

Improving link capacity by multi-user MMSE-SVD with ICI information in a distributed MIMO cellular network

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Abstract: Recently, we proposed a multi-user spatial multiplexing technique called the minimum mean square error filtering combined with singular value decomposition (MMSE-SVD) for a distributed multiple input multiple output (MIMO) network. Multi-user MMSE-SVD applies the MMSE filter at macro base station (MBS) to suppress inter-user interference (IUI) and inter-antenna interference (IAI), while the eigenmode filter constructed by SVD at user equipments (UEs) to suppress IAI. To improve the link capacity in multi-cell environment, the inter-cell interference (ICI) from adjacent macro-cells is taken into account in generating the MMSE filter. In this paper, we apply multi-user MMSE-SVD with ICI information to OFDM downlink and SC uplink to discuss the impact of number of multiplexed UEs.

Keywords: distributed antenna, MU-MIMO, MMSE-SVD, co-channel interference

Classification: Wireless Communication Technologies

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1 Introduction

In the 5th generation (5G) networks, broader data services and higher link capacity than 4G networks are required [1]. The authors have been investigating the distributed multiple input multiple output (MIMO) cooperative transmission techniques to improve the link capacity and recently proposed a multi-user spatial multiplexing technique called the minimum mean square error filtering combined with singular value decomposition (MMSE-SVD) [2]. Multi-user MMSE-SVD applies the MMSE filter at macro base station (MBS) and the eigenmode filter constructed by SVD at user equipments (UEs). The multi-user MMSE-SVD can achieve higher link capacity compared to the conventional zero-forcing (ZF) and channel inversion (CI) [3]. However, in cellular environment, the presence of inter-cell interference (ICI) from adjacent macro-cells limits the capacity improvement as well as inter-user interference (IUI) and inter-antenna interference (IAI) (note that in the SC transmission, suppression of inter-symbol interference (ISI) is also necessary). Therefore, the ICI information needs to be incorporated in constructing the MMSE filter. However, how much the link capacity in a multi-cell environment can be improved by taking into account the ICI has not been fully investigated.

In this paper, we consider a distributed MIMO cellular network with orthogonal frequency division multiplex (OFDM) downlink and single-carrier (SC) uplink. We evaluate the sum capacity achievable with MMSE-SVD with ICI information by computer simulation to discuss the impact of number of multiplexed UEs and compare with conventional CI and ZF. It is shown that MMSE-SVD with ICI information can achieve higher sum capacity as the number of multiplexed UEs increases, the sum capacity achievable by conventional CI and ZF reduces due to increased ICI from adjacent macro-cells.

2 Over view of multi-user MMSE-SVD

Multi-user spatial multiplexing of U UEs, each is equipped N_{ue} antennas, is considered. N_{mbs} distributed antennas are selected from N_{macro} distributed antennas to simultaneously transmit the N_{strm} data streams per UE using N_c subcarriers.

2.1 Signal representation for OFDM downlink

The u th UE's $N_{strm} \times 1$ downlink frequency-domain transmit symbol vector is represented by $\mathbf{D}_{\downarrow u}(k) = [d_{\downarrow u,0}(k), \dots, d_{\downarrow u,n_{strm}}(k), \dots, d_{\downarrow u,N_{strm}-1}(k)]^T$, where $\{d_{\downarrow u,n_{strm}}(k); k = 0 \sim N_c - 1\}$ is an N_c -length data symbol block. An $N_{mbs} \times 1$ transmit signal vector after transmit filtering can be expressed as

$$\mathbf{S}_{\downarrow}(k) = \sqrt{2E_s/T_s} \mathbf{W}_{\downarrow mmse}(k) [\mathbf{D}_{\downarrow 0}^T(k), \dots, \mathbf{D}_{\downarrow u}^T(k), \dots, \mathbf{D}_{\downarrow U-1}^T(k)]^T, \quad (1)$$

where E_s is the transmit symbol energy and T_s is the symbol duration. $\mathbf{W}_{\downarrow mmse}(k) = [\mathbf{W}_{\downarrow mmse,0}(k), \dots, \mathbf{W}_{\downarrow mmse,u}(k), \dots, \mathbf{W}_{\downarrow mmse,U-1}(k)]$ is the $N_{mbs} \times U \cdot N_{strm}$ MMSE transmit filter matrix. Then, N_c -point inverse discrete Fourier transform (IDFT) is applied to transform the frequency domain signal $\{\mathbf{S}_{\downarrow}(k); k = 0 \sim N_c - 1\}$ into time-domain signal block. Finally, the last N_g samples of time-domain signal block are copied as a cyclic prefix (CP) and inserted into the guard interval. At u th UE, CP removal is employed and then, each time-domain received signal block is

