rm total}$), and U UEs which have $N_{\rm UE}$ antennas are randomly located within the macro cell.

B. Channel Model

The broadband wireless channel is characterized by distance-dependent path loss, log-normally distributed shadowing loss, and multipath fading. Assuming that the channel is composed of L distinct paths, the channel impulse response $h_{u,n_{\rm r},n_{\rm t}}(\tau)$ and the transfer function $H_{u,n_{\rm r},n_{\rm t}}(k)$ between antenna#$n_{\rm r}$ of UE#u and distributed antenna#$n_{\rm t}$ can be represented as

$$h_{u,n_{\rm r},n_{\rm t}}(\tau) = \sqrt{d_{u,n_{\rm t}}^{-\alpha} 10^{-\frac{\eta_{u,n_{\rm t}}}{10}}} \times \left\{ \begin{array}{l} \sqrt{\dfrac{K}{K+1}} \exp\left(j\theta_{u,n_{\rm r},n_{\rm t}}\right)\delta\left(\tau - \tau_{u,n_{\rm r},n_{\rm t},1}\right) \\ + \sqrt{\dfrac{1}{K+1}} \sum_{l=1}^{L} \xi_{u,n_{\rm r},n_{\rm t},l}\,\delta\left(\tau - \tau_{u,n_{\rm r},n_{\rm t},l}\right) \end{array} \right\}, \qquad (1)$$

and

$$H_{u,n_{\rm r},n_{\rm t}}(k) = \sqrt{d_{u,n_{\rm t}}^{-\alpha} 10^{-\frac{\eta_{u,n_{\rm t}}}{10}}} \times \left\{ \begin{array}{l} \sqrt{\dfrac{K}{K+1}} \exp\left(j\theta_{u,n_{\rm r},n_{\rm t}}\right)\exp\left(-j\dfrac{2\pi k \tau_{u,n_{\rm r},n_{\rm t},1}}{N_{\rm c}}\right) \\ + \sqrt{\dfrac{1}{K+1}} \sum_{l=1}^{L} \xi_{u,n_{\rm r},n_{\rm t},l} \exp\left(-j\dfrac{2\pi k \tau_{u,n_{\rm r},n_{\rm t},l}}{N_{\rm c}}\right) \end{array} \right\}, \qquad (2)$$

respectively. In this paper, the channel is assumed to be a Nakagami-Rice fading channel (i.e. direct-to-delay path power ratio K>0) when the distance $d_{u,n_{\rm t}}$ between UE#u and distributed antenna#$n_{\rm t}$ is equal to or smaller than R', and a Rayleigh fading channel (i.e. K=0) when $d_{u,n_{\rm t}}$ is larger than R'. α and $\eta_{u,n_{\rm t}}$ denote the path loss exponent and the shadowing loss in dB having zero-mean and standard deviation $\sigma_{\rm S}$, respectively. $\theta_{u,n_{\rm r},n_{\rm t}}$ is the phase of direct path and is assumed to be distributed uniformly. $\xi_{u,n_{\rm r},n_{\rm t},l}$ and $\tau_{u,n_{\rm r},n_{\rm t},l}$ are respectively the complex-valued path gain and the time delay of path#l with $\mathrm{E}[\sum_{l=1}^{L}\xi_{u,n_{\rm r},n_{\rm t},l}] = 1$ for all u, $n_{\rm r}$, $n_{\rm t}$. In this paper, we assume a sample-spaced time delay (i.e., $\tau_{u,n_{\rm r},n_{\rm t},l}$ =l–1 for all u, $n_{\rm r}$, $n_{\rm t}$). $N_{\rm c}$ is the block size.

The average signal power $P_{{\rm r},u,n_{\rm t}}$ received at UE#u for the signal transmitted from distributed antenna#$n_{\rm t}$ can be modeled as

$$P_{{\rm r},u,n_{\rm t}}(\tau) = \hat{P}_{\rm t}\left(\hat{d}_{u,n_{\rm t}}\right)^{-\alpha} 10^{-\frac{\eta_{u,n_{\rm t}}}{10}}, \qquad (3)$$

where $\hat{P}_{\rm t} = P_{\rm t}R^{-\alpha}$ is the normalized Tx power with $P_{\rm t}$ being the actual Tx power. $\hat{d}_{u,n_{\rm t}} = d_{u,n_{\rm t}}/R$ is the normalized distance.

