IEICE TRANS. COMMUN., VOL.E88–B, NO.4 APRIL 2005

LETTER

Frequency-Domain Adaptive Prediction Iterative Channel Estimation for OFDM Signal Reception

Shinsuke TAKAOKA[†a)], *Student Member and* Fumiyuki ADACHI[†], *Member*

SUMMARY In this letter, pilot-assisted adaptive prediction iterative channel estimation in frequency-domain is presented for the antenna diversity reception of orthogonal frequency division multiplexing (OFDM) signals. A frequency-domain adaptive prediction filtering is applied to iterative channel estimation for improving the tracking capability against frequency-domain variations in a severe frequency-selective fading channel. Also, in order to track the changing fading environment, the tap weights of frequency-domain prediction filter are updated using the simple NLMS algorithm. Updating of tap weights is incorporated into the iterative channel estimation loop to achieve faster convergence rate. The average bit error rate (BER) performance in a frequency-selective Rayleigh fading channel is evaluated by computer simulation. It is confirmed that the frequency-domain adaptive prediction iterative channel estimation provides better BER performance than the conventional iterative channel estimation schemes.

key words: *OFDM, iterative channel estimation, adaptive prediction, frequency-selective fading*

1. Introduction

For coherent detection of orthogonal frequency division multiplexing (OFDM) signals [1], [2], accurate channel estimation is necessary under a severe frequency-selective fading environment. There have been a number of research activities on channel estimation [3]–[7]. Pilot-assisted iterative channel estimation using decision feedback and reverse modulation is known to be able to improve the channel estimation accuracy. In [6], frequency-domain iterative channel estimation with simple averaging filter using fixed tap weights is presented. However, the propagation environment changes according to user's movement. Consequently, the use of the fixed tap weights optimized for a particular propagation environment may cause a mismatch in other environments. Therefore, using the fixed tap weights cannot always minimize the bit error rate (BER) in changing propagation environments. Recently, adaptive selection of the tap weights of frequency-domain filter, which uses a set of pre-designed filters, was proposed [7]. However, its tracking capability is limited.

The objective of this letter is to improve the tracking capability of frequency-domain iterative channel estimation in a severe frequency-selective fading channel. Adaptive prediction filtering based on the minimum mean square error (MMSE) criterion is applied to frequency-domain iterative channel estimation. According to the user's movement, the fading environment changes and accordingly, the average received signal-to-noise power ratio (SNR) and the frequency correlation of the fading channel change. The optimum tap weights of the frequency-domain prediction filter depend on the frequency correlation and average received SNR. Therefore, the optimum tap weights change according to user's movement. In order to track the changing channel environment, the tap weights are updated using the normalized least mean square (NLMS) algorithm [8]. The NLMS algorithm has the advantage of low computational complexity but has a slow convergence rate. In order to make the convergence rate faster, updating of filter tap weights is incorporated into the iterative channel estimation loop to increase the number of updates per OFDM symbol. A higher tracking capability against frequency-domain variations in the fading channel gain is achieved compared to an adaptive selection of fixed tap filters [7].

The rest of this letter is organized as follows. In Sect. 2, the frequency-domain adaptive prediction iterative channel estimation method is described. Then, Sect. 3 presents the computer simulation results on the achievable BER performance in a frequency-selective Rayleigh fading channel. Finally, Sect. 4 offers some conclusions.

2. Frequency-Domain Adaptive Prediction Iterative Channel Estimation

2.1 Received Signal Representation

OFDM signal transmission using N_c subcarriers is assumed. In the transmitter, the binary data sequence is transformed into quadrature phase shift keying (QPSK) modulated data symbol sequence. Then, known pilot symbols are periodically inserted into the transmitted data symbol sequence. The OFDM signal is transmitted over a frequency-selective fading channel and received by M antennas for diversity reception. After the removal of guard interval (GI) at the receiver, the OFDM signal received on the m-th antenna at the i-th OFDM signaling period is decomposed into N_c subcarrier components $\{R_m(n,i);\ n = 0 \sim N_c - 1\}$ by applying N_c-point fast Fourier transform (FFT). We obtain

$$R_m(n,i) = \sqrt{2S}\, d(n,i) H_m(n,i) + \Pi_m(n,i) \tag{1}$$

for the n-th subcarrier component at the i-th OFDM symbol, where $H_m(n,i)$ and $\Pi_m(n,i)$ are the channel gain and the

Manuscript received June 11, 2004.
Manuscript revised September 17, 2004.