transformed into the frequency-domain receive signal block by N_c -point DFT. The $N_{ue} \times 1$ frequency-domain received signal vector $\mathbf{R}_{\downarrow u}(k)$ at k th subcarrier is expressed as

$$\mathbf{R}_{\downarrow u}(k) = \mathbf{H}_{\downarrow u}(k)\mathbf{S}_{\downarrow}(k) + \mathbf{N}_{\downarrow u}(k), \quad (2)$$

where $\mathbf{H}_{\downarrow u}(k)$ is the $N_{ue} \times N_{mbs}$ downlink MU-MIMO channel matrix of u th UE, $\mathbf{N}_{\downarrow u}(k)$ is the $N_{ue} \times 1$ noise plus ICI vector. The $N_{strm} \times 1$ frequency-domain soft-output symbol vector is obtained by applying the eigenmode receive filtering on $\mathbf{R}_{\downarrow u}(k)$ as

$$\hat{\mathbf{D}}_{\downarrow u}(k) = \mathbf{W}_{\downarrow svd,u}(k)\mathbf{R}_{\downarrow u}(k), \quad (3)$$

where $\mathbf{W}_{\downarrow ue,u}(k)$ is the $N_{strm} \times N_{ue}$ eigenmode receive filter matrix.

2.2 Signal representation for SC uplink

The u th UE's frequency-domain uplink transmit symbol vector is represented by $\mathbf{D}_{\uparrow u}(k) = [D_{\uparrow u,0}(k), \dots, D_{\uparrow u,n_{strm}}(k), \dots, D_{\uparrow u,N_{strm}-1}(k)]^T$, where $\{D_{\uparrow u,n_{strm}}(k); k = 0 \sim N_c - 1\}$ is obtained by applying N_c -point DFT to the data symbol block $\{d_{\uparrow u,n_{strm}}(n); n = 0 \sim N_c - 1\}$. An $N_{ue} \times 1$ transmit signal vector after transmit filtering can be expressed as

$$\mathbf{S}_{\uparrow u}(k) = \sqrt{2E_s/T_s}\mathbf{W}_{\uparrow svd,u}(k)\mathbf{D}_{\uparrow u}(k), \quad (4)$$

where $\mathbf{W}_{\uparrow svd,u}(k)$ is the $N_{ue} \times N_{strm}$ eigenmode transmit filter matrix. N_c -point IDFT is applied to each frequency-domain transmit symbol block, and then is transmitted after CP insertion. Received signal at the MBS after CP removal is transformed into the frequency-domain receive signal block by N_c -point DFT, obtaining the frequency-domain receive signal vector $\mathbf{R}_{\uparrow}(k)$ is expressed as

$$\mathbf{R}_{\uparrow}(k) = \sum_{u=0}^{U-1} \mathbf{H}_{\uparrow u}(k)\mathbf{S}_{\uparrow u}(k) + \mathbf{N}_{\uparrow}(k). \quad (5)$$

The $U \cdot N_{strm} \times 1$ frequency-domain soft-output symbol vector $\hat{\mathbf{D}}_{\uparrow}(k)$ is obtained by applying the receive filtering on $\mathbf{R}_{\uparrow}(k)$ as

$$\hat{\mathbf{D}}_{\uparrow}(k) = [\hat{\mathbf{D}}_{\uparrow 0}^T(k), \dots, \hat{\mathbf{D}}_{\uparrow u}^T(k), \dots, \hat{\mathbf{D}}_{\uparrow U-1}^T(k)]^T = \mathbf{W}_{\uparrow mmse}(k)\mathbf{R}_{\uparrow}(k), \quad (6)$$

where $\mathbf{W}_{\uparrow mmse}(k)$ is the $U \cdot N_{strm} \times N_{mbs}$ MMSE receive filter matrix.

