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RLS Channel Estimation with Forgetting Factor Adaptation for The Downlink of MC-CDMA System

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Abstract - *In this paper, two pilot-aided-channel-estimation schemes modified from the ordinary Recursive Least Squares (RLS) algorithm for the downlink of Multicarrier Code Division Multiple Access (MC-CDMA) are proposed. Both techniques employ the method of adjusting the adaptive weigh (forgetting factor) of RLS algorithm for utilizing the correlation in time domain of the channel response in order to improve the estimation accuracy and tracking capability of the system. The simulation results show that our proposed algorithms outperform the customary RLS algorithm channel estimation schemes in both BER performance and tracking capability over the frequency selective fading channel.*

Key words: MC-CDMA, channel estimation, RLS algorithm, forgetting factor adaptation

1. Introduction

MC-CDMA [1],[2], based on the combination of Orthogonal Frequency Division Multiplexing (OFDM) and Code Division Multiple Access (CDMA), is considered as one of the most promising techniques for the future generation mobile communications. For MC-CDMA, the data symbols are spread in the frequency domain into several parallel subcarriers by using the spreading sequence that makes the symbol intervals are lengthened. Moreover, the guard interval can be added in order to make this system more robust to the Intersymbol Interference (ISI) occurred in the mutipath channel environment.

The MC-CDMA system employs the efficient modulation schemes such as Quadrature Amplitude Modulation (QAM) which requires the accurate carrier recovery for coherent detection. To accomplish the carrier recovery, several methods to estimate the channel response have been proposed. The RLS channel estimation is one of the most efficient methods due to its performance in term of estimation accuracy and convergence rate [3]. One of the most important factors that indicates the performance of RLS algorithm is the forgetting factor value. The forgetting factor should be properly selected in order to track the statistical variations of the channel response.

Since the channel response is naturally time-varying, it is not suitable to use only one constant value of forgetting factor in all channel's conditions. In addition, an appropriate selection of forgetting factor can improve the accuracy of estimation. Therefore, in this paper, we propose two forgetting factor determining techniques for RLS channel estimation, called two step forgetting factor technique and forgetting factor adaptation technique.

The rest of this paper is organized as follows. The system model is presented in Section 2. In Section 3, the RLS pilot aided channel estimation algorithm is analyzed and the two modified versions of it are proposed, while the simulation results are shown in Section 4 to demonstrate the effectiveness of our proposed estimation techniques . Finally, in section 5, the conclusion is drawn.

2. System and channel model

The block diagram of a downlink MC-CDMA system is depicted in figure 1. At the transmitter, the user's input data symbols, $b_m[i]$, are spread with a unique signature sequence, $c_{m,n}$, in the frequency domain. Each chip of the spread signature waveforms is modulated into the narrowband subcarriers, which are mutually orthogonal to each other. The subcarrier modulation is performed by using inverse discrete Fourier transform (IDFT). The guard interval (GI) is also added to mitigate the effect of ISI. Then, the modulated data are transmitted over the multipath channel. After removing the GI at the receiver, the received signals in each subcarrier are demodulated by discrete Fourier transform (DFT). Finally, after the equalization process, the original data symbols will be recovered by the recovery circuit.

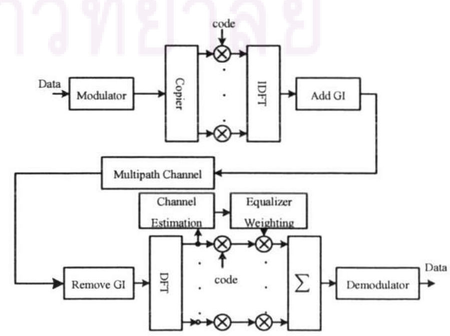

Figure 1. The system model of MC-CDMA

2.1 Signal model

The transmitted signal corresponding to the i^{th} data symbol of the m^{th} user can be written as

$$s_m(t) = \sum_{n=0}^{N-1} d_{m,n} b_m[i] p_{T_s}(t - iT_s) e^{j2\pi(f_c + \frac{n}{T_b})(t - T_G)} \quad (1)$$

where $d_{m,n} \in \{-1, \ 1\}$ represent the n^{th} spreading sequence chip of the m^{th} user, $T_s = T_b + T_G$ is a symbol duration, T_b, T_G, N and f_c are the bit duration, GI duration, carrier frequency and numbers of subcarrier, respectively. $p_{T_s}(t)$ denotes an unit amplitude pulse waveform that is non-zero in the interval of $[0, \ T_s]$.

