Impact of CSI Error on OFDM-MU-MIMO Downlink of Distributed Antenna Small-cell Network

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***Abstract*—An introduction of multi-user multiple-input multiple-output (MU-MIMO) into distributed antenna small-cell network can further increase the spectrum efficiency. Recently, we proposed a joint transmit and receive minimum mean square error (MMSE) filtering (joint Tx/Rx MMSE filtering) for the orthogonal-frequency division multiplexing (OFDM)-MU-MIMO downlink. For joint Tx/Rx MMSE filtering, both sides of baseband unit (BBU) and user equipment (UE) need to share the channel state information (CSI). In this paper, we model the CSI error as a sum of estimation errors due to the Gaussian background noise and the time-varying fading. We discuss how the CSI error affects the sum capacity performance of OFDM-MU-MIMO downlink using joint Tx/Rx MMSE filtering in distributed antenna small-cell network.**

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

I. Introduction

Small-cell structured network improves both the spectrum and energy efficiencies simultaneously. One approach for constructing the small-cell structured network is to deploy a number of distributed antennas in a traditional macro-cell area. Distributed antennas are connected to a baseband unit (BBU) which is equivalent to the macro-cell base station [1, 2]. The distributed antenna small-cell network can be a good candidate for the fifth generation (5G) mobile networks. Further improvement of the spectrum efficiency is possible by introducing the multi-user multiple-input multiple-output (MU-MIMO) transmission. Recently, an introduction of MU-MIMO into downlink transmission has been under extensive study [3, 4].

Minimum mean square error (MMSE) precoding [5] for MU-MIMO provides a good throughput performance with low complexity. However, the sum capacity achievable with MU-MIMO degrades due to the presence of residual inter-antenna interference (IAI) and the inter-user interference (IUI). Recently, we proposed a joint transmit and receive (Tx/Rx) MMSE filtering called MMSE-SVD [6] and compared with BD-SVD [7] for MU-MIMO downlink in distributed antenna small-cell network. Joint Tx/Rx MMSE filtering applies the singular value decomposition (SVD) to transform the MIMO channel between BBU and each UE into eigenmodes, to each of which the water filling (WF) based transmit power allocation (PA) is applied. BD-SVD firstly applies the block diagonalization (BD) to remove the IUI at BBU and then, transform the equivalent channel after BD into eigenmodes by SVD to remove IAI. On the other hand, MMSE-SVD directly transforms the channel into eigenmodes without BD. IUI and IAI are jointly suppressed by a MMSE precoding at BBU assuming that each UE applies the unitary matrix comprising of the left singular vectors of MIMO channel for the reception (i.e., eigenmode reception). As a consequence, joint Tx/Rx MMSE filtering achieves higher sum capacity than the use of MMSE precoding only (hereafter, called the conventional MMSE precoding [5]). For joint Tx/Rx MMSE filtering, the channel state information (CSI) needs to be shared by both sides of BBU and UEs. In our previous study of joint Tx/Rx MMSE filtering [6], the ideal CSI estimation was assumed. However, in a practical situation, the estimation error exists due to the Gaussian background noise. Furthermore, in the case of time division duplex (TDD) system, the time lag exists between the uplink reception and the downlink transmission. The estimated CSI is old for downlink Tx filter composition due to the time-varying fading. Therefore, it is necessary to investigate the impact of the CSI error on the sum capacity achievable with joint Tx/Rx MMSE filtering.

In this paper, we consider MMSE-SVD [6] and BD-SVD [7] for OFDM-MU-MIMO downlink. We investigate the CSI error on the sum capacity achievable with BD-SVD and MMSE-SVD. We model the CSI error as a sum of estimation errors due to the Gaussian noise and the time-varying fading channel. Numerical results show that BD-SVD and MMSE-SVD achieve higher sum capacity than the conventional MMSE precoding [5] even in the presence of the CSI error.

The remainder of this paper is organized as follows. Sect. II introduces the signal representations for our previously proposed MMSE-SVD and BD-SVD for OFDM-MU-MIMO downlink of distributed antenna small-cell network. Sect. III presents the cell model, the channel model, and the CSI error model, and shows the numerical results, and Sect. IV 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.

II. Signal Transmission for OFDM-MU-MIMO Downlink

The signal representations for our previously proposed MMSE-SVD [6] and BD-SVD [7] for OFDM-MU-MIMO downlink transmission are introduced. Below, perfect knowledge of CSI is assumed at both BBU and UE. The impact of imperfect CSI on the downlink sum capacity is discussed in Sect. III.

