Frequency Offset Compensated RLS-MLSE for TDMA Systems in Frequency Selective Rayleigh Fading Channels

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Abstract— **A new baseband signl processing method for estimating frequency offset in coherent demodulation of PSK and QAM signals, transmitted over frequency selective fading channels is introduced. This method estimates frequency offset from the intersymbol interference (ISI) caused by the fading channel as well as from the information symbol. Its structure resembles that of rake receivers for CDMA receivers, and thus it is called the rake frequency estimator. Computer simulation results demonstrate that the rake frequency estimator can perform much better than existing methods in frequency selective fading channels.**

I. INTRODUCTION

In coherent demodulation of PSK and QAM signals, carrier frequency offset due to either limited oscillator precesion or Doppler effect can cause a significant loss in performance. Correcting the frequency offset in such demodulation is usuful for improving the receiver performance and for relieving the stringent requirements on the oscillator's accuracy. Various techniques have been introduced for frequency offset compensation: use of an automatic frequency control (AFC) loop is proposed in [1]–[4]; estimating the frequency offset from sample autocorrelation functions of demodulated symbols, which are obtained either with the aid of pilot symbols or by taking the M-th power of M-ary PSK symbols, is proposed in [5]–[9]. These techniques are designed either for nonfading channels or for flat fading channels. Consequently, their performance tends to degrade severely in frequency selective fading environments.

The objective of this paper is to develop a frequency offset compensation method for frequency selective fading channels. It will be observed that the carrier frequency offset can be estimated from the intersymbol interference (ISI) as well as from the information symbol. Based on this observation, the proposed method evaluates autocorrelations of the demodulated pilot symbols corresponding to information and of those corresponding to ISI, and estimates the frequency offset from the autocorrelations. The structure of this method resembles, to a certain degree, that of rake receivers for CDMA communications, and thus it is called the rake frequency estimator. To examine the performance of the rake frequency estimator, it is applied to the maximum likelihood sequence estimation (MLSE) receiver [10]–[12]—which employes the Recursive Least Squares (RLS) algorithm for channel estimation, and is called the RLS-MLSE receiver—for IS-136 TDMA mobile communication systems [13]. It will be shown through simulation that considerable performance gain can be achieved by the rake frequency estimator in frequency selective fading channel environments.

II. COMMUNICATION SYSTEM MODEL

The baseband system model considered in this paper is shown in Fig.1. Here $d(j)$ denotes the transmitted M-ary PSK (DPSK) or QAM symbols; $h(t)$ is the baseband pulse shape; $\eta(t)$ is additive white Gaussian noise (AWGN) and Δf represents the carrier frequency offset. Assuming perfect symbol timing recovery, the output of the receiver filter sampled at $t = kT$ is

$$r(k) = e^{j2\pi\Delta f kT} \sum_{i=0}^{L} d(k-i) g_k(i) + \eta(k) \tag{1}$$

where $g_k(i)$ is the impulse response of the equivalent channel at time k due to an impulse that was applied i time units earlier; it describes both $h(t)$ and the Rayleigh fading channel block in Fig.1 in the descrete time domain, and its total length is $L+1$. In (1), $\{d(k-i)g_k(i) | \ i = 1, ..., L\}$ are ISI caused by the channel. For the case of flat fading, $L = 0$ (ISI-free), and for frequency selective fading channels, $L \geq 1$.

III. CARRIER FREQUENCY OFFSET ESTIMATION

Suppose that pilot symbols $\{d(k) | \ k = 0, ..., N\}$ are available, and that $\{g_k(i)\}$ is a fixed ISI channel over the pilot period, i.e., $g_k(i) = g(i)$ for $k = 0, ..., N$. The demodulated pilot symbol, say $\gamma_0(k)$, is expressed as

$$\gamma_0(k) \ = \ r(k)/d(k)$$

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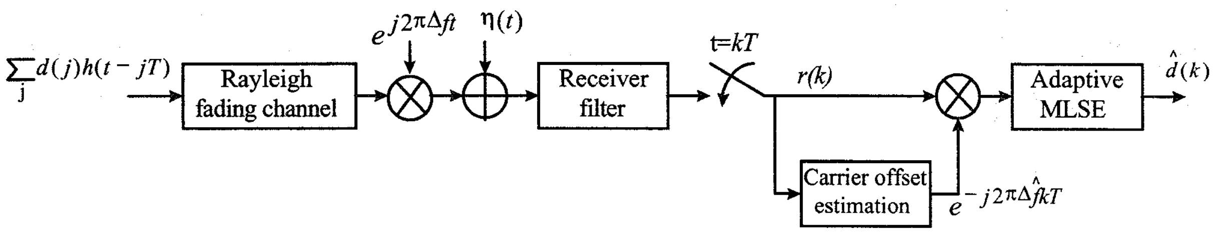