2.3 MMSE-SVD filter considering ICI information

The signals transmitted from multiple antennas of adjacent macro-cells arrive as ICI to receive antennas of macro-cell of interest. ICIs information received on the receive antennas can be assumed to be an independent and identically distributed (i.i.d) complex white Gaussian variable according to the central limit theorem. In OFDM downlink, the transmit and receive filter matrices for MMSE-SVD are respectively expressed as

$$\left\{ \begin{array}{l} \mathbf{W}_{\downarrow\text{mmse}}(k) = (\mathbf{U}_{\downarrow}^H(k)\mathbf{H}_{\downarrow}(k))^H \\ \quad \times \left(\begin{array}{l} (\mathbf{U}_{\downarrow}^H(k)\mathbf{H}_{\downarrow}(k))(\mathbf{U}_{\downarrow}^H(k)\mathbf{H}_{\downarrow}(k))^H \\ + \left(\frac{E_s}{N_0}\right)^{-1} \frac{N_{\text{ue}}}{U \cdot N_{\text{strm}}} \sum_{u=0}^{U-1} \left(1 + \frac{I_{\downarrow 0}(u)}{N_0}\right) \mathbf{I}_{U \cdot N_{\text{strm}}} \end{array} \right)^{-1} \mathbf{P}_{\downarrow}^{1/2}(k), \quad (7) \\ \mathbf{W}_{\downarrow\text{svd},u}(k) = \mathbf{U}_{\downarrow u}^H(k) \end{array} \right.$$

where $\mathbf{H}_{\downarrow}(k) = [\mathbf{H}_{\downarrow 0}^T(k), \dots, \mathbf{H}_{\downarrow u}^T(k), \dots, \mathbf{H}_{\downarrow U-1}^T(k)]^T$ is the $U \cdot N_{\text{ue}} \times N_{\text{mbs}}$ down-link MU-MIMO channel matrix. $\mathbf{U}_{\downarrow}(k) = \text{diag}[\mathbf{U}_{\downarrow 0}(k), \dots, \mathbf{U}_{\downarrow u}(k), \dots, \mathbf{U}_{\downarrow U-1}(k)]$, and $\mathbf{U}_{\downarrow u}(k)$ is obtained by applying SVD to $\mathbf{H}_{\downarrow u}(k)$ as

$$\mathbf{H}_{\downarrow u}(k) = \mathbf{U}_{\downarrow u}(k)\mathbf{\Lambda}_{\downarrow u}^{1/2}(k)\mathbf{V}_{\downarrow u}^H(k), \quad (8)$$

where $\mathbf{\Lambda}_{\downarrow u}(k)$ is $N_{\text{strm}} \times N_{\text{strm}}$ eigenmode diagonal matrix. $\mathbf{U}_{\downarrow}^H(k)\mathbf{H}_{\downarrow}(k)$ is the equivalent channel when each UE applies eigenmode reception (i.e. UE uses $\mathbf{U}_{\downarrow u}^H(k)$ as the receive filter matrix). $\mathbf{P}_{\downarrow}(k) = \text{diag}[\mathbf{P}_{\downarrow 0}(k), \dots, \mathbf{P}_{\downarrow u}(k), \dots, \mathbf{P}_{\downarrow U-1}(k)]$, and $\mathbf{P}_{\downarrow u}(k)$ of size $N_{\text{strm}} \times N_{\text{strm}}$ represents the water-filling based power allocation [4] across eigenmodes and subcarriers. N_0 and $I_{\downarrow 0}(u)$ are the noise and ICI power spectrum density, respectively.

In SC uplink, the transmit and receive filter matrices for MMSE-SVD are respectively expressed as

$$\left\{ \begin{array}{l} \mathbf{W}_{\uparrow\text{svd},u}(k) = \mathbf{V}_{\uparrow u}(k)\mathbf{P}_{\uparrow u}^{1/2}(k) \\ \mathbf{W}_{\uparrow\text{mmse}}(k) = (\mathbf{H}_{\uparrow}(k)\mathbf{W}_{\uparrow\text{svd}}(k))^H \\ \quad \times \left(\begin{array}{l} (\mathbf{H}_{\uparrow}(k)\mathbf{W}_{\uparrow\text{svd}}(k))(\mathbf{H}_{\uparrow}(k)\mathbf{W}_{\uparrow\text{svd}}(k))^H + \left(\frac{E_s}{N_0}\right)^{-1} \\ \times \text{diag}\left(1 + \frac{I_{0\uparrow}(0)}{N_0}, \dots, 1 + \frac{I_{0\uparrow}(N_{\text{mbs}} - 1)}{N_0}\right) \end{array} \right)^{-1}, \quad (9) \end{array} \right.$$

where $\mathbf{H}_{\uparrow}(k) = [\mathbf{H}_{\uparrow 0}(k), \dots, \mathbf{H}_{\uparrow u}(k), \dots, \mathbf{H}_{\uparrow U-1}(k)]$ is the $N_{\text{mbs}} \times U \cdot N_{\text{ue}}$ uplink MU-MIMO channel matrix. $\mathbf{V}_{\uparrow u}(k)$ is obtained by applying SVD to the $\mathbf{H}_{\uparrow u}(k)$ same as eq. (8). $\mathbf{P}_{\uparrow u}(k)$ is of size $N_{\text{strm}} \times N_{\text{strm}}$ represents the MMSE power allocation [5] across eigenmodes and subcarriers.

