Joint Transmit/Receive MMSE Filtering for Single-carrier MIMO Spatial Multiplexing

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Abstract— **Multiple-input multiple-output (MIMO) spatial multiplexing is a powerful technique to increase the transmission data rate. However, if MIMO spatial multiplexing is applied to single-carrier (SC) block transmissions, it suffers from the inter-symbol interference (ISI) as well as the inter-antenna interference (IAI). In this paper, we propose a joint transmit/receive frequency-domain (FD) filtering using the channel state information (CSI) at both the transmitter and receiver for SC-MIMO spatial multiplexing. The transmit and receive FD filters are derived based on the minimum mean square error (MMSE) criterion. The proposed filters transform the MIMO channel to the multiple orthogonal channels (i.e., eigenmodes) so as to avoid the IAI. The ISI can be significantly suppressed by applying the joint transmit/receive MMSE based frequency-domain equalization (MMSE-FDE) to each eigenmode. The throughput performance achievable with the proposed joint transmit/receive MMSE-FD filtering is evaluated by computer simulation. It is shown that the proposed method outperforms the conventional receive MMSE-FD filtering which uses the CSI at the receiver only.**

Keywords; Single-carrier transmission, MIMO spatial multiplexing, MMSE filtering

I. INTRODUCTION

The broadband services are demanded in the next generation mobile communication systems. However, the available bandwidth is limited. Multiple-input multiple-output (MIMO) spatial multiplexing [1] can increase the transmission data rate without increasing the signal bandwidth. MIMO spatial multiplexing with orthogonal frequency-division multiplexing (OFDM) [2] has been attracting much attention because of its robustness against the frequency-selective fading [3]. However, the OFDM signal has a disadvantage of its high peal-to-average ratio (PAPR) property.

Recently, single-carrier (SC) block transmission with MIMO spatial multiplexing has been gaining an increasing popularity because of its lower PAPR property [4]. The low-complexity minimum mean square error based frequency domain receive filtering (receive MMSE-FD filtering) [4] can be used for SC-MIMO spatial multiplexing. However, SC-MIMO spatial multiplexing suffers not only from the inter-antenna interference (IAI) but also from the inter-symbol interference (ISI). In order to improve the transmission performance, non-linear signal detection techniques such as the iterative interference cancellation [4,5] and the maximum likelihood detection [6,7] have been studied. However, their computational complexity is extremely high.

Another interesting technique to improve the transmission performance is a joint transmit/receive linear signal detection. If the channel state information (CSI) is available at both the transmitter and receiver, the transmission performance can be improved while keeping the computational complexity low. In [8,9], joint transmit/receive MMSE based frequency-domain equalization (MMSE-FDE) was proposed for the single-input single-output (SISO) SC block transmissions in a frequency-selective fading channel and the transmit and receive FDE weights which jointly minimize the MSE between the input and output of the equivalent channel (i.e., transmit FDE + channel + receive FDE) were derived. Since joint transmit/receive MMSE-FDE allocates the transmit power so as to sufficiently suppress the residual ISI, it outperforms the receive MMSE-FDE [10,11] which uses the CSI at the receiver only.

In this paper, we propose joint transmit/receive MMSE based frequency-domain filtering (joint transmit/receive MMSE-FD filtering) for SC-MIMO spatial multiplexing. The proposed joint transmit/receive MMSE-FD filtering transforms the MIMO channel to the multiple orthogonal channels (i.e., eigenmodes) so as to avoid the IAI and at the same time suppresses the ISI by applying joint transmit/receive MMSE-FDE to each eigenmode. We derive such transmit and receive filters. The throughput performance using the proposed method is evaluated by computer simulation. It is shown that the proposed joint transmit/receive MMSE-FD filtering outperforms the receive MMSE-FD filtering which uses the CSI at the receiver only.

The remainder of this paper is organized as follows. In Sect. II, the transmit and received signal expressions for SC-MIMO spatial multiplexing with joint transmit/receive MMSE-FD filtering are presented. In Sect. III, we derive the transmit and receive MMSE-FD filters and discuss their behaviors. In Sect. IV, we evaluate by computer simulation the throughput performance achievable with the proposed method and discuss the effect of transmit/receive MMSE-FD filters. Section V offers some conclusions.