[†]The authors are with Electrical and Communication Engineering, Graduate School of Engineering, Tohoku University, Sendai-shi, 980-8579 Japan.
a) E-mail: takaoka@mobile.ecei.tohoku.ac.jp

DOI: 10.1093/ietcom/e88–b.4.1730

zero-mean Gaussian noise having variance $2N_0/T_s$ ($1/T_s$ is the subcarrier separation), respectively. S denotes the average received signal power. Then, after parallel-to-serial (P/S) conversion, antenna diversity reception using maximum ratio combining (MRC) [9] is carried out to obtain the coherently detected received symbol for data decision.

For MRC diversity reception, estimation of $\{H_m(n, i)\}$ is necessary. In Sect. 2.2, the pilot-assisted frequency-domain adaptive prediction iterative channel estimation is described. In this letter, the estimate of $H_m(n, i)$ at the p-th stage in the iterative channel estimation process is denoted by $\tilde{H}_m^{(p)}(n, i)$, where $p = 1 \sim P$.

2.2 Application of Adaptive Prediction Filtering to Iterative Channel Estimation

For channel estimation, time-multiplexed pilot is considered, as illustrated in Fig. 1. A pilot symbol is periodically inserted every N_p OFDM symbols. A $2K$-tap frequency-domain adaptive prediction filter as illustrated in Fig. 2 is used. Without loss of generality, the pilot symbol is assumed to be $d_p(n, i) = 1 + j0$.

First, adaptive prediction filtering is performed using the received pilot OFDM signal at the signaling period of i mod N_p=0. The resultant channel gain estimates are used as the first stage channel gain estimates $\{\tilde{H}_m^{(1)}(n, i)\}$ for the iterative channel estimation at time i mod N_p=1. For i mod $N_p > 1$, the P-th stage channel gain estimates $\{\tilde{H}_m^{(P)}(n, i-1)\}$ in the previous signaling period of $i-1$ are utilized as the first stage channel gain estimates $\{\tilde{H}_m^{(1)}(n, i)\}$. As a consequence, $\tilde{H}_m^{(1)}(n, i)$ is given by

$$\tilde{H}_m^{(1)}(n,i) = \begin{cases} R_m(n, i-1) & \text{for } n = 0, N_c - 1 \\ \dfrac{\sum\limits_{\substack{k=-\alpha(n)\\ \neq 0}}^{\alpha(n)} w_m(j,k) R_m(n+k, i-1)}{\sum\limits_{\substack{k=-\alpha(n)\\ \neq 0}}^{\alpha(n)} |w_m(j,k)|} & \text{otherwise} \end{cases} \tag{2}$$

when i mod N_p=1, and

$$\tilde{H}_m^{(1)}(n,i) = \tilde{H}_m^{(P)}(n, i-1) \tag{3}$$

when i mod $N_p > 1$, where $w_m(j, k)$ denotes the filter tap weight after the j-th updating (which will be described in Sect. 2.3) and $\alpha(n)$ is defined as

$$\alpha(n) = \begin{cases} n & \text{for } 1 \le n \le K-1 \\ K & \text{for } K \le n \le N_c - K - 1 \\ N_c - 1 - n & \text{for } N_c - K \le n \le N_c - 2 \end{cases}. \tag{4}$$

Then, MRC antenna diversity reception is carried out to obtain the decision variable $\eta^{(1)}(n, i)$ for the data symbol $d(n, i)$:

$$\eta^{(p)}(n,i) = \sum_{m=0}^{M-1} R_m(n,i) \tilde{H}_m^{(p)^*}(n,i) \Bigg/ \sum_{m=0}^{M-1} \left| \tilde{H}_m^{(p)}(n,i) \right|^2 \tag{5}$$

with p=1, where * denotes the complex conjugate operation. Using $\eta^{(1)}(n, i)$, the tentative symbol decision $\hat{d}^{(1)}(n, i)$ is obtained as

$$\hat{d}^{(p)}(n,i) = \underset{d \in \{\exp(jk\pi/2);\, k=0\sim3\}}{\arg\min} \left| \eta^{(p)}(n,i) - d \right| \tag{6}$$

with p=1.

