Adaptive MMSE-SVD for OFDM downlink MU-MIMO in a high mobility environment

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Abstract: In this paper, we propose an adaptive minimum mean square error filtering combined with singular value decomposition (MMSE-SVD) for OFDM downlink multi-user multi-input multi-output (MU-MIMO) transmission. During data transmission, base station (BS) updates the multi-user MMSE transmit filter by using linear channel prediction, while user equipments (UEs) update their eigenmode receive filters, constructed by SVD, by using decision feedback adaptive channel estimation. The uncoded BER performance achievable by adaptive MMSE-SVD is evaluated by computer simulation. It is shown that proposed adaptive MMSE-SVD can increase an allowable maximum Doppler frequency ($f_D T$) for keeping BER $< 10^{-2}$ by about 4 times.

Keywords: MU-MIMO, MMSE-SVD, decision feedback channel estimation, linear prediction

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]. A promising approach under the limited radio bandwidth is multi-user multi-input multi-output (MU-MIMO) [2]. MU-MIMO can further improve the spectrum efficiency without bandwidth expansion. Recently, the authors proposed a minimum mean square error filtering combined with singular value decomposition (MMSE-SVD) for spatially multiplexing user equipments (UEs) [3]. For performing MMSE-SVD, the MIMO channel state information (CSI) must be shared by the base station (BS) and UEs to construct the transmit and receive filters prior to the data transmission. Assuming the time-division duplex (TDD), BS and UEs can share the MIMO CSI without feedback.

Recently, we proposed a TDD subframe structure which simplifies the MIMO CSI sharing. The proposed TDD subframe consists of uplink pilot slot, downlink pilot slot, and 12 user data slots as shown in Fig. 1 [4]. Firstly, UEs, to be spatially multiplexed, transmit the frequency-division multiplexed (FDM) uplink pilot. Then, BS transmits the FDM downlink pilot. By doing so and exploiting channel reciprocity, both BS and UEs sides can share the MIMO CSI between transmit antennas and UEs' receive antennas prior to data transmission without feedback. However, in a high mobility environment, MIMO CSI acquired by using uplink and downlink pilots will become outdated during data transmission period. In this paper, we propose an adaptive MMSE-SVD for OFDM downlink. In the adaptive MMSE-SVD, the BS updates the multi-user MMSE transmit filter using linear channel prediction while UEs update their eigen-mode reception filters, constructed by SVD, using decision feedback adaptive channel estimation.

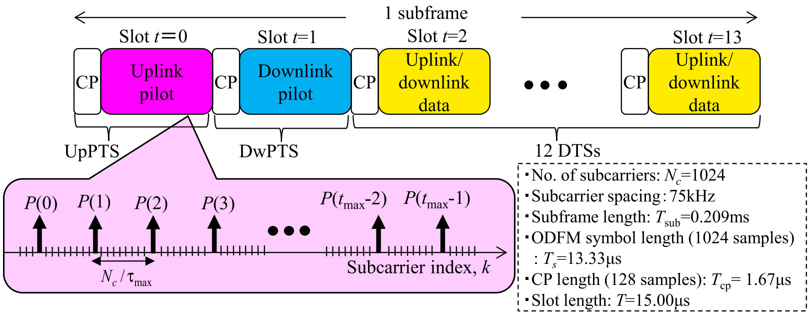

Fig. 1. Subframe structure (UL pilot + DL pilot + 12data slots)

2 Adaptive MMSE-SVD for high mobility environment

(a) Principle of MMSE-SVD

Multi-user spatial multiplexing of U UEs, each is equipped N_{ue} antennas, is considered. BS simultaneously transmits N_{strm} data streams for each UE (therefore, a total number of streams becomes $U \cdot N_{\mathrm{strm}}$) from N_{bs} transmit antennas using N_{c} subcarriers. In OFDM downlink, the transmit and receive filter matrices for MMSE-SVD are respectively expressed as [3]

