Single-carrier Hybrid ARQ Using Joint Transmit/Receive MMSE-FDE

Kazuki TAKEDA and Fumiyuki ADACHI

Dept. of Electrical and Communication Engineering, Graduate School of Engineering, Tohoku University
6-6-05, Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579, Japan
kazuki@mobile.ecei.tohoku.ac.jp and adachi@ecei.tohoku.ac.jp

Abstract—**In the next generation high-speed wireless packet access systems, hybrid automatic repeat request (HARQ) is necessary to achieve higher throughput performance. An HARQ with Chase combining (CC) transmits the same coded packet until it is correctly received. The received packets are combined to achieve the time-diversity gain. Recently, we proposed a joint transmit/receive frequency-domain equalization (FDE) based on the minimum mean square error (MMSE) criterion for a broadband single-carrier (SC) signal transmission in a frequency-selective channel. In this paper, we consider SC-HARQ using joint transmit/receive MMSE-FDE and derive a suboptimal set of transmit and receive FDE weights for packet combining. We show by computer simulation that the joint transmit/receive MMSE-FDE offers improved throughput compared to the conventional receive MMSE-FDE.**

Keywords-component; Frequency-domain equalization, packet combining, HARQ

I. INTRODUCTION

The broadband wireless channel comprises many propagation paths having different time delays [1]. The throughput performance of single-carrier (SC) packet access significantly degrades due to strong inter-symbol interference (ISI) in a severe frequency-selective channel. Simple one-tap frequency-domain equalization (FDE) based on the minimum mean square error (MMSE) criterion provides good bit error rate (BER) performance [2-4]. SC with MMSE-FDE combined with FDMA (called SC-FDMA) is adopted for the uplink access in the 3G long-term evolution (LTE) systems [5].

To further improve the BER performance of SC with MMSE-FDE, we recently proposed a joint transmit/receive MMSE-FDE [6]. In the joint transmit/receive MMSE-FDE, one-tap FDE is applied not only at the receiver but also at the transmitter. In [6], we derived a suboptimal set of transmit and receive FDE weights which minimizes the total mean square error (MSE) of the transmit SC block and then, showed its BER performance improvement by numerical evaluation and computer simulation.

Hybrid automatic repeat request (HARQ) is a key technique to realize a high-speed wireless packet access [7]. Throughput performance of SC-HARQ using the receive MMSE-FDE was evaluated in [8]. In HARQ using the Chase combining (CC) strategy (or type I), if any error is detected in a received packet after decoding, the same coded packet is retransmitted until it is correctly received [9,10]. The retransmitted packets are combined to achieve the time-diversity gain. In [8], SC-HARQ using the receive MMSE-FDE was presented. All the received packets are combined in the frequency-domain based on the MMSE criterion. Every time the same packet is retransmitted, the receiver updates the FDE and packet combining weights of all the received packets so that the mean square error (MSE) after the packet combining is minimized, similar to the combined receive antenna diversity and receive MMSE-FDE [11].

If the set of transmit and receive FDE weights of our proposed scheme is chosen by taking into account the packet combining, throughput of SC-HARQ may be significantly improved. The joint transmit/receive ARQ strategy was presented in [12] for multi-input multi-output (MIMO) multiplexing in a frequency-nonselective channel. In this paper, SC-HARQ using joint transmit/receive MMSE-FDE is presented. A suboptimal set of transmit and receive FDE weights for packet combining is derived using similar way to [12]. We show by computer simulation that joint transmit/receive MMSE-FDE offers improved throughput compared to the conventional receive MMSE-FDE.

The remainder of this paper is organized as follows. Section II describes the system model of SC-HARQ using joint transmit/receive MMSE-FDE. In Sect. III, a suboptimal set of transmit and receive FDE weights is derived. Section IV shows the performance evaluation. Section V concludes this paper.

II. SYSTEM MODEL

A conceptual diagram of SC-HARQ using joint transmit/receive MMSE-FDE is illustrated in Fig. 1. In this paper, we consider the CC strategy for SC-HARQ. The proposed packet combining method can be easily extended to the incremental redundancy (IR) strategy [10].