At succeeding iteration stages ($p \ge 2$), the tentative decisions $\{\hat{d}^{(p-1)}(n, i)\}$ at the $(p-1)$-th iteration stage are fedback as pilots to remove data modulation from the received subcarrier components $\{R_m(n, i)\}$. The instantaneous channel gain estimate $\hat{H}_m^{(p)}(n, i)$ is obtained as

$$\hat{H}_m^{(p)}(n,i) = R_m(n,i) \hat{d}^{(p-1)^*}(n,i) \quad \text{for } p \ge 2. \tag{7}$$

Adaptive prediction filtering using the $2K$ taps is applied to the instantaneous channel gain estimates $\{\hat{H}_m^{(p)}(n, i)\}$ to obtain the improved channel gain estimates $\{\tilde{H}_m^{(p)}(n, i)\}$. The adaptively estimated channel gain at the p-th iteration stage is given by

$$\tilde{H}_m^{(p)}(n,i) = \begin{cases} \hat{H}_m^{(p)}(n,i) & \text{for } n = 0, N_c - 1 \\ \dfrac{\sum\limits_{\substack{k=-\alpha(n)\\ \neq 0}}^{\alpha(n)} w_m(j,k) \hat{H}_m^{(p)}(n+k, i)}{\sum\limits_{\substack{k=-\alpha(n)\\ \neq 0}}^{\alpha(n)} |w_m(j,k)|} & \text{otherwise} \end{cases}. \tag{8}$$

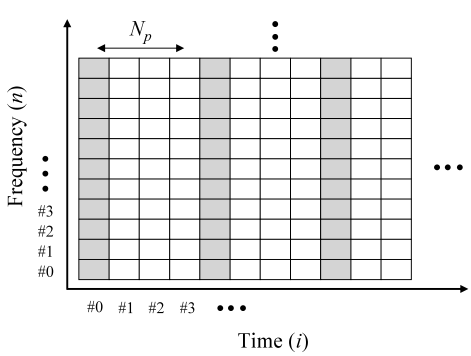

Fig. 1 Pilot insertion method.

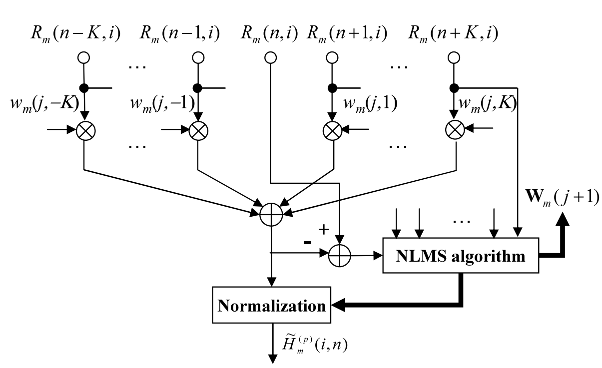

Fig. 2 Adaptive prediction filter structure.

Again, using $\{\tilde{H}_m^{(p)}(n,i)\}$, MRC antenna diversity reception of Eq. (5) is carried out. After repeating the above process for $(P-1)$ times, the final decision variable $\eta^{(P)}(n,i)$ at the P-th iteration stage is obtained from Eq. (5) to yield the final symbol decision $\hat{d}^{(P)}(n,i)$.

2.3 Tap Weight Adaptation Using NLMS Algorithm

Since the optimum tap weights of the frequency-domain prediction filter depend on the frequency correlation and average received SNR, the optimization of tap weights is necessary in various channel conditions. Here, the tap adaptation method using simple NLMS algorithm [8] is used. However, NLMS has slow convergence rate of tap weights. For achieving faster convergence rate, updating of tap weights is incorporated into the iterative channel estimation loop within one OFDM signaling period to increase the number of updates.