A. Signal Representations

Fig. 1 shows the Tx/Rx structure of OFDM-MU-MIMO downlink assumed in this paper. BBU transmits U UEs' signals simultaneously using N_t distributed antennas. Each UE is equipped with N_{UE} antennas.

At BBU, the information bit sequence to be transmitted to each UE is serial-to-parallel (S/P) converted to N_{UE} parallel bit sequences, each of which is transformed into a sequence of N_c-symbol blocks after data-modulation. A totality of U UEs' N_{UE} symbol blocks is represented by $\mathbf{d}(k)=[\mathbf{d}_0(k)\cdots\mathbf{d}_u(k)\cdots\mathbf{d}_{U-1}(k)]\in\mathbb{C}^{U\cdot N_{UE}\times 1}$, where $\mathbf{d}_u(k)\in\mathbb{C}^{N_{UE}\times 1}$. The transmit signals after Tx filtering to be transmitted from N_t distributed antennas can be expressed as

$$\mathbf{S}(k)=[S_0(k)\cdots S_{n_t}(k)\cdots S_{N_t-1}(k)]^{\mathrm{T}}=\sqrt{\frac{2E_s}{T_s}}\mathbf{F}(k)\mathbf{d}(k)\,,\quad (1)$$

where $\mathbf{F}(k)=[\mathbf{F}_0(k)\cdots\mathbf{F}_u(k)\cdots\mathbf{F}_{U-1}(k)]\in\mathbb{C}^{N_t\times U\cdot N_{UE}}$ is the Tx filter matrix. $E_s=P_t\cdot T_s$ is the transmit symbol energy with P_t being the total transmit power and T_s being the symbol duration. N_c-point inverse discrete Fourier transform (IDFT) is applied to transform the n_tth symbol block $\{S_{n_t}(k);\ k=0\sim N_c-1\}$ to the time-domain OFDM signal block for $n_t=0\sim N_t-1$. Finally, N_t cyclic prefix (CP) inserted OFDM signal blocks are transmitted from N_t distributed antennas.

The CP-inserted signals transmitted from N_t distributed antennas are received by N_{UE} antennas of UE. After removing CP, the received signal on each antenna is transformed by N_c-point DFT into the frequency-domain received signal block. A totality of N_{UE} frequency-domain received signal blocks can be expressed as

$$\mathbf{R}_u(k)=\mathbf{H}_u(k)\mathbf{S}(k)+\mathbf{Z}_u(k)\,,\quad (2)$$

where $\mathbf{H}_u(k)\in\mathbb{C}^{N_{UE}\times N_t}$ is the channel matrix between the uth UE and BBU, whose (n_r,n_t)th element is given by $H_{u,n_r,n_t}(k)$. $\mathbf{Z}_u(k)\in\mathbb{C}^{N_{UE}\times 1}$ is the noise vector whose elements are iid zero-mean complex-valued random variables having variance $2N_0/T_s$ with N_0 being the one-sided power spectrum density of additive white Gaussian noise (AWGN). A totality of the uth UE's received symbol blocks obtained by applying the Rx filtering on $\mathbf{R}_u(k)$ can be expressed as

$$\hat{\mathbf{d}}_u(k)=[\hat{d}_{u,0}(k)\cdots\hat{d}_{u,N_{UE}-1}(k)]^{\mathrm{T}}=\mathbf{W}_u(k)\mathbf{R}_u(k)\,,\quad (3)$$

where $\mathbf{W}_u(k)\in\mathbb{C}^{N_{UE}\times N_{UE}}$ is the Rx filter matrix.

The channel capacity C_u (bps/Hz) of the uth UE when using the above joint Tx/Rx filtering can be computed from

$$C_u=\frac{1}{N_c}\sum_{n_r=0}^{N_{UE}-1}\sum_{k=0}^{N_c-1}\log_2\left(1+\Gamma_{u,n_r}(k)\right),\quad (4)$$