II. TRANSMIT AND RECEIVED SIGNAL EXPRESSIONS

System model of SC-MIMO spatial multiplexing with joint transmit/receive MMSE-FD filtering is illustrated in Fig. 1. At the transmitter, the information bit sequence is transformed into a data-modulated symbol sequence. Then the data-modulated symbol sequence is serial-to-parallel (S/P) converted to N_t parallel symbol sequences, each to be transmitted from different transmit antenna and each parallel symbol sequence is divided into a sequence of symbol blocks of N_c symbols each. Each symbol block is transformed into a frequency-domain symbol block by N_c-point discrete Fourier transform (DFT). After the transmit MMSE-FD filtering is applied to these N_t frequency-domain symbol blocks, each block is transformed back to time-domain symbol block by N_c-point inverse DFT (IDFT). Finally, the last N_g symbols of each transmit block are copied as a cyclic prefix (CP) and inserted into the guard interval (GI) placed at the beginning of each transmit block and transmitted from N_t antennas.

At the receiver, each CP is removed from the signal blocks received by N_r antennas and then, each block is transformed into the frequency-domain signal block by N_c-point DFT. After the receive MMSE-FD filtering is applied to these N_r frequency-domain signal blocks, each block is transformed back to time-domain soft-output block by N_c-point IDFT.

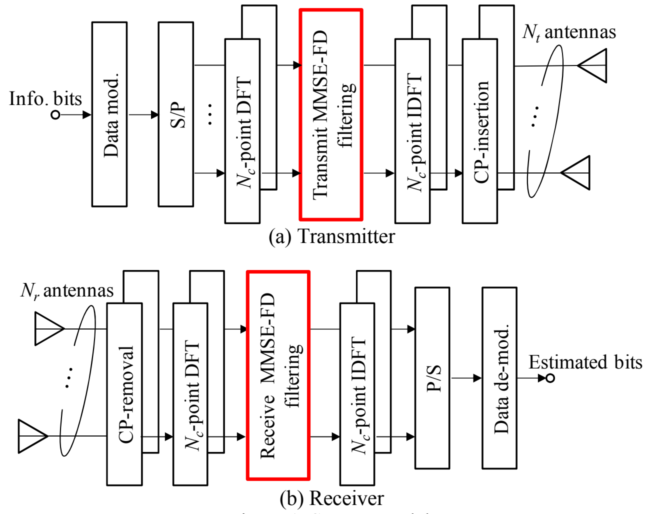


Figure 1. System model.

A. Transmit signal

At the transmitter, the N_t×1 transmit symbol vector $\mathbf{S}(k)$ at the kth frequency is obtained by applying the transmit MMSE-FD filtering into the N_t×1 frequency-domain symbol vector $\mathbf{D}(k)=[D_0(k),\ldots, D_n(k),\ldots, D_{N_t-1}(k)]^T$ at the kth frequency, which is expressed as

$$\begin{aligned}\mathbf{S}(k) &= [S_0(k),\ldots,S_n(k)\ldots,S_{N_t-1}(k)]^T \\ &= \mathbf{W}_t(k)\mathbf{D}(k)\end{aligned}, \quad (1)$$

where $\mathbf{W}_t(k)$ is the N_t×N_t transmit MMSE-FD filter matrix. N_c-point IDFT is applied into each transmit symbol block $\{S_n(k); k=0\sim N_c-1\}$, $n=0\sim N_t-1$, and each block is transmitted after CP-insertion.

B. Received signal

The N_r×1 frequency-domain received signal vector $\mathbf{R}(k)$ at the kth frequency after N_c-point DFT is expressed as

$$\begin{aligned}\mathbf{R}(k) &= [R_0(k),\ldots,R_m(k)\ldots,R_{N_r-1}(k)]^T \\ &= \sqrt{2E_s/T_s}\,\mathbf{H}(k)\mathbf{S}(k)+\mathbf{Z}(k)\end{aligned}, \quad (2)$$

where E_s and T_s are respectively the symbol energy and the symbol duration, $\mathbf{H}(k)$ is the N_r×N_t MIMO channel matrix and $\mathbf{Z}(k)=[Z_0(k),\ldots, Z_m(k),\ldots, Z_{N_r-1}(k)]^T$ is the noise vector each of which is zero-mean complex-valued random variable having variance $2N_0/T_s$ with N_0 being the one-sided power spectrum density of additive white Gaussian noise (AWGN).