The tap weight adaptation is carried out for $K \le n \le N_c - K - 1$ in the frequency direction. Thus, the number of updating within one OFDM signaling period is $(N_c-2K)\times(P-1)$ for $i \bmod N_p \neq 0$, while it is $(N_c-2K)\times P$ when $i \bmod N_p=0$ (this is because at the first iteration stage (p=1), we can obtain the instantaneous channel gain estimates $\{\hat{H}_m^{(1)}(n,i)\}$ from pilot symbols). The recursive relation for updating the tap weight vector is represented as

$$\mathbf{w}_m(j+1) = \mathbf{w}_m(j) + \begin{cases} 0 & \text{for } 0 \le n \le K-1 \text{ and } N_c-K \le n \le N_c-1 \\ \mu \dfrac{e_m(j)}{\sum\limits_{\substack{k=-K\\ \neq 0}}^{K} \left|\hat{H}_m^{(p)}(n+k,i)\right|^2} \mathbf{x}_m^*(n,i) & \text{for } K \le n \le N_c-K-1 \end{cases}, \quad (9)$$

where $e_m(j)$ is the estimation error given by

$$e_m(j) = \hat{H}_m^{(p)}(n,i) - \mathbf{w}_m^T(j)\mathbf{x}_m(n,i), \quad (10)$$

μ is the step size, and $[.]^T$ denotes transpose. In Eqs. (9) and (10),

$$\begin{cases} \mathbf{w}_m(j) = [w_m(j,-K),\cdots,w_m(j,-1), w_m(j,1),\cdots,w_m(j,K)]^T \\ \mathbf{x}_m(n,i) = [\hat{H}_m^{(p)}(n-K,i),\cdots,\hat{H}_m^{(p)}(n-1,i), \hat{H}_m^{(p)}(n+1,i),\cdots,\hat{H}_m^{(p)}(n+K,i)]^T \end{cases} \quad (11)$$

are the complex tap weight vector after the j-th updating and the instantaneous channel gain vector, respectively.

3. Computer Simulation

The number of OFDM subcarriers and the number of GI samples are N_c=256 and N_g=32, respectively. The multipath fading channel is assumed to have an L=8-path exponentially decaying power delay profile with time separation between adjacent paths of $\Delta\tau$=4 samples and decay factor of β dB. Each path is subjected to an independent Rayleigh fading. It is assumed that the maximum time delay is shorter than the GI of N_g samples and the complex path gains remain almost constant over one OFDM signaling period T. At the receiver, M=2-branch MRC antenna diversity reception is assumed. The number of taps of adaptive prediction filter is $2K$=24.

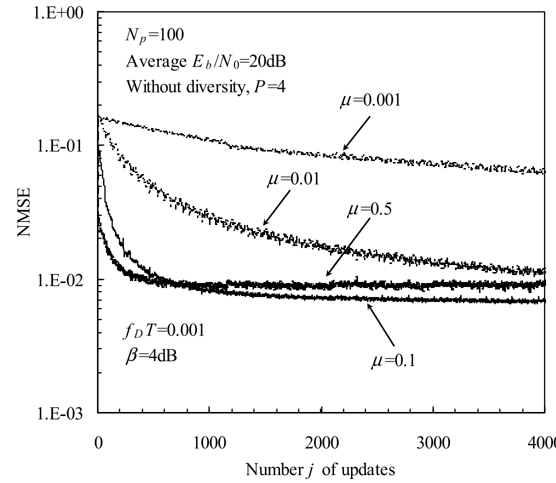

Fig. 3 Tap weight convergence performance.

