# Minimum Mean Partial Interference Criterion for Serial Processing Structure of Equalizer and MLD in Multipath Fading MIMO Channel

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*Abstract*—**This paper proposes a new criterion for equalizer combining weight called the minimum mean partial interference (MMPI) criterion, which is used with a serial processing structure of the equalizer and the maximum likelihood detection (MLD) for single-carrier signals in a multipath fading Multiple-Input Multiple-Output (MIMO) channel. The equalizer with the MMPI weight effectively suppresses multipath interference (MPI) as partial interference when compared with the conventional minimum mean square error (MMSE) equalizer by allowing leaving the inter-antenna interference (IAI) in the MIMO channel, and then the remaining IAIs are effectively suppressed by the MLD. We show that the additional complexity for modifying the MMSE equalizer to be the MMPI equalizer is quite small. Our computer simulation for the combination of the proposed MMPI equalizer and the MLD shows maximum 5.0-dB gain when compared with the conventional MMSE receiver. We also show that the throughput performance of HSDPA is improved by using the MMPI equalizer and MLD.**

***Keywords: MLD; MMSE; Multipath Interference; Inter-Antenna Interference; Equalizer; CDMA***

## I. Introduction

A new long-term evolution (LTE) commercial service was started in December 2010 in Japan. The LTE is a standard in the mobile phone network, and it is a project of the 3rd generation partnership project (3GPP). The LTE provides high-speed downlink transmission by using OFDM MIMO multiplexing. Among the decoding schemes for OFDM MIMO, maximum likelihood detection (MLD) [1] can reduce the required signal energy per bit-to-noise power-spectrum density ratio ($E_b/N_0$) satisfying the required average bit error rate or block error rate (BLER) better than the other methods. Thus, the MLD approach is the most promising. Moreover, recent several efforts for the MLD algorithm [2][3] realize a remarkable reduction in the computational complexity compared to that of the full MLD for OFDM MIMO multiplexing.

The High Speed Packet Access (HSPA) system is an enhancement of Wideband Code Division Multiple Access (W-CDMA) system based on direct sequence CDMA (DS-CDMA), which is also standardized by the 3GPP, and it is widely used in the world. However, most of the HSPA MIMO terminals make use of the MMSE equalizer-based receiver or RAKE receiver instead of the MLD receiver. This is because the impact of severe multi-path interference (MPI) for complexity is significantly large in the DS-CDMA system with high-speed transmission. Namely, if the MLD method considering the multipath propagation is directly applied to broadband DS-CDMA, the complexity is exponentially increased according to the increase in the number of multipaths. Accordingly, the level of the computational complexity must be decreased to the appropriate level of an actual implementation to make the application of the MLD approach practical. To mitigate those computational complexities, the receiver structure for the DS-CDMA receiver that is utilizing the MLD after applying the MPI canceller is proposed [4]. The MPI canceller generally needs, however, a large amount of computational complexity when compared with the typical MMSE receiver used for the HSPA receiver.

In this paper, we investigate a new criterion for equalizer combining weight called the minimum mean partial interference (MMPI) criterion, which is used with a serial processing structure of the equalizer and the MLD in the multipath fading MIMO channel. The equalizer with the MMPI weight effectively suppresses the MPI as partial interference when compared with the conventional MMSE equalizer by allowing leaving the inter-antenna interference (IAI) in the MIMO channel, and then the remaining IAIs are effectively suppressed by the MLD. Therefore, the serial processing structure with the MMPI weight shows better performance than that with the conventional MMSE weight. Moreover, the additional complexity for the MMPI equalizer itself is quite small.

This paper is organized as follows. In the following section, we will describe a simulation model for the serial processing structure of the MMSE equalizer and the MLD in multipath fading MIMO channel, followed by a description in Section III of the MMPI criterion equalizer. We present our computer simulations in Section IV before presenting our conclusions in Section V.