The N_t×1 frequency-domain soft-output vector $\hat{\mathbf{D}}(k)$ is obtained by applying the receive MMSE-FD filtering into $\mathbf{R}(k)$ as

$$\begin{aligned}\hat{\mathbf{D}}(k) &= [\hat{D}_0(k),\ldots,\hat{D}_n(k)\ldots,\hat{D}_{N_t-1}(k)]^T \\ &= \mathbf{W}_r(k)\mathbf{R}(k) \\ &= \sqrt{2E_s/T_s}\,\mathbf{W}_r(k)\mathbf{H}(k)\mathbf{W}_t(k)\mathbf{D}(k)+\mathbf{W}_r(k)\mathbf{Z}(k)\end{aligned}, \quad (3)$$

where $\mathbf{W}_r(k)$ is the N_t×N_r receive MMSE-FD filter matrix. N_c-point IDFT is applied into each frequency-domain soft-output block $\{\hat{D}_n(k); k=0\sim N_c-1\}$, $n=0\sim N_t-1$, and the time-domain soft-output block is obtained.

III. DERIVATION OF TRANSMIT AND RECEIVE MMSE-FD FILTERS

A. Formulation of objective function

The total MSE of the blocks between the transmit symbol vector $\mathbf{D}(k)$ and the soft-output vector $\hat{\mathbf{D}}(k)$ is defined as

$$\varepsilon \equiv E\left[\sum_{k=0}^{N_c-1} tr\left\{\left(\mathbf{D}(k)-\hat{\mathbf{D}}(k)\Big/\sqrt{\frac{2E_s}{T_s}}\right)\left(\mathbf{D}(k)-\hat{\mathbf{D}}(k)\Big/\sqrt{\frac{2E_s}{T_s}}\right)^H\right\}\right]. \quad (4)$$

From Eq. (3) and (4), the total MSE can be rewritten as

$$\begin{aligned}\varepsilon = &\sum_{k=0}^{N_c-1} tr\left[\left\{\mathbf{I}_{N_t}-\mathbf{W}_r(k)\mathbf{H}(k)\mathbf{W}_t(k)\right\}\left\{\mathbf{I}_{N_t}-\mathbf{W}_r(k)\mathbf{H}(k)\mathbf{W}_t(k)\right\}^H\right] \\ &+\gamma^{-1}\sum_{k=0}^{N_c-1} tr\left\{\mathbf{W}_r(k)\mathbf{W}_r^H(k)\right\}\end{aligned}, \quad (5)$$

where $\mathbf{I}_{N_t}$ is the N_t×N_t identity matrix and $\gamma=E_s/N_0$. The minimization of the total MSE given by Eq. (5) under the total transmit power constraint is rewritten by the optimization problem as

$$\begin{aligned}&\min_{\{\mathbf{W}_t(k),\mathbf{W}_r(k);k=0\sim N_c-1\}} \varepsilon \\ &\text{s.t.} \sum_{k=0}^{N_c-1} tr\left\{\mathbf{W}_t(k)\mathbf{W}_t^H(k)\right\}=N_tN_c\end{aligned}. \quad (6)$$

We want to find the transmit and receive MMSE-FD filters which satisfy Eq. (6). However, it is quite difficult to derive a set of MMSE-FD filters $\{\mathbf{W}_t(k), \mathbf{W}_r(k)\}$ at the same time since $\mathbf{W}_t(k)$ (or $\mathbf{W}_r(k)$) is the function of $\mathbf{W}_r(k)$ (or $\mathbf{W}_t(k)$). Therefore, in this paper, as is the case in [8,9], we first derive the receive MMSE-FD filter matrix $\mathbf{W}_r(k)$ considering (the transmit MMSE-FD filter + channel) as the equivalent channel. Then, we derive the transmit MMSE-FD filter matrix $\mathbf{W}_t(k)$ by solving the optimization problem of Eq. (6) for the given $\mathbf{W}_r(k)$.

