페이딩 채널에서 DS-CDMA 시스템을 위한 선형제약 변형 MMSE 검출의 성능 해석

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Performance Analysis of Linearly Constrained, Modified MMSE Detection for DS-CDMA Systems in Fading Channels

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요 약

이 논문은 페이딩 채널에서 직접확산 부호분할다중접속(DS-CDMA) 시스템을 위한 선형제약 변형 최소평균자승오차(MMSE) 검출의 이전 연구에 대한 후속 연구이다 변형된 MMSE 검출과 파일로트 심볼의 도움을 받는 채널추정(PSACE)의 결합시 발생하는 시스템 동작불능을 방지하는 조건을 구하였다 선형제약 변형 MMSE의 해가 레일레이 페이딩에서의 시간변화에 대해 이론적으로 강건함을 보였다 이 사실은 시뮬레이션 결과와 일치한다 아울러 어떤 조건에서 선형제약 변형 MMSE 검출이 출력 신호대간섭-잡음비(SINR)를 최대화하였다

Key Words Fading channels, interference suppression, CDMA, spread spectrum communications

ABSTRACT

This paper follows up the previous work on the linearly constrained, modified minimum mean-squared error (MMSE) detection for direct-sequence code-division multiple-access (DS-CDMA) systems in fading channels. We find a condition to avoid the breakdown of joint modified MMSE detection and pilot symbol-aided channel estimation (PSACE) The linearly constrained, modified MMSE solution is theoretically shown to be robust against time variations in Rayleigh fading channels This fact is consistent with the simulation results. We also show that under some conditions the linearly constrained, modified MMSE detection maximizes the output signal-to-interference-plus-noise ratio (SINR)

I Introduction

In [1] the authors of the paper proposed the linearly constrained, modified MMSE detection for direct-sequence code-division multiple-access (DS-CDMA) systems in fading channels, which is combined with the *pilot symbol-aided channel estimation (PSACE)* at the output of the modified MMSE filter. The simulation results showed that the linearly constrained, modified MMSE detection is nearly insensitive to fading rates The performance of the linearly constrained, modified MMSE detection was mainly considered through computer simulation but little attention was paid

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논문번호 #KICS2004-05-013, 접수일자 2004년 10월 16일

to theoretical analysis of the linearly constrained, modified MMSE detection

This paper theoretically justify the linearly constrained, modified MMSE detection proposed in [1] We will focus our attention on the time variations of the channel induced by a Doppler spread

This paper is organized as follows In Section II, we describe the system model Section III and IV address the optimum solution to the problem of the modified MMSE detection and the performance of joint modified MMSE detection and PSACE, respectively. Section V presents the performance of linearly constrained, modified MMSE detection In Section VI, we discuss numerical results Section VII gives the conclusions

II System Model

Consider an asynchronous binary phase shift keyed (BPSK) DS-CDMA system over additive white Gaussian noise (AWGN) and Rayleigh fading channels We assume that K users share the channels and that, without any loss of generality, user 1 is the desired user After the front-end chip-matched filtering, the received signal is sampled at the chip rate of $1/T_c$, where T_c is the chip interval The signal samples over a bit interval T_b is taken to be a signal vector It is assumed that $T_b = NT_c$, where N is the processing gain Then the received signal vector $\boldsymbol{r}(i) \in \mathbb{C}^N$ at time $t = iT_b$ can be of the equivalent synchronous form[2]

$$\boldsymbol{r}(i) = b_1(i)c_1(i)\boldsymbol{s}_1 + \sum_{l=2}^{L} \bar{b}_l(i)\bar{\boldsymbol{s}}_l(i) + \boldsymbol{n}(i),$$