3.1 Convergence Rate

The tap weight convergence performance in terms of the normalized mean square error (NMSE) $E[|e_m(j)|^2/2S]$ is shown in Fig. 3 as a function of the number j of updates with step size μ as a parameter when the average received signal energy per bit-to-AWGN power spectrum density ratio E_b/N_0=20 dB, the decay factor β=4 dB, the normalized fading maximum Doppler frequency f_DT=0.001 and the number of iterations P=4. Antenna diversity reception is not used. The NMSE is obtained as the average of $|e_m(j)|^2$ obtained from 5000 trials. The initial tap weight vector $\mathbf{w}_m(0)$ was set as $w_m(0,k)$=1/14+j0 for $|k| \le 7$ ($k \neq 0$) and $w_m(0,k)$=0, otherwise. As the step size μ becomes larger, the tap weight convergence rate becomes faster, but the achievable NMSE becomes larger when the tap weights have converged. Considering the tradeoff between the convergence rate and the achievable NMSE after convergence, μ=0.1 will be used in the following simulations. Since the NMSE with μ=0.1 converges after around 1200 updates, the tap weights can converge within two OFDM signaling period when P=4 (the possible number of updates during the signaling period of $i \bmod N_p$=0 is $(N_c-2K)\times P$=928 and that during the signaling period of $i \bmod N_p \neq 0$ is $(N_c-2K)\times(P-1) = 696$).

3.2 Impact of Number of Iterations

Figure 4 plots the average BER as a function of the number P of iterations with the decay factor β as a parameter at the average received E_b/N_0=20 dB for the pilot in-

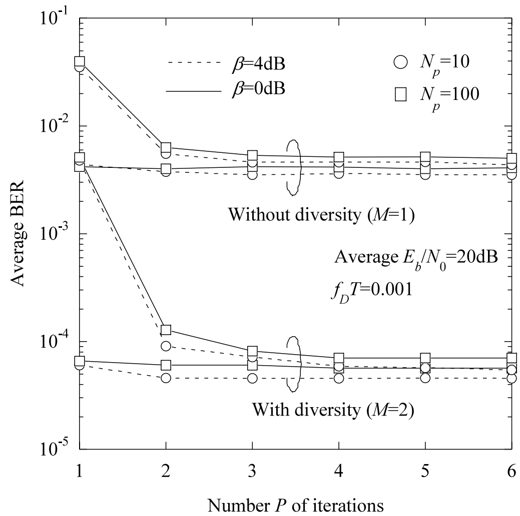

Fig. 4 Impact of number of iterations.