All users' information bits are summed together and transmitted through the multipath channel. The received signal can be given by

$$y(t) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} h_{m,n} d_{m,n} b_m[i] p_s(t - iT_s) e^{j2\pi(f_c + \frac{n}{T_b})(t - T_G)} + n(t) \quad (2)$$

where $h_{m,n}$ is the channel response of each subcarrier assumed to be time-invariant within T_s and $n(t)$ is an additive white Gaussian noise (AWGN) with zero mean and variance σ_n^2.

2.2 Channel model

Though, the total wide bandwidth is normally considered as the frequency selective fading occurred from the mutipath fading, each carrier is usually a small fraction of the total bandwidth and mainly subjected to the frequency flat fading. We assume that guard interval is longer than the channel memory. Therefore, the ISI-free assumption is hold and the channel can be modeled by sampled spaced tapped delay line (TDL) as

$$h_m(\tau, t) = \sum_{n=0}^{L-1} g_{m,n}(t) \delta(\tau - \tau_l) \quad (3)$$

where $L = \lfloor W/(\Delta f)_c \rfloor + 1$ is the total number of resolvable paths, W, $(\Delta f)_c$, τ_l are the total bandwidth, coherence bandwidth and propagation delay time of the l^{th} path, respectively. The complex fading path distortion weight coefficients of the m^{th} user, $g_{m,n}(t)$, are assumed to be mutually uncorrelated and complex-valued stationary random processes of which magnitudes are Rayleigh distribution and phases are uniformly distribution. By using the discrete Fourier transform (DFT), the transfer function of each subchannel for the m^{th} user can be written as $h_{m,n}$. It should be noted that the maximum delay difference of the channel is not larger than the inserted GI duration to yield the ISI-free assumption.

3. The RLS channel estimation

For the time multiplexed pilot channel estimation, each data packet has a preamble including the pilot signal, of which length is N_p symbols in time domain. The pilot signal is located in all subcarriers. The receiver will use these known symbols, which lie on the beginning part of each packet, to estimate the response of the channel. The estimated response is also utilized as the response of channel in the remaining data period of the packet until the next pilot signal. Noted that, the position of all pilot symbols must be known at the receiver and the symbol synchronization is assumed to be perfect.

3.1 The exponentially weighed RLS channel estimation

The exponentially weighed RLS algorithm is one of the most efficient techniques for estimating the channel response because it not only employs the correlation of the received pilot signal and the reference signal in the frequency domain to estimate the channel impulse response, but it also utilizes the correlation of adjacent pilot symbol in the time domain to improve the performance of estimation. The most important key factor affected the performance of the algorithm is the forgetting factor, λ, that we have to select the appropriate value for the conditions of the channel.

The forgetting factor, $0 < \lambda \le 1$, is the weighting factor ,which intends to ensure that the characteristic of channel in the distant past are forgotten in order to afford the possibility of following the statistical variations of the channel when the filter operates in a non-stationary environment.

Following the derivation of the exponentially weighed RLS channel estimation by using the matrix inversion lemma [4],[5] in [3] and applying to the MC-CDMA system, the recursive form of estimated channel impulse response can be given by

In the case of $n = 0$,

$$k(0,i) = \frac{\lambda^{-1} P_s(N-1, i-1) c_s(0,i)}{1 + \lambda^{-1} c_s^H(0,i) P_s(N-1, i-1) c_s(0,i)} \quad (4)$$

$$\xi(0,i) = Y_s[0,i] - \hat{h}^H(N-1, i-1) c_s(0,i) \quad (5)$$

$$\hat{h}_s(0,i) = \hat{h}_s(N-1, i-1) + k_s(0,i) \xi^*(0,i) \quad (6)$$

$$P_s(0,i) = \lambda^{-1} P_s(N-1, i-1) - \lambda^{-1} k_s(0,i) c_s^H(0,i) P_s(N-1, i-1) \quad (7)$$