For the first transmission, joint transmit/receive MMSE-FDE [6] recently proposed by authors is applied. At the receiver, after the channel decoding, error detection is performed. If any error is detected, the receiver sends the NACK signal to the transmitter to request the retransmission. The transmit FDE is applied to a retransmitting packet. At the receiver, after receiving the retransmitted packet, receive FDE and frequency-domain packet combining are jointly performed. After the channel decoding, error detection is performed. If no error is detected, the ACK signal is sent to the transmitter to request the transmission of a new packet.

In this paper, turbo coding is used for SC-HARQ. The information bit sequence is turbo encoded with the coding rate R. A packet is generated by data-modulating the resultant codeword. The data sequence of the packet is grouped in a sequence of N_c-symbol blocks, where N_c is the size of fast Fourier transform (FFT) and inverse FFT (IFFT). The joint transmit/receive MMSE-FDE is performed block-by-block. In Sects. II and III, without loss of generality, we consider one N_c-symbol block in a packet (which consists of multiple blocks) and the block number in a packet is omitted for the sake of simplicity.

We assume that both the transmitter and the receiver have the perfect knowledge of channel state information (CSI). Below, it is assumed that the same packet has been retransmitted M times (including the first transmission).

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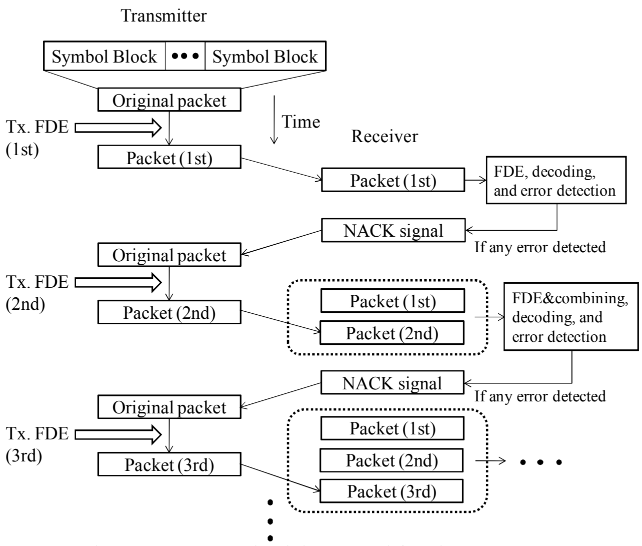


Fig.1 SC-HARQ using joint transmit/receive MMSE-FDE.

A. Transmit signal

The N_c-symbol block is represented as $\mathbf{d}=[d(0), \ldots, d(t), \ldots, d(N_c-1)]^T$. N_c-point FFT is carried out on $\mathbf{d}$ to obtain the frequency-domain transmit signal $\mathbf{D}=[D(0), \ldots, D(k), \ldots, D(N_c-1)]^T$, where $\mathbf{D}$ is given by

$$\mathbf{D}=\mathbf{F}\mathbf{d} \tag{1}$$

with

$$\mathbf{F}=\frac{1}{\sqrt{N_c}}\begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & e^{-j2\pi\frac{(1\times 1)}{N_c}} & \cdots & e^{-j2\pi\frac{(1\times(N_c-1))}{N_c}} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & e^{-j2\pi\frac{((N_c-1)\times 1)}{N_c}} & \cdots & e^{-j2\pi\frac{((N_c-1)\times(N_c-1))}{N_c}} \end{bmatrix} \tag{2}$$

being an $N_c \times N_c$ FFT matrix.

The transmit FDE weight, which is multiplied to the kth frequency component $D(k)$ of a block in the mth retransmitting packet is denoted by $\{W_t^{(m)}(k)\,;\, k=0\sim N_c-1\}$, $m=0\sim M-1$. Before transmitting the $(M-1)$th retransmitting packet, the transmit FDE weight $\{W_t^{(M-1)}(k)\,;\, k=0\sim N_c-1\}$ is multiplied to $\{D(k); k=0\sim N_c-1\}$ as

$$\begin{aligned}\mathbf{S}^{(M-1)} &= [S^{(M-1)}(0),\ldots,S^{(M-1)}(k),\ldots,S^{(M-1)}(N_c-1)]^T \\ &= C^{(M-1)}\cdot \mathbf{W}_t^{(M-1)}\mathbf{D}\end{aligned}, \tag{3}$$