C. Signal Representation

Fig. 2 shows the Tx/Rx structure of MU-MIMO downlink assumed in this paper. In this section, we express the signal representation. BBU communicates with U UEs which have $N_{\rm UE}$ antennas using $N_{\rm t}$ distributed antennas.

At BBU, information bit sequence to each UE is serial-to-parallel (S/P) converted to $N_{\rm UE}$ parallel bit sequences, and then each sequence is data-modulated. Each data symbol sequence is divided to $N_{\rm c}$-symbol blocks, and Tx filtering is applied to each data symbol block in the case of OFDM. In the case of SC, each data symbol block is transformed into a frequency-domain data symbol block by $N_{\rm c}$-point discrete Fourier transform (DFT). In SC, the Tx symbol vector $\mathbf{S}(k)\in\mathbb{C}^{N_{\rm t}\times 1}$ at subcarrier#k is obtained by applying the Tx filtering to the frequency-domain data symbol vector $\mathbf{D}(k)$=[$\mathbf{D}_1^{\rm T}(k)\cdots\mathbf{D}_U^{\rm T}(k)$]$^{\rm T}\in\mathbb{C}^{UN_{\rm UE}\times 1}$, which is expressed as

$$\mathbf{S}(k) = [S_1(k)\cdots S_{N_{\rm t}}(k)]^{\rm T} = \sqrt{\frac{2E_{\rm s}}{T_{\rm s}}}\mathbf{F}(k)\mathbf{D}(k), \qquad (4)$$

where $\mathbf{F}(k)$=[$\mathbf{F}_1(k)\cdots\mathbf{F}_U(k)$]$\in\mathbb{C}^{N_{\rm t}\times UN_{\rm UE}}$ is the Tx filter matrix. $E_{\rm s} = \hat{P}_{\rm t}T_{\rm s}$ is the normalized Tx symbol energy with $T_{\rm s}$ being the symbol duration. In OFDM, $\mathbf{D}(k)$ in (4) is replaced with the time-domain data symbol vector $\mathbf{d}(k) = [\mathbf{d}_1^{\rm T}(k)\cdots\mathbf{d}_U^{\rm T}(k)]^{\rm T}\in\mathbb{C}^{UN_{\rm UE}\times 1}$. $N_{\rm c}$-point inverse DFT (IDFT) is applied to each Tx symbol block {$S_{n_{\rm t}}(k)$; k=1~$N_{\rm c}$}, $n_{\rm t}$=1~$N_{\rm t}$, to transform back into time-domain Tx blocks in SC or to transform into OFDM symbol in OFDM. Finally, the last $N_{\rm g}$ samples of each Tx block or OFDM symbol are copied as a cyclic prefix (CP) and inserted into the guard interval (GI) at the beginning of each Tx block or OFDM symbol and then transmitted from $N_{\rm t}$ distributed antennas.

At UE#u, each CP is removed from the signal blocks received by $N_{\rm UE}$ antennas and then, each block is transformed into the frequency-domain Rx signal block by $N_{\rm c}$-point DFT.

The frequency-domain received signal vector $\mathbf{R}_u(k)\in\mathbb{C}^{N_{\rm UE}\times 1}$ at subcarrier#k is expressed as

$$\mathbf{R}_u(k)=\mathbf{H}_u(k)\mathbf{S}(k)+\mathbf{Z}_u(k)\,, \tag{5}$$

where $\mathbf{H}_u(k)\in\mathbb{C}^{N_{\rm UE}\times N_{\rm t}}$ is the channel matrix between UE#u and BBU whose $(n_{\rm r},n_{\rm t})$-th component is given by $H_{u,n_{\rm r},n_{\rm t}}(k)$. $\mathbf{Z}_u(k)\in\mathbb{C}^{N_{\rm UE}\times 1}$ is the noise vector whose elements are zero-mean complex-valued random variables having variance $2N_0/T_{\rm s}$ with N_0 being the one-sided power spectrum density of additive white Gaussian noise (AWGN). In SC, the frequency-domain soft-output symbol vector $\hat{\mathbf{D}}_u(k)\in\mathbb{C}^{N_{\rm UE}\times 1}$ is obtained by applying the Rx filtering on $\mathbf{R}_u(k)$ as