In the case of $1 \le n \le N-1$,

$$k(n,i) = \frac{P_s(n-1,i)c_s(n,i)}{1 + c_s^H(n,i)P_s(n-1,i)c_s(n,i)} \quad (8)$$

$$\xi(n,i) = Y_s[n,i] - \hat{h}^H(n-1,i)c_s(n,i) \quad (9)$$

$$\hat{h}_s(n,i) = \hat{h}_s(n-1,i) + k_s(n,i)\xi^*(n,i) \quad (10)$$

$$P_s(n,i) = P_s(n-1,i) - k_s(n,i)c_s^H(n,i)P_s(n-1,i) \quad (11)$$

where the Fourier transform vector, $a(n)$, is given by

$$a^H(n) = \begin{bmatrix} 1 & e^{j2\pi n/N} & \ldots & e^{j2\pi(L-1)/N} \end{bmatrix} \quad (12)$$

and

$$c_s(n,i) = b_m(i)d_{m,n}a(n) \quad (13)$$

A reasonable choice of the initial condition for the above recursion is

$$\hat{h}_s(N-1,0) = \vec{0} \quad (14)$$

$$P_s(N-1,0) = \delta^{-1}I \quad (15)$$

where $\vec{0}$, I and δ are the N-by-1 null vector, the N-by-N identity matrix and small positive constant, respectively.

3.2 Proposed algorithms

Our two proposed algorithms modified from the conventional RLS channel estimation derived in [5] are mainly emphasized on the adaptation of forgetting factor value to be suitable for the characteristic of the channel at each time. There are two different techniques in the proposed algorithm, the two step forgetting factor technique and the adaptive forgetting factor technique based on the MMSE criterion. Both techniques can provide the better performance than the conventional RLS algorithm as shown in the simulation results.

3.2.1 RLS algorithm with two step forgetting factor

Indeed, the contemporary response of channel deviate significantly from the last estimated channel response approximated by the previous packet due to the long duration of data period. Therefore, for this technique, instead of applying the equal forgetting factor value to all pilot symbols in each packet as conventional RLS algorithm, we apply a low forgetting factor value (much less than 1) to the beginning part of pilot region and a high one (close to 1) to the remaining pilot region as shown in figure 2.

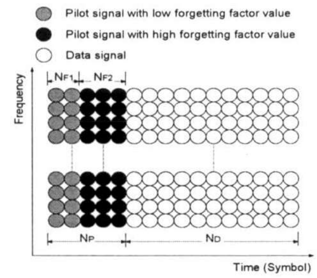

Figure 2. Packet structure of the proposed method

Hence, it is reasonable that we apply the low forgetting factor value to the first part of pilot symbol that make the system mostly relies on the channel's information, which is estimated from the recent correct pilot symbol. At the second part, the high forgetting factor value is applied to make the system relies on the statistical information of channel response determined by the prior estimation.

The performance of proposed technique is verified by the computer simulation results as shown in the simulation results part.

3.2.2 RLS algorithm with forgetting factor adaptation

For this technique, the forgetting factor, λ, is adaptable in order to match with the instantaneous channel conditions. In this case, the objective is to find the particular value of λ that derived by the minimum mean squared error (MMSE) criterion that the error between the received signal and pilot replica signal should be minimized.

Applying the derivation of RLS algorithm with adaptive memory in [4] and incorporating into the standard RLS algorithm in (4) – (15), we may summarize the RLS algorithm with adaptive forgetting factor as follows:

Starting with the initial value $\hat{h}_s(0,0)$, $P_s(0,0)$, $\lambda(0,0)$, $S(0,0)$ and $\hat{\psi}(0,0)$, compute for $n > 0$:

$$k(n,i) = \frac{\lambda^{-1}(n-1,i)P_s(n-1,i)c_s(n,i)}{1 + \lambda^{-1}(n-1,i)c_s^H(n,i)P_s(n-1,i)c_s(n,i)} \quad (16)$$

$$\xi(n,i) = Y_s[n,i] - \hat{h}_s^H(n-1,i)c_s(n,i) \quad (17)$$

$$\hat{h}_s(n,i) = \hat{h}_s(n-1,i) + k(n,i)\xi^*(n,i) \quad (18)$$

$$P_s(n,i) = \lambda^{-1}(n-1,i)P_s(n-1,i) - \lambda^{-1}(n-1,i)k(n,i)c_s^H(n,i)P_s(n-1,i) \quad (19)$$

$$\lambda(n,i) = \left[\lambda(n-1,i) + \alpha \mathrm{Re}\left[\hat{\psi}^H(n-1)c_s(n,i)\xi^*(n,i)\right]\right]_{\lambda-}^{\lambda+} \quad (20)$$

$$S(n,i) = \lambda^{-1}(n,i)\left[I - k(n,i)c_s^H(n,i)\right]S(n-1,i) \cdot \left[I - c_s(n,i)k^H(n,i)\right] + \lambda^{-1}(n,i)k(n,i)k^H(n,i) - \lambda^{-1}(n,i)P_s(n,i) \quad (21)$$