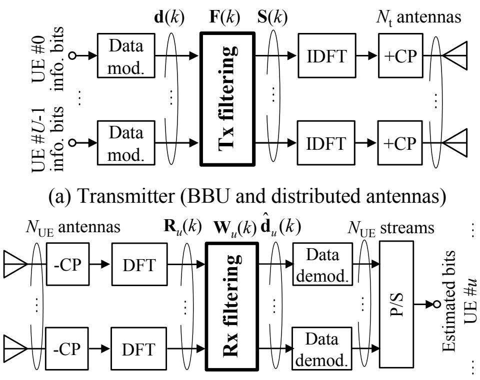
where $\Gamma_{u,n_r}(k)$ is the received signal-to-interference plus noise power ratio (SINR) of the n_rth eigenmode of the uth UE given by

$$\Gamma_{u,n_r}(k)=\frac{\left|\hat{H}_{u,n_r,u,n_r}(k)\right|^2}{M_{\mathrm{IAI},u,n_r}(k)+M_{\mathrm{IUI},u,n_r}(k)+M_{\mathrm{noise},u,n_r}(k)}\quad (5)$$

with

$$\begin{cases}\hat{H}_{u,n_r,u',n'}(k)=\sum_{m=0}^{N_{UE}-1}W_{u,n_r,m}(k)\sum_{n_t=0}^{N_t-1}H_{u,m,n_t}(k)F_{u',n_t,n_r'}(k)\\ M_{\mathrm{IAI},u,n_r}(k)=\sum_{\substack{n_r'=0\\ n_r'\neq n_r}}^{N_{UE}-1}\left|\hat{H}_{u,n_r,u,n_r'}(k)\right|^2\\ M_{\mathrm{IUI},u,n_r}(k)=\sum_{\substack{u'=0\\ u'\neq u}}^{U-1}\sum_{n_r'=0}^{N_{UE}-1}\left|\hat{H}_{u,n_r,u',n'}(k)\right|^2\\ M_{\mathrm{noise},u,n_r}(k)=\left(\frac{E_s}{N_0}\right)^{-1}\sum_{m=0}^{N_{UE}-1}\left|W_{u,n_r,m}(k)\right|^2\end{cases}.\quad (6)$$

In Eq. (6), E_s/N_0 denotes the transmit symbol energy-to-AWGN power spectrum density ratio, $W_{u,n_r,m}(k)$ represents the (n_r,m)th element of $\mathbf{W}_u(k)$ and $F_{u,n_t,n_r}(k)$ represents the (n_t,n_r)th element of $\mathbf{F}_u(k)$. M_{IAI,u,n_r}, M_{IUI,u,n_r}, and M_{noise,u,n_r} are the variances of normalized residual IAI, IUI, and noise, respectively.



(a) Transmitter (BBU and distributed antennas)

(b) Receiver (UE)

Fig. 1. Tx/Rx structure of OFDM-MU-MIMO downlink.

B. Derivation Of Optimal Tx/Rx Filter Matrices

The optimal Tx and Rx filter matrices are given based on the MSE minimization between the transmit symbol vector $\mathbf{d}(k)$ and the received symbol vector $\hat{\mathbf{d}}(k)=[\hat{\mathbf{d}}_0^{\mathrm{T}}(k)\cdots\hat{\mathbf{d}}_{U-1}^{\mathrm{T}}(k)]^{\mathrm{T}}$ for BD-SVD[6] and MMSE-SVD[7]. The MSE minimization under the total Tx power constraint is formulated as

$$\min_{\{\mathbf{F}(k),\mathbf{W}_u(k)\}} MSE\quad (7a)$$

$$\text{s.t.}\ \sum_{k=0}^{N_c-1}\mathrm{tr}\left(\mathbf{F}(k)\mathbf{F}^{\mathrm{H}}(k)\right)=N_c\,,\quad (7b)$$

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

$$MSE\equiv\mathrm{E}\left[\sum_{k=0}^{N_c-1}\mathrm{tr}\left\{\left(\mathbf{d}(k)-\frac{\hat{\mathbf{d}}(k)}{\sqrt{2E_s/T_s}}\right)\left(\mathbf{d}(k)-\frac{\hat{\mathbf{d}}(k)}{\sqrt{2E_s/T_s}}\right)^{\mathrm{H}}\right\}\right].\quad (8)$$

(a) BD-SVD [7]

At first, IUI is removed by BD. The BD precoding matrix for the uth UE is given as $\overline{\mathbf{V}}_{\mathrm{noise},u}(k) \in \mathbb{C}^{N_\mathrm{t}\times\{N_\mathrm{t}-(U-1)N_\mathrm{UE}\}}$ which is the right null-space of $[\mathbf{H}_0^\mathrm{T}(k)\cdots\mathbf{H}_{u-1}^\mathrm{T}(k),\mathbf{H}_{u+1}^\mathrm{T}(k)\cdots\mathbf{H}_{U-1}^\mathrm{T}(k)]^\mathrm{T}$ [7]. The equivalent channel matrix $\dot{\mathbf{H}}_u(k)=\mathbf{H}_u(k)\overline{\mathbf{V}}_{\mathrm{noise},u}(k)$ after BD can be regarded as a single-user MIMO channel matrix since IUI is removed. Therefore, the optimal Tx and Rx filter matrices are given as [8],