where $b_1(i) \in \{1, -1\}, c_1(i) \in \mathbb{C}$, and $\boldsymbol{s}_1 \in \mathbb{R}^N$ are the data bit, the complex channel coefficient, and the spreading code vector of the desired user, respectively, and $\{\bar{b}_l(i)\}_{l=2}^{L} \in \{1, -1\}$, $\{\bar{\boldsymbol{s}}_l(i)\}_{l=2}^{L} \in \mathbb{C}$, and $\boldsymbol{n}(i) \in \mathbb{C}^N$ are the interfering bits, the interference vectors generated by interfering users' parameters such as the associated data bits, spreading vectors, path delays, and channel coefficients, and the noise vector, respectively It is assumed that $\bar{b}_l(i)$ and $\bar{\boldsymbol{s}}_l(i)$ are independent. The number of interference vectors $L-1$ can range from $K-1$ to $2(K-1)$ according to the relative delays of the $K-1$ interfering users Each of the complex channel coefficients $c_k, k=1,2,\cdot\cdot,K$ in the presence of Rayleigh fading is modeled as a complex Gaussian process with zero mean and variance $\sigma_{c_k}^2$ [3][4] The complex channel coefficients are assumed to be wide-sense-stationary. We also assume that the transmitted bits $\bar{b}_l(i), 2 \le l \le L$, are independent and of zero mean and that the noise vector $\boldsymbol{n}(i)$ is Gaussian with zero mean and covariance matrix $\sigma_n^2 \boldsymbol{I}$, where $\boldsymbol{I} \in \mathbb{R}^{N \times N}$ is the identity matrix.

III. Optimum Solution to the Problem of the Modified MMSE Detection

In this section we will analyze the optimum solution to the problem of the modified MMSE detection presented in [1] The estimation error of the modified MMSE detection scheme is defined as $\tilde{e}(i) = \tilde{d}_1(i) - \boldsymbol{w}(i)^H \boldsymbol{r}(i)$, where $\boldsymbol{w}(i)$ is the tap-weight vector of a linear transversal filter and the modified, desired signal $\tilde{d}_1(i)$ is the product of the desired signal $d_1(i)$ and the estimate of the complex channel coefficient $\hat{c}_1(i)$ That is, $\tilde{d}_1(i) = d_1(i)\hat{c}_1(i)$ Here the superscript "H" denotes Hermitian (or complex conjugate) transpose The estimate of the complex channel coefficient is defined as $\hat{c}_1(i) = \hat{\alpha}_1(i)e^{j\hat{\varphi}_1(i)}$, where $\hat{\alpha}_1(i)$ and $\hat{\varphi}_1(i)$ denote the amplitude and phase of the estimate of the complex channel coefficient at ith bit interval, respectively. For simplicity of our mathematical analysis, we herein assume that $d_1(i) = b_1(i)$, where $b_1(i)$ is the known ith bit transmitted by user 1

The optimum tap-weight (or Wiener solution [5]) vector for $w(i)$, $w_{o,MMMSE}$, which is herein referred to as the N-by-1 *modified MMSE* (*MMMSE*) solution vector for $w(i)$, is known to be $w_{o,MMMSE} = R^{-1}\tilde{p}$, where $\tilde{p}$ denotes the N-by-1 cross-correlation vector between the tap-input vector of the filter and the modified, desired signal $\tilde{d}_1(i)$ of user 1. The vector $\tilde{p}$ is given by

$$\tilde{p} = E[\tilde{d}_1(i)^* r(i)] = E[c_1(i)\hat{c}_1(i)^*]s_1,$$

where the superscript "$*$" denotes complex conjugate. The matrix R can be written as $R = E[r(i)r(i)^H] = \sigma_{c_1}^2 s_1 s_1^H + A$, where the matrix $A \in \mathbb{C}^{N\times N}$ is defined as $A = \sum_{l=2}^{L} E[\tilde{s}_l(i)\tilde{s}_l(i)^H] + \sigma_n^2 I$ Therefore the MMMSE solution vector $w_{o,MMMSE}$ is given by

$$w_{o,MMMSE} = E[c_1(i)\hat{c}_1(i)^*](\sigma_{c_1}^2 s_1 s_l^H + A)^{-1} s_1. \tag{1}$$

From (1) we can observe that the MMMSE solution vector $w_{o,MMMSE}$ depends on the second-order moment of the complex channel coefficient and its estimate, not on the first-order moment of the complex channel coefficient as shown in the standard MMSE solution vector $w_{o,MMSE}$, which is easily shown to be $w_{o,MMSE} = E[c_1(i)](\sigma_{c_1}^2 s_1 s_1^H + A)^{-1} s_1$ Thus the standard MMSE solution vector $w_{o,MMSE}$ becomes a zero vector because the mean of $c_1(i)$ is zero for Rayleigh fading processes