$$\hat{\psi}(n,i) = \left[I - k(n,i)c_s^H(n,i)\right]\hat{\psi}(n-1,i) + S(n,i)c_s^H(n,i)\xi^*(n,i) \quad (22)$$

where the small positive learning rate parameter, α , indicates the sensitivity of adaptation. The bracket with $\lambda-$ and $\lambda+$ in (20) indicates the truncation. The upper level of truncation, $\lambda+$, may be set closely to (but less than) unity. The lower level of truncation, $\lambda-$, play a more crucial role, and its value may be determined by the user through experimentation.

4. Computer simulations

To evaluate the performance of our proposed algorithms, the computer simulations are conducted over the multipath fading channel. The simulation conditions are summarized in table 1.

Table 1. Simulation parameters

Number of user	1
Spreading code	Walsh
Spreading factor	16
Number of subcarriers	16
Symbol duration	15.6 microseconds
Modulation scheme	QPSK
Packet length	55 symbols
- Data	50 symbols
- Pilot	5 symbols
Channel	4-path Rayleigh
Receiver type	MRC

4.1 BER performance over the frequency selective fading channel

In figure 3, the BER performance of the proposed methods over the frequency selective fading channel of which the maximum Doppler frequency is 91 Hz, is shown. All simulation parameters of each method, determined by user through the experimentations, are presented in table 2. The BER of two proposed methods are compared to that of the conventional RLS algorithm and the perfect channel estimator. It is obvious that both of our proposed method outperform the conventional RLS algorithm in term of BER performance and decreasing rate of BER when SNR is increasing. The forgetting factor adaptation can provide better BER performance than two step forgetting factor and conventional RLS algorithm, respectively.

Table 2. Simulation parameters

Conventional RLS algorithm	
Forgetting factor	0.9
Two step forgetting factor	
Low forgetting factor	0.65
Length of low forgetting factor	1 symbol
High forgetting factor	0.9
Length of high forgetting factor	4 symbols
Forgetting factor adaptation	
Initial forgetting factor	0.9
Learning rate	0.00001

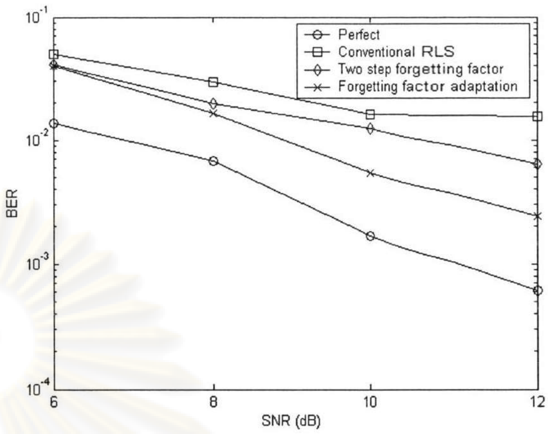

Figure 3. BER performance over the frequency selective fading channel

4.2 Error of estimation

Figure 4 presents the Mean Squared Error (MSE) of estimated channel response over frequency selective fading channel at maximum Doppler frequency 91 Hz and SNR 10. The MSE of our two proposed method are significantly lower than that of the conventional RLS method. Moreover, they also have less amplitude fluctuation than the conventional RLS algorithm. Conforming with the BER performance, the forgetting factor adaptation offers the minimum MSE following by the two step forgetting factor and conventional RLS algorithm comes with the third place.

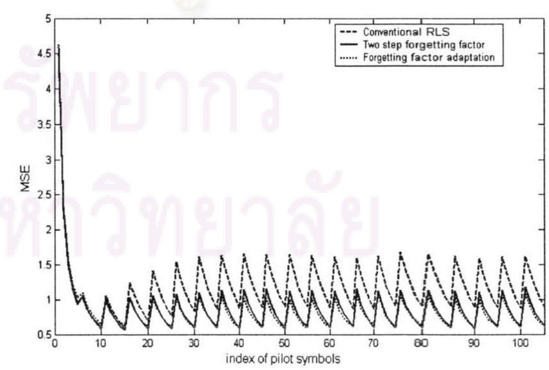

Figure 4. MSE performance over the frequency selective fading channel

4.3 Robustness and sensitivity of the algorithm

As shown in figure 5, the BER performance of two proposed methods are less sensitive to the increasing of the maximum Doppler frequency than that of the conventional RLS method. Moreover, it is obviously seen that our proposed methods can effectively perform in the high fading condition.