## II. Simulation Model for Serial Processing Structure of MMSE Equalizer and MLD in Multipath Fading MIMO Channel

Fig. 1 shows an outline of simulation model. In this chapter, we describe the serial processing receiver structure of MMSE equalizer and MLD in the figure except for the MMPI modification block. As shown in the figure, we have assumed a MIMO system with two transmit antennas denoted by $p$ (= 0 or 1) and two receive antennas denoted by $q$ (= 0 or 1). In this case, the received signal of the $q$-th receive antenna, $v_q(t)$, at the mobile terminal can be written as follows:

$$v(t) = \begin{pmatrix} v_0(t) \\ v_1(t) \end{pmatrix} = \sum_{l=0}^{L-1} \sum_{k=-\infty}^{\infty} H_l W d_k c(t - kT - \tau_l) + n(t) \quad (1)$$

where $H_l$ is a channel matrix for the $l$-th path ($l = 0 \ldots L$-1) written by complex-valued channel gains $h'_{q,p,l}$ between the $p$-th transmitter antenna branch and the $q$-th receiver antenna branch associated with the $l$-th path

$$H_l = \begin{pmatrix} h'_{0,0,l} & h'_{0,1,l} \\ h'_{1,0,l} & h'_{1,1,l} \end{pmatrix}, \tag{2}$$

$W$ is the precoding unitary 2x2 matrix, $d_k = (d_{0,k}, d_{1,k})^T$ is the $k$-th modulated symbol vector, $c(t)$ is a symbol waveform, $T$ is the symbol duration, and $\tau_l$ is delay time for the $l$-th path. Then, the sampling data vector $v_i$ consists of $v_{q,i} = v_q(iT)$

$$v_i = (v_{0,i-(N_w-1)/2}, \ldots, v_{0,i+(N_w-1)/2}, v_{1,i-(N_w-1)/2}, \ldots, v_{1,i+(N_w-1)/2})^T \tag{3}$$

is equalized by using conventional MMSE weight $w_p$

$$v_i' = W^H (w_0 \quad w_1)^H v_i, \tag{4}$$

where $v'_i$ is an equalized symbol, $N_w$ is the window size of the equalizer, the superscript H denotes Hermitian transposition, and the MMSE weight $w_p$ is written as

$$w_p = R^{-1} h_p \tag{5}$$

$$R = (HH^H + \sigma^2 I_{2N_w}) \tag{6}$$

where $I_n$ is an identity matrix of dimension $n$, $\sigma^2$ is the average noise power, $H$ is the channel matrix for the MMSE weight given by the channel gain $h_{q,p,i}$ of the $i$-th sample

$$H = \begin{pmatrix} conv2(h''_{0,0}, I_{N_w})^T & conv2(h''_{0,1}, I_{N_w})^T \\ conv2(h''_{1,0}, I_{N_w})^T & conv2(h''_{1,1}, I_{N_w})^T \end{pmatrix}, \tag{7}$$

$$h''_{q,p} = (h_{q,p,i+(N_w-1)/2}, \ldots, \quad h_{q,p,i}, \quad \ldots \quad h_{q,p,i-(N_w-1)/2})^T, \tag{8}$$

$$h_{q,p,i} = \sum_{l=0}^{L-1} h'_{q,p,l}\, c(t - iT - \tau_l), \tag{9}$$

and $h_p$ is the channel response vector for the transmit antenna $p$

$$h_p = (h_{0,p,i-(N_w-1)/2}, \ldots, h_{0,p,i+(N_w-1)/2}, h_{1,p,i-(N_w-1)/2}, \ldots, h_{1,p,i+(N_w-1)/2})^T \tag{10}$$

The function $conv2$ in (7) is the 2D convolution function used in the Matlab system. For example, it works as follows:

$$conv2\left(\begin{pmatrix}1\\2\\3\end{pmatrix}, \begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}\right) = \begin{pmatrix}1&0&0\\2&1&0\\3&2&1\\0&3&2\\0&0&3\end{pmatrix}. \tag{11}$$