$$\hat{\mathbf{D}}_u(k)=\mathbf{W}_u(k)\mathbf{R}_u(k)\,, \tag{6}$$

where $\mathbf{W}_u(k)\in\mathbb{C}^{N_{\rm UE}\times N_{\rm UE}}$ is the Rx filter matrix. In OFDM, $\hat{\mathbf{D}}_u(k)$ in (6) is replaced with the time-domain soft-output symbol vector $\hat{\mathbf{d}}_u(k)\in\mathbb{C}^{N_{\rm UE}\times 1}$. In SC, $N_{\rm c}$-point IDFT is applied to each frequency-domain soft-output symbol block $\{\hat{D}_{u,n_{\rm r}}(k)$; k=1~$N_{\rm c}\}$, $n_{\rm r}$=1~$N_{\rm UE}$, and then, the time-domain soft-output symbol blocks are obtained.

Based on Shannon's channel capacity, the throughput C_u (bps/Hz) of UE#u using the above joint Tx/Rx filtering is expressed as

$$C_u=\begin{cases}\displaystyle\sum_{n_{\rm r}=1}^{N_{\rm UE}}\log_2\left(1+\Gamma_{{\rm SC},u,n_{\rm r}}\right) & \text{in SC}\\ \displaystyle\frac{1}{N_{\rm c}}\sum_{n_{\rm r}=1}^{N_{\rm UE}}\sum_{k=1}^{N_{\rm c}}\log_2\left(1+\Gamma_{{\rm OFDM},u,n_{\rm r}}(k)\right) & \text{in OFDM}\end{cases}, \tag{7}$$

where $\Gamma_{{\rm SC},u,n_{\rm r}}$ is the received signal-to-interference plus noise power ratio (SINR) of UE#u's $n_{\rm r}$-th eigenmode after joint Tx/Rx MMSE filtering in SC, and $\Gamma_{{\rm OFDM},u,n_{\rm r}}(k)$ is that at subcarrier#k in OFDM, which are respectively expressed as

$$\Gamma_{{\rm SC},u,n_{\rm r}}=\frac{\left|\tilde{h}_{u,n_{\rm r}}\right|^2}{\mu_{{\rm ISI},u,n_{\rm r}}+\mu_{{\rm IAI},u,n_{\rm r}}+\mu_{{\rm IUI},u,n_{\rm r}}+\mu_{{\rm noise},u,n_{\rm r}}}\,, \tag{8}$$

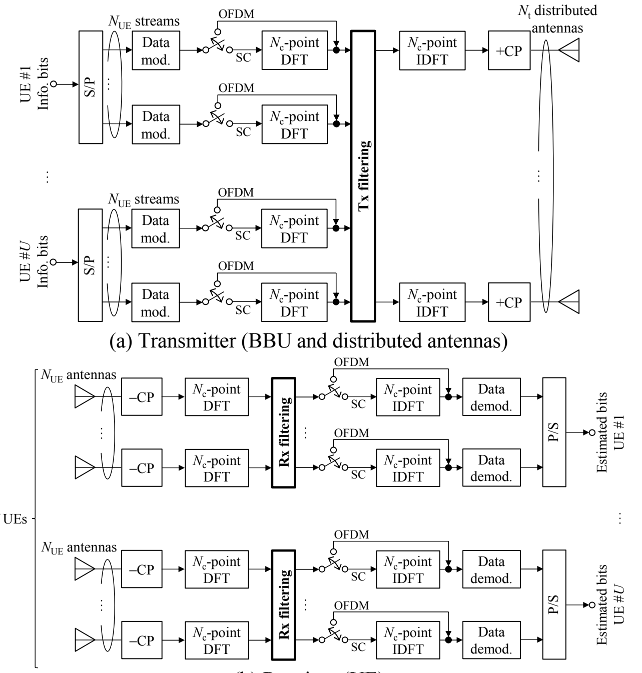
and

$$\Gamma_{{\rm OFDM},u,n_{\rm r}}(k)=\frac{\left|\hat{H}_{u,n_{\rm r},u,n_{\rm r}}(k)\right|^2}{M_{{\rm IAI},u,n_{\rm r}}(k)+M_{{\rm IUI},u,n_{\rm r}}(k)+M_{{\rm noise},u,n_{\rm r}}(k)}, \tag{9}$$