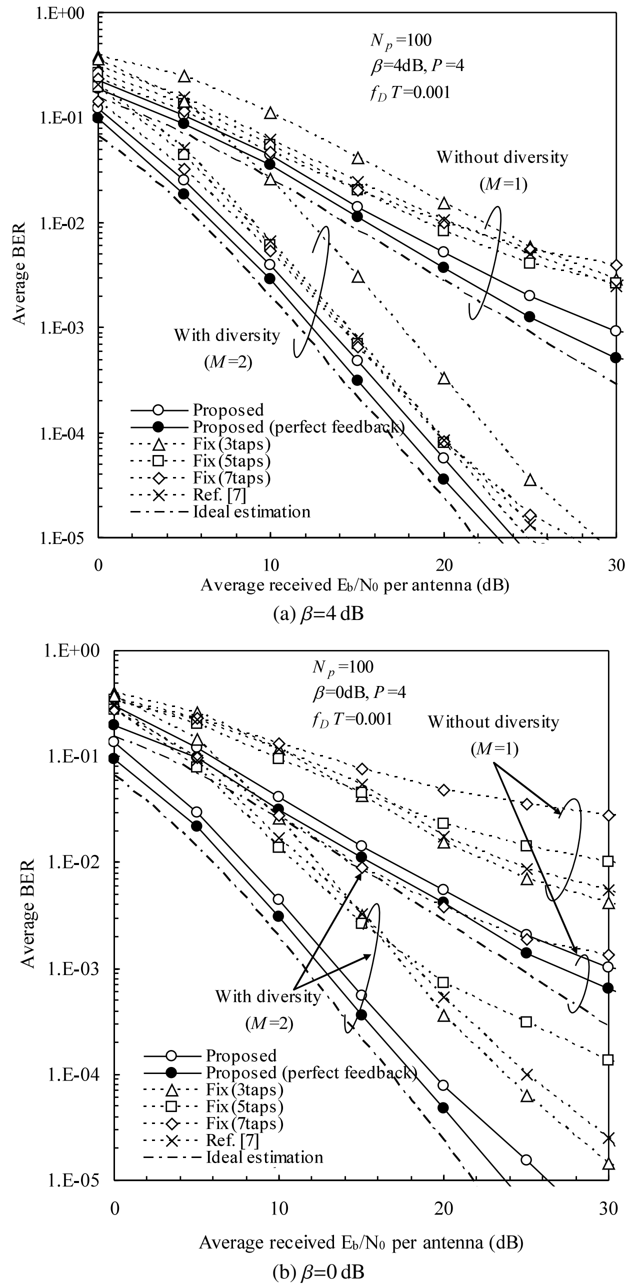

Fig. 5 BER performance comparison.

sertion of N_p=10 and 100 and the normalized Doppler frequency f_DT=0.001. It is clearly seen from Fig. 4 that iterative channel estimation can significantly reduce the BER. The BER decreases as P increases; however, almost no additional improvement is obtained after five iterations. Therefore, the use of four iterations (P=4) is considered to be sufficient. Also, even if the pilot insertion interval N_p increases from 10 to 100 symbols, almost the same BER can be achieved, when the iterative channel estimation with frequency-domain adaptive prediction filter is used. Thus, the use of the proposed scheme can allow a larger pilot insertion interval for achieving the same BER and improve the transmission efficiency.

3.3 BER Performance Comparison

The BER performance achievable by the adaptive prediction iterative channel estimation is compared with the conventional schemes; i.e., iterative channel estimation using fixed tap filter and adaptive selection of fixed tap filters [7]. The tap weight vector for the fixed tap filter is set to {1/8, 1, 1/8}, {1/8, 1/4, 1, 1/4, 1/8} and {1/8, 1/4, 1/2, 1, 1/2, 1/4, 1/8} for 3, 5 and 7 taps, respectively [7]. Figure 5 plots the average BER performance as a function of the average received E_b/N_0 per antenna for β=0 dB and 4 dB. It is found from Fig. 5 that when fixed tap filter is used, for any given average received E_b/N_0 and β, there exists an optimum number of taps such that the BER is minimized. When β=4 dB, the 5- or 7-tap filter provides a better BER performance than 3-tap filter in the all regions of average received E_b/N_0. In the case of β=0 dB, however, the optimum number of taps is 5 (3) in a low (high) E_b/N_0 region. This means that the fixed tap filter designed for a certain propagation environment causes a mismatch in other channel conditions. Adaptive selection of tap weights of frequency-domain filter shows an overall superior BER performance to the fixed tap filters. However, our proposed adaptive prediction channel estimation always provides better BER performance than the conventional channel estimation schemes [7]. In the case of β=4 dB, the adaptive prediction iterative channel estimation with antenna diversity reception reduces the required average E_b/N_0 per antenna for achieving BER=10^{-3} by about 0.7, 0.9 and 4.2 dB compared with fixed tap filters with 7, 5 and 3 taps, respectively. An E_b/N_0 improvement of 0.9 dB is obtained over the channel estimation using adaptive selection of fixed tap filters.

In iterative channel estimation, tentative decision results are feedback as pilot symbols. Feeding back decision errors limits the channel estimation accuracy. To evaluate how the feedback errors affect the BER performance, the

BER performance without feedback errors labeled as "perfect feedback" is also plotted in Fig. 5. The BER performance with ideal channel estimation is also plotted for comparison. The E_b/N_0 degradations of the proposed scheme with antenna diversity from ideal channel estimation for achieving a BER=10^{-3} are about 1.9 and 2.6 dB for β=4 dB and 0 dB, respectively. The E_b/N_0 degradations of perfect feedback case with antenna diversity from ideal channel estimation are about 0.9 and 1.5 dB for β=4 dB and 0 dB, respectively. Thus, the E_b/N_0 degradations due to feedback errors are 1.0 and 1.1 dB for β=4 dB and 0 dB, respectively. The above suggests that the BER performance could be further improved if the effect of feedback errors can be minimized. For this purpose, incorporating error correction coding, like turbo coding, into iterative channel estimation is feasible (but, this study is out of the scope of this letter and left as a future research topic).