where $\mathbf{W}_t^{(M-1)}=diag\{W_t^{(M-1)}(0),\ldots,W_t^{(M-1)}(k),\ldots,W_t^{(M-1)}(N_c-1)\}$ is an $N_c\times N_c$ diagonal transmit FDE weight matrix for the $(M-1)$th retransmitting packet. $C^{(M-1)}$ is the normalization factor, which is introduced to keep the transmit power always the same, given by

$$C^{(M-1)}=\sqrt{N_c/tr[\{\mathbf{W}_t^{(M-1)}\}\{\mathbf{W}_t^{(M-1)}\}^H]}\,. \tag{4}$$

An N_c-point IFFT is applied to $\mathbf{S}^{(M-1)}$ to obtain a block $\mathbf{s}^{(M-1)}=[s^{(M-1)}(0),\ldots,s^{(M-1)}(t),\ldots,s^{(M-1)}(N_c-1)]^T=\mathbf{F}^H\mathbf{S}^{(M-1)}$ in the time-domain $(M-1)$th retransmitting signal packet. After the insertion of N_g-sample cyclic prefix (CP) into the guard interval (GI), the packet is transmitted.

B. Received signal

The propagation channel is assumed to be an L-path frequency-selective block fading channel. M copies of the same packet have been received. The complex-valued path gain and time delay of the lth path of the mth retransmitting packet are denoted by $h_l^{(m)}$ and $\tau_l^{(m)}$, $l=0\sim L-1$, $m=0\sim M-1$, respectively. The CP-length is assumed to be equal to or longer than the maximum channel time delay τ_{L-1}. The received signal block $\mathbf{r}^{(m)}=[r^{(m)}(0), \ldots, r^{(m)}(t), \ldots, r^{(m)}(N_c-1)]^T$ after the CP-removal in the mth retransmitted packet can be expressed as

$$\mathbf{r}^{(m)}=\sqrt{2E_s/T_s}\,\mathbf{h}^{(m)}\mathbf{s}^{(m)}+\mathbf{n}^{(m)}, \tag{5}$$

where E_s and T_s are the average transmit symbol energy and symbol duration, respectively, $\mathbf{h}^{(m)}$ is an $N_c\times N_c$ circulant channel matrix given by

$$\mathbf{h}^{(m)}=\begin{bmatrix} h_0^{(m)} & & & h_{L-1}^{(m)} & \cdots & h_1^{(m)} \\ h_1^{(m)} & \ddots & & & \ddots & \vdots \\ \vdots & & h_0^{(m)} & \mathbf{0} & & h_{L-1}^{(m)} \\ h_{L-1}^{(m)} & & h_1^{(m)} & \ddots & & \\ & \ddots & \vdots & & \ddots & \\ \mathbf{0} & & h_{L-1}^{(m)} & \cdots & \cdots & h_0^{(m)} \end{bmatrix}, \tag{6}$$

and $\mathbf{n}^{(m)}=[n^{(m)}(0), \ldots, n^{(m)}(t), \ldots, n^{(m)}(N_c-1)]^T$ is the noise vector with $n^{(m)}(t)$ being a zero-mean additive white Gaussian noise (AWGN) having variance $2N_0/T_c$ (N_0 is the one-sided noise power spectrum density).

An N_c-point FFT is carried out on M copies of the same signal block, $\mathbf{r}^{(m)}$, $m=0\sim M-1$, to obtain the frequency-domain received signals $\mathbf{R}^{(m)}$, $m=0\sim M-1$. $\mathbf{R}^{(m)}=[R^{(m)}(0), \ldots, R^{(m)}(k), \ldots, R^{(m)}(N_c-1)]^T$ is given as

$$\mathbf{R}^{(m)}=\mathbf{F}\mathbf{r}^{(m)}=\sqrt{2E_s/T_s}\,C^{(m)}\cdot\mathbf{H}^{(m)}\mathbf{W}_t^{(m)}\mathbf{D}+\mathbf{N}^{(m)}, \tag{7}$$