with

$$\begin{cases}\hat{H}_{u,n_{\rm r},u',n'}(k)=\displaystyle\sum_{m=1}^{N_{\rm UE}}W_{u,n_{\rm r},m}(k)\sum_{n_{\rm t}=1}^{N_{\rm t}}H_{u,m,n_{\rm t}}(k)F_{u',n_{\rm t},n'_{\rm r}}(k)\\ M_{{\rm IAI},u,n_{\rm r}}(k)=\displaystyle\sum_{\substack{n'_{\rm r}=1\\ n'_{\rm r}\neq n_{\rm r}}}^{N_{\rm UE}}\left|\hat{H}_{u,n_{\rm r},u,n'_{\rm r}}(k)\right|^2\\ M_{{\rm IUI},u,n_{\rm r}}(k)=\displaystyle\sum_{\substack{u'=1\\ u'\neq u}}^{U}\sum_{n'_{\rm r}=1}^{N_{\rm UE}}\left|\hat{H}_{u,n_{\rm r},u',n'}(k)\right|^2\\ M_{{\rm noise},u,n_{\rm r}}(k)=\gamma^{-1}\displaystyle\sum_{m=1}^{N_{\rm UE}}\left|W_{u,n_{\rm r},m}(k)\right|^2\end{cases}, \tag{10}$$

and



(a) Transmitter (BBU and distributed antennas)

(b) Receiver (UE)

Fig. 2. Tx/Rx structure of MU-MIMO downlink.

$$\begin{cases}\tilde{h}_{u,n_{\rm r}}=\displaystyle\frac{1}{N_{\rm c}}\sum_{k=1}^{N_{\rm c}}\hat{H}_{u,n_{\rm r},u,n_{\rm r}}(k)\\ \mu_{{\rm ISI},u,n_{\rm r}}=\displaystyle\frac{1}{N_{\rm c}}\sum_{k=1}^{N_{\rm c}}\left|\hat{H}_{u,n_{\rm r},u,n_{\rm r}}(k)\right|^2-\left|\tilde{h}_{u,n_{\rm r}}\right|^2\\ \mu_{{\rm IAI},u,n_{\rm r}}=\displaystyle\frac{1}{N_{\rm c}}\sum_{k=1}^{N_{\rm c}}M_{{\rm IAI},u,n_{\rm r}}(k)\\ \mu_{{\rm IUI},u,n_{\rm r}}=\displaystyle\frac{1}{N_{\rm c}}\sum_{k=1}^{N_{\rm c}}M_{{\rm IUI},u,n_{\rm r}}(k)\\ \mu_{{\rm noise},u,n_{\rm r}}=\displaystyle\frac{1}{N_{\rm c}}\sum_{k=1}^{N_{\rm c}}M_{{\rm noise},u,n_{\rm r}}(k)\end{cases}. \tag{11}$$

$W_{u,n_{\rm r},m}(k)$ is the $(n_{\rm r},m)$-th component of $\mathbf{W}_u(k)$ and $F_{u,n_{\rm t},n_{\rm r}}(k)$ is the $(n_{\rm t},n_{\rm r})$-th component of $\mathbf{F}_u(k)$. $\mu_{{\rm ISI},u,n_{\rm r}}$, $\mu_{{\rm IAI},u,n_{\rm r}}$, $\mu_{{\rm IUI},u,n_{\rm r}}$, and $\mu_{{\rm noise},u,n_{\rm r}}$ are the variances of normalized residual ISI, IAI, IUI, and noise in SC, respectively. $M_{{\rm IAI},u,n_{\rm r}}$, $M_{{\rm IUI},u,n_{\rm r}}$, and $M_{{\rm noise},u,n_{\rm r}}$ are those in OFDM. $\gamma=E_{\rm s}/N_0$.