Finally, the number of multiplications per slot (each slot consists of one pilot OFDM symbol and succeeding $N_p - 1$ data OFDM symbols) is compared for the proposed channel estimation scheme and the conventional schemes using $(2K + 1)$-tap fixed filter [7]. The number of multiplications of the proposed scheme is $2 \cdot \{2K(N_c - K) - 2K + 2\} \cdot \{N_p(P-1) + 1\}$, while that of the conventional scheme is $\{2K(N_c - K) - 2K + N_c\} \cdot \{N_p(P-1) - P + 2\}$. Thus, the computational complexity of the proposed scheme with K=12 is approximately 15.4, 9.3 and 6.7 times higher than the conventional scheme [7] using 3(K=1), 5(K=2) and 7(K=3)-tap fixed filter, respectively, for N_p=100 and P=4. As seen from Fig. 5, the proposed channel estimation scheme can improve the BER performance at the cost of increased complexity.

4. Conclusion

In this letter, a pilot-assisted frequency-domain adaptive prediction iterative channel estimation scheme was proposed for the antenna diversity reception of OFDM signals in a frequency-selective fading channel. A frequency-domain adaptive prediction filtering using NLMS algorithm is applied to iterative channel estimation in order to improve the tracking capability of channel estimation in a severe frequency-selective fading channel. For achieving faster convergence rate of tap weights in NLMS, updating of tap weights is incorporated into iterative channel estimation loop. The average BER performance achievable by the proposed channel estimation was evaluated by computer simulation. The tap weights of frequency-domain prediction filter can converge within two OFDM signaling periods although a simple NLMS algorithm is used. It was found from simulation results that the adaptive prediction iterative channel estimation can significantly reduce the BER as the number of iteration increases and the use of four iterations is sufficient. Also, it was confirmed that the proposed channel estimation scheme provides better BER performance than the conventional channel estimation schemes [7].

Acknowledgment

This work is supported by Research Fellowship of the Japan Society for the Promotion of Science for Young Scientists.

References

[1] F. Adachi, "Wireless past and future—Evolving mobile communications systems," IEICE Trans. Fundamentals, vol.E84-A, no.1, pp.55–60, Jan. 2001.
[2] H. Atarashi, S. Abeta, and M. Sawahashi, "Variable spreading factor-orthogonal frequency and code division multiplexing (VSF-OFCDM) for broadband packet wireless access," IEICE Trans. Commun., vol.E86-B, no.1, pp.291–299, Jan. 2003.
[3] V. Mignone and A. Morello, "CD3-OFDM: A novel demodulation scheme for fixed and mobile receivers," IEEE Trans. Commun., vol.44, no.9, pp.1144–1151, Sept. 1996.
[4] O. Edfors, M. Sandell, J.-J. van de Beek, S.K. Wilson, and P.O. Borjesson, "OFDM channel estimation by singular value decomposition," IEEE Trans. Commun., vol.46, no.7, pp.931–939, July 1998.
[5] Y. (G.) Li, L.J. Cimini, Jr., and N.R. Solenberger, "Robust channel estimation for OFDM systems with rapid dispersive fading channels," IEEE Trans. Commun., vol.46, no.7, pp.902–915, July 1998.
[6] H. Atarashi, S. Abeta, and M. Sawahashi, "Performance of forward link broadband packet TD-OFCDM with iterative channel estimation," IEICE Technical Report, RCS2000-186, Jan. 2001.
[7] T. Onizawa, M. Mizoguchi, and M. Morikura, "A novel channel estimation scheme employing adaptive selection of frequency-domain filters for OFDM systems," IEICE Trans. Commun., vol.E82-B, no.12, pp.1923–1931, Dec. 1999.
[8] S. Haykin, Adaptive filter theory, Prentice Hall, 1996.
[9] W.C. Jakes, Jr., ed., Microwave mobile communications, Wiley, New York, 1974.