Then, we need to obtain the channel gain matrix for the MLD. The equalized symbol $v'_i$ in (4) has the desired signal term

$$W^H (w_0 \quad w_1)^H (h_0 \quad h_1) W d_i = W^H \begin{pmatrix} w_0^H h_0 & w_0^H h_1 \\ w_1^H h_0 & w_1^H h_1 \end{pmatrix} W d_i. \tag{12}$$

Therefore, the channel gain matrix $H_{2\times 2}$ after the MMSE equalization is given by a 2×2 matrix as follows:

$$H_{2x2} = W^H \begin{pmatrix} w_0^H h_0 & w_0^H h_1 \\ w_1^H h_0 & w_1^H h_1 \end{pmatrix} W. \tag{13}$$

Before executing the MLD process, we need to normalize the mean squared error of the equalized symbols for each transmit antenna branch because the MLD based on the minimum squared Euclidian distance assumes that all equalized symbols have the same mean squared error. The $i$-th equalized symbol of $p$-th antenna branch $v'_{p,i}$ has the minimum mean-square error $E_p$ for each transmit antenna branch $p$

$$E_p = (1 - w_p^H h_p). \tag{14}$$

Therefore, the mean squared error for the equalized symbols is normalized using matrix $C$

$$C = \begin{pmatrix} 1/\sqrt{E_0} & 0 \\ 0 & 1/\sqrt{E_1} \end{pmatrix}. \tag{15}$$

Then, we can execute hard detection of the equalized symbol by using MLD by selecting $\tilde{d}_i$ giving the minimum squared Euclidian distance.

$$\tilde{d}_i = \arg\min_d \| CH_{2z2} d - Cv_i' \|^2 \tag{16}$$

We call this receiver the MMSE-MLD receiver.

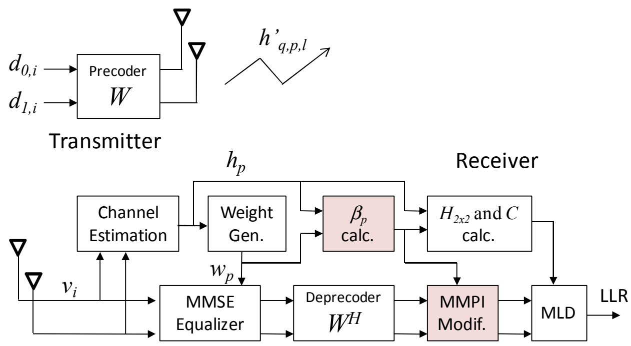


Figure 1. Transmitter and receiver structure used for simulation model

## III. Minimum Mean Partial Interference Criterion Equalizer for Serial Processing Structure of Equalizer and MLD

The conventional MMSE weight is obtained from the cost function $J(w_p)$

$$\begin{aligned} J(w_p) &= \left\langle \left| w_p^H v_i - d_{p,i} \right|^2 \right\rangle \\ &= w_p^H \left\langle v_i v_i^H \right\rangle w_p - \left\langle v_i^H d_{p,i} \right\rangle w_p + w^H \left\langle v_i d_{p,i}^* \right\rangle + \left\langle \left| d_{p,i} \right|^2 \right\rangle \\ &= w_p^H R w_p - h_p^H w_p - w_p^H h_p + 1, \end{aligned} \tag{17}$$

where $<x>$ denotes the expected value of $x$, and we assume that the average power of $d_{p,i}$ is one. Then, the conventional MMSE weight (5) to minimize $J(w_p)$ can be easily obtained using the following condition [5]:

$$\frac{\partial J(w_p)}{\partial w_p^H} = 0. \tag{18}$$

The sampled data $v_i$ before equalization includes an MPI and an IAI caused by the interference from another transmit antenna branch; both the interferences are reduced by the equalizer with the MMSE weight. However, in our serial processing structure, we do not need to reduce the IAI because it will be reduced efficiently by the latter MLD block. Therefore, we devise a new cost function $J'(w'_0)$ that excludes the IAI by subtracting not only the desired signal term $d_{0,i}$ but also the interference term $d_{1,i}$ from the another branch.