$$\mathbf{F}_u(k)=\overline{\mathbf{V}}_{\mathrm{noise},u}(k)\dot{\mathbf{V}}_u(k)\mathbf{P}_{\mathrm{BD-SVD},u}^{1/2}(k)\,, \tag{9}$$

and

$$\mathbf{W}_u(k)=\left\{\left(\mathbf{H}_u(k)\mathbf{F}_u(k)\right)^\mathrm{H}\mathbf{H}_u(k)\mathbf{F}_u(k)+\left(\frac{E_\mathrm{s}}{N_0}\right)^{-1}\mathbf{I}_{N_\mathrm{UE}}\right\}^{-1}\times\left(\mathbf{H}_u(k)\mathbf{F}_u(k)\right)^\mathrm{H} \tag{10}$$

In Eq. (9), $\dot{\mathbf{V}}_u(k)\in\mathbb{C}^{\{N_\mathrm{t}-(U-1)N_\mathrm{UE}\}\times\{N_\mathrm{t}-(U-1)N_\mathrm{UE}\}}$ is the unitary matrix having the right singular vectors of $\dot{\mathbf{H}}_u(k)$ as its column vectors. $\mathbf{P}_{\mathrm{BD\text{-}SVD},u}(k)\in\mathbb{R}^{\{N_\mathrm{t}-(U-1)N_\mathrm{UE}\}\times N_\mathrm{UE}}$ is the PA matrix whose n_rth diagonal element $P_{u,n_\mathrm{r}}(k)$ represents the transmit power allocated to the n_rth eigenmode. PA is done based on WF theory both across eigenmodes and subcarriers to maximize the throughput. $P_{u,n_\mathrm{r}}(k)$ is given as

$$P_{u,n_\mathrm{r}}(k)=\left(\frac{1}{\sqrt{\nu_{u,n_\mathrm{r}}}}-\frac{1}{\dfrac{E_\mathrm{s}}{N_0}\dot{\Lambda}_{u,n_\mathrm{r}}(k)}\right)^+\,, \tag{11}$$

where $\dot{\Lambda}_{u,n_\mathrm{r}}(k)$ is the eigenvalue of the n_rth eigenmode and ν_{u,n_r} is determined to keep the UE transmit power constant (i.e. $\sum_{k=0}^{N_\mathrm{c}-1}\sum_{n_\mathrm{r}=0}^{N_\mathrm{UE}-1}P_{u,n_\mathrm{r}}(k)\sum_{n_\mathrm{t}=0}^{N_\mathrm{t}-1}\left|A_{u,n_\mathrm{t},n_\mathrm{r}}(k)\right|^2=N_\mathrm{c}/U$).

(b)MMSE-SVD [6]

Unlike BD-SVD, SVD is applied directly to the channel matrix $\mathbf{H}_u(k)$ between BBU and the uth UE. $\mathbf{H}_u(k)$ is rewritten by SVD as

$$\mathbf{H}_u(k)=\mathbf{U}_u(k)\mathbf{\Lambda}_u^{1/2}(k)\mathbf{V}_{\mathrm{signal},u}^H(k)\,, \tag{12}$$

where $\mathbf{U}_u(k)\in\mathbb{C}^{N_\mathrm{UE}\times N_\mathrm{UE}}$ is the unitary matrix composing of left singular vectors of $\mathbf{H}_u(k)$ as its columns, $\mathbf{\Lambda}_u(k)\in\mathbb{R}^{N_\mathrm{UE}\times N_\mathrm{UE}}$ is the diagonal matrix whose n_r-th diagonal element $\Lambda_{u,n_\mathrm{r}}(k)$ has the eigenvalue of the n_r-th eigenmode, and $\mathbf{V}_{\mathrm{signal},u}(k)\in\mathbb{C}^{N_\mathrm{t}\times N_\mathrm{UE}}$ is the unitary matrix composing of right singular vectors of $\mathbf{H}_u(k)$ as its columns. Assuming that each UE does eigenmode reception (i.e., $\mathbf{W}_u(k)=\mathbf{U}_u^\mathrm{H}(k)$), $\hat{\mathbf{d}}(k)$ can be given as

$$\hat{\mathbf{d}}(k)=\sqrt{\frac{2E_\mathrm{s}}{T_\mathrm{s}}}\mathbf{U}^\mathrm{H}(k)\mathbf{H}(k)\mathbf{F}(k)\mathbf{d}(k)+\mathbf{U}^\mathrm{H}(k)\mathbf{Z}(k)\,, \tag{13}$$