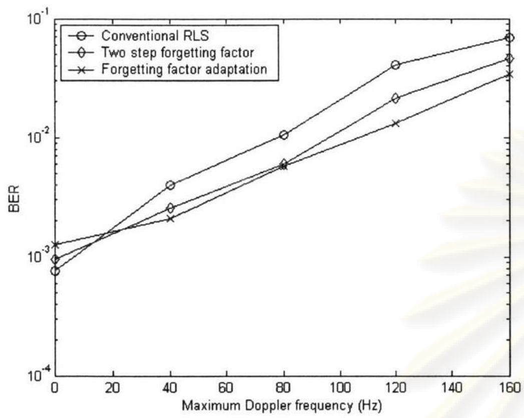

Figure 5. BER performance versus maximum Doppler Frequency

5. Conclusions

Two new techniques for adjusting the exponential weighting factor of RLS algorithm in the pilot-aided-channel-estimation for the downlink of MC-CDMA system are proposed.

Both of our proposed methods base on an adaptive scheme for tuning the exponential weighting factor λ of the RLS algorithm. They employ the selected forgetting factor to exploit the temporal correlation of the received signal in the fading process. The first method, two step forgetting factor are used in order to make the system mostly relies on the recent correct pilot symbols. For the other method, the forgetting factor is adaptively determined according to the propagation environment such as SNR and maximum Doppler frequency based on the MMSE criterion.

The computer simulations show that our proposed methods outperform the conventional RLS algorithm in term of both estimation accuracy and the robustness in combating the variation of channel response. In addition, for some cases that the forgetting factor is unsuitably selected, the conventional RLS algorithm may easily unstable. In contrast, our proposed methods are more robust to that case than the conventional RLS algorithm. Especially, the forgetting factor adaptation can adaptively adjust the forgetting factor to the appropriate value according to the propagation environment. Therefore, the system can work properly in the bad channel conditions.

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ON THE IMPROVEMENT OF RLS CHANNEL ESTIMATION IN FORWARD LINK OF MC-CDMA SYSTEMS

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Abstract

In this paper, the two modified schemes of the Recursive Least Squares (RLS) channel estimation algorithm are proposed. The proposed techniques employ the method for adjusting the adaptive weigh (forgetting factor) of the RLS algorithm to exploit the time correlation of channel response to improve the estimation accuracy and tracking capability. To verify the effectiveness of the algorithms, the proposed techniques are used for estimating the forward link channel response of MC-CDMA systems. The simulation results show that our proposed algorithms outperform the customary RLS algorithm channel estimation scheme over the frequency selective fading channel.

Key words: *MC-CDMA, channel estimation, forward link, RLS algorithm, forgetting factor*

1. INTRODUCTION

Recently, multicarrier code division multiple access (MC-CDMA) [1],[2], based on the combination of Code Division Multiple Access (CDMA) and Orthogonal Frequency Division Multiplexing (OFDM) [3] has drawn a lot of attention for the future generation mobile communications. By spreading the user's data symbols into narrowband subcarriers, the MC-CDMA symbol interval is lengthened, moreover, the guard interval (GI) is also introduced, therefore, the MC-CDMA is effective to cope with the Inter-Symbol Interference (ISI) problem occurred from mutipath channel environment.

The MC-CDMA employs the coherent detection for accurate carrier recovery. To accomplish the carrier recovery, several methods to estimate the channel response (CIR) have been proposed. Due to the accuracy of estimation and tracking capability of the RLS algorithm, it has been used extensively in system identification problem [4]. The key factor that indicates the performance of RLS algorithm is the forgetting factor, which should be properly selected in order to track the statistical variations of the channel response efficiently.

Since the channel response is naturally time-varying, therefore, it is not suitable to apply the fixed forgetting factor value to all channel conditions. Consequently, in this paper, the two methods of selecting forgetting factor value of the RLS channel estimation are proposed.

The rest of this paper is organized as follows. The MC-CDMA system model is presented in Section 2. In Section 3, the RLS pilot aided channel estimation algorithm is analyzed and the two modified versions of it are presented, while the simulation results are shown in Section 4 to demonstrate the effectiveness of our proposed estimation techniques. Finally, in section 5, the conclusion is drawn.

2. SYSTEM AND CHANNEL MODEL

The block diagram of a forward link MC-CDMA systems with channel equalization is depicted in figure 1.

