Adaptive Prediction Iterative Channel Estimation for OFDM Signal Reception in a Frequency Selective Fading Channel

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Abstract- In this paper, pilot-assisted adaptive prediction iterative channel estimation is proposed for the antenna diversity reception of orthogonal frequency division multiplexing (OFDM) signals. Adaptive prediction filtering is incorporated into iterative channel estimation process with decision feedback and reverse modulation. The filter tap weights are adaptively updated according to changes in the multipath propagation environment. For the adaptation of tap weights, the normalized least mean square (NLMS) algorithm is applied that uses the noisy instantaneous channel gains obtained by reverse modulation and from pilot symbols as the reference signal. The average bit error rate (BER) performance in a frequency selective fading channel is evaluated by computer simulation for the frequency and time multiplexed pilot cases. It is confirmed that adaptive prediction iterative channel estimation provides better BER performance than using fixed-tap filter.

1. Introduction

Ultra high-speed (100Mbps~1Gbps) data transmission capability will be required in the next generation broadband wireless communication systems. In mobile radio, the transmitted signal is reflected and diffracted by many obstacles and is received as a multipath signal with different time delays at a receiver. The frequency transfer function of the multipath channel varies randomly both in frequency and in time, that is, the transmitted signal undergoes doubly (frequency and time) selective fading. For achieving high-speed and high-quality data transmission in such a doubly selective fading channel, orthogonal frequency division multiplexing (OFDM) is considered as a promising wireless transmission technique [1], [2].

For coherent detection of OFDM signals, accurate channel estimation is necessary. Many channel estimation methods have been proposed [3]-[6]. Pilot-assisted iterative channel estimation using decision feedback and reverse modulation is known to be able to improve the channel estimation accuracy. In [7], iterative channel estimation with fixed-tap filter was applied. However, multipath propagation environment between the transmitter and receiver changes rapidly according to user’s movement. Therefore, using the time invariant tap weights cannot always minimize the bit error rate (BER) in changing propagation environments. Recently proposed adaptive selection of the tap weights of frequency-domain filter [8] provides superior performance to the fixed-tap filter. However, its adaptability to rapidly changing channel conditions is limited.

In this paper, pilot-assisted adaptive prediction iterative channel estimation is proposed for the antenna diversity reception of OFDM signals. Adaptive prediction filtering is incorporated into the iterative channel estimation process. The filter tap weights are adaptively updated according to changes in the propagation environment. For the adaptation of tap weights, the normalized least mean square (NLMS) algorithm is applied that uses the noisy instantaneous channel gains obtained by reverse modulation and from pilot symbols as the reference signal.

The rest of this paper is organized as follows. In Sect. 2, the OFDM signal transmission system model is presented. Section 3 describes the proposed adaptive prediction iterative channel estimation methods for the frequency and time multiplexed pilot cases. Then, Sect. 4 presents the computer simulation results on the achievable BER performance in a frequency selective Rayleigh fading channel. Finally, Sect. 5 offers some conclusions.

2. OFDM Signal Transmission System Model

The OFDM transmission system model considered in this paper is illustrated in Fig. 1. OFDM signal transmission using N_c subcarriers is assumed. In the transmitter, the binary information date sequence is transformed into the quadrature phase shift keying (QPSK) modulated symbol sequence $\{d_n\}$. Then, the known pilot symbols are periodically inserted into the transmitted data symbol sequence. After the transmitted symbol sequence is serial-parallel (S/P) converted into N_c parallel data sequences each with a lower rate, OFDM signal waveform with N_c subcarriers are generated by applying N_c-point inverse fast Fourier transform (IFFT). Finally, the cyclic prefix of N_g samples is inserted as the guard interval in order to eliminate the inter-carrier interference (ICI) resulting from frequency selective fading.