$$\begin{aligned} J'(w'_0) &= \left\langle \left| w'^H_0 v_i - d_{0,i} - \beta_0 d_{1,i} \right|^2 \right\rangle + A|\beta_0|^2 \\ &= w'^H_0 Rw'_0 - h_0{}^H w'_0 - w'^H_0 h_0 - \beta_0 h_1{}^H w'_0 - \beta_0^* w'^H_0 h_1 \\ &\quad + 1 + (1+A)|\beta_0|^2 \end{aligned} \tag{19}$$

where $\beta_0$ is unknown complex-valued coefficient and $A$ is a average residual IAI rate after MLD. Although $A$ is thought to be a function of the channel gain matrix $H_{2\times2}$, we treat it as a constant value, and it will be determined using computer simulations in the next section. Likewise the MMSE weight, we can find a new equalizer weight and a coefficient $\beta_0$ for which the cost function $J'(w'_0)$ is minimal by using the following conditions:

$$\frac{\partial J'(w'_0)}{\partial w'^H_0} = 0, \quad \frac{\partial J'(w'_0)}{\partial \beta_0} = 0 \cdot \tag{20}$$

Then, the resultant weight vector $w'_0$ and $\beta_0$ are given as

$$w'_0 = R^{-1}h_0 + \beta_0{}^* R^{-1}h_1 = w_0 + \beta_0{}^* w_1 \tag{21}$$

$$\beta_0 = \frac{h_0^H R^{-1} h_1}{1 + A - h_1^H R^{-1} h_1} \cdot \tag{22}$$

$w'_0$ is obtained by minimizing the cost function $J'(w'_0)$, which contains only a part of interferences; therefore, we call this new weight minimum mean partial interference (MMPI) weight in this paper. Another MMPI weight $w'_1$ and coefficient $\beta_1$ are obtained by interchanging the subscript number 0 and 1. By substituting $w'_0$ and $\beta_0$ in (19), the minimum mean-square error with the MMPI weight is given as

$$E_0' = (1 - h_0^H R^{-1} h_0) - \frac{\left| h_0^H R^{-1} h_1 \right|^2}{1 + A - h_1^H R^{-1} h_1}, \tag{23}$$

and $E_1'$ is also given by interchanging the subscript number 0 and 1.

Though the MMPI weight is written using the linear combination of the conventional MMSE weight, the channel gain matrix $H'_{2\times2}$ for the MMPI weight is written as follows:

$$H'_{2x2} = BH_{2x2} \tag{24}$$

where $B$ is given by

$$B = \begin{pmatrix} 1 & \beta_0 \\ \beta_1 & 1 \end{pmatrix}. \tag{25}$$

We call this receiver the MMPI-MLD receiver.

Table 1. Simulation conditions

| | |
|---|---|
| Number of Tx and Rx antennas | Tx = 2, Rx = 2 |
| Fading environment | PA, Two-path equal strength Rayleigh fading |
| Channel gain | Known value |
| Residual IAI rate A | A = 0.2 |
| Path timing | Known value |
| No. of taps for Equalizer | 15 taps per antenna |
| Modulation | QPSK |

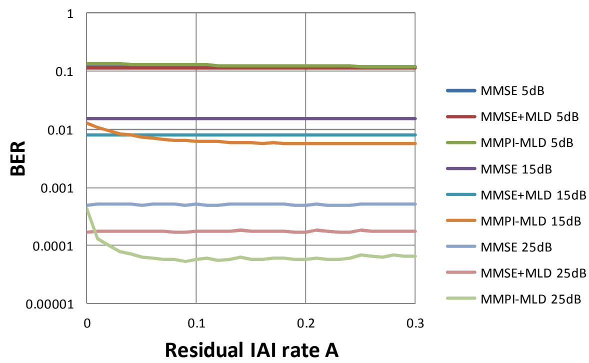


Figure 2. BER performance as a function of the residual IAI rate $A$ in PA propagation environment in SNR 5 dB, 15 dB, and 25 dB

We can realize the MMPI equalizer either using the MMPI weight at the equalizer block or with MMPI modification by multiplying the matrix $B$ after conventional MMSE equalizer, as shown in Fig. 1. Though MMPI modification is done with one multiplication and one addition per receive antenna, its additional complexity corresponds to that for an additional tap to the FIR filter in the MMSE equalizer. Therefore, the additional complexity for the MMPI equalizer itself is quite small.