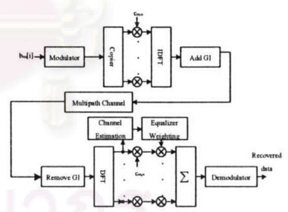

Figure 1. The system model of MC-CDMA

At the transmitter, each user's data symbol is spread in the frequency domain by the user's unique signature sequence. Each chip of the spread signature waveforms is modulated into the narrowband subcarriers, which are mutually orthogonal to each other. For simplicity, the subcarrier spacing is set to be equal and the subcarrier modulation is performed by using inverse discrete Fourier transform (IDFT). The guard interval (GI) are introduced in time domain to avoid the effect of ISI and Inter-carrier Interference (ICI). Then, the modulated data are transmitted over the multipath channel. After

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removing the GI at the receiver, the received signal in each subcarrier is demodulated by discrete Fourier transform (DFT). Finally, the original data symbols can be recovered by the recovery circuit.

2.1 Signal Model

Considering a M -user, single cell MC-CDMA systems, the transmitted signal corresponding to the i^{th} data symbol of the m^{th} user can be written as

$$s_m(t) = \sum_{n=0}^{N-1} c_{m,n} b_m[i] p_{T_s}(t - iT_s) e^{j2\pi(f_c + \frac{n}{T_b})(t - iT_G)} \quad (1)$$

where $b_m[i]$ represents the user's baseband data symbol, $c_{m,n} \in \{-1, \; 1\}$ is n^{th} spreading sequence chip of the m^{th} user, $T_s = T_b + T_G$ is a symbol duration, while, T_b, T_G, N and f_c are the bit duration, GI duration, carrier frequency and number of subcarriers, respectively. $p_{T_s}(t)$ denotes an unit amplitude pulse waveform that is non-zero in the interval of $[0, \; T_s]$.

For the forward link, all user's information bits are confronted with the same channel response. Therefore, the received signal can be written as

$$y(t) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} h_{m,n}[i] c_{m,n} b_m[i] p_s(t - iT_s) e^{j2\pi(f_c + \frac{n}{T_b})(t - iT_G)} + n(t) \quad (2)$$

where $h_{m,n}$ represents the complex gain channel response assumed to be time-invariant within T_s and $n(t)$ is an additive white Gaussian noise (AWGN) with zero mean and variance σ_n^2.

2.2 Channel Model

Though, the total wide bandwidth is normally considered as the frequency selective fading occurred from the mutipath fading, each carrier is usually a small fraction of the total bandwidth and mainly subjected to the frequency flat fading. We assume that the maximum delay difference of channel is not larger than the inserted GI duration. Therefore, the ISI-free assumption is hold and channel response can be modeled by sampled spaced tapped delay line (TDL) [5] as

$$h_m(\tau, t) = \sum_{n=0}^{L-1} g_{m,n}(t) \delta(\tau - \tau_l) \quad (3)$$

where $L = \lfloor W/(\Delta f)_c \rfloor + 1$ is the total number of resolvable paths, W, $(\Delta f)_c$, τ_l are the total bandwidth, coherent bandwidth and propagation delay time of the l^{th} path, respectively. The complex fading path distortion weight coefficients of the m^{th} user, $g_{m,n}(t)$, are assumed to be mutually uncorrelated and complex-valued stationary random processes of which magnitudes are Rayleigh distribution and phases are uniformly distribution. By using DFT, the transfer function of each sub-channel in frequency domain for the m^{th} user can be written as $h_{m,n}$.

3. THE RLS CHANNEL ESTIMATIION

To estimate the channel response, the known pilot preamble is inserted in the beginning part of every data packet. In the case of time-multiplexed-pilot-channel estimation, the pilot sequence, of which length is N_p symbols in time, is located at all subcarriers in the definite time. At the receiver, these known symbols are used as reference symbols to estimate the channel response. The estimated response is also utilized as the response of channel in the remaining data period of the packet until the next pilot signal. Noted that, the position of all pilot symbols must be known at the receiver and the symbol synchronization is assumed to be perfect.

3.1 The Exponentially Weighed RLS Channel Estimation

The exponentially weighed RLS algorithm is one of the most efficient techniques for estimating the channel response. The exponentially weighed RLS algorithm not only employs the correlation of the received pilot signal and the reference signal in the frequency domain to estimate the channel impulse response, but it also utilizes the correlation of adjacent pilot symbol in the time domain to improve the performance of estimation.