III. Derivation of Optimal Tx/Rx Filter Matrices

In this section, we derive the optimal Tx and Rx filter matrices which minimize the total MSE of the blocks between the Tx data symbol vector $\mathbf{D}(k)$ (or $\mathbf{d}(k)$) and the soft output symbol vector $\hat{\mathbf{D}}(k)=[\hat{\mathbf{D}}_1^{\rm T}(k)\cdots\hat{\mathbf{D}}_U^{\rm T}(k)]^{\rm T}$ (or $\hat{\mathbf{d}}(k)=[\hat{\mathbf{d}}_1^{\rm T}(k)\cdots\hat{\mathbf{d}}_U^{\rm T}(k)]^{\rm T}$) in BD-SVD and MMSE-SVD with SC and OFDM transmissions. The minimization of total MSE under the total Tx power constraint is formulated as

$$\min_{\{\mathbf{F}(k),\mathbf{W}_u(k)\}}\varepsilon \tag{12a}$$

$$\text{s.t.} \sum_{k=1}^{N_c} \mathrm{tr}\left(\mathbf{F}(k)\mathbf{F}^{\mathrm{H}}(k)\right) = N_c, \tag{12b}$$

where ε is the total MSE between $\mathbf{D}(k)$ (or $\mathbf{d}(k)$) and $\hat{\mathbf{D}}(k)$ (or $\hat{\mathbf{d}}(k)$) defined as

$$\varepsilon \equiv \mathrm{E}\left[\sum_{k=1}^{N_c} \mathrm{tr}\left\{\left(\mathbf{D}(k) - \frac{\hat{\mathbf{D}}(k)}{\sqrt{2E_s/T_s}}\right)\left(\mathbf{D}(k) - \frac{\hat{\mathbf{D}}(k)}{\sqrt{2E_s/T_s}}\right)^{\mathrm{H}}\right\}\right], \tag{13}$$

in SC. In OFDM, $\mathbf{D}(k)$ and $\hat{\mathbf{D}}(k)$ in (13) are replaced with $\mathbf{d}(k)$ and $\hat{\mathbf{d}}(k)$, respectively.

A. BD-SVD

In BD-SVD, at first, IUI is removed by BD at BBU. The BD precoding matrix $\mathbf{F}_{\mathrm{BD},u}(k) \in \mathbb{C}^{N_t \times \{N_t-(U-1)N_{\mathrm{UE}}\}}$ corresponding to UE#u is expressed as

$$\mathbf{F}_{\mathrm{BD},u}(k) = \overline{\mathbf{V}}_{\mathrm{noise},u}(k), \tag{14}$$

where $\overline{\mathbf{V}}_{\mathrm{noise},u}(k)$ is the matrix which expresses the right null-space of $\overline{\mathbf{H}}_u(k) = [\mathbf{H}_1^{\mathrm{T}}(k) \cdots \mathbf{H}_{u-1}^{\mathrm{T}}(k), \mathbf{H}_{u+1}^{\mathrm{T}}(k) \cdots \mathbf{H}_U^{\mathrm{T}}(k)]^{\mathrm{T}}$. The equivalent channel matrix $\dot{\mathbf{H}}_u(k) = \mathbf{H}_u(k)\overline{\mathbf{V}}_{\mathrm{noise},u}(k)$ of UE#u after BD can be regarded as a single-user MIMO channel matrix since IUI does not occur. Therefore, as [8], the optimal Tx and Rx filter matrices are derived by applying SVD to $\dot{\mathbf{H}}_u(k)$ as

$$\mathbf{F}_u(k) = \overline{\mathbf{V}}_{\mathrm{noise},u}(k)\dot{\mathbf{V}}_u(k)\mathbf{P}_{\mathrm{BD-SVD},u}^{1/2}(k), \tag{15}$$

and

$$\begin{aligned}\mathbf{W}_u(k) = &\left\{\left(\mathbf{H}_u(k)\mathbf{F}_u(k)\right)^{\mathrm{H}}\mathbf{H}_u(k)\mathbf{F}_u(k) + \gamma^{-1}\mathbf{I}_{N_{\mathrm{UE}}}\right\}^{-1} \\ &\times\left(\mathbf{H}_u(k)\mathbf{F}_u(k)\right)^{\mathrm{H}},\end{aligned} \tag{16}$$