B. Receive MMSE-FD filter

In this section, we derive the receive MMSE-FD filter matrix $\mathbf{W}_r(k)$ by considering $\overline{\mathbf{H}}(k)=\mathbf{H}(k)\mathbf{W}_t(k)$ as the equivalent channel transfer function. In this case, the objective function is a concave function so that it is minimized when $\partial\varepsilon/\partial\mathbf{W}_r(k)=0$. Therefore, the optimal $\mathbf{W}_r(k)$ is given as

$$\mathbf{W}_r(k)=\overline{\mathbf{H}}^H(k)\left\{\overline{\mathbf{H}}(k)\overline{\mathbf{H}}^H(k)+\gamma^{-1}\cdot\mathbf{I}_{N_r}\right\}^{-1}. \tag{7}$$

C. Transmit MMSE-FD filter

The objective function is expressed as the function only of the transmit MMSE-FD filter matrix $\mathbf{W}_t(k)$ by substituting the optimal $\mathbf{W}_r(k)$ which is derived in the foregoing section into the objective function. The optimization problem is rewritten by substituting Eq. (7) into Eq. (6) and using the matrix inversion lemma [12] as

$$\begin{aligned}&\min_{\{\mathbf{W}_t(k);k=0\sim N_c-1\}}\varepsilon=\sum_{k=0}^{N_c-1}tr\left\{\gamma\cdot\mathbf{H}(k)\mathbf{W}_t(k)\mathbf{W}_t^H(k)\mathbf{H}^H(k)+\mathbf{I}_{N_r}\right\}^{-1}\\&\text{s.t. }\sum_{k=0}^{N_c-1}tr\left\{\mathbf{W}_t(k)\mathbf{W}_t^H(k)\right\}=N_tN_c\end{aligned}. \tag{8}$$

$\mathbf{H}(k)$ and $\mathbf{W}_t(k)$ can be transformed by singular value decomposition (SVD) [12] as

$$\begin{aligned}\mathbf{H}(k)&=\mathbf{U}_h(k)\sqrt{\mathbf{\Lambda}_h(k)}\mathbf{V}_h^H(k)\\\mathbf{W}_t(k)&=\mathbf{U}_t(k)\sqrt{\mathbf{P}_t(k)}\mathbf{V}_t^H(k)\end{aligned}, \tag{9}$$

where $\mathbf{V}_h(k)$, $\mathbf{U}_t(k)$, and $\mathbf{V}_t(k)$ are respectively the $N_t\times N_t$ unitary matrices. $\mathbf{U}_h(k)$ is the $N_r\times N_r$ unitary matrix. $\mathbf{\Lambda}_h(k)$ is the $N_r\times N_t$ matrix whose (j,j) element has the jth eigenvalue of $\mathbf{H}(k)\mathbf{H}^H(k)$; j=0~rank[$\mathbf{H}(k)\mathbf{H}^H(k)$]=$J$, and any other elements are zero. $\mathbf{P}_t(k)$ is the $N_t\times N_t$ diagonal matrix whose diagonal elements have the eigenvalues of $\mathbf{W}_t(k)\mathbf{W}_t^H(k)$. Since $tr[\mathbf{AB}]=tr[\mathbf{BA}]$, where $\mathbf{A}$ and $\mathbf{B}$ are respectively a $N_r\times N_t$ and $N_t\times N_r$ matrices, Eq. (8) can be rewritten by substituting Eq. (9) as

$$\begin{aligned}&\min_{\{\mathbf{P}_t(k),\mathbf{U}_t(k);k=0\sim N_c-1\}}\varepsilon\\&=\sum_{k=0}^{N_c-1}tr\left\{\gamma\cdot\sqrt{\mathbf{\Lambda}_h(k)}\mathbf{V}_h^H(k)\mathbf{U}_t(k)\mathbf{P}_t(k)\mathbf{U}_t^H(k)\mathbf{V}_h(k)\sqrt{\mathbf{\Lambda}_h(k)}+\mathbf{I}_{N_r}\right\}^{-1}\\&\text{s.t. }\sum_{k=0}^{N_c-1}tr\left\{\mathbf{P}_t(k)\right\}=N_tN_c.\end{aligned} \tag{10}$$

It can be seen from Eq. (10) that the optimization problem does not depend on $\mathbf{V}_t(k)$ (i.e., $\mathbf{V}_t(k)$ can be set to arbitrary $N_t\times N_t$ unitary matrix). In this paper, we set $\mathbf{V}_t(k)=\mathbf{I}_{N_t}$ for the sake of brevity. In general, $tr[\mathbf{A}^{-1}]$ is minimized when $\mathbf{A}$ is a diagonal matrix [12]. Therefore, the objective function expressed as Eq. (10) is minimized when $\mathbf{U}_t(k)=\mathbf{V}_h(k)$. From the above, $\mathbf{W}_t(k)$ is expressed as