The forgetting factor of the exponentially weighed RLS algorithm, $0 < \lambda \leq 1$, is the weighting factor ,which intends to ensure that the characteristic of channel in the distant past are forgotten in order to afford the possibility of following the statistical variations of the channel when the filter operates in a non-stationary environment.

Following the derivation of the exponentially weighed RLS channel estimation by using the matrix inversion lemma [6],[7] in [4] and applying to the MC-CDMA systems, the recursive form of estimated channel impulse response can be given by

$$k(n,i) = \frac{\lambda^{-1}(n,i) P_s(n-1,i) c_s(n,i)}{1 + \lambda^{-1}(n,i) c_s^H(n,i) P_s(n-1,i) c_s(n,i)} \quad (4)$$

$$\xi(n,i) = Y_s[n,i] - \hat{h}^H(n-1,i) c_s(n,i) \quad (5)$$

$$\hat{h}_s(n,i) = \hat{h}_s(n-1,i) + k_s(n,i) \xi^*(n,i) \quad (6)$$

$$P_s(n,i) = \lambda^{-1}(n,i) P_s(n-1,i) - \lambda^{-1}(n,i) k_s(n,i) c_s^H(n,i) P_s(n-1,i) \quad (7)$$

where, $\lambda(n,i)$ denotes the forgetting factor value that is set to be 1 in the case of $n=0$. $P_s(-1,i)=P_s(N-1,i-1)$, $\hat{h}^H(-1,i)=\hat{h}^H(N-1,i-1)$, and the Fourier transform vector, $a(n)$, is given by

$$a^H(n)=\begin{bmatrix}1 & e^{j2\pi n/N} & \dots & e^{j2\pi(L-1)/N}\end{bmatrix} \qquad (8)$$

and

$$c_s(n,i)=p_i(n)a(n) \qquad (9)$$

where $p_i(n)$ denotes the n^{th} chip of the i^{th} pilot sequence symbol.

A reasonable choice of the initial condition for the above recursion is

$$\hat{h}_s(N-1,0)=\vec{0} \qquad (10)$$

$$P_s(N-1,0)=\delta^{-1}I \qquad (11)$$

where $\vec{0}$, I and δ are the N-by-1 null vector, the N-by-N identity matrix and small positive constant, respectively.

3.2 Proposed Algorithms

Indeed, the contemporary response of channel deviate significantly from the last estimated channel response approximated by the previous packet due to the long duration of data periods. Therefore, it is not practical that we apply the fixed constant value of forgetting factor to all pilot symbols in pilot region as conventional RLS algorithm case.

Therefore, in this section, the method for adjusting the forgetting factor value are presented. There are two different techniques in the proposed algorithm, the linearly increasing forgetting factor method and the adaptive forgetting factor method based on the MMSE criterion. It is obviously seen from the simulation result that both techniques can provide the better performance than the conventional RLS algorithm as shown in the simulation results.

3.2.1 RLS Algorithm with Linearly Increasing Forgetting Factor

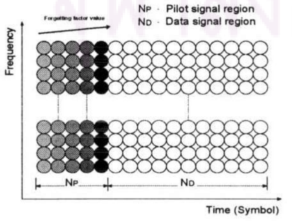

Figure 2. Packet structure of the linearly increasing forgetting factor method

For this method, the low forgetting factor value is applied at first, to make the system mostly relies on the channel's information estimated from the recent correct pilot symbol, and will be linearly increased at the next coming symbols of pilot preamble, to make the system relies on the statistical information of channel response determined by the prior estimation, as shown in figure 2.

3.2.2 RLS Algorithm with Adaptive Forgetting Factor

In order to track the variation of channel response, for this technique, the forgetting factor is adaptively adjusted depending on the instantaneous channel conditions. The objective is to find the particular value of λ that is derived by the minimum mean squared error (MMSE) criterion that the error between the received signal and pilot replica signal should be minimized.