## IV. Simulation Results

### *A. Residual IAI Rate Optimization and BER Performance without Pre-coding*

We investigated the appropriate residual IAI rate $A$ and compared the bit error rate (BER) performance without pre-coding (W = I) for the conventional MMSE receiver, the MMSE-MLD receiver, and the MMPI-MLD receiver by using computer simulations. Table 1 lists the simulation conditions. During simulation, channel gains are known values, the transmission environments are a two-path equal-strength Rayleigh fading channel, and pedestrian A (PA) defined in 3GPP specifications [6].

Fig. 2 shows BER performance as a function of the residual IAI rate $A$ in 2-path equal strength Rayleigh fading propagation environment for the average signal–to-noise power ratio (SNR) of 5 dB, 15 dB, and 25 dB. For the SNR of 5 dB, the BER of the MMPI-MLD receiver is almost a constant value and almost same as that of MMSE and MMSE-MLD at any residual IAI rate $A$. On the other hand, for SNRs 15 dB and 25 dB, the BERs of the MMPI-MLD receiver depend on $A$. The BERs in $A = 0$ are higher than that of the MMSE-MLD receiver; the BERs decrease rapidly as $A$ increases, and they become almost a constant value that is lower than that of the MMSE-MLD receiver at $A > 1.5$. From these results, it is thought that an excess MMPI modification is done when $A = 0$ because $A = 0$ means that we assume that the MLD block can completely eliminate the IAI, and an appropriate value of $A$ is greater than 1.5. Therefore, we use $A = 2.0$ in the following computer simulations.

Fig. 3 shows the BER performance as a function of SNR for each receive antenna in PA propagation environment. From this figure, we find that the BER curve of the MMSE-MLD receiver shows about 2.5-dB gain when compared with the MMSE receiver for a high SNR of 20 dB to 25 dB. This is because the non-diagonal elements of the channel gain matrix $H_{2\times 2}$ are still non-negligible when compared with the diagonal elements of $H_{2\times 2}$. Although the BER curve of the MMPI-MLD receiver with $A = 0.2$ is almost the same as that of the MMSE-MLD receiver for the SNR lower than 10 dB, it becomes better than that of the MMSE-MLD receiver for the SNR greater than 10 dB. The MMPI-MLD receiver shows about 4.5-dB gain when compared with the conventional MMSE receiver for a high SNR of 20 dB to 25 dB.

Fig. 4 shows the BER performance as a function of the average SNR for each receive antenna in two-path equal strength Rayleigh fading channel. From this figure, we also find that the BER curve of the MMSE-MLD receiver shows about 1.5-dB gain when compared with the MMSE receiver for a high SNR of 20 dB to 25 dB, and the MMPI-MLD receiver at $A = 0.2$ shows about 2.5-dB gain when compared with the conventional MMSE receiver.

### *B. BER Performance with Precoding*

We also compared the BER performance with pre-coding for the three types of receivers using computer simulations. In the simulations here, the residual IAI rate $A = 0.2$ and the pre-coding matrix $W$ specified for the HSDPA MIMO system [7] were used. $W$ is written as

$$W = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} \\ w_m & -w_m \end{pmatrix}, \quad w_m = (\pm 1 \pm j)/2,$$

where the value of $w_m$ is selected so as to maximize the receiving power of $d_0$ according to the channel gain matrix $H$. Then, $d_0$ and $d_1$ are called primary stream and secondary stream, respectively.