where $\mathbf{N}^{(m)}=\mathbf{F}\mathbf{n}^{(m)}$ and $\mathbf{H}^{(m)}=\mathbf{F}\mathbf{h}^{(m)}\mathbf{F}^H$. Due to the circulant property of $\mathbf{h}^{(m)}$, the channel gain matrix $\mathbf{H}^{(m)}$ of size $N_c\times N_c$ is diagonal. The kth diagonal element of $\mathbf{H}^{(m)}$ is given by

$$H(k)=\sum_{l=0}^{L-1}h_l^{(m)}\exp(-j2\pi k\tau_l^{(m)}/N_c)\,. \tag{8}$$

$\mathbf{R}^{(m)}$, $m=0\sim M-1$, are combined as

$$\begin{aligned}\hat{\mathbf{R}} &= \sum_{m=0}^{M-1}\frac{\mathbf{W}_r^{(m)}\mathbf{R}^{(m)}}{C^{(m)}} \\ &= \sqrt{\frac{2E_s}{T_s}}\sum_{m=0}^{M-1}\mathbf{W}_r^{(m)}\mathbf{H}^{(m)}\mathbf{W}_t^{(m)}\mathbf{D}+\sum_{m=0}^{M-1}\frac{\mathbf{W}_r^{(m)}\mathbf{N}^{(m)}}{C^{(m)}},\end{aligned} \tag{9}$$

where $\mathbf{W}_r^{(m)}=diag\{W_r^{(m)}(0),\ldots,W_r^{(m)}(k),\ldots,W_r^{(m)}(N_c-1)\}$ is an $N_c\times N_c$ diagonal receive FDE weight matrix for the mth retransmitting packet, $m=0\sim M-1$. An N_c-point IFFT is applied to $\hat{\mathbf{R}}$ to obtain the decision variable vector $\hat{\mathbf{d}}=[\hat{d}(0), \ldots, \hat{d}(t), \ldots, \hat{d}(N_c-1)]^T$ as

$$\begin{aligned}\hat{\mathbf{d}}=\mathbf{F}^H\hat{\mathbf{R}} &= \sqrt{2E_s/T_s}\sum_{m=0}^{M-1}\mathbf{F}^H\mathbf{W}_r^{(m)}\mathbf{H}^{(m)}\mathbf{W}_t^{(m)}\mathbf{F}\mathbf{d} \\ &\quad +\sum_{m=0}^{M-1}\frac{\mathbf{F}^H\mathbf{W}_r^{(m)}\mathbf{N}^{(m)}}{C^{(m)}}.\end{aligned} \tag{10}$$

III. SUBOPTIMAL TRANSMIT AND RECEIVE FDE WEIGHTS

In this section, we derive the suboptimal set of transmit and receive FDE weights assuming that the same packet has been retransmitted M times. First, we derive the receive FDE weights. Then, assuming that the derived receive FDE weights have been used, we derive the transmit FDE weight.

A. Receive FDE weights

A concatenation of the transmit FDE and the propagation channel can be viewed as an equivalent channel. This is used to derive the receive FDE weights. We define the expanded received signal vector $\mathbf{R}$ of size $MN_c\times 1$ as

$$\mathbf{R}=[\{\mathbf{R}^{(0)}\}^T \quad \cdots \quad \{\mathbf{R}^{(M-1)}\}^T]^T=\sqrt{\frac{2E_s}{T_s}}\mathbf{C}\overline{\mathbf{H}}\mathbf{D}+\overline{\mathbf{N}}, \quad (11)$$

where

$$\begin{cases}\mathbf{C}=diag\{C^{(0)}\cdot\mathbf{I}, \quad ..., \quad C^{(m)}\cdot\mathbf{I}, \quad ..., \quad C^{(M-1)}\cdot\mathbf{I}\}\\ \overline{\mathbf{H}}=[\mathbf{H}^{(0)}\mathbf{W}_t^{(0)} \quad \cdots \quad \mathbf{H}^{(M-1)}\mathbf{W}_t^{(M-1)}]^T\\ \overline{\mathbf{N}}=[\{\mathbf{N}^{(0)}\}^T \quad \cdots \quad \{\mathbf{N}^{(M-1)}\}^T]^T.\end{cases} \quad (12)$$

Eq. (10) can be rewritten as

$$\hat{\mathbf{d}}=\mathbf{F}^H\mathbf{W}_r\mathbf{C}^{-1}\mathbf{R}=\sqrt{\frac{2E_s}{T_s}}\mathbf{F}^H\mathbf{W}_r\overline{\mathbf{H}}\mathbf{F}\mathbf{d}+\mathbf{F}^H\mathbf{C}^{-1}\mathbf{W}_r\overline{\mathbf{N}}, \quad (13)$$

where $\mathbf{W}_r=[\mathbf{W}_r^{(0)},...,\mathbf{W}_r^{(m)},...,\mathbf{W}_r^{(M-1)}]$.