By applying the derivation of RLS algorithm with adaptive memory in [6] and incorporating into the standard RLS algorithm in (4) – (7), the recursive update equations of forgetting factor can be as follows:

Starting with the initial value $\hat{h}_s(0,0)$, $P_s(0,0)$, $\lambda(0,0)$, $S(0,0)$ and $\hat{\psi}(0,0)$, compute for $n>0$:

$$\lambda(n,i)=\left[\lambda(n-1,i)+\alpha\,\mathrm{Re}\left[\hat{\psi}^H(n-1)c_s(n,i)\xi^*(n,i)\right]\right]_{\lambda-}^{\lambda+} \qquad (12)$$

$$\begin{aligned}S(n,i)=\ &\lambda^{-1}(n,i)\left[I-k(n,i)c_s^H(n,i)\right]S(n-1,i)\cdot\\&\left[I-c_s(n,i)k^H(n,i)\right]+\lambda^{-1}(n,i)k(n,i)k^H(n,i)\\&-\lambda^{-1}(n,i)P_s(n,i)\end{aligned} \qquad (13)$$

$$\begin{aligned}\hat{\psi}(n,i)=\ &\left[I-k(n,i)c_s^H(n,i)\right]\hat{\psi}(n-1,i)\\&+S(n,i)c_s^H(n,i)\xi^*(n,i)\end{aligned} \qquad (14)$$

where the small positive learning rate parameter, α, indicates the sensitivity of adaptation. The bracket with $\lambda-$ and $\lambda+$ in (12) indicates the truncation to ensure the stability of the system. The upper level of truncation, $\lambda+$, may be set closely to (but less than) unity, while, the lower level of truncation, $\lambda-$, play a more crucial role, and its value may be determined by the user through experimentation.

4. COMPUTER SIMULATIONS

To evaluate the performance of our proposed algorithms, the computer simulations are conducted over the multipath fading channel. In the simulations, only one user in the system is assumed and the modulated scheme is Quadrature Phase Shift Keying (QPSK). The modulated data is spread by Walsh spreading sequence, of which length is equal to 16 as well as the number of subcarriers. The symbol period is set to 15.6 microseconds and each data packet is consisted of 5 preceding pilot symbols and 50 following data symbols. After passing through the 4-path Rayleigh distributed channel with the 91-Hz maximum Doppler frequency, the user's data symbols are detected by Maximum Ratio Combining (MRC) equalizing technique. Finally, the data symbols will be recovered.

In figure 3, the bit error rate (BER) performance of two proposed method is shown compared to that of the perfect channel estimation and conventional RLS channel estimation case. The simulation parameters determined by user through the experimentations are presented in table 1. Additionally, to illustrate the estimation accuracy of proposed methods, the computer simulation is performed over the fixed-10-dB signal to noise ratio (SNR) condition and the mean squared error (MSE) of the estimated channel response is measured in figure 4. Finally, in figure 5, the BER performance is plotted against the varying maximum Doppler frequency at the 20 dB SNR condition to evaluate the robustness and sensitivity of the algorithm.

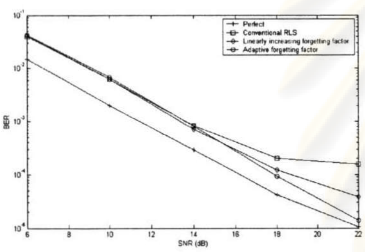

Figure 3. BER performance over the frequency selective fading channel

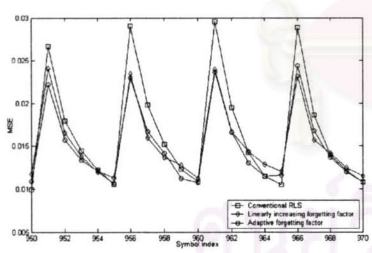

Figure 4. MSE performance over the frequency selective fading channel

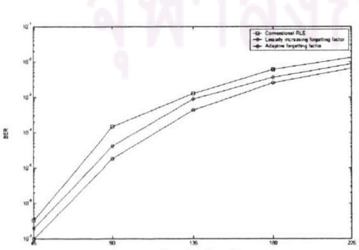

Figure 5. BER performance versus maximum Doppler Frequency

Table 1. Simulation parameters

Conventional RLS algorithm	
Forgetting factor	0.69
Linearly increasing forgetting factor	
Lower forgetting factor	0.55
Upper forgetting factor	0.69
Adaptive forgetting factor	
Initial forgetting factor	0.69
Learning rate	0.00001

5. CONCLUSIONS

In this paper, the two methods for tuning the forgetting factor of the RLS-pilot-aided-channel-estimation for the forward link of MC-CDMA systems are proposed. Both of proposed methods based on the adaptive scheme for tuning the weighting factor of RLS algorithm to exploit the temporal correlation of the received signal in time domain to improve the estimation accuracy and tracking capability of the system.

It is obviously seen from the simulation results that our proposed techniques outperform the conventional RLS algorithm in term of both estimation accuracy and the robustness in combating the variation of channel response.

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