The baseband equivalent representation of the OFDM signal waveform for the i-th OFDM signaling period is given by

$$s(k)=\sqrt{\frac{2E_s}{(N_c+N_g)T_c}}\sum_{n=0}^{N_c-1}d_{iN_c+n} \times\exp\left(-j2\pi\frac{n}{N_c}(k-N_g-i(N_c+N_g))\right) \quad (1)$$

for $k=i(N_c+N_g)\sim(i+1)\cdot(N_c+N_g)-1$, where E_s represents the transmitted signal energy per data symbol and T_c represents

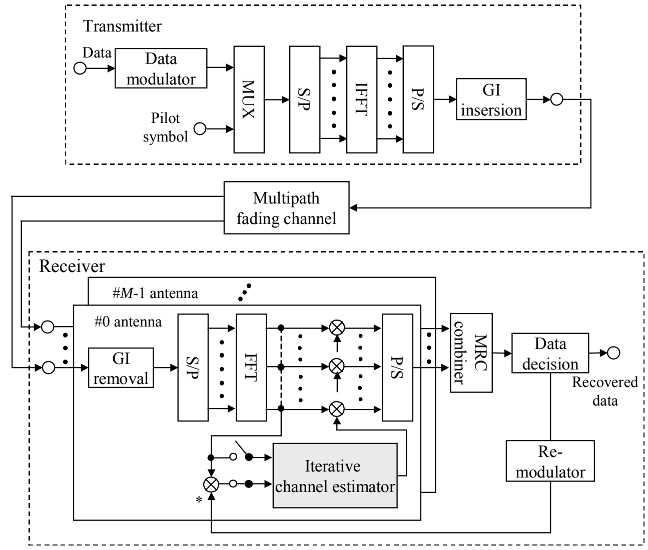


Fig. 1 OFDM signal transmission system model.

the IFFT sample interval given by $T/(N_c+ N_g)$ when the data symbol rate per subcarrier is $1/T$. The resultant OFDM signal waveform is transmitted via a frequency selective fading channel and received by M antennas for diversity reception.

A T_c-spaced delay-time model of the propagation channel is assumed. Assuming that the channel has L independent propagation paths with distinct time delays $\{lT_c\}$, the discrete-time impulse response $h_m(t)$ of the multipath channel experienced by the mth antenna, m=0~M-1, may be expressed as

$$h_m(t)=\sum_{l=0}^{L-1}h_{m,l}\delta(t-lT_c) \quad (2)$$

with $\sum_{l=0}^{L-1}\mathrm{E}[\left|h_{m,l}\right|^2]=1$, where $\delta(t)$ is the delta function and E[.] denotes ensemble average operation. Assuming very slow fading so that the channel impulse response remains constant over one OFDM signaling interval, time dependency of the channel has been dropped for simplicity. It is assumed that the maximum time delay of the channel is shorter than GI.

The received signal sample sequence on the mth antenna is

$$r_m(k)=\sum_{l=0}^{L-1}h_{m,l}s(k-l)+\mu_m(k)\,, \quad (3)$$

where $\mu_m(k)$ is the additive white Gaussian noise (AWGN) process with zero mean and variance $2N_0/T_c$. After removal of the guard interval, the received signal sample sequence is resolved into N_c-subcarrier components by applying N_c-point FFT to $\{r_m(k)\}$ to obtain

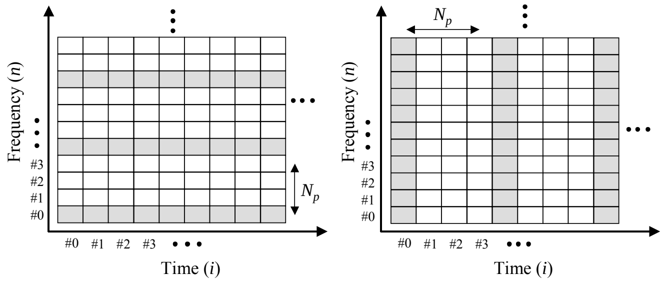
$$R_m(i,n)=\sqrt{\frac{2E_s}{(N_c+N_g)T_c}}d_{iN_c+n}H_m(i,n)+\Pi_m(i,n) \quad (4)$$

for the n-th frequency component, where $H_m(i,n)$ and $\Pi_m(i,n)$ are the channel gain and the zero-mean noise sample having variance $2(N_0/T_c)N_c$, respectively, at the nth frequency. Then, after parallel-to-serial (P/S) conversion, antenna diversity reception using maximum ratio combining (MRC) and data decision is carried out to obtain the received binary data sequence $\{\hat{d}_n\}$.