$$\mathbf{W}_t(k)=\mathbf{V}_h(k)\sqrt{\mathbf{P}_t(k)}. \tag{11}$$

The optimization problem is rewritten by substituting Eq. (11) into Eq. (10) as

$$\begin{aligned}&\min_{\{P_j(k);j=0\sim J-1,k=0\sim N_c-1\}}\varepsilon=\sum_{k=0}^{N_c-1}\sum_{j=0}^{J-1}\frac{1}{\gamma P_j(k)\Lambda_j(k)+1}\\&\text{s.t. }\sum_{k=0}^{N_c-1}\sum_{j=0}^{J-1}P_j(k)=N_tN_c\end{aligned}, \tag{12}$$

where $P_j(k)$ and $\Lambda_j(k)$ are respectively the jth diagonal elements of $\mathbf{P}_t(k)$ and $\mathbf{\Lambda}_h(k)$. Following [13], the optimal solution is given as (for the sake of brevity, the derivation is omitted)

$$P_j(k)=\max\left\{\frac{1}{\sqrt{\mu}}\frac{1}{\sqrt{\gamma\Lambda_j(k)}}-\frac{1}{\gamma\Lambda_j(k)},0\right\}, \tag{13}$$

where μ is chosen to satisfy the constraint condition.

D. Discussion of joint transmit/receive MMSE-FD filtering

In this section, we discuss the behavior of joint transmit/receive MMSE-FD filtering derived in Sect. III-*B* and *C*. The equivalent channel matrix $\hat{\mathbf{H}}(k)$ is expressed as

$$\begin{aligned}\hat{\mathbf{H}}(k)&=\mathbf{W}_r(k)\mathbf{H}(k)\mathbf{W}_t(k)\\&=diag\left[\frac{P_0(k)\Lambda_0(k)}{P_0(k)\Lambda_0(k)+\gamma^{-1}},\ldots,\frac{P_{J-1}(k)\Lambda_{J-1}(k)}{P_{J-1}(k)\Lambda_{J-1}(k)+\gamma^{-1}},\mathbf{0}\right]\\&\equiv diag\left[\hat{H}_{0,0}(k),\ldots,\hat{H}_{J-1,J-1}(k),\mathbf{0}\right]\end{aligned}. \tag{14}$$

It can be seen from Eq. (14) that the MIMO channel matrix $\mathbf{H}(k)$ is diagonalized (i.e., the IAI is avoided) by joint transmit/receive MMSE-FD filtering. It can be also seen that $P_j(k)$ expressed as Eq. (13) is the transmit power allocation factor to the jth eigenmode at the kth frequency. Therefore, joint transmit/receive MMSE-FD filtering achieves the eigenbeam-space division multiplexing (E-SDM) [14].

The transmit weight of joint transmit/receive MMSE-FDE for SC-SISO transmission is expressed as [8,9]

$$|W_t(k)|^2=\max\left\{\frac{1}{\sqrt{\mu}}\frac{1}{\sqrt{\gamma|H(k)|^2}}-\frac{1}{\gamma|H(k)|^2},0\right\}, \tag{15}$$

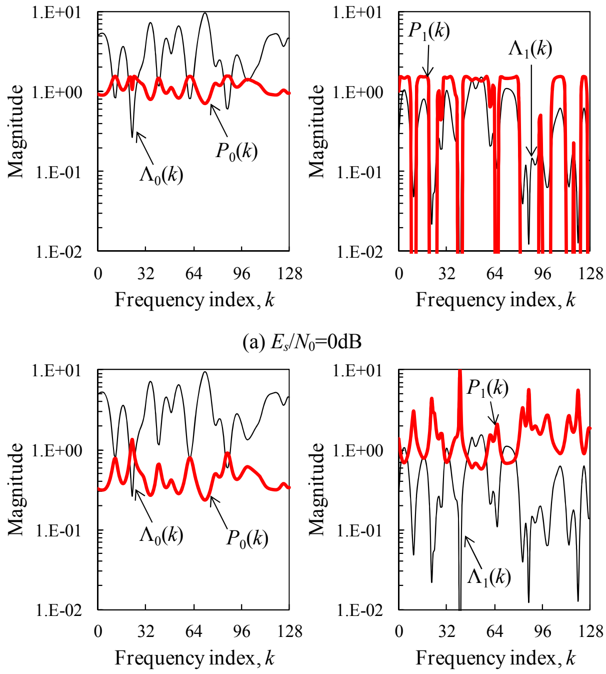
where $H(k)$ is the channel transfer function at the kth frequency. Comparing Eq. (13) to Eq. (15), it can be seen that joint transmit/receive MMSE-FDE is applied into each eigenmode in the case of MIMO transmission.