Fig. 5 shows the BER performance with pre-coding as a function of the SNR for each receive antenna in PA propagation environment. There are two groups of the BER curves in the figure; the left and the right groups correspond to the primary stream and the secondary stream, respectively. In the primary stream, all kinds of receiver show relatively the same level of BER performance, and the MMPI-MLD receiver shows maximum 1-dB gain when compared with the MMSE receiver in high SNR region. On the other hand, we can observe a relatively large BER performance gain in the secondary stream by using MLD; the MMSE-MLD and the MMPI-MLD receiver show about 3.0-dB and 5.0-dB gains, respectively, when compared with the MMSE receiver for a high SNR of 25 dB to 30 dB.

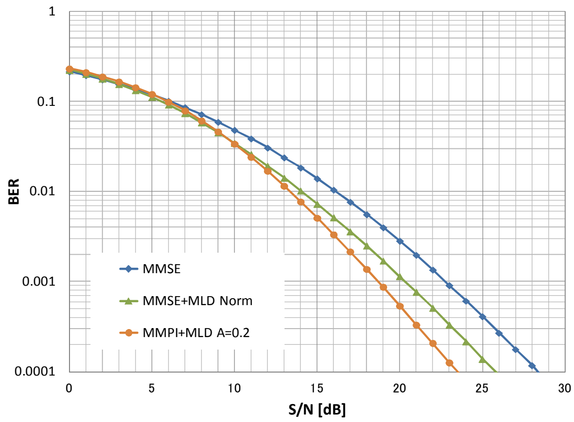


Figure 3. The BER performance without precoding in PA propagation environment.

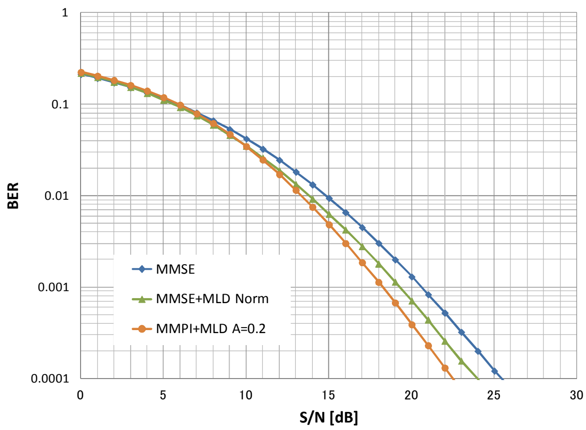


Figure 4. The BER performance without precoding in 2-path equal strength Rayleigh fading propagation environment.

Fig. 6 shows the BER performance with pre-coding as a function of the SNR for each receive antenna in two-path equal strength Rayleigh fading channel. From this figure, we also find that the MMPI-MLD receiver in the primary stream shows the maximum 1-dB gain when compared with the MMSE receiver in the primary stream. The MMSE-MLD receiver and the MMPI-MLD receiver show about 1.6-dB and 3.0-dB gains, respectively, when compared with the MMSE receiver for a high SNR of 25 dB to 30 dB. From Fig. 5 and Fig. 6, we find that the MLD-assisted receivers are more effective in PA propagation environment, which has a small multipath channel gain.

### C. *Throughput Performance in the HSPDA MIMO system*

Finally, we compared the throughput performance in the HSDPA MIMO system. Fig. 7 shows the receiver structure of the MMPI equalizer and the MLD for the HSDPA MIMO system. The MMPI modification block is placed between de-precoder block and the MLD block after the normal MMSE chip level equalizer and de-spreading block. Table 2 lists the simulation conditions.

Fig. 8 shows the simulation results of the throughput performance in the HSDPA MIMO system. From this figure, we can see that the MMSE-MLD receiver and the MMPI-MLD receiver show about 3% and 5% better throughput performance than the conventional MMSE receiver, respectively.