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$$\begin{cases} \mathbf{W}_{\mathrm{mmse}}(k) = [\mathbf{W}_{\mathrm{mmse},0}(k), \cdots, \mathbf{W}_{\mathrm{mmse},u}(k) \cdots, \mathbf{W}_{\mathrm{mmse},U-1}(k)] \\ \quad = (\mathbf{U}^H(k)\mathbf{H}(k))^H \left((\mathbf{U}^H(k)\mathbf{H}(k))(\mathbf{U}^H(k)\mathbf{H}(k))^H + \left(\frac{E_s}{N_0}\right)^{-1} \frac{N_{\mathrm{ue}}}{N_{\mathrm{strm}}} \mathbf{I}_{U \cdot N_{\mathrm{strm}}} \right)^{-1} \mathbf{P}^{1/2}(k) \\ \mathbf{W}_{\mathrm{svd},u}(k) = \mathbf{U}_u^H(k) \end{cases}, \quad (1)$$

where E_s is the symbol energy and N_0 is the single-sided power spectrum density of the additive white Gaussian noise (AWGN). $\mathbf{I}_{U \cdot N_{\mathrm{strm}}}$ represents the $U \cdot N_{\mathrm{ue}} \times U \cdot N_{\mathrm{ue}}$ identity matrix. $\mathbf{H}(k) = [\mathbf{H}_0^T(k), \cdots, \mathbf{H}_u^T(k), \cdots, \mathbf{H}_{U-1}^T(k)]^T$ is the $U \cdot N_{\mathrm{ue}} \times N_{\mathrm{mbs}}$ downlink MU-MIMO channel matrix. $\mathbf{U}(k) = diag[\mathbf{U}_0(k), \cdots, \mathbf{U}_u(k), \cdots, \mathbf{U}_{U-1}(k)]$, and $\mathbf{U}_u(k)$ is obtained by applying SVD to $\mathbf{H}_u(k)$ as

$$\mathbf{H}_u(k) = \mathbf{U}_u(k)\mathbf{\Lambda}_u^{1/2}(k)\mathbf{V}_u^H(k), \quad (2)$$

where $\mathbf{\Lambda}_u(k)$ is the $N_{\mathrm{strm}} \times N_{\mathrm{strm}}$ eigenmode diagonal matrix. $\mathbf{U}^H(k)\mathbf{H}(k)$ is the equivalent channel when each UE applies eigenmode reception (i.e. UE uses $\mathbf{U}_u^H(k)$ as the receive filter matrix). $\mathbf{P}(k) = diag[\mathbf{P}_0(k), \cdots, \mathbf{P}_u(k), \cdots, \mathbf{P}_{U-1}(k)]$, and $\mathbf{P}_u(k)$ of size $N_{\mathrm{strm}} \times N_{\mathrm{strm}}$ represents the water filling based power allocation [5] across eigenmodes and subcarriers. BS estimates MIMO CSI $\hat{\mathbf{H}}_{\mathrm{bs}}(k; t = 0)$ using uplink pilot signal at time slot $t = 0$, and UEs estimate each MIMO CSI $\hat{\mathbf{H}}_{\mathrm{UE},u}(k; t = 1)$ by using downlink pilot signal at time slot $t = 1$ [4]. Accordingly, BS constructs the transmit filter $\mathbf{W}_{\mathrm{mmse}}(k; t = 0)$ and UE constructs the receive filter $\mathbf{W}_{\mathrm{svd},u}(k; t = 1)$ by using $\hat{\mathbf{H}}_{\mathrm{bs}}(k; t = 0)$ and $\hat{\mathbf{H}}_{\mathrm{ue},u}(k; t = 1)$ instead of $\mathbf{H}(k)$ in eq. (1), respectively.

In a high mobility environment, when $\mathbf{W}_{\mathrm{mmse}}(k; t = 0)$ and $\mathbf{W}_{\mathrm{svd},u}(k; t = 1)$ are used continuously during data transmission (i.e. $t = 2{\sim}13$), BER performance degrades significantly due to the filter mismatch among the transmit filter, the receive filter and the actual propagation MIMO channel. To avoid the BER degradation in a high mobility environment, in this paper, we propose an adaptive MMSE-SVD for high mobility environment. Fig. 2 illustrates a transmitter/receiver structure of adaptive MMSE-SVD.

(b) Updating the MMSE transmit filter

BS applies a linear prediction to obtain the channel estimate $\hat{\mathbf{H}}_{\mathrm{bs}}(k; t)$ at $t = 2{\sim}13$ using $\hat{\mathbf{H}}_{\mathrm{bs}}(k; t = 0)$ and $\hat{\mathbf{H}}_{\mathrm{bs}}(k; t = -N_{\mathrm{slot}})$ (which is the channel estimate using the uplink pilot in previous subframe ($N_{\mathrm{slot}} = 14$ slots)) as

$$\hat{\mathbf{H}}_{\mathrm{bs}}(k; t) = \hat{\mathbf{H}}_{\mathrm{bs}}(k; t = 0) + \frac{\hat{\mathbf{H}}_{\mathrm{bs}}(k; t = 0) - \hat{\mathbf{H}}_{\mathrm{bs}}(k; t = -N_{\mathrm{slot}})}{N_{\mathrm{slot}}} \times t. \quad (3)$$

By substituting $\hat{\mathbf{H}}_{\mathrm{bs}}(k; t)$ into eq. (1), $\mathbf{W}_{\mathrm{mmse}}(k; t)$ is updated.