From the above, joint transmit/receive MMSE-FD filtering can improve the transmission performance by avoiding the IAI by the E-SDM and reducing the ISI by joint transmit/receive MMSE-FDE.

Fig. 2 shows one shot observation of the power allocation of the proposed method. $N_t=N_r=J=2$, $N_c=128$, and an L=16-path frequency-selective block Rayleigh fading having uniform power delay profile is assumed. It can be seen from Eq. (13) that the power allocation of the proposed method is similar to the power allocation based on the well-known water-filling theory [1]. Therefore, much power is allocated to the eigenmodes and frequencies which have high $\Lambda_j(k)$, and no power is allocated to those which have significantly low $\Lambda_j(k)$. However, unlike the conventional power allocation based on the water-filling theory, in the proposed method, each eigenmode and frequency has different threshold (first term of right side of Eq. (13)) because it depends on $\Lambda_j(k)$. Therefore, the proposed method avoids the ISI increase by allocating power to the eigenmodes and frequencies which have comparatively low $\Lambda_j(k)$.

Fig. 2 (a) shows the power allocation when E_s/N_0=0dB. In this case, the impact of noise is much larger than the residual ISI because the received signal-to-noise ratio (SNR) is low especially at the 1st eigenmode which has low $\Lambda_j(k)$. Therefore, the proposed method allocates no power to the frequencies which has low $\Lambda_j(k)$ but allocates much power to the other frequencies to improve the received SNR. On the other hand, at the 0th eigenmode which has comparatively high $\Lambda_j(k)$, the impact of the residual ISI is dominant. Therefore, the power is allocated like the inverse function of $\Lambda_j(k)$ to suppress the residual ISI.

Fig. 2 (b) shows the power allocation when E_s/N_0=20dB. In this case, the impact of the residual ISI is dominant for all eigenmodes. Therefore, the proposed method allocates power like the inverse function of $\Lambda_j(k)$ to suppress the residual ISI. In addition, the proposed method allocates more power to the 1st eigenmode than the 0th eigenmode to reduce the received SNR gap between eigenmodes.



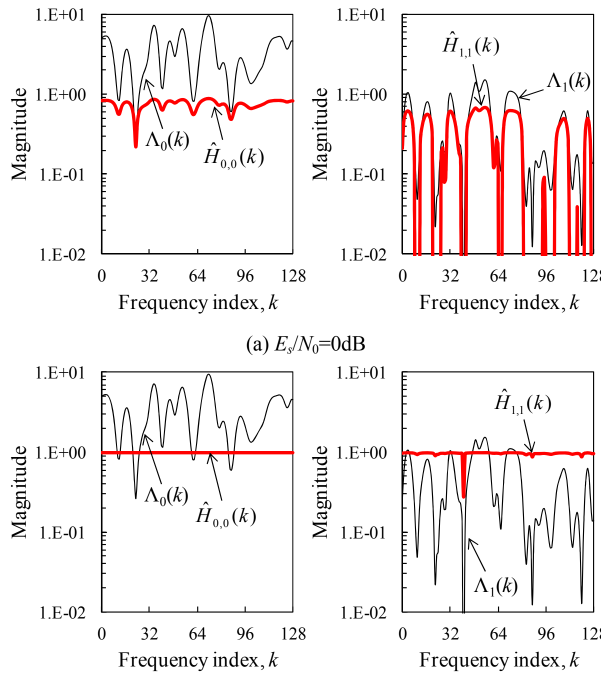
(a) E_s/N_0=0dB

(b) E_s/N_0=20dB

Figure 2. One shot observation of the power allocation.

Fig. 3 shows one shot observation of the equivalent channel $\hat{\mathbf{H}}(k)$ when the power allocation shown in Fig. 2 has been done. Fig. 3 (a) shows $\hat{\mathbf{H}}(k)$ when E_s/N_0=0dB. As noted above, the power allocation is done to improve the received SNR at the 1st eigenmode. Therefore, the residual ISI is larger. On the other hand, at the 0th eigenmode, the residual ISI is suppressed.