For coherent detection, estimation of $\{H_m(i,n)\}$ is necessary. In Sect. 3, we will propose the pilot-assisted adaptive prediction iterative channel estimation.

3. Adaptive Prediction Iterative Channel Estimation

For channel estimation, the frequency multiplexed pilot and time multiplexed pilot are considered, as illustrated in Fig. 2. For the former, pilot subcarrier is inserted every N_p subcarriers in frequency, while pilot symbol is inserted every N_p symbols in time for the latter. A 2K-tap adaptive prediction filter illustrated in Fig. 3 is used in the pilot-assisted adaptive prediction iterative channel estimation. The operation principle of the adaptive iterative channel estimation is described below.



(a) Frequency multiplexed pilot

(b) Time multiplexed pilot

Fig. 2 Pilot insertion methods.

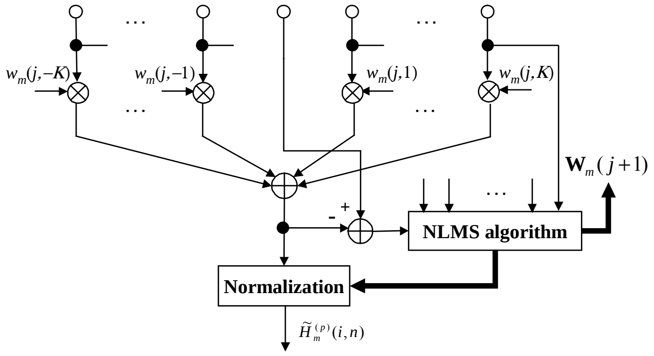


Fig. 3 Adaptive prediction filter structure.

3.1 Frequency multiplexed pilot case

At the first iteration stage (p=1), the channel gains $\{\hat{H}_m^{(1)}(i,n);\, n=0,\, N_p,\, 2N_p,\cdots\}$ at the pilot subcarriers are estimated using the received pilot subcarriers only. Next, the first order interpolation and extrapolation are applied to obtain the channel gain estimates $\{\tilde{H}_m^{(1)}(i,n);\, n=0\sim N_c-1\}$ at all subcarriers. Then, antenna diversity using MRC is applied after P/S conversion. The decision variables $\{\eta^{(1)}(i,n)\}$ for the data symbol sequence $\{d_{iNc+n};\, n=0\sim N_c-1\}$ are obtained as

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

for p=1, where * denotes complex conjugate operations. Using decision variables $\{\eta^{(1)}(i,n)\}$, the tentative decisions data $\{\hat{d}^{(1)}(i,n)\}$ are obtained as

$$\hat{d}^{(p)}(i,n)=\min_{d\in\{\exp(jk\pi/2);\ k=0\sim 3\}}\left|\eta^{(p)}(i,n)-d\right| \quad (6)$$

for p=1.

At succeeding iteration stages ($p\geq 2$), the tentative decisions $\{\hat{d}^{(p-1)}(i,n)\}$ at the (p-1)th iteration stage are fedback as pilots to remove data modulation from the received signal frequency components $\{R_m(i,n)\}$ and the instantaneous channel gain estimates $\{\hat{H}_m^{(p)}(i,n); n=0\sim N_c-1\}$ of all subcarriers are obtained :

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

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

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

where $w_m(j,k)$ denotes the filter tap weight and $\alpha(n)$ is defined as

$$\alpha(n)=\begin{cases}n & \text{for } 1\leq n\leq K-1\\ K & \text{for } K\leq n\leq N_c-K-1\\ N_c-1-n & \text{for } N_c-K\leq n\leq N_c-2\end{cases}. \quad (9)$$

Again, using the adaptively estimated channel gain estimates $\{\tilde{H}_m^{(p)}(i,n)\}$, MRC antenna diversity reception of Eq. (5) is carried out. After repeating the above-mentioned process for (P-1) times, the final decision variables $\{\eta^{(P)}(i,n)\}$ at the Pth iteration stage are obtained from Eq. (5). In the proposed iterative channel estimation accurate channel estimation is possible, since the tentative decision using Eq. (6) is carried out after antenna diversity reception.