(c) Updating the eigenmode reception filter

Each UE estimates the equivalent channel $\mathbf{H}_{\mathrm{eq},u}(k; t) = \mathbf{H}_u(k; t)\mathbf{W}_{\mathrm{mmse},u}(k; t)$ by applying decision feedback channel estimation. Assuming the time-varying of fading over consecutive slots is small, an $N_{\mathrm{ue}} \times N_{\mathrm{strm}}$ matrix $\dot{\mathbf{R}}_u(k; t)$ representing the received signal vector of the previous N_{strm} time slots is expressed as

$$\begin{aligned} \dot{\mathbf{R}}_u(k; t) &= [\mathbf{R}_u(k; t - N_{\mathrm{strm}}), \cdots, \mathbf{R}_u(k; t - 1)] \\ &= \sqrt{\frac{2E_s}{T_s}}\mathbf{H}_u(k; t)\mathbf{W}_{\mathrm{mmse},u}(k; t)\dot{\mathbf{D}}_u(k; t) \\ &\quad + \sqrt{\frac{2E_s}{T_s}} \sum_{\substack{u'=0 \\ u' \neq u}}^{U-1} \mathbf{H}_{u'}(k; t)\mathbf{W}_{\mathrm{mmse},u'}(k; t)\dot{\mathbf{D}}_{u'}(k; t) + \dot{\mathbf{N}}_u(k; t) \end{aligned}, \quad (4)$$

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where $\mathbf{R}_u(k;t)$ is an $N_{\rm ue}\times 1$ receive signal vector of the uth UE. $\dot{\mathbf{D}}_u(k;t)=[\mathbf{D}_u(k;t-N_{\rm strm}),\cdots,\mathbf{D}_u(k;t-1)]$ is an $N_{\rm strm}\times N_{\rm strm}$ transmitted data symbol matrix consisting of the transmitted data symbol vectors of previous $N_{\rm strm}$ time slots and $\dot{\mathbf{N}}_u(k;t)=[\mathbf{N}_u(k;t-N_{\rm strm}),\cdots,\mathbf{N}_u(k;t-1)]$ is an $N_{\rm ue}\times N_{\rm strm}$ noise matrix. The estimated equivalent channel $\hat{\mathbf{H}}_{{\rm eq},u}(k;t)$ is obtained by multiplying inverse matrix of decision feedback data symbol matrix $\dot{\bar{\mathbf{D}}}_u(k;t)=[\bar{\mathbf{D}}_u(k;t-N_{\rm strm}),\cdots,\bar{\mathbf{D}}_u(k;t-1)]$ to the right side of eq. (4) as

$$\hat{\mathbf{H}}_{{\rm eq},u}(k;t)=\begin{cases}\dot{\mathbf{R}}_u(k;t)\dot{\bar{\mathbf{D}}}_u^{-1}(k;t) & rank(\dot{\bar{\mathbf{D}}}_u(k;t))=N_{\rm strm}\\ \hat{\mathbf{H}}_{{\rm eq},u}(k;t-1) & rank(\dot{\bar{\mathbf{D}}}_u(k;t))<N_{\rm strm}\end{cases}. \tag{5}$$

Then, frequency-domain moving average filtering is applied to $\hat{\mathbf{H}}_{{\rm eq},u}(k;t)$, yielding

$$\tilde{\mathbf{H}}_{{\rm eq},u}(k;t)=\frac{1}{Q}\sum_{q=-Q/2}^{Q/2}\hat{\mathbf{H}}_{{\rm eq},u}(k+q;t). \tag{6}$$

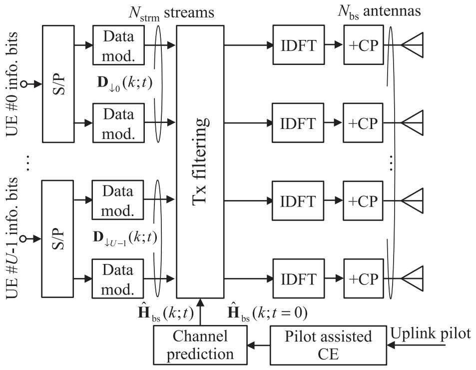
Each UE generates the receive filter using equivalent channel $\tilde{\hat{\mathbf{H}}}_u(k;t)$ as

$$\mathbf{W}_{{\rm svd},u}(k;t)=(\tilde{\mathbf{H}}_{{\rm eq},u}(k;t))^H\left(\tilde{\mathbf{H}}_{{\rm eq},u}(k;t)(\tilde{\mathbf{H}}_{{\rm eq},u}(k;t))^H+\left(\frac{E_s}{N_0}\right)^{-1}\mathbf{I}_{N_{\rm ue}}\right)^{-1}. \tag{7}$$