where $\mathbf{U}(k)=\mathrm{diag}[\mathbf{U}_0(k)\cdots\mathbf{U}_u(k)\cdots\mathbf{U}_{U-1}(k)]\in\mathbb{C}^{U\cdot N_\mathrm{UE}\times U\cdot N_\mathrm{UE}}$, $\mathbf{H}(k)=[\mathbf{H}_0^\mathrm{T}(k)\cdots\mathbf{H}_u^\mathrm{T}(k)\cdots\mathbf{H}_{U-1}^\mathrm{T}(k)]^\mathrm{T}\in\mathbb{C}^{U\cdot N_\mathrm{UE}\times N_\mathrm{t}}$, and $\mathbf{Z}(k)=[\mathbf{Z}_0^\mathrm{T}(k)\cdots\mathbf{Z}_u^\mathrm{T}(k)\cdots\mathbf{Z}_{U-1}^\mathrm{T}(k)]^\mathrm{T}\in\mathbb{C}^{U\cdot N_\mathrm{UE}\times 1}$. Therefore, $\mathbf{U}^\mathrm{H}(k)\mathbf{H}(k)$ in Eq.(13) can be viewed as the equivalent channel. Similar approach in [9], by substituting (13) into (8), the optimal Tx filter matrix is given as

$$\mathbf{F}(k)=\left\{\left(\mathbf{U}^\mathrm{H}(k)\mathbf{H}(k)\right)^\mathrm{H}\mathbf{U}^\mathrm{H}(k)\mathbf{H}(k)+\left(\frac{E_\mathrm{s}}{N_0}\right)^{-1}UN_\mathrm{UE}\mathbf{I}_{N_\mathrm{t}}\right\}^{-1}\times\left(\mathbf{U}^\mathrm{H}(k)\mathbf{H}(k)\right)^\mathrm{H}\mathbf{P}_{\mathrm{MMSE-SVD}}^{1/2}(k), \tag{14}$$

where $\mathbf{P}_{\mathrm{MMSE\text{-}SVD}}(k)=\mathrm{diag}[\mathbf{P}_{\mathrm{MMSE\text{-}SVD},0}(k)\cdots\mathbf{P}_{\mathrm{MMSE\text{-}SVD},U\text{-}1}(k)]\in\mathbb{R}^{U\cdot N_\mathrm{UE}\times U\cdot N_\mathrm{UE}}$ is the PA matrix. The n_rth diagonal element $P_{u,n_\mathrm{r}}(k)$ of $\mathbf{P}_{\mathrm{MMSE\text{-}SVD},u}(k)$ is given by (11) by replacing $\dot{\Lambda}_{u,n_\mathrm{r}}(k)$ with $\Lambda_{u,n_\mathrm{r}}(k)$. As in BD-SVD, PA is done, based on WF theory, across both eigenmodes and subcarriers.

III. Impact of Imperfect CSI

The CSI error model is given after introducing the cell and propagation channel models. Then, using theory described in Sect.II for MMSE-SVD we proposed in [6] and BD-SVD [7], the impact of imperfect CSI is evaluated by Monte Carlo numerical simulation method.

A. Single-cell Model

In the distributed antenna small-cell network, N_total antennas are uniformly distributed in each macro-cell area of radius R and each antenna covers the small area (equivalent to the small-cell) of radius R'. Fig. 2 shows the cell model [6] with N_total=7 and $R'=R/\sqrt{7}$ assumed in this paper. In this paper, the single macro-cell is considered (i.e., no co-channel interference from adjacent macro-cells is considered) and U UEs equipped with N_UE antennas are randomly located within the macro-cell.

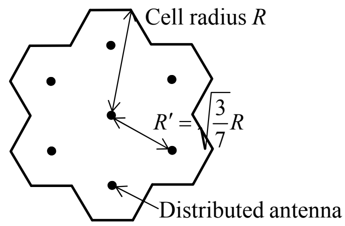


Fig. 2. Cell model.