3.2 Time multiplexed pilot case

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

$$\tilde{H}_m^{(1)}(i,n)=\begin{cases}R_m(i-1,n) \quad \text{for } n=0,N_c-1\\ \dfrac{1}{\sum_{\substack{k=-\alpha(n)\\k\neq 0}}^{k=\alpha(n)}\left|w_m(j,k)\right|}\sum_{\substack{k=-\alpha(n)\\k\neq 0}}^{k=\alpha(n)}w_m(j,k)R_m(i-1,n+k) \quad (10)\\ \text{otherwise } n\neq 0,N_c-1\end{cases}$$

when i mod N_p=1, and

$$\tilde{H}_m^{(1)}(i,n)=\tilde{H}_m^{(P)}(i-1,n), \quad (11)$$

when i mod N_p>1; (1+j0) is assumed for the pilot symbol. The succeeding iteration stages ($p\geq 2$) are the same as in the frequency multiplexed pilot case.

3.3 Tap weight adaptation

Updating of tap weights is incorporated into the iterative channel estimation loop within one OFDM signaling period. NLMS adaptation algorithm [9] is applied that uses the noisy instantaneous channel gain estimates $\{\hat{H}_m^{(p)}(i,n)\}$. The recursive relation for updating the tap weight vector is represented as

$$\mathbf{W}_m(j+1)=\mathbf{W}_m(j)+\begin{cases}0 \quad \text{for } 0\leq n\leq K-1 \text{ and}\\ \qquad N_c-K\leq n\leq N_c-1\\ \mu\dfrac{e_m(n)}{\sum_{\substack{k=-K\\k\neq 0}}^{K}\left|\hat{H}_m^{(p)}(i,n+k)\right|^2}\mathbf{X}_m^*(i,n)\\ \qquad \text{for } K\leq n\leq N_c-K-1\end{cases}, \quad (12)$$

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

$$e_m(n)=\hat{H}_m^{(p)}(i,n)-\mathbf{W}_m^T(j)\mathbf{X}_m(i,n) \quad , (13)$$

μ is the step size, and $[.]^{\mathrm{T}}$ denotes transpose. In Eq. (12),

$$\begin{cases} \mathbf{W}_m(j) = [w_m(j,-K),\cdots,w_m(j,-1), \\ \qquad\qquad w_m(j,1),\cdots,w_m(j,K)]^{\mathrm{T}} \\ \mathbf{X}_m(i,n) = [\hat{H}_m^{(p)}(i,n-K),\cdots,\hat{H}_m^{(p)}(i,n-1), \\ \qquad\qquad \hat{H}_m^{(p)}(i,n+1),\cdots,\hat{H}_m^{(p)}(i,n+K)]^{\mathrm{T}} \end{cases} \tag{14}$$

are the complex tap weight vector and the instantaneous channel gain vector, respectively.

4. Computer Simulation

The simulation condition is summarized in Table 1. The number of OFDM subcarriers is N_c=256. The multipath fading channel is assumed to have an L=8-exponentially decaying power delay profile with time delay separation of four FFT sample $4T_c$, as shown in Fig. 4. Each path is subject to an independent Rayleigh fading. It is assumed that the maximum time delay is shorter than the guard interval of N_g samples and the complex channel gain remains almost constant over the one OFDM signaling period $T=(N_c+N_g)T_c$. At the receiver, M=2-branch MRC antenna diversity reception is assumed. The number of taps of adaptive prediction filter is $2K$=24 for both frequency and time multiplexed pilot cases.

Table 1 Simulation condition

OFDM	Data modulation	QPSK
	Number of subcarriers	N_c=256
	Guard interval length: N_g	N_s/8
Channel model		L=8-path Rayleigh, Exponential power delay profile
Antenna diversity		M=2-MRC

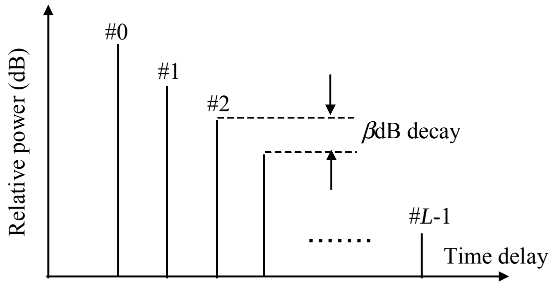


Fig. 4 Power delay profile of multipath channel.