Fig. 1. Baseband system model.

$$= g(0)e^{j2\pi\Delta fkT} + e^{j2\pi\Delta fkT}\sum_{i=1}^{L}\frac{d(k-i)}{d(k)}g(i) + \frac{\eta(k)}{d(k)},\ k=0,...,N. \qquad (2)$$

Since

$$\gamma_0(k)\gamma_0^*(k-i) = |g(0)|^2e^{j2\pi\Delta fiT} + \text{residual terms}, \qquad (3)$$

the frequency offset Δf can be estimated from the argument of $\gamma_0(k)\gamma_0^*(k-i)$. Extending this result, an estimate of Δf is given by

$$\Delta\tilde{\mathrm{f}}_0 = \frac{1}{2\pi T}\sum_{i=1}^{M}\frac{1}{i}arg\{R_{\gamma_0}(i)\},\ M \le N-1 \qquad (4)$$

where $R_{\gamma_0}(i)$ is the sample autocorrelation

$$R_{\gamma_0}(i) = \frac{1}{N-i}\sum_{k=i+1}^{N}\gamma_0(k)\gamma_0^*(i-k),\ 0 \le i \le N-1. \qquad (5)$$

This estimate is identical to the one in [7] and [9]. Now, it is important to note that the estimate is based on only the term corresponding to the information symbol which is multiplied with $g(0)$. Since the frequency offset affects the ISI as well as the information symbol, it should be possible to estimate Δf from the ISI terms in (1). Following the procedure in (2)–(4), we evaluate the demodulated pilot symbol corresponding to the l-th ISI, say $\gamma_l(k)$, which is given by

$$\begin{aligned}\gamma_l(k) &= r(k)/d(k-l)\\ &= g(l)e^{j2\pi\Delta fkT} + e^{j2\pi\Delta fkT}\sum_{i=0,i\neq l}^{L}\frac{d(k-i)}{d(k-l)}g(i)\\ &\quad + \frac{\eta(k)}{d(k-l)},\ 1 \le l \le L. \end{aligned} \qquad (6)$$

An estimate of Δf based on this equation is

$$\Delta\tilde{\mathrm{f}}_l = \frac{1}{2\pi T}\sum_{i=1}^{M}\frac{1}{i}arg\{R_{\gamma_l}(i)\},\ M \le N-1 \qquad (7)$$

where $R_{\gamma_l}(i)$ is the sample autocorrelation of $\gamma_l(k)$. A useful estimator that can outperform the individual estimators in (4) and (7) is written as

$$\Delta\hat{\mathrm{f}} = \sum_{l=0}^{L}\alpha_l\Delta\tilde{\mathrm{f}}_l \qquad (8)$$

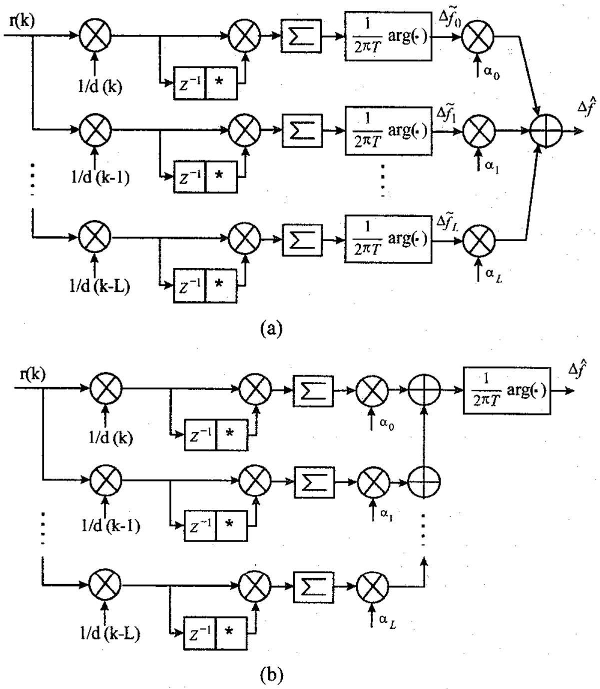
where

$$\alpha_l = \frac{\sum_{i=1}^{M}|R_{\gamma_l}(i)|}{\sum_{l=0}^{L}\sum_{i=1}^{M}|R_{\gamma_l}(i)|}. \qquad (9)$$

As an alternative, we may average the sample autocorrelation values $R_{\gamma_l}(i)$ before taking their arguments, as shown below.

$$\Delta\hat{\mathrm{f}} = \frac{1}{2\pi T}\sum_{i=1}^{M}\frac{1}{i}arg\{\sum_{l=0}^{L}\alpha_lR_{\gamma_l}(i)\},\ M \le N-1. \qquad (10)$$

These estimators are illustrated in Fig. 2 when $M = 1$. It is seen that their structures resemble to a certain degree those



(a)

(b)

Fig. 2. Block diagram of (a) rake 1 frequency estimator and (b) rake 2 frequency estimator ($M = 1$).

of rake receivers; and thus the estimators in (8) and (9) are called the rake 1 and rake 2 frequency estimators, respectively.