IV Performance of Joint Modified MMSE Detection and PSACE

In this section we will investigate the effect of channel estimation on the MMMSE solution vector Let $w_{o,MMMSE-PSACE}$ and $\hat{c}_{1,PSACE}(i)$ denote the MMMSE solution vector for $w(i)$ of the transversal filter combined with the pilot symbol-aided channel estimator and the estimate of the complex channel coefficient $c_1(i)$ associated with $w_{o,MMMSE-PSACE}$, respectively Since the estimate of the complex channel coefficient is based on the Qth order linear prediction[1] with equal weights of $1/Q$, the estimate $\hat{c}_{1,PSACE}(i)$ is given by

$$\hat{c}_{1,PSACE}(i) = \frac{1}{Q}\sum_{q=1}^{Q}\{b_1(i-qM) \times w_{o,MMMSE-PSACE}^H r(i-qM)\}, \tag{2}$$

where M denotes the pilot symbol insertion period Substituting (2) into $E[c_1(i)\hat{c}_{1,PSACE}(i)^*]$ yields

$$E[c_1(i)\hat{c}_{1,PSACE}(i)^*] = s_1^H w_{o,MMMSE-PSACE}\frac{1}{Q}\sum_{q=1}^{Q}\Phi_{c_1}(qMT_b), \tag{3}$$

where we have used the independence and zero mean assumptions made in Section II. Here the spaced-time correlation function[3][4] of the complex channel coefficient $c_1(i)$ is defined as $\Phi_{c_1}(qMT_b) = E[c_1(i)c_1(i-qM)^*]$. This function denotes the time variations of the channel measured by the parameter qMT_b. The use of (3) in (1) gives

$$w_{o,MMMSE-PSACE} = \left(\frac{1}{Q}\sum_{q=1}^{Q}\Phi_{c_1}(qMT_b)\right) \times (\sigma_{c_1}^2 s_1 s_1^H + A)^{-1} s_1\, s_1^H w_{o,MMMSE-PSACE}. \tag{4}$$

Define the N-by-N matrix $B = \left(\frac{1}{Q}\sum_{q=1}^{Q}\Phi_{c_1}(qMT_b)\right)(\sigma_{c_1}^2 s_1 s_1^H + A)^{-1}$ Then it implies that B is nonsingular. Let $\mathbf{0}$ denote the N-by-1 zero vector. Applying the defined matrix B to (4) and solving for $w_{o,MMMSE-PSACE}$ lead to

$$\{\boldsymbol{B}\boldsymbol{s}_1\boldsymbol{s}_1^H - \boldsymbol{I}\}\boldsymbol{w}_{o,MMMSE-PSACE} = \boldsymbol{0}. \quad (5)$$

Using the rank equality and inequality properties [6], it follows that $rank(\boldsymbol{B}\boldsymbol{s}_1\boldsymbol{s}_1^H) = rank(\boldsymbol{s}_1\boldsymbol{s}_1^H)$ and

$$rank(\boldsymbol{B}\boldsymbol{s}_1\boldsymbol{s}_1^H - \boldsymbol{I}) \leq rank(\boldsymbol{B}\boldsymbol{s}_1\boldsymbol{s}_1^H) + rank(-\boldsymbol{I}) = 1 + N, \quad (6)$$

where we have used the facts $rank(\boldsymbol{B}) = N$, $rank(\boldsymbol{s}_1\boldsymbol{s}_1^H) = 1$, and $rank(-\boldsymbol{I}) = N$. Since $rank(\boldsymbol{B}\boldsymbol{s}_1\boldsymbol{s}_1^H - \boldsymbol{I})$ is at most N for $(\boldsymbol{B}\boldsymbol{s}_1\boldsymbol{s}_1^H - \boldsymbol{I}) \in \mathbb{C}^{N\times N}$, (6) reduces to $(\boldsymbol{B}\boldsymbol{s}_1\boldsymbol{s}_1^H - \boldsymbol{I}) \leq N$. Therefore, if $rank(\boldsymbol{B}\boldsymbol{s}_1\boldsymbol{s}_1^H - \boldsymbol{I}) = N$, then the unique MMMSE solution vector $\boldsymbol{w}_{o,MMMSE-PSACE}$ to (5) becomes a zero vector. This implies that the feedback of the tap-weight vector of the filter caused by the PSACE forces the MMMSE solution to be zero. Therefore, the modified MMSE detection scheme completely breaks down in this case. In other words, the approximated value of the MMMSE solution, which is computed by using the LMS algorithm[5], dies out in the long run as shown in [1].