where $\dot{\mathbf{V}}_u(k) \in \mathbb{C}^{\{N_t-(U-1)N_{\mathrm{UE}}\}\times\{N_t-(U-1)N_{\mathrm{UE}}\}}$ is the unitary matrix whose each column has the right singular vector of $\dot{\mathbf{H}}_u(k)$. $\mathbf{P}_{\mathrm{BD\text{-}SVD},u}(k) \in \mathbb{R}^{\{N_t-(U-1)N_{\mathrm{UE}}\}\times N_{\mathrm{UE}}}$ is the matrix whose n_r-th diagonal component $P_{u,n_r}(k)$ gives the PA to the n_r-th eigenmode (whose eigenvalue is expressed as $\dot{\Lambda}_{u,n_r}(k)$) at subcarrier#k and any others are zero. In SC, MMSE-PA both across eigenmodes and subcarriers minimizes the MSE. However, in terms of throughput, MMSE-PA is not optimal as shown in [6]. Therefore, as [6], PA in SC is designed based on water-filling (WF) theory across eigenmodes and MMSE criterion across subcarriers. The WF-MMSE-PA is given as

$$P_{u,n_r}(k) = \left(\frac{1}{\sqrt{\nu_{u,n_r}}}\frac{1}{\sqrt{\gamma\dot{\Lambda}_{u,n_r}(k)}} - \frac{1}{\gamma\dot{\Lambda}_{u,n_r}(k)}\right)^+, \tag{17}$$

where ν_{u,n_r} is chosen to satisfy $\sum_{k=1}^{N_c} P_{u,n_r}(k) = Q_{u,n_r}$. Q_{u,n_r} is expressed as

$$P_{u,n_r}(k) = \left(\frac{1}{\kappa_u} - \frac{1}{\gamma\widetilde{\Lambda}_{u,n_r}}\right)^+, \tag{18}$$

where $\sum_{k=1}^{N_c} \dot{\Lambda}_{u,n_r}(k)/N_c = \widetilde{\Lambda}_{u,n_r}$ and κ_u is chosen to keep the total Tx power to each UE constant (i.e. $\sum_{n_r=1}^{N_{\mathrm{UE}}} Q_{u,n_r} \sum_{k=1}^{N_c}\sum_{n_t=1}^{N_t} \left|A_{u,n_t,n_r}(k)\right|^2 = N_c/U$). $A_{u,n_t,n_r}(k)$ is the (n_t,n_r)-th component of $\mathbf{F}_u(k)\mathbf{P}_{\mathrm{BD-SVD},u}^{-1/2}(k)$. In OFDM, PA is done based on WF theory both across eigenmodes and subcarriers to maximize the throughput.

B. MMSE-SVD

In MMSE-SVD, SVD is applied to the original channel matrix $\mathbf{H}_u(k)$ between BBU and UE#u unlike BD-SVD. $\mathbf{H}_u(k)$ is rewritten by SVD as

$$\mathbf{H}_u(k) = \mathbf{U}_u(k)\mathbf{\Lambda}_u^{1/2}(k)\mathbf{V}_{\mathrm{signal},u}^H(k), \tag{19}$$

where $\mathbf{U}_u(k) \in \mathbb{C}^{N_{\mathrm{UE}}\times N_{\mathrm{UE}}}$ is the unitary matrix whose each column has the left singular vector of $\mathbf{H}_u(k)$. $\mathbf{\Lambda}_u(k) \in \mathbb{R}^{N_{\mathrm{UE}}\times N_{\mathrm{UE}}}$ is the diagonal matrix whose n_r-th diagonal component $\Lambda_{u,n_r}(k)$ has the eigenvalue of the n_r-th eigenmode. $\mathbf{V}_{\mathrm{signal},u}(k) \in \mathbb{C}^{N_t\times N_{\mathrm{UE}}}$ is the matrix which expresses the row space of $\mathbf{H}_u(k)$. By assuming each UE does eigenmode reception (i.e. $\mathbf{W}_u(k) = \mathbf{U}_u^{\mathrm{H}}(k)$), $\hat{\mathbf{D}}(k)$ in SC can be rewritten as

$$\hat{\mathbf{D}}(k) = \sqrt{\frac{2E_s}{T_s}}\mathbf{U}^{\mathrm{H}}(k)\mathbf{H}(k)\mathbf{F}(k)\mathbf{D}(k) + \mathbf{U}^{\mathrm{H}}(k)\mathbf{Z}(k), \tag{20}$$