We define the error vector $\mathbf{e}=[e(0), \ldots, e(t), \ldots, e(N_c-1)]^T$ between $\mathbf{d}$ and $\hat{\mathbf{d}}$, similar to [6], as

$$\mathbf{e}=\mathbf{F}^H\mathbf{W}_r\overline{\mathbf{H}}\mathbf{F}\mathbf{d}+(2E_s/T_s)^{-1/2}\mathbf{F}^H\mathbf{W}_r\mathbf{C}^{-1}\overline{\mathbf{N}}-\mathbf{d}. \quad (14)$$

The total MSE is given by $e=tr[E(\mathbf{e}\mathbf{e}^H)]$. The MMSE solution of $\mathbf{W}_r$ that minimizes e can be obtained according to the Wiener theory as

$$\mathbf{W}_r=\overline{\mathbf{H}}^H\{\overline{\mathbf{H}}\overline{\mathbf{H}}^H+(E_s/N_0)^{-1}\mathbf{C}^{-1}\mathbf{C}^{-H}\}^{-1}, \quad (15)$$

which can be rewritten using the matrix inversion lemma [1] as

$$\mathbf{W}_r=\left\{\mathbf{I}+\overline{\mathbf{H}}^H\left(\frac{E_s}{N_0}\right)\mathbf{C}^H\mathbf{C}\overline{\mathbf{H}}\right\}^{-1}\overline{\mathbf{H}}^H\left(\frac{E_s}{N_0}\right)\mathbf{C}^H\mathbf{C}. \quad (16)$$

From Eq. (16), we obtain the receive FDE weight matrix $\mathbf{W}_r^{(m)}$, when M copies of the same packet have been received, as

$$\mathbf{W}_r^{(m)}=\left\{\mathbf{I}+(E_s/N_0)\sum_{m'=0}^{M-1}\{C^{(m')}\}^2 \times\{\mathbf{H}^{(m')}\mathbf{W}_t^{(m')}\}^H\{\mathbf{H}^{(m')}\mathbf{W}_t^{(m')}\}\right\}^{-1}\{\mathbf{H}^{(m)}\mathbf{W}_t^{(m)}\}^H\{C^{(m)}\}^2, \quad m=0\sim M-1. \quad (17)$$

If the transmit FDE is not used, $\mathbf{W}_t^{(m)}=\mathbf{I}$ and Eq. (17) reduces to

$$\mathbf{W}_r^{(m)}=\left\{\mathbf{I}+(E_s/N_0)\sum_{m'=0}^{M-1}\{\mathbf{H}^{(m')}\}^H\{\mathbf{H}^{(m')}\}\right\}^{-1}\{\mathbf{H}^{(m)}\}^H, \quad (18)$$

which is identical to the packet combining using the conventional receive MMSE-FDE [8]. Every time the same packet is received, the receive FDE weight matrix $\mathbf{W}_r^{(m)}$ of Eq. (17) is updated.

B. Transmit FDE

Substituting Eq. (16) into Eq. (14), we obtain

$$e=tr\left[\left\{\mathbf{I}+\left(\frac{E_s}{N_0}\right)N_c\sum_{m=0}^{M-1}\frac{\mathbf{P}^{(m)}\cdot\mathbf{H}^{(m)}\{\mathbf{H}^{(m)}\}^H}{tr[\mathbf{P}^{(m)}]}\right\}^{-1}\right], \quad (19)$$

where $\mathbf{P}^{(m)}=\{\mathbf{W}_t^{(m)}\}^H\mathbf{W}_t^{(m)}$. Similar to [6], we introduce the transmit power constraint $tr[\mathbf{P}^{(m)}]=N_c$, $m=0\sim M-1$. The optimality problem can be expressed as

$$\begin{aligned}&\min. \quad e\\ &s.t. \quad tr[\mathbf{P}^{(m)}]=N_c, \quad m=0\sim M-1.\end{aligned} \quad (20)$$