IV. APPLICATION TO RLS-MLSE FOR IS-136 TDMA TRANSMISSIONS

The RLS-MLSE receiver which is often used for TDMA systems consists of an MLSE which is implemented using Viterbi algorithm, a channel estimator using an RLS algorithm, and a transversal filter modeling a channel. Fig.3 illustrates an RLS-MLSE receiver that employes the rake frequency estimator. The frequency compensated input signal $r'(k)$ enters the MLSE block, which produces tentative decision $\mathrm{d}'(\mathrm{k})$ as well as the final decision $\hat{\mathrm{d}}(\mathrm{k})$. Tentative decision values are used for evaluating the error signal $e(k)$, from which channel parameters are estimated. These parameters are then used for evaluating the metric of Viterbi algorithm in the MLSE block and supplied to the transversal filter as its coefficients. In the following, the frequency compensated RLS-MLSE receiver using per-surviving processing [10]–[12]—where each surviving path keeps and updates its own channel estimate—is applied to the IS-136 TDMA mobile communication system [13]. In the IS-136 TDMA system the modulation scheme is $\pi/4$ DQPSK with a symbol rate of 24.3ksymbol/s, and the data sequence is arranged into 162 symbol frames. The first 14 symbols of each frame is a pilot sequence. The transmitting and receiving filters are square root raised cosine filters with excess bandwidth of 35%. In our simulation, the fading channel is assumed to be a two-ray Rayleigh fading channel, in which two fading paths are independent with equal strength, and are implemented as shown in Fig.4 [10]. Typically for IS-136 communications, the channel delay parameter τ is set around T; we use τ=T and τ=5T/4. For these values of τ, it is sufficient to consider L=2, because the energy of channel impulse response is mostly confined in 3 symbol periods. We set M=1 in equations (7) and (9), and the forgetting factor of the RLS algorithm estimating L channel parameters is fixed at 0.85. Fig.5 and Fig.6 show the estimation error performances of the rake frequency estimators when E_b/N_0 is fixed at 25dB. The rake frequency estimators considerably outperform the conventional method in (4); and the rake 2 estimator acts better than the rake 1 estimator. To examine the performance gain of the RLS-MLSE that can be achieved by the frequency compensation, BER values of the frequency compensated RLS-MLSE are empirically estimated when $\Delta fT = 0.1$. The results are shown in Fig.7. It is seen that the rake frequency compensation provides significant performance gain over the conventional method.

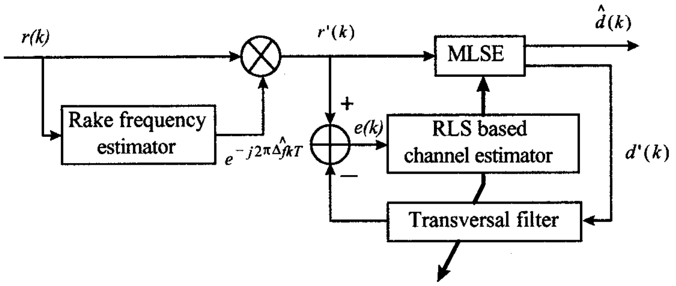


Fig. 3. The frequency offset compensated RLS-MLSE.

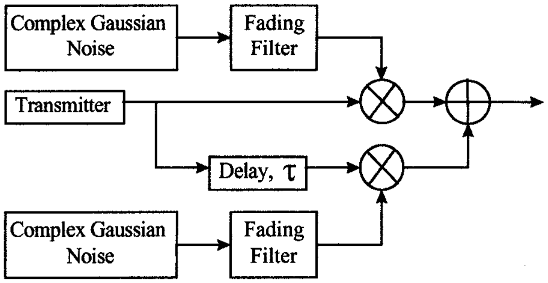


Fig. 4. The two-ray Rayleigh fading channel model.

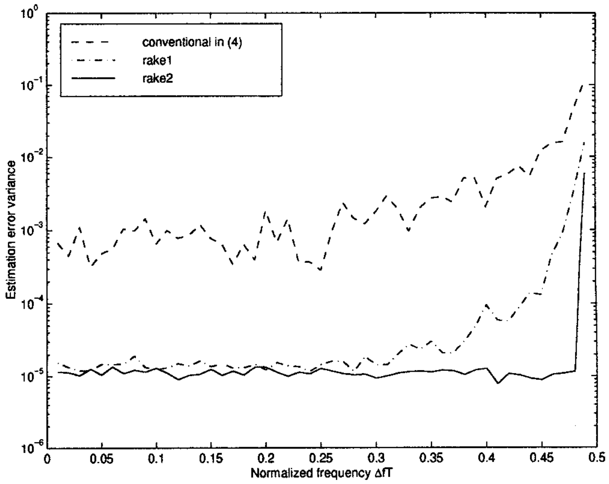


Fig. 5. Frequency offset estimation performance in a frequency selective fading channel, τ=T.