B. Propagation 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 $h_{u,n_\mathrm{r},n_\mathrm{t}}(\tau)$ and the transfer function $H_{u,n_\mathrm{r},n_\mathrm{t}}(k)$ between the n_rth antenna of the uth UE and the #n_tth distributed antenna can be represented as

$$h_{u,n_\mathrm{r},n_\mathrm{t}}(\tau)=\sqrt{\left(d_{u,n_\mathrm{t}}\right)^{-\alpha}10^{-\frac{\eta_{u,n_\mathrm{t}}}{10}}}\times\left\{\begin{array}{l}\sqrt{\dfrac{K}{K+1}}\exp\left(j\theta_{u,n_\mathrm{r},n_\mathrm{t}}\right)\delta\left(\tau-\tau_{u,n_\mathrm{r},n_\mathrm{t},l=0}\right)\\+\sqrt{\dfrac{1}{K+1}}\sum_{l=0}^{L-1}\xi_{u,n_\mathrm{r},n_\mathrm{t},l}\delta\left(\tau-\tau_{u,n_\mathrm{r},n_\mathrm{t},l}\right)\end{array}\right\}, \tag{15}$$

and

$$H_{u,n_r,n_t}(k)=\sqrt{\left(d_{u,n_t}\right)^{-\alpha}10^{-\frac{\eta_{u,n_t}}{10}}}\times\left\{\begin{array}{l}\sqrt{\frac{K}{K+1}}\exp\left(j\theta_{u,n_r,n_t}\right)\exp\left(-j\frac{2\pi k\tau_{u,n_r,n_t,l=0}}{N_c}\right)\\+\sqrt{\frac{1}{K+1}}\sum_{l=0}^{L-1}\xi_{u,n_r,n_t,l}\exp\left(-j\frac{2\pi k\tau_{u,n_r,n_t,l}}{N_c}\right)\end{array}\right\},\quad(16)$$

respectively. In this paper, the channel is assumed to be a Nakagami-Rice fading channel (i.e., the direct-to-delay path power ratio K>0) when the distance d_{u,n_t} between the uth UE and the n_tth distributed antenna is equal to or smaller than R' and a Rayleigh fading channel (i.e., K=0) when d_{u,n_t} is larger than R'. α and η_{u,n_t} denote the path loss exponent and the shadowing loss in dB having zero-mean and standard deviation σ_S, respectively. θ_{u,n_r,n_t} is the phase of direct path and is assumed to be distributed uniformly. $\xi_{u,n_r,n_t,l}$ and $\tau_{u,n_r,n_t,l}$ are respectively the complex-valued path gain and the time delay of the lth path with $\mathrm{E}[\sum_{l=0}^{L-1}\xi_{u,n_r,n_t,l}]=1$ for all u, n_r, and n_t. In this paper, we assume a sample-spaced time delay (i.e., $\tau_{u,n_r,n_t,l}$ $=l-1$ for all u, n_r, and n_t). N_c is the block size. $H_{u,n_r,n_t}(k)$ is the $((u-1)N_r+n_r,\ n_t)$-th element of channel matrix $\mathbf{H}(k)$.

The average signal power P_{r,u,n_t} received at the uth UE for the signal transmitted from the n_tth distributed antenna can be modeled as

$$P_{r,u,n_t}(\tau)=\hat{P}_t\left(\hat{d}_{u,n_t}\right)^{-\alpha}10^{-\frac{\eta_{u,n_t}}{10}},\quad(17)$$

where $\hat{P}_t=P_tR^{-\alpha}$ is defined as the normalized Tx power with P_t being the actual Tx power. By introducing the normalized distance $\hat{d}_{u,n_t}=d_{u,n_t}/R$, the normalized transmit symbol energy $E_s=\hat{P}_t\cdot T_s$, and the noise variance $2\sigma^2=2N_0/T_s$, the average received signal-to-noise power ratio (SNR) γ_{u,n_t} at the distance d_{u,n_t} is given as

$$\gamma_{u,n_t}=\frac{P_{r,u,n_t}}{\sigma^2}=\gamma\hat{d}_{u,n_t}^{-\alpha}10^{-\frac{\eta_{u,n_t}}{10}},\quad(18)$$

where γ is the normalized SNR (equivalent to the cell-edge received SNR) defined as $(E_s/N_0)\cdot R^{-\alpha}$. In this paper, N_t transmit antennas are selected from N_{total} distributed antennas in descending order of γ_{u,n_t}.