Obviously, the transmit FDE weights cannot be optimized for already retransmitted packets. We can only optimize the transmit FDE weight for the presently retransmitting packet. The MMSE solution $\mathbf{W}_t^{(M-1)}$ (or $\mathbf{P}^{(M-1)}$) can be derived using the Lagrange multiplier method [1] under the transmit power constraint. The solution satisfies the Karush-Kuhn-Tucker (KKT) condition [14, 15]. The MMSE solution is obtained as

$$\mathbf{P}_{opt}^{(M-1)}=diag\left\{P_{opt}^{(M-1)}(0), \quad \ldots, \quad P_{opt}^{(M-1)}(k), \quad \ldots, \quad P_{opt}^{(M-1)}(N_c-1)\right\} \quad (21)$$

with

$$P_{opt}^{(M-1)}(k)=\max\left\{\theta^{(M-1)}\sqrt{\Omega}/|H^{(M-1)}(k)| -\left(N_c\Omega+\sum_{m<M-1}P_{opt}^{(m)}(k)\left|H^{(m)}(k)\right|^2\right)/|H^{(M-1)}(k)|^2, \quad 0\right\}, \quad (22)$$

where $\theta^{(M-1)}$ is chosen so as to satisfy $tr[\mathbf{P}^{(M-1)}]=N_c$.

It can be understood from Eq. (22) that the transmit FDE weight $\mathbf{W}_t^{(M-1)}$ can be found recursively for the given transmit power, the present channel matrix $\mathbf{H}^{(M-1)}$, the past channel matrices $\{\mathbf{H}^{(m)}; m< M-1\}$, and the past transmit FDE weights $\{\mathbf{W}_t^{(m)}; m<M-1\}$. When $M>1$, the transmit FDE weights for past retransmitted packets cannot be changed and hence, in our proposed scheme, only the transmit FDE weight for the present retransmission is modified based on the MMSE criterion. At the receiver, upon the reception of the (M–1)th retransmitted packet, the receive FDE weights for M copies of the same packet are updated. Eqs. (18) and (21) are the diagonal matrices and therefore, the joint transmit/receive MMSE-FDE for packet combining still remains as one-tap FDE.

IV. PERFORMANCE EVALUATION

In this section we present the performance evaluation of SC-HARQ using joint transmit/receive MMSE-FDE. A frequency-selective block Rayleigh fading channel having an L=16-path uniform power delay profile is assumed. A turbo encoder with the original coding rate 1/3 using two (13, 15) recursive systematic encoders, a block channel interleaver/deinterleaver, and log-MAP turbo decoding with 8 iterations are used. As for data modulation, QPSK and 16QAM are considered. Information bit length K=6144 with the coding rate R=1/2 and block size of N_c=256 are assumed (i.e., each packet contains 24 (12) symbol blocks for QPSK (16QAM)). GI length of N_g=32 is considered. Independent channel is assumed for each retransmission. Also we assume ideal ACK/NACK transmissions.

A. Equivalent channel gain

How the channel is altered when using the frequency-domain packet combining is discussed. We assume that the same packet has been retransmitted M=4 times. Figure 2 illustrates the channel transfer functions seen at the mth (m=0~3) retransmission. Figure 3 illustrates the equivalent channels seen after packet combining using the joint transmit/receive MMSE-FDE when the average transmit symbol energy-to-noise power spectrum density ratio E_s/N_0= −5dB and +5dB. For comparison, the equivalent channels obtained by conventional receive MMSE-FDE are also plotted in Fig. 4. For both cases, the same propagation channels shown in Fig. 2 are assumed.

The advantage of the use of joint transmit/receive MMSE-FDE for the first transmission in a frequency-selective channel was discussed in [6]. The joint transmit/receive MMSE-FDE reduces the channel variation to suppress the residual ISI when E_s/N_0 is large enough. On the other hand, when E_s/N_0 is small, it enhances the degree of channel variations but increases the received signal-to-noise power ratio (SNR) since most of the total energy tends to be allocated to the frequencies having a good condition. In case M>1, due to the third term of Eq. (22), as the number of packet retransmissions increases, the equivalent channel becomes more likely flat.