Fig. 3 (b) shows $\hat{\mathbf{H}}(k)$ when E_s/N_0=20dB. It can be seen from Fig. 3 (b) that the residual ISI at each eigenmode is suppressed. It can also be seen that there is almost no gain gap between eigenmodes.



(a) E_s/N_0=0dB

(b) E_s/N_0=20dB

Figure 3. One shot observation of the equivalent channel.

IV. Performance Evaluation

A. Computer simulation condition

Computer simulation condition is summarized in Table I. The channel is assumed to be an L=16-path frequency-selective block Rayleigh fading having uniform power delay profile. No antenna correlation and ideal channel estimation at both the transmitter and receiver are assumed.

TABLE I. Computer simulation condition.

Transmitter & Receiver	Data moduration	16QAM, 64QAM
	Packet size	6144bits
	No. of DFT points	N_c=128
	Guard interval length	N_g=16
	Channel estimation	Ideal
	No. of transmit antennas	N_t=2
	No. of receive antennas	N_r=2
Channel	Fading	Frequency-selective block Rayleigh
	Path model	L=16-path with uniform power delay profile
	Time delay difference	1 Symbol

B. Throughput performance

Fig. 4 shows the throughput performance achievable with the proposed method. In this paper, Throughput η (bps/Hz) is defined as

$$\eta \equiv N_t \cdot \log_2 M \cdot (1-\mathrm{PER}) \cdot \frac{N_c}{N_c+N_g}, \tag{16}$$

where M is the modulation level and PER is the average packet error rate. The throughput performance achievable with receive MMSE-FD filtering is also plotted for comparison. It can be seen from Fig. 4 that the proposed method achieves better throughput performance than receive MMSE-FD filtering. This is because, as noted in Section III-*D*, the proposed method avoids the IAI by E-SDM, and suppresses the ISI and improves the received SNR (i.e., improves the received signal-to-interference plus noise ratio (SINR)) by applying joint transmit/receive MMSE-FDE into each eigenmode.

It can also be seen that the proposed method produces more improvement when the modulation level becomes high. For example, the proposed method can reduce the required transmit E_s/N_0 to achieve the 90% value of the peak rate in 16QAM (6.4bps/Hz) about 3dB, but can reduce the required transmit E_s/N_0 to achieve the 90% value of the peak rate in 64QAM (9.6bps/Hz) about 5dB. This is because the throughput performance is very sensitive to the received SINR since the Euclidean distance between the signal points in the signal space is shorter for higher modulation level.

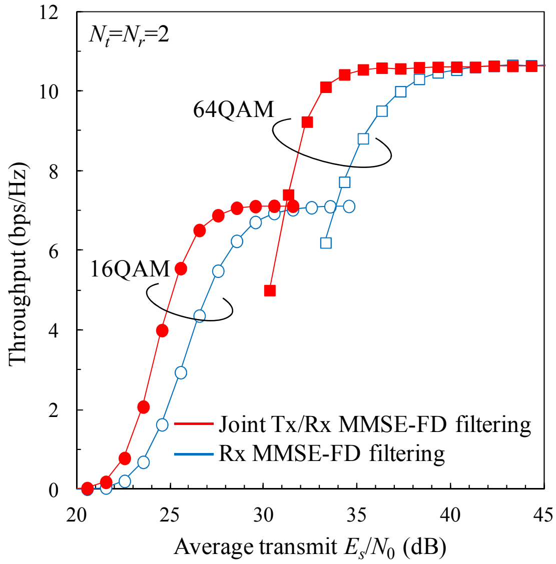


Figure 4. Throughput performance.

V. Conclusion

In this paper, we proposed a joint transmit/receive MMSE-FD filtering for SC-MIMO spatial multiplexing. The proposed joint transmit/receive MMSE-FD filtering transforms the MIMO channel to orthogonal channels (i.e., eigenmodes) so as to avoid the IAI and at the same time suppresses the ISI by applying joint transmit/receive MMSE-FDE to each eigenmode. It was shown by computer simulation that the proposed joint transmit/receive MMSE-FD filtering can achieve better throughput performance than the receive MMSE-FD filtering. Modification of joint transmit/receive MMSE-FD filtering for SC-MIMO spatial multiplexing using adaptive modulation [14] and/or hybrid automatic repeat-request (HARQ) [15,16] is left as an interesting future study.

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