To solve the problem of the zero solution, we can use one possible approach. This approach imposes an unit constraint of $\boldsymbol{s}_1^H\boldsymbol{w}_{o,MMMSE-PSACE} = 1$ on (4). Note that the constraint $\boldsymbol{s}_1^H\boldsymbol{w}_{o,MMMSE-PSACE} = 1$ is equivalent to $\boldsymbol{w}_{o,MMMSE-PSACE}^H\boldsymbol{s}_1 = 1$. Incorporating $\boldsymbol{s}_1^H\boldsymbol{w}_{o,MMMSE-PSACE} = 1$ and thus $\boldsymbol{w}_{o,MMMSE-PSACE}^H\boldsymbol{s}_1 = 1$ into (4) gives

$$\boldsymbol{w}_{o,MMMSE-PSACE} = \boldsymbol{B}\boldsymbol{s}_1. \quad (7)$$

We can observe that the MMMSE solution vector $\boldsymbol{w}_{o,MMMSE-PSACE}$ depends on the spaced-time correlation function of the complex channel coefficient $c_1(i)$. Therefore, under the condition of $\boldsymbol{w}_{o,MMMSE-PSACE}^H\boldsymbol{s}_1 = 1$, the modified MMSE criterion combined with the PSACE does work well in Rayleigh fading channels.

V. Performance of Linearly Constrained, Modified MMSE Detection

The constraint of $\boldsymbol{w}_{o,MMMSE-PSACE}^H\boldsymbol{s}_1 = 1$ given in Section IV is actually impractical since it is not easy to apply the constraint to the modified MMSE detection. However, the derived constraint gives an insight to design a linearly constrained, modified MMSE detection introduced in [1], where the constraint of $\boldsymbol{w}(i)^H\boldsymbol{s}_1 = 1$ was used instead of $\boldsymbol{w}_{o,MMMSE-PSACE}^H\boldsymbol{s}_1 = 1$. It is well known that the LMS algorithm is *convergent in the mean* (*i.e.*, $\lim_{i\to\infty} E[\boldsymbol{w}(i)] = \boldsymbol{w}_{o,MMMSE-PSACE}$ for a wide-sense stationary environment under the condition of $0 < \mu < 2/\lambda_{\max}$, where μ and $\lambda_{\max}$ are the step-size parameter of the LMS algorithm and the largest eigenvalue of the correlation matrix $\boldsymbol{R}$, respectively)[5]. Under this condition, the mean of $\boldsymbol{w}(i)^H\boldsymbol{s}_1$, where $\boldsymbol{w}(i)$ is computed by using the LMS algorithm, also converges to $\boldsymbol{w}_{o,MMMSE-PSACE}^H\boldsymbol{s}_1$ as the number of iterations, i, approaches infinity. We may therefore say that the constraint of $\boldsymbol{w}(i)^H\boldsymbol{s}_1 = 1$ implies the constraint of $\boldsymbol{w}_{o,MMMSE-PSACE}^H\boldsymbol{s}_1 = 1$ in the case of convergence of the LMS algorithm in the mean. In this section we will investigate the performance of the modified MMSE detection subject to the linear constraint of $\boldsymbol{w}(i)^H\boldsymbol{s}_1 = 1$.

1. Optimum Solution

Let $\boldsymbol{w}_{o,CMMMSE}$ denote the linearly constrained MMMSE solution for $\boldsymbol{w}(i)$ such that

$$w_{o,CMMMSE} = arg\,min_{w(i)} E\left[\left|\tilde{d}_1(i) - w(i)^H r(i)\right|^2\right]$$

subject to $w(i)^H s_1 = 1$ Using the method of Lagrange multipliers[5], it is easily shown that the linearly constrained, optimum MMMSE solution $w_{o,CMMMSE}$ for $w(i)$ is given by

$$w_{o,CMMMSE} = w_{o,MMMSE} - \frac{s_1^H w_{o,MMMSE} - 1}{s_1^H R^{-1} s_1} R^{-1} s_1 \quad (8)$$

Also, let $w_{o,CMMMSE-PSACE}$ denote the linearly constrained MMMSE solution vector associated with the PSACE Then the use of $R = \sigma_{c_1}^2 s_1 s_1^H + A$ and (4) in (8) yields

$$w_{o,CMMMSE-PSACE} = \frac{(\sigma_{c_1}^2 s_1 s_1^H + A)^{-1} s_1}{s_1^H (\sigma_{c_1}^2 s_1 s_1^H + A)^{-1} s_1}. \quad (9)$$