We can see from Figs. 3 and 4 that in both cases of E_s/N_0= −5dB and +5dB, the frequency-domain packet combining using the joint transmit/receive MMSE-FDE provides better channel conditions. Comparison of Figs. 3 and 4 confirms that the joint transmit/receive MMSE-FDE can make the frequency-selectivity of the equivalent channel much weaker than the conventional receive MMSE-FDE.

B. Packet error rate performance

Figure 5 plots the turbo coded PER performance with M=1~4 obtained by computer simulation. For comparison, the PER performance with frequency-domain packet combining using the conventional receive MMSE-FDE (i.e., $\mathbf{W}_t^{(m)}=\mathbf{I}$, m=0~M−1) is also plotted. It can be seen from Fig. 5 that SC-HARQ using joint transmit/receive MMSE-FDE provides better PER performance than that using the conventional receive MMSE-FDE. As seen from Fig. 5, the PER performance improvement of joint transmit/receive MMSE-FDE over the conventional receive MMSE-FDE gets larger as M increases. For example, when M=1 (4) and QPSK is used, the joint transmit/receive MMSE-FDE can reduce the required E_s/N_0 for achieving PER=10^{-2} by about 0.5dB (2.0dB) compared to the conventional receive MMSE-FDE.

C. Throughput performance

Figure 6 plots the achievable throughput performance of SC-HARQ using joint transmit/receive MMSE-FDE. The throughput performance using the conventional receive MMSE-FDE is also plotted for comparison. It can be seen from Fig. 6 that the joint transmit/receive MMSE-FDE provides always better throughput performance than the conventional receive MMSE-FDE. In a low transmit E_s/N_0 region, the packet retransmission happens more likely. However, the joint transmit/receive MMSE-FDE offers higher packet combining gain than the conventional receive MMSE-FDE and therefore, throughput improves. On the other hand, in a high transmit E_s/N_0 region, since the first packet transmission is most likely successful, the joint transmit/receive MMSE-FDE provides only slightly higher throughput than the conventional receive MMSE-FDE.

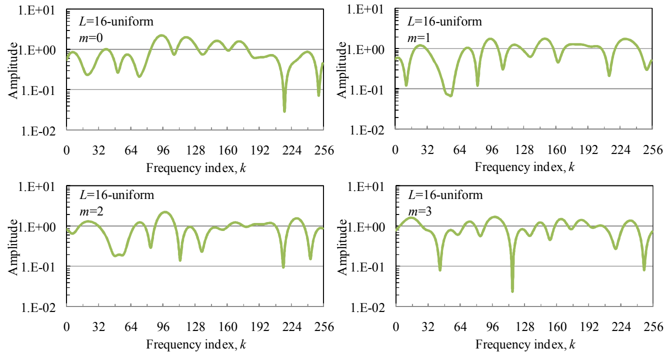
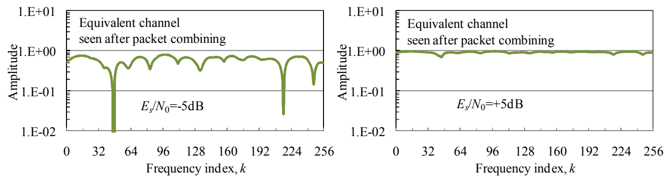
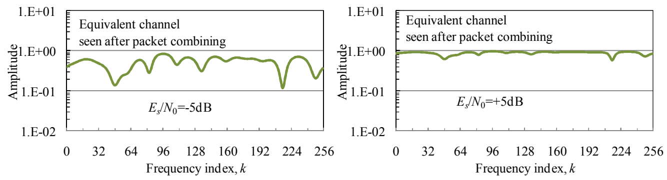


Fig. 2 Autual channels for four times transmitted packet.



(a) E_s/N_0=−5dB (b) E_s/N_0=+5dB

Fig. 3 Equivalent channels after packet combining using the joint transmit/receive MMSE-FDE.