3 Monte-Carlo computer simulation

3.1 Simulation setting

We consider a cellular model shown in Fig. 1. The macro-cell of interest is surrounded by 6 co-channel macro-cells. In the small-cell network, $N_{\text{macro}} = 19$ distributed antennas are deployed over each macro-cell uniformly. U UEs equipped with $N_{\text{ue}} = 2$ antennas are randomly located within a macro-cell with radius of R . The number of data streams per UE is assumed to be $N_{\text{strm}} = 2$ using $N_c = 1024$ subcarriers. $N_{\text{mbs}} = U \cdot N_{\text{ue}}$ distributed antennas are selected from N_{macro} distributed antennas in a descending order of the instantaneous received signal power level.

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 $L = 16$ distinct paths, the transfer function $H_u(k; n_{\text{ue}}, n_{\text{mbs}})$ between n_{ue} th antenna of u th UE in macro-cell and distributed n_{mbs} th antenna can be represented as

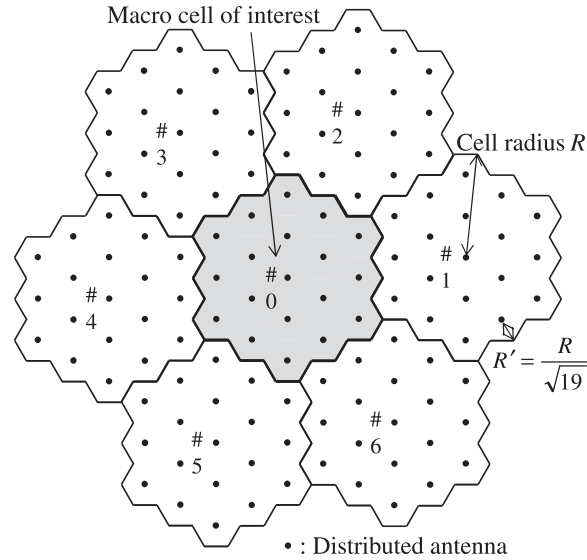


Fig. 1. Cellular model.

$$H_u(k; n_{ue}, n_{mbs}) = \sqrt{d_{u,n_{mbs}}^{-\alpha} 10^{-\frac{\eta_{u,n_{mbs}}}{10}}} \times \left\{ \begin{aligned} & \sqrt{\frac{K}{K+1}} \exp(j\theta_{u,n_{ue},n_{mbs}}) \exp\left(-j\frac{2\pi k\tau_{u,n_{ue},n_{mbs}}(0)}{N_c}\right) \\ & + \sqrt{\frac{1}{K+1}} \sum_{l=0}^{L-1} \zeta_{u,n_{ue},n_{mbs}}(l) \exp\left(-j\frac{2\pi k\tau_{u,n_{ue},n_{mbs}}(l)}{N_c}\right) \end{aligned} \right\}. \quad (10)$$

In this paper, the channel is assumed to be a Nakagami-Rice fading channel (i.e., dominant path to scattered path power ratio $K = 10$ (dB)) when the distance $d_{u,n_{mbs}}$ between u th UE in macro-cell and n_{mbs} th distributed antenna is equal to or smaller than $R' = R/\sqrt{19}$, and a Rayleigh fading channel (i.e., $K = 0$) when $d_{u,n_{mbs}}$ is larger than R' . Path loss exponent $\alpha = 3.5$, shadowing loss standard deviation $\eta_{u,n_{mbs}} = 7$ (dB) are assumed. $\theta_{u,n_{ue},n_{mbs}}$ is the phase of dominant path and is assumed to be distributed uniformly. $\zeta_{u,n_{ue},n_{mbs}}(l)$ and $\tau_{u,n_{ue},n_{mbs}}$ are respectively the complex-valued path gain and the time delay of the l th path with $E[\sum_{l=0}^{L-1} |\zeta_{u,n_{ue},n_{mbs}}(l)|^2] = 1$ for all u, n_{ue}, n_{mbs} . We assume a sample-spaced time delay. The OFDM downlink sum capacity C_{\downarrow} (bps/Hz) and the SC uplink sum capacity C_{\uparrow} (bps/Hz) are respectively computed using Shannon formula as