The linearly constrained MMMSE solution of (9) is not a function of the spaced-time correlation function anymore unlike $w_{o,MMMSE-PSACE}$ of (7) Accordingly, it is evident that the linearly constrained MMMSE solution is irrelevant to the Doppler spread of the underlying Rayleigh fading channel of the desired user since the solution is just a scaled version of the optimum solution for time-invariant channels (*i.e.*, $w_{o,MMMSE-PSACE} = (\sigma_{c_1}^2 s_1 s_1^H + A)^{-1} s_1$, which is given by the use of $\Phi_{c_1}(qMT_b) = \sigma_{c_1}^2$ for all $q \in [0, \infty)$ in (7)) Therefore the linearly constrained, modified MMSE criterion is robust against the time variations of the underlying Rayleigh fading channels. The orthogonal decomposition-based LMS algorithm given in [1] and [7] can approximate the linearly constrained MMMSE solution of (9). On the other hand, with $(\sigma_{c_1}^2 s_1 s_1^H + A)$ and A assumed to be positive definite and therefore nonsingular, we may apply the matrix inversion lemma[5] to $(\sigma_{c_1}^2 s_1 s_1^H + A)^{-1}$ of (9). It is thus shown that (9) reduces to

$$w_{o,CMMMSE-PSACE} = \frac{A^{-1} s_1}{s_1^H A^{-1} s_1}. \quad (10)$$

2 Signal-to-Interference-plus-Noise Ratio (SINR)

We define the signal-to-interference-plus-noise ratio (SINR) as

$$SINR_o = \frac{E\left[\left|b_1(i) c_1(i) w(i)^H s_1\right|^2\right]}{E\left[\left|w(i)^H\left(\sum_{l=2}^{L} \bar{b}_l(i)\bar{s}_l(i) + n(i)\right)\right|^2\right]} = \frac{\sigma_{c_1}^2 w(i)^H s_1 s_1^H w(i)}{w(i)^H A w(i)} \quad (11)$$

We will investigate the relationship between the linearly constrained MMMSE solution vector and the tap-weight vector corresponding to a maximum SINR under the assumption that the matrix A is positive definite and thus nonsingular Letting $A = A^{1/2} A^{1/2}$ and using the approach given in [5], we can show that the maximum SINR, $SINR_{o,max}$, is $SINR_{o,max} = \sigma_{c_1}^2 s_1^H A^{-1} s_1$ and the corresponding tap-weight vector is

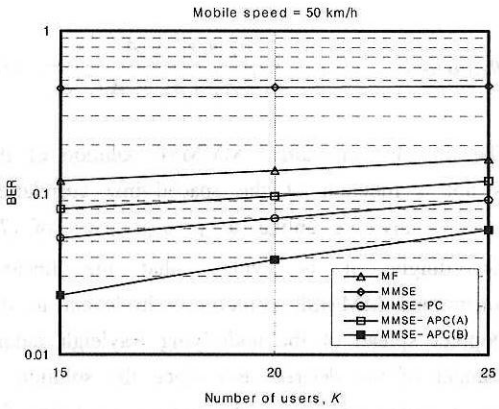
$$w_{SINR_{o,max}} = A^{-1} s_1. \quad (12)$$

Taking the Hermitian of both sides of (12) and postmultiplying by s_1 give $w_{SINR_{o,max}}^H s_1 = s_1^H A^{-1} s_1$ The use of $w_{SINR_{o,max}}^H s_1 = 1$ in $w_{SINR_{o,max}}^H s_1 = s_1^H A^{-1} s_1$ yields $s_1^H A^{-1} s_1 = 1$. Now if we apply $s_1^H A^{-1} s_1 = 1$ into (10), we obtain $w_{o,CMMMSE-PSACE} = A^{-1} s_1$ Hence under the conditions that $w_{SINR_{o,max}}^H s_1 = 1$ and that the matrices, A and $(\sigma_{c_1}^2 s_1 s_1^H + A)$, are positive definite, the two criteria: maximum output SINR and modified MMSE subject to the constraint of $w(i)^H s_1 = 1$ provide the identical tap-weight vector for $w(i)$. That is, $w_{o,CMMMSE-PSACE} = w_{SINR_{o,max}}$.