C. CSI Error Model

Below, $\mathbf{H}(k)$, θ_{u,n_r,n_t} and $\xi_{u,n_r,n_t,l}$ are rewritten by $\mathbf{H}(k,t)$, $\theta_{u,n_r,n_t}(t)$, and $\xi_{u,n_r,n_t,l}(t)$, respectively to represent time variations of the channel. Assuming TDD frame length of T, the time lag T exists between uplink reception (channel estimation is done for downlink Tx filter computation) at time t-T and downlink transmission at time t. The channel estimation is done using uplink received signal. The estimated channel matrix is denoted by $\hat{\mathbf{H}}_{BBU}(k,t)=[\hat{\mathbf{H}}_{BBU,0}(k,t)\cdots\hat{\mathbf{H}}_{BBU,u}(k,t)\cdots\hat{\mathbf{H}}_{BBU,U-1}(k,t)]$ which is used for computing the Tx filter matrix at BBU for the downlink transmission at time t. However, this CSI is old. The actual propagation channel at time t is denoted by $\mathbf{H}(k,t)$. $\hat{\mathbf{H}}_{BBU}(k,t)$ can be modeled as

$$\hat{\mathbf{H}}_{BBU}(k,t)=\mathbf{H}(k,t-T)+\boldsymbol{\varepsilon}(k).\quad(19)$$

where the first term is the CSI error due to the time-varying channel and the second term due to the background noise. Each element of $\boldsymbol{\varepsilon}(k)\in\mathbb{C}^{U\cdot N_{UE}\times N_t}$ is assumed to be iid zero-mean complex-valued Gaussian random variable having variance $\varepsilon\gamma_{u,n_t}^{-1}$ with γ_{u,n_t} being the average received SNR given by Eq.(18) and ε being the noise impact factor which describes how strongly estimation error is affected by the noise.

The $((u-1)N_r+n_r,\ n_t)$-th element of $\mathbf{H}(k,t-T)$ is given as

$$\hat{H}_{u,n_r,n_t}(k,t)=\sqrt{d_{u,n_t}^{-\alpha}10^{-\frac{\eta_{u,n_t}}{10}}}\left\{\begin{array}{l}\sqrt{\frac{K}{K+1}}\exp\left(j\theta_{u,n_r,n_t}(t-T)\right)\exp\left(-j\frac{2\pi k\tau_{u,n_r,n_t,l=0}}{N_c}\right)\\+\sqrt{\frac{1}{K+1}}\sum_{l=0}^{L-1}\xi_{u,n_r,n_t,l}(t-T)\exp\left(-j\frac{2\pi k\tau_{u,n_r,n_t,l}}{N_c}\right)\end{array}\right\},\quad(20)$$

In this paper, it is assumed that UEs are moving in random directions with the same speed. Assuming the Jakes model [10], the autocorrelation at time difference T of $\xi_{u,n_r,n_t,l}(t)$ is given as

$$\rho(f_dT)=\mathrm{E}[\xi_{u,n_r,n_t,l}(t)\left(\xi_{u,n_r,n_t,l}(t-T)\right)^*]=J_0(2\pi f_dT),\quad(21)$$

where f_dT denotes the normalized maximum Doppler frequency and $J_0(x)$ is the zero-order Bessel function of the first kind.

At UE, the equivalent channel defined by $\mathbf{H}_u(k)\mathbf{F}_u(k)$ needs to be estimated from the downlink signal for computing the Rx filter. The estimated channel matrix is modeled as

$$\hat{\mathbf{H}}_{UE,u}(k,t)=\mathbf{H}_u(k,t)\mathbf{F}_u(k)+\boldsymbol{\varepsilon}_u(k),\quad(22)$$

where $\boldsymbol{\varepsilon}_u(k)\in\mathbb{C}^{N_{UE}\times N_{UE}}$ is the estimation error matrix, whose elements are assumed to be iid zero-mean complex-valued Gaussian random variables having variance $\varepsilon\gamma_{u,n_t}^{-1}$.

In the presence of CSI error, BBU must compute the Tx filter weights, $\mathbf{F}_u(k)$ given by Eq.(9) for BD-SVD and $\mathbf{F}(k)$ given by Eq.(14) for MMSE-SVD by using $\hat{\mathbf{H}}_{BBU}(k,t)$ instead of $\mathbf{H}(k)$. Similarly, UE must compute the Rx filter weight $\mathbf{W}_u(k)$ given by Eq.(10) for both BD-SVD and MMSE-SVD by using $\hat{\mathbf{H}}_{UE,u}(k,t)$ instead of $\mathbf{H}_u(k)\mathbf{F}_u(k)$.

D. Numerical Results

It is assumed that U=2 UEs having N_{UE}=2 antennas each are located randomly in the macro-cell area, N_t=4 distributed antennas are used for downlink transmission, the DFT/IDFT size is N_c=128, and the cell-edge SNR γ=10 dB. The channel consisting of the path loss, shadowing loss, and Nakagami-Rice fading, with the path loss exponent α=3.5, shadowing loss standard deviation σ_S=7 dB, and an L=16-path uniform power delay profile. The K factor of Nakagami-Rice fading is K=10 dB. Uncorrelated fading is assumed.