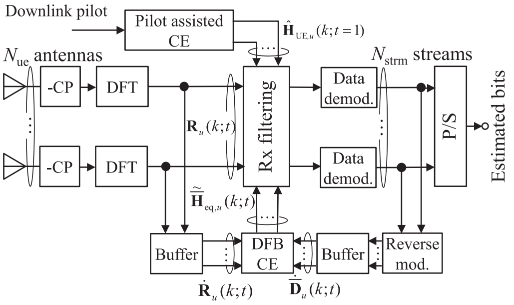
The updated filter $\mathbf{W}_{{\rm svd},u}(k;t)$ has smaller filter mismatch than $\mathbf{W}_{{\rm svd},u}(k;t=1)$, but it could produce the noise enhancement. Then, each UE selects the receive filter as

$$\tilde{\mathbf{W}}_{{\rm svd},u}(k;t)=\arg\min_{\mathbf{W}_{{\rm svd},u}(k;t')\in\{\mathbf{W}_{{\rm svd},u}(k;1),\mathbf{W}_{{\rm svd},u}(k;t)\}}\left(\sum_{k=0}^{N_{\rm c}-1}\min_{\mathbf{D}_u\in\Psi_{\rm mod}}\|\mathbf{W}_{{\rm svd},u}(k;t')\mathbf{R}_u(k;t)-\mathbf{D}_u\|\right), \tag{8}$$

where $\|\cdot\|$ represents the Euclidean norm and $\mathbf{D}_u\in\Psi_{\rm mod}^{N_{\rm strm}\times 1}$ is an $N_{\rm strm}\times 1$ vector consisting of $N_{\rm strm}$ candidate symbols in the modulation constellation set $\Psi_{\rm mod}$.



(a) Transmitter (BS)



(b) Receiver (UE)

Fig. 2. Transmitter/receiver structure of adaptive MMSE-SVD

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Finally, each UE obtains the received signal vector $\hat{\mathbf{D}}_u(k;t) = \tilde{\mathbf{W}}_{\mathrm{svd},u}(k;t)\mathbf{R}_u(k;t)$ to perform symbol decision.

3 Monte-Carlo computer simulation

We evaluate the uncoded BER performance of adaptive MMSE-SVD by computer simulation. $U = 2$ UEs having $N_{\mathrm{ue}} = 2$ antennas are spatially multiplexed. BS simultaneously transmits $N_{\mathrm{strm}} = 2$ data streams for each UE from $N_{\mathrm{bs}} = 4$ transmit antennas. Each data stream consists of $N_{\mathrm{c}} = 128$ data-modulated symbols, where the modulation is assumed to be 16QAM. Pilot is generated using Zadoff-Chu sequence. Assuming that the channel is composed of $L = 16$ distinct paths, the transfer function $H_u(k; n_{\mathrm{ue}}, n_{\mathrm{mbs}})$ between n_{ue}th antenna of uth UE in macro-cell and n_{mbs}th transmit antennas can be represented as

$$H_u(k; n_{\mathrm{ue}}, n_{\mathrm{mbs}}) = \sum_{l=0}^{L-1} \xi_{u,n_{\mathrm{ue}},n_{\mathrm{mbs}}}(l) \exp\left(-j\frac{2\pi k\tau_{u,n_{\mathrm{ue}},n_{\mathrm{mbs}}}(l)}{N_{\mathrm{c}}}\right), \tag{9}$$

where $\xi_{u,n_{\mathrm{ue}},n_{\mathrm{mbs}}}(l)$ and $\tau_{u,n_{\mathrm{ue}},n_{\mathrm{mbs}}}$ are respectively the complex-valued path gain and the time delay of the lth path with $\mathrm{E}[\sum_{l=0}^{L-1} |\xi_{u,n_{\mathrm{ue}},n_{\mathrm{mbs}}}(l)|^2] = 1$ for all u, n_{ue}, n_{mbs}. We assume a sample-spaced time delay (i.e., $\tau_{u,n_{\mathrm{ue}},n_{\mathrm{mbs}}} = l$ for all u, n_{ue}, n_{mbs}).