Figure 5 plots the average BER as a function of number P of iterations with the normalized delay spread τ_{rms}/T_s of the channel as a parameter at the average received E_b/N_0=20dB, where $1/T_s$ $(=(1+N_g/N_c)/T)$ is the subcarrier separation. The pilot insertion of N_p=10 (100) for the frequency (time) multiplexed pilot case and the normalized Doppler frequency f_DT=0.001 are assumed. It is clearly seen that iterative channel estimation can significantly reduce the BER. The BER reduces as the number of iterations increases; however, almost no additional improvement is obtained after five iterations. Therefore, the use of five iterations (P=5) is considered to be sufficient. Also, it is observed that the time multiplexed pilot case provides almost same or smaller BERs than the frequency multiplexed pilot case. This is because in the time multiplexed pilot case, more accurate channel estimation is available at the first iteration stage. Hence, in the following, only the time multiplexed pilot case is considered.

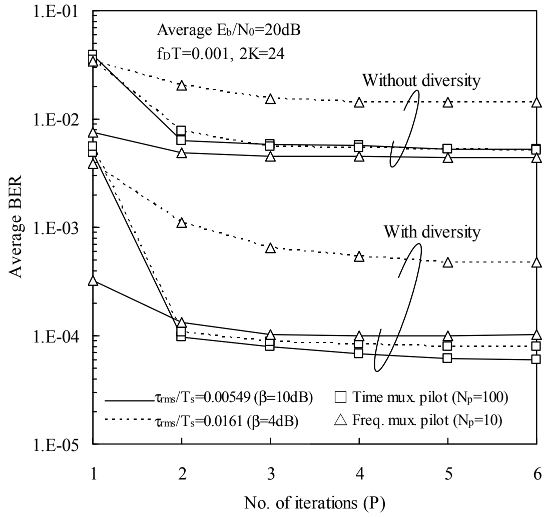
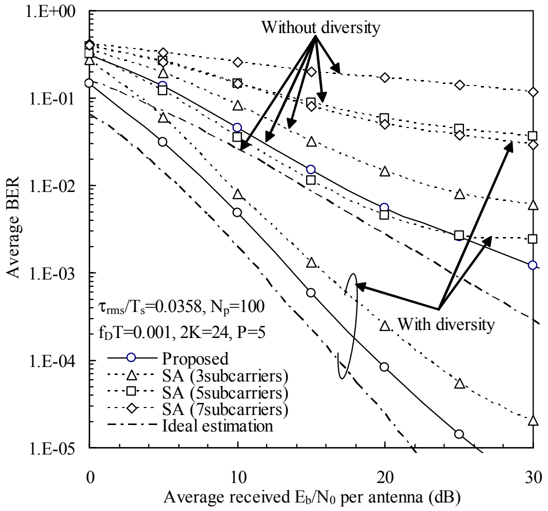


Fig. 5 Impact of number of iterations.