Fig. 3 shows how the OFDM downlink channel estimation error impacts the 50% outage sum capacity (below which the the sum capacity falls with probability of 50%) achievable with joint Tx/Rx filtering (BD-SVD and MMSE-SVD). For comparison, the 50% outage sum capacity achievable with the conventional MMSE precoding is also plotted in Fig. 3. It is worthy to note that BD-SVD and MMSE-SVD provide almost the same capacity irrespective of the presence of CSI error. Fist we discuss the case of static fading, i.e., f_dT =0 (the CSI error due to background noise exists only). In joint Tx/Rx MMSE filtering, jointly use of Rx filtering together with Tx filtering can suppress IAI and IUI more significantly than the use of Tx filtering (MMSE precoding) only. The sum capacity can be significantly improved compared to conventional MMSE precoding. The sum capacity reduces as ε gets larger, but its superiority is kept. ε=1.0 means that the CSI error due to background noise is equivalent to the noise level.

Next we discuss time-selective fading, i.e., f_dT >0 (the CSI error is caused by both time-varying fading and background noise). f_dT = 0.1 corresponds to the UE speed of approximately 10.8 km/h for TDD frame length of T=0.2msec and the carrier frequency of 5GHz. In time-selective fading environment, the impact of the CSI error due to time-varying fading becomes stronger and the sum capacity degrades significantly compared to the static fading case. However, significant improvement of BD-SVD and MMSE-SVD over the conventional MMSE precoding is kept.

We have shown that BD-SVD and MMSE-SVD provide almost same sum capacity. Below, we discuss why this happens by evaluating the residual IUI and IAI. Fig. 4 shows the complementary cumulative distribution function (CCDF) of residual IUI and IAI for BD-SVD and MMSE-SVD. In the case of no CSI error, BD-SVD removes IAI and IUI completely, while MMSE-SVD cannot (there exists the residual IAI and IUI to some extent). However, in the presence of the CSI error, even BD-SVD cannot remove IAI and IUI and produces residual IAI and IUI of almost the same level as MMSE-SVD. It is worthy note that the residual IUI is higher than the residual IAI for both BD-SVD and MMSE-SVD and is a dominant factor to determine the sum capacity. This suggests how effectively suppress the residual IUI more is important in the time-selective fading which is encountered in most of the mobile communications scenarios.

IV. Conclusion

In this paper, we modeled the CSI error as a sum of errors due to background noise and time-varying fading and evaluated its impact on the OFDM-MU-MIMO downlink of distributed antenna small-cell network. Numerical results showed that BD-SVD and MMSE-SVD achieve higher sum capacity than the conventional MMSE precoding even in the presence of CSI error. However, the capacity reduces as the fading varies faster. When using higher frequency bands, e.g., mm wave bands, the fading Doppler frequency is very high even when UE moves slowly. For both BD-SVD and MMSE-SVD, residual IUI is a dominant factor to determine the sum capacity in the presence of CSI error. Therefore, the CSI prediction is necessary to suppress the residual IUI. This is an important future study.

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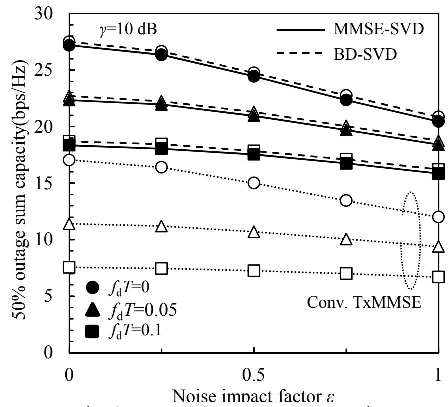

Fig. 3. 50% outage sum capacity.

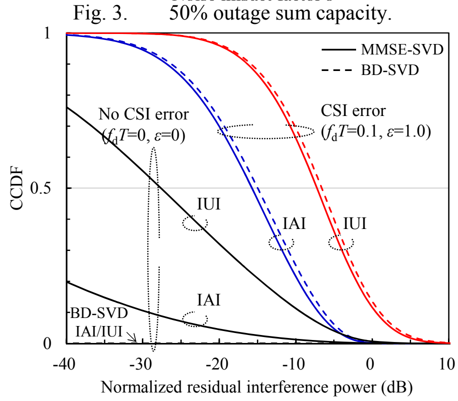

Fig. 4. CCDF of residual interference power.