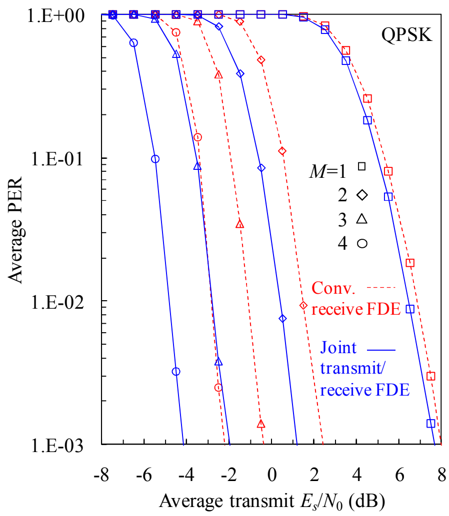
(a) E_s/N_0=−5dB (b) E_s/N_0=+5dB

Fig. 4 Equivalent channels after packet combining using the conventional receive MMSE-FDE.

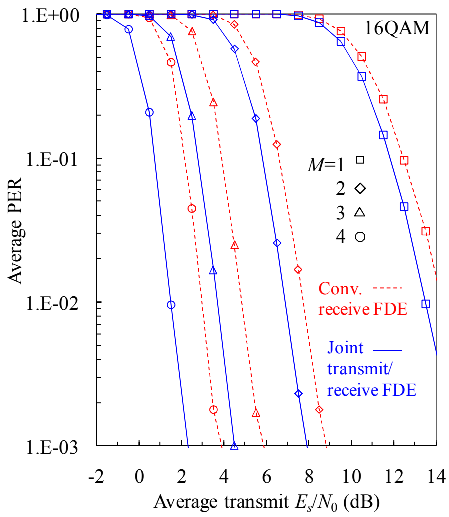
V. CONCLUSION

In this paper, we proposed SC-HARQ using the joint transmit/receive MMSE-FDE and evaluated the achievable PER and throughput performances by computer simulation. It was shown that the proposed packet combining offers a significant improvement of the PER performance. This results in the throughput improvement in a low E_s/N_0 region. However, only a slight throughput improvement can be obtained in a high E_s/N_0 region. To obtain improved throughput performance in a high E_s/N_0 region, the introduction of an iterative ISI cancellation technique [16] is effective. The introduction of the iterative ISI cancellation into SC-HARQ is left as an interesting future study.

In this paper, we assumed the perfect knowledge of CSI at both the transmitter and the receiver. In a practical system, however, the CSI should be estimated. How the channel estimation error affects the SC transmission performance using joint transmit/receive MMSE-FDE is also left as an important future study topic.

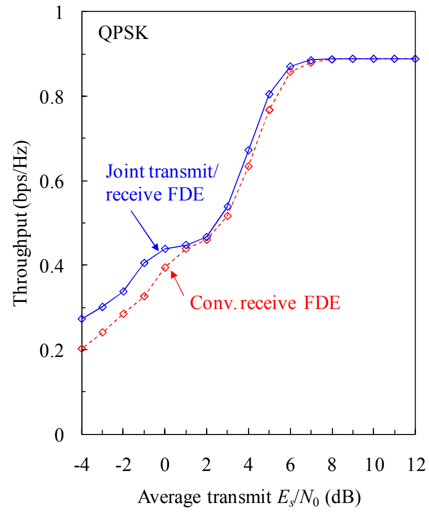


(a) QPSK

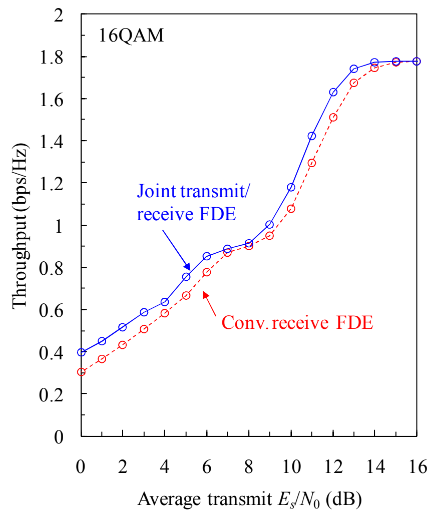


(b) 16QAM

Fig. 5 PER performance.



(a) QPSK



(b) 16QAM

Fig. 6 Throughput performance.

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