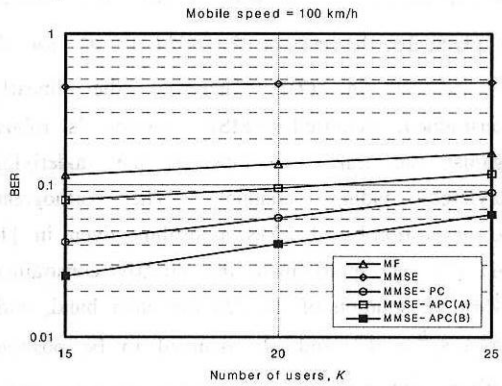
VI. Numerical Results

We perform Monte Carlo simulations to evaluate the bit error rate (BER) performance of the linearly constrained, modified MMSE detector proposed in [1] for two different fading channels. The BERs of the linearly constrained, modified MMSE detector are compared with those of the conventional MF detector, the standard MMSE detector, and the modified MMSE detectors. We use the following acronyms for the detectors in all figures: MF stands for the conventional MF detector, MMSE for the standard MMSE detector, MMSE-PC for the modified MMSE detector with phase compensation, MMSE-APC (A) and (B) for the modified MMSE detectors with amplitude and phase compensation. The design concept given in [8] and [9] is used to implement the modified MMSE detector, denoted by MMSE-PC, where the channel phase compensation is conducted in front of the adaptive linear transversal filter and the channel phase estimation is made at the output of the adaptive filter. The MMSE detector, denoted by MMSE-APC (A), is similar to the detector proposed in [10]. In this detector, the channel coefficient estimation is made using the input (more noisy) signal of the adaptive filter. The linearly constrained, modified MMSE detector, denoted by MMSE-APC (B), uses the output (less noisy) signal of the adaptive filter to perform the channel coefficient estimation. We consider an asynchronous BPSK DS-CDMA system for a reverse link with K users over AWGN and Rayleigh fading channels. The channel bandwidth is 3.968MHz, the carrier frequency is 2.0GHz, and E_b/N_o is set to 20dB. We use the Gold code of length $N=31$ chips as the spreading code. Transmitter powers of all users are set to be equal. The pilot symbol insertion period M is set to 8. The tap-weight vector $\boldsymbol{w}(i)$ of the adaptive filter is initialized as s_1.

Fig. 1 (a) and Fig. 1 (b) show the BER performance as a function of the number of users K for two different values of a mobile speed v: (a) $v=50$Km/h and (b) $v=100$Km/h. The linearly constrained, modified MMSE detector, denoted by MMSE-APC (B), significantly outperforms the remaining detectors, denoted by MF, MMSE, MMSE-PC, and MMSE-APC (A), for all the number of users. In particular, its BER performance is nearly identical for two different values of v: $v=50$Km/h and $v=100$Km/h. This means that the linearly constrained, modified MMSE detector is nearly insensitive to the Doppler spread of the underlying Rayleigh fading channel of the desired user as theoretically shown in (9).



(a)



(b)

Fig. 1. BER as a function of the number of users K for an asynchronous DS-CDMA system in Rayleigh fading channels: (a) $v=50$Km/h and (b) $v=100$Km/h.

VII. Conclusions

In this paper, we have assessed the performance of the linearly constrained, modified MMSE detection presented in [1]. We derived a condition to overcome the breakdown of the modified MMSE detection when it is combined with the PSACE at the output of the modified MMSE filter in frequency-nonselective Rayleigh fading channels. We observed that the constraint of $w(i)^H s_1 = 1$ used in the linearly constrained, modified MMSE detection is sufficient to meet the derived constraint of $w^H_{o,MMMSE-PSACE} s_1 = 1$ in the case of convergence of the LMS algorithm in the mean. We showed that the linearly constrained, modified MMSE solution is irrelevant to the Doppler spread of the underlying fading channels and thus channel-invariant for the underlying Rayleigh fading. Hence the linearly constrained, modified MMSE detection is robust against time variations in Rayleigh fading channels. This fact is consistent with the simulation results. It was also shown that under some conditions the two criteria: maximum output SINR and linearly constrained, modified MMSE provide the identical tap-weight vector.

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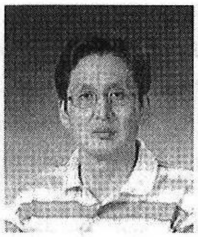

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