$$\left\{ \begin{aligned} C_{\downarrow} &= \frac{1}{N_c} \sum_{u=0}^{U-1} \sum_{n_{strm}=0}^{N_{strm}-1} \sum_{k=0}^{N_c-1} \log_2(1 + \gamma_{\downarrow u}(k; n_{strm})) \\ C_{\uparrow} &= \sum_{u=0}^{U-1} \sum_{n_{strm}=0}^{N_{strm}-1} \log_2(1 + \gamma_{\uparrow u}(n_{strm})) \end{aligned} \right. \quad (11)$$

where $\gamma_{\downarrow u}(k; n_{strm})$ and $\gamma_{\uparrow u}(n_{strm})$ denote the instantaneous SINR after eigenmode reception for OFDM downlink and the instantaneous SINR after MMSE reception for SC uplink.

3.2 Simulation result

Fig. 2 plots the outage sum capacities of OFDM downlink and SC uplink with MMSE-SVD with ICI information as a function of the number U of multiplexed

UEs. The 5% and 95% outage capacities are defined as levels below which the sum capacity falls at the probabilities of 5% and 95% respectively. For comparison, we also plot those with MMSE-SVD without ICI information. Furthermore, we plot those of OFDM downlink with CI and SC uplink with ZF. The maximum number of multiplexed UEs is $U = 9$ when $N_{\text{macro}} = 19$ and $N_{\text{ue}} = 2$. It can be seen from Fig. 2 that MMSE-SVD with ICI information can better suppress ICI and achieves higher sum capacity than CI, ZF and MMSE-SVD without ICI information for larger U . When $U = 4$ ($U = 9$), MMSE-SVD with ICI information can achieve 4.2 times (12.1 times) higher 5% outage sum capacity and 2.3 times (6.5 times) 95% outage sum capacity than CI in the case of OFDM downlink, while it can achieve 28 times (337 times) higher 5% outage sum capacity and 2.9 times (29.9 times) 95% outage sum capacity than ZF in the case of SC uplink.

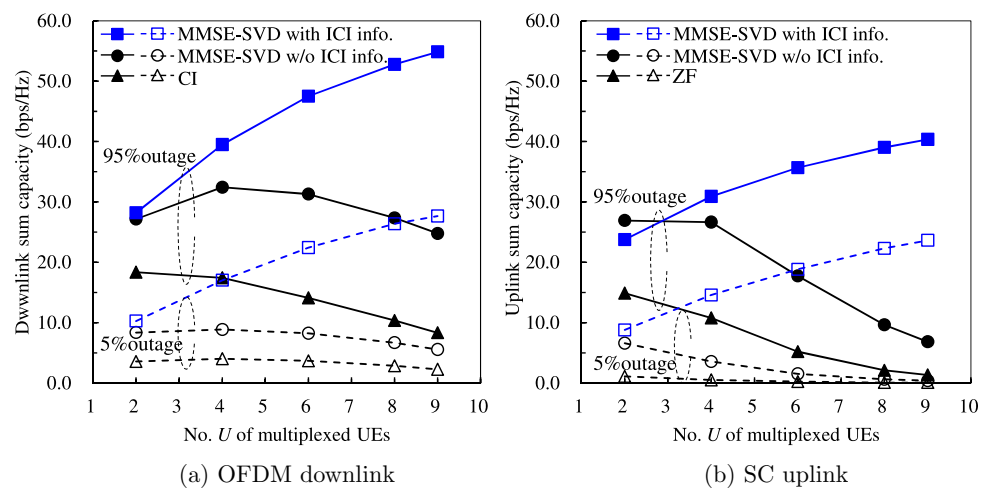


Fig. 2. Sum capacity of MMSE-SVD.

4 Conclusion

In this paper, we evaluate by computer simulation the OFDM downlink sum capacity and SC uplink sum capacity when using MMSE-SVD with and without ICI information in a multi-cell environment. We showed that MMSE-SVD with ICI information can achieve higher sum capacity than CI, ZF, and MMSE-SVD without ICI information.

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