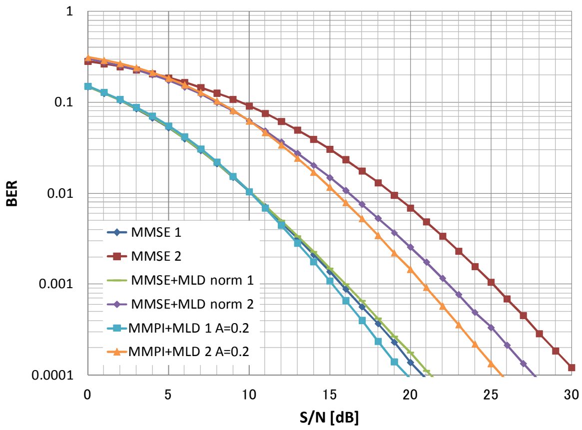


Figure 5. BER performance with precoding in PA propagation environment

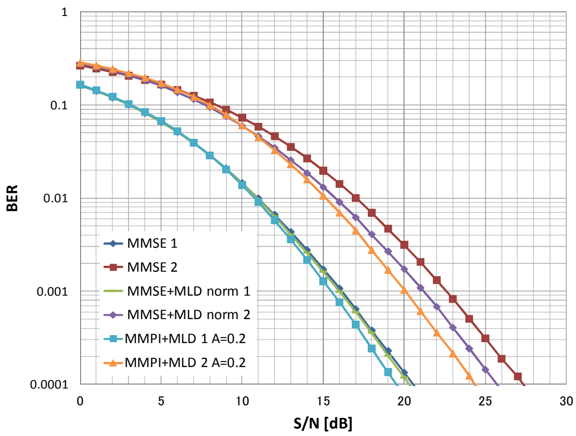


Figure 6. BER performance with precoding in 2-path equal strength Rayleigh fading propagation environment

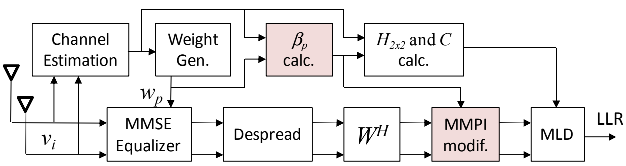


Figure 7. Receiver structure of the MMPI-MLD receiver for the HSDPA MIMO system used for the simulation of HSDPA system

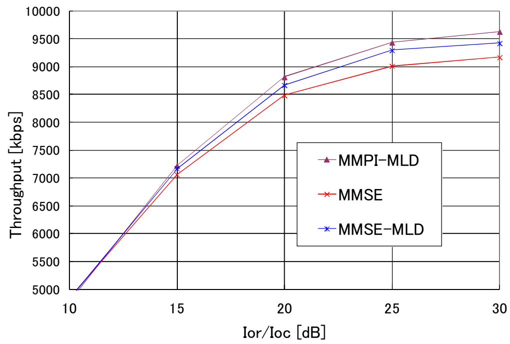


Figure 8. Throughput performance with precoding for HSDPA MIMO system

Table 2. HSDPA Simulation conditions

| | |
|---|---|
| Number of antenna | Tx = 2, Rx = 2 |
| Fading environment | Two-path equal strength Rayleigh |
| Channel estimation | 4-slot CPICH average |
| Residual IAI rate A | A = 0.5 |
| Tx Format | QPSK, 15 code, TBS=11032 (CQI=5 in Table 7Ia [7]) |
| No. of equalizer taps | 15 taps per antenna |

## Conclusions

This paper proposed a new criterion for equalizer combining weight called the MMPI criterion, which is used with a serial processing structure of the equalizer and the MLD in multipath fading MIMO channel. By computer simulation, we showed that the MMPI equalizer effectively suppresses the MPI in multipath fading MIMO channel when compared with the conventional MMSE equalizer by allowing leaving the IAI. We showed the additional complexity for the MMPI equalizer itself was quite small. Our computer simulation for the combination of the proposed MMPI equalizer and the MLD showed the maximum 5.0-dB gain when compared with the conventional MMSE receiver. We also showed that the throughput performance of HSDPA is improved by using the MMPI equalizer and MLD.


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