where $\mathbf{U}(k)=\mathrm{diag}[\mathbf{U}_1(k)\cdots \mathbf{U}_U(k)]$, $\mathbf{H}(k) = [\mathbf{H}_1^{\mathrm{T}}(k)\cdots\mathbf{H}_U^{\mathrm{T}}(k)]^{\mathrm{T}}$, and $\mathbf{Z}(k) = [\mathbf{Z}_1^{\mathrm{T}}(k)\cdots\mathbf{Z}_U^{\mathrm{T}}(k)]^{\mathrm{T}}$. In OFDM, $\mathbf{D}(k)$ and $\hat{\mathbf{D}}(k)$ in (20) are replaced with $\mathbf{d}(k)$ and $\hat{\mathbf{d}}(k)$, respectively. By substituting (20) into (13), as [9], the optimal Tx filter matrix is derived as

$$\begin{aligned}\mathbf{F}(k) = &\left\{\left(\mathbf{U}^{\mathrm{H}}(k)\mathbf{H}(k)\right)^{\mathrm{H}}\mathbf{U}^{\mathrm{H}}(k)\mathbf{H}(k) + \gamma^{-1}UN_{\mathrm{UE}}\mathbf{I}_{N_t}\right\}^{-1} \\ &\times\left(\mathbf{U}^{\mathrm{H}}(k)\mathbf{H}(k)\right)^{\mathrm{H}}\mathbf{P}_{\mathrm{MMSE-SVD}}^{1/2}(k),\end{aligned} \tag{21}$$

where $\mathbf{P}_{\mathrm{MMSE\text{-}SVD}}(k)=\mathrm{diag}[\mathbf{P}_{\mathrm{MMSE\text{-}SVD},1}(k) \cdots \mathbf{P}_{\mathrm{MMSE\text{-}SVD},U}(k)] \in \mathbb{R}^{UN_{\mathrm{UE}}\times UN_{\mathrm{UE}}}$ is the PA matrix and the n_r-th diagonal component $P_{u,n_r}(k)$ of $\mathbf{P}_{\mathrm{MMSE\text{-}SVD},u}(k)$ is given by (17) by replacing $\dot{\Lambda}_{u,n_r}(k)$ with $\Lambda_{u,n_r}(k)$. As BD-SVD, PA is done based on WF theory both across eigenmodes and subcarriers to maximize the throughput in OFDM. The optimal Rx filter matrix is given by (16) as BD-SVD.

IV. NUMERICAL RESULTS

In the numerical evaluation, U=2 UEs having N_{UE}=2 antennas are located randomly in the macro-cell and the normalized Tx E_s/N_0, γ=10(dB). N_{total}=N_t=7 distributed antennas are used for transmission at BBU. The size N_c=128 of DFT/IDFT. The channel is assumed to have the path loss exponent α=3.5, shadowing loss standard deviation σ_S=7 (dB), and an L=16-path uniform power delay profile. K=10(dB) in Nakagami-Rice environment. Uncorrelated fading among paths/antennas/UEs is assumed. Ideal channel estimation is assumed both at BBU and UEs.

Fig. 3 shows the cumulative distribution function (CDF) of sum throughput using the proposed joint Tx/Rx filtering (BD-SVD and MMSE-SVD) with OFDM. For comparison, the performance of conventional MMSE precoding is also shown in Fig. 3. It is seen from Fig. 3 that both BD-SVD and MMSE-SVD can achieve higher sum throughput than MMSE precoding. This is because BD-SVD and MMSE-SVD can suppress IAI significantly by using eigenmode transmission and BD-SVD removes IUI. Note that BD-SVD provides slightly higher sum throughput than MMSE-SVD since BD-SVD can remove IAI and IUI completely while MMSE-based Tx/Rx filtering cannot.

Fig. 4 shows the CDF of sum throughput using the proposed joint Tx/Rx filtering with SC. It is seen from Fig. 4 that BD-SVD and MMSE-SVD can achieve higher sum throughput than MMSE precoding, but on the condition that CDF is less than 10%, the sum throughput of BD-SVD is worse than conventional MMSE precoding. This is because BD-SVD has severer frequency selectivity of equivalent channel than both MMSE-SVD and conventional MMSE precoding and therefore, the residual ISI limits the sum throughput performance of BD-SVD with SC.

V. CONCLUSION

In this paper, we proposed two joint Tx/Rx filtering schemes (BD-SVD and MMSE-SVD) for SC and OFDM-MU-MIMO downlinks in distributed antenna-based small-cell networks. Numerical results showed that BD-SVD and MMSE-SVD achieve a higher sum throughput than the conventional MMSE precoding with SC and OFDM transmissions.