Fig. 3(a) plots average uncoded BER as a function of average transmit E_s/N_0 with normalized maximum Doppler frequency ($f_{\mathrm{D}}T$) as a parameter, where T represents the slot length. It is seen from Fig. 3, BER degradation and error floor occur in the case of conventional MMSE-SVD without transmit/receive filter updating due to the filter mismatch among the transmit filter, the receive filter and the actual propagation MIMO channel. On the other hand, our proposed adaptive MMSE-SVD with transmit/receive filter updating can reduce the error floor.

Fig. 3(b) plots the average uncoded BER as a function of $f_{\mathrm{D}}T$. BER performance of the conventional MMSE-SVD without transmit/receive filter updating degrades BER performance when $f_{\mathrm{D}}T$ is higher than 0.0001. Below, we will discuss the performance improvement achievable if either one of transmit and receive filters is updated. If the receive filter is updated only, almost no performance improvement is obtained, i.e., the allowable $f_{\mathrm{D}}T$ for keeping the BER below BER $< 10^{-2}$ is 0.001, which is almost the same as using the conventional MMSE-SVD. This is because the receive filter updating has no effect to reduce the inter-user interference (IUI) while it can mitigate the inter-antenna interference (IAI). If the transmit filter is updated only, the BER performance improvement obtained and accordingly, the allowable $f_{\mathrm{D}}T$ can be increased to 0.003. This performance improvement is because the transmit filter updating can mitigate both IAI and IUI. On the other hand, if updating both the transmit and the receive filters, this is our proposed adaptive MMSE-SVD, updating the transmit filter mitigates IUI and IAI and updating the receive filter mitigate IAI. Therefore, a further performance improvement is obtained and the allowable $f_{\mathrm{D}}T$ increases to 0.004. Note that $f_{\mathrm{D}}T = 0.001$ (0.004) corresponds to the velocity of 14.4 km/h (57.6 km/h) when assuming 5 GHz carrier frequency and subcarrier spacing of 75 kHz.

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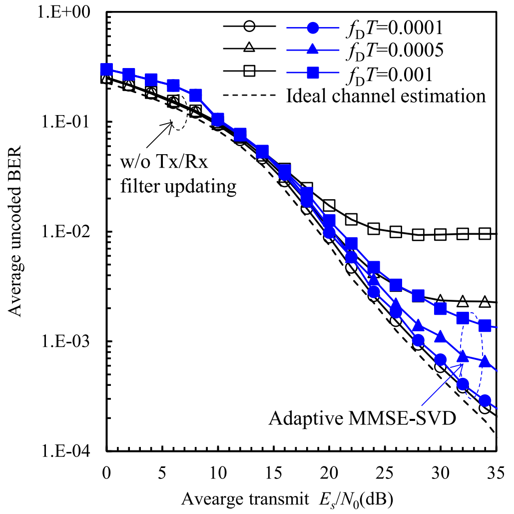
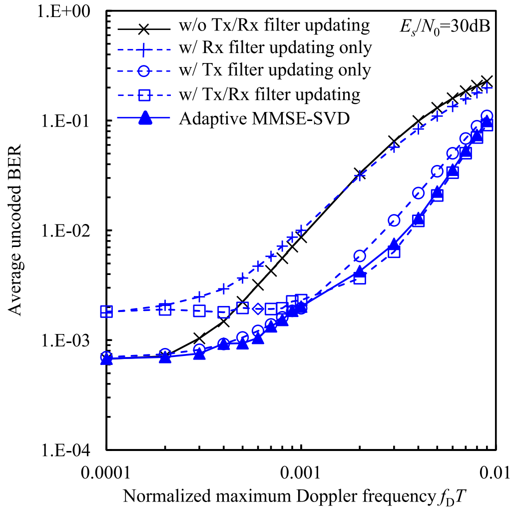


(a) Average E_s/N_0 vs average uncoded BER performance



(b) f_DT vs average uncoded BER performance

Fig. 3. Performance of adaptive MMSE-SVD

4 Conclusion

In this paper, we proposed an adaptive MMSE-SVD for OFDM downlink. In the adaptive MMSE-SVD during data transmission, MBS updates transmit filter using linear channel prediction while each UE updates receive filter using decision feedback channel estimation. It is shown by computer simulation that proposed adaptive multi-user MMSE-SVD can increase the allowable f_DT for keeping the BER below BER $< 10^{-2}$ about 4 times. Applying the adaptive MMSE-SVD to the uplink is our future work.

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