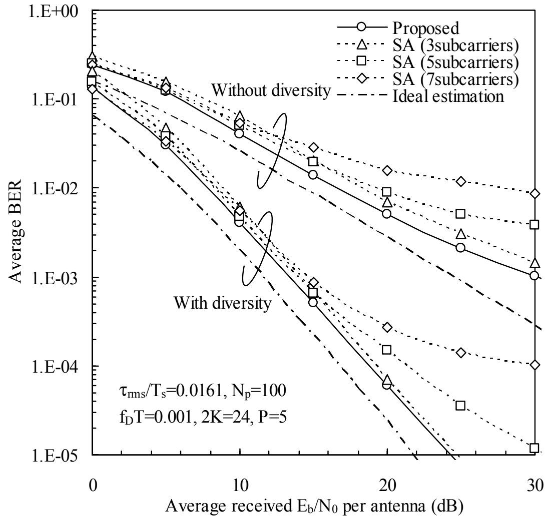


(a) τ_{rms}/T_s =0.0358

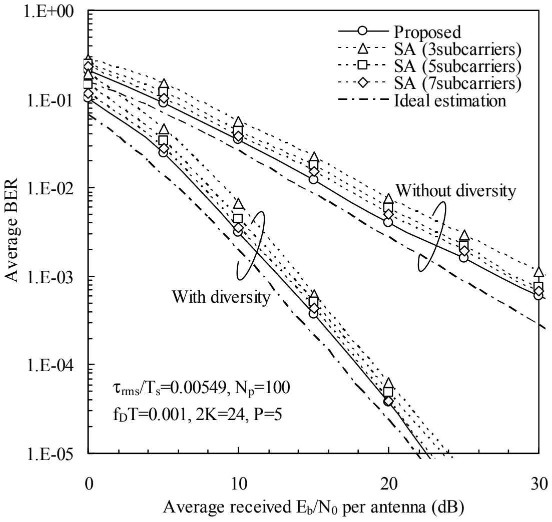
Fig. 6 Performance comparison.

The BER performances achievable by the adaptive prediction iterative channel estimation are compared with the iterative channel estimation using simple averaging (SA) filter as a fixed-tap filter. Figure 6 plots the average BER performance as a function of the average received signal energy per bit-to-background noise power spectrum density ratio (E_b/N_0) per antenna for τ_{rms}/T_s=0.00549 (β=10dB), 0.0161 (β=4dB) and 0.0358 (β=0dB). It is found from Fig. 6 that the optimum SA filter size is different for different value of τ_{rms}/T_s and that the use of adaptive prediction filter always provides better BER performance than the SA filter for both pilot cases. In the case of τ_{rms}/T_s=0.0161, the adaptive prediction iterative channel estimation (time multiplexed pilot case) reduces the required average E_b/N_0 per antenna for achieving BER=10^{-3} by about 0.3, 0.4 and 1.0 dB than SA filter with 5, 3 and 7 taps, respectively, and approaches the ideal channel estimation case by about 1.9 dB.

Reducing the pilot insertion interval N_p improves the tracking ability of channel estimation against channel variations in time and frequency, however reduces the transmission rate. N_p=10 (100) produces the reduction in the data rate of 10 (1) %. Therefore, the use of longer pilot interval is desirable. Figure 7 plots how the pilot insertion interval impacts the achievable BER. As the value of N_p increases, the BER increases since the tracking ability of channel estimation tends to be lost. It is observed from Fig. 7 that for achieving the same BER, the use of the proposed adaptive prediction filter can enlarge the pilot insertion interval compared to the SA filter.



(b) τ_{rms}/T_s=0.0161



(c) τ_{rms}/T_s=0.00549

Fig. 6 Performance comparison.

5. Conclusion

In this paper, an adaptive prediction iterative channel estimation scheme was proposed for the antenna diversity reception of OFDM signals in a frequency selective fading channel. The adaptive prediction filter is incorporated into the iterative channel estimation process. The average BER performance achievable by the use of the proposed pilot-assisted channel estimation was evaluated by computer simulation. Frequency multiplexed pilot and time multiplexed pilot were considered. It was found that the use of time multiplexed pilot provides better BER performance because the channel estimation accuracy at the first stage is better with time multiplexed pilot than with frequency multiplexed pilot. The performance comparison of iterative channel estimation using adaptive prediction filtering and fix-tap filtering showed that the former always provides a better BER performance. Also, confirmed by the computer simulation was that for achieving the same BER, the use of adaptive filtering can enlarge the pilot insertion interval and therefore can increase the transmission rate.

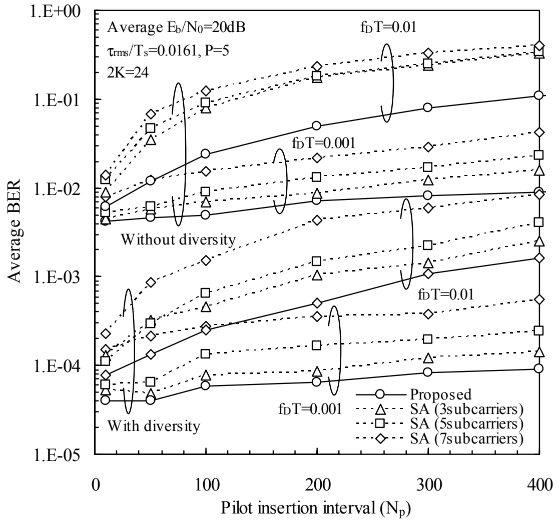


Fig. 7 Impact of pilot insertion interval.

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