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REFERENCES

[1] F. Adachi, K. Takeda, T. Yamamoto, R. Matsukawa, and S. Kumagai, "Recent advances in single-carrier distributed antenna network," Wirel. Commun. Mob. Comput., vol. 11, no. 12, pp. 1551-1563, Dec. 2011.

[2] W. Choi and J. G. Andrews, "Downlink performance and capacity of distributed antenna systems in a multicell environment," IEEE Trans. Wirel. Commun., vol. 6, no. 1, pp. 69-73, Apr. 2007.

[3] D. Gesbert, M. Kountouris, R. Heath, C. Chae, and T. Sälzer, "Shifting the MIMO paradigm," IEEE Signal Process. Mag., vol. 24, no. 5, pp. 36-46, Oct. 2007.

[4] R. Heath, S. Peters, Y. Wang, and J. Zhang, "A current perspective on distributed antenna systems for the downlink of cellular systems," IEEE Commun. Mag., vol. 51, no. 4, pp. 161-167, Apr. 2013.

[5] C. Peel, B. Hochwald, and A. Swindlehurst, "A vector-perturbation technique for near-capacity multiantenna multiuser communication—part I: channel inversion and regularization," IEEE Trans. Commun., vol. 53, no. 1, pp. 195-202, Jan. 2005.

[6] S. Kumagai, S. Yoshioka, and F. Adachi, "Joint Tx/Rx signal processing for uplink distributed antenna network using single-carrier MU-MIMO," in Proc. of 10th International Conference on Information, Communications and Signal Processing (ICICS 2015), Singapore, Dec. 2015.

[7] Q. Spencer, A. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser MIMO channels," IEEE Trans. Signal Processing, vol. 52, no. 2, pp. 461-471, Feb. 2004.

[8] S. Kumagai, T. Obara, T. Yamamoto, and F. Adachi, "Joint Tx/Rx MMSE filtering for single-carrier MIMO transmission," IEICE Trans. Commun., vol. E97-B, no. 9, pp. 1967-1976, Sept. 2014.

[9] M. Joham, W. Utschick, and J. A. Nossek "Linear transmit processing in MIMO communications systems," IEEE Trans. Signal Processing, vol. 53, no. 8, pp. 2700-2712, Aug. 2005.

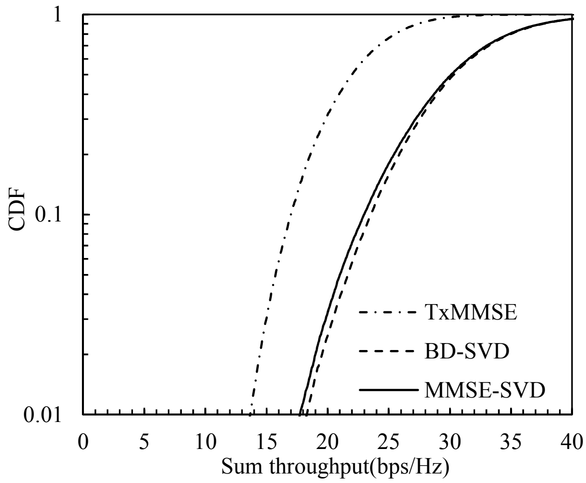

Fig. 3. CDF of sum throughput with OFDM.

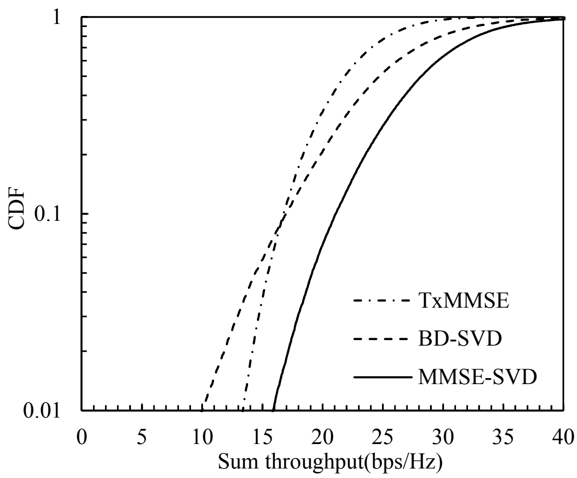

Fig. 4. CDF of sum throughput with SC.