V. CONCLUSION

A new baseband signal processing method for estimating frequency offset in frequency selective fading channel, called the rake frequency estimator, was proposed. This estimator extracts frequency offset from both the ISI and the information symbol. Its performance was examined through computer simulation, and the results show that the rake frequency

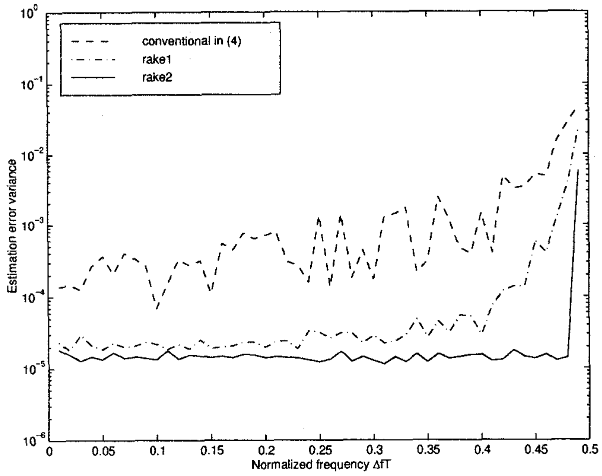


Fig. 6. Frequency offset estimation performance in a frequency selective fading channel, τ=5T/4.

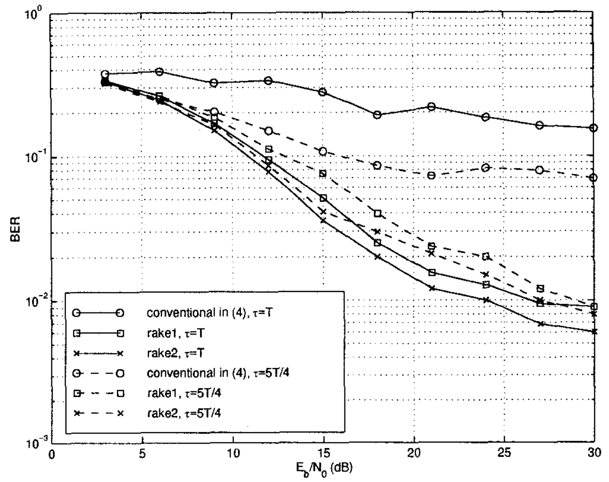


Fig. 7. Comparison of BER performances.

estimator performs much better than existing techniques at the expense of additional computation.

REFERENCES

[1] F. D. Natali, "AFC tracking algorithms," *IEEE Trans. Commun.*, vol. COM-32, pp. 935–947, Aug. 1984.

[2] F. M. Gardner, "Characteristics of frequency-tracking loops," *IEEE Trans. Commun.*, vol. COM-33, pp. 131–139, Feb. 1985.

[3] T. Alberty and V. Hespelt, "A new pattern jitter free frequency error detector," *IEEE Trans. Commun.*, vol. 37, pp. 159–163, Feb. 1989.

[4] S. Saito and H. Suzuki, "Fast carrier-tracking coherent detection with dual-mode carrier recovery circuit for digital land mobile radio transmission," *IEEE J. Select. Areas Commun.*, vol. 7, pp. 130–139, Jan. 1989.

[5] Andrew J. Viterbi and Audrey M. Viterbi, "Nonlinear estimation of psk-modulated carrier phase with application to burst digital transmission," *IEEE Trans. Inform. Theory*, vol. IT-29, pp. 543–551, July 1983.

[6] Justin C.-I. Chuang and Nelson R. Sollenberger, "Burst coherent demodulation with combined symbol timing, frequency offset estimation, and diversity selection," *IEEE Trans. Commun.*, vol. 39, pp. 1157–1164, July 1991.

[7] M. Luise and R. Reggiannini, "Carrier frequency recovery in all-digital modems for burst-mode transmissions," *IEEE Trans. Commun.*, vol. 13, pp. 1169–1178, Feb./Mar./Apr. 1994.

[8] Z. Y. Choi and Y. H. Lee, "Compensating frequency drift in dpsk systems via baseband signal processing," *IEEE Trans. Commun.*, vol. 45, pp. 921–924, Aug. 1997.

[9] W. Y. Kuo and M. P. Fitz, "Frequency offset compensation of pilot symbol assisted modulation in frequency flat fading," *IEEE Trans. Commun.*, vol. 45, pp. 1412–1416, Nov. 1997.

[10] M. J. Omidi, S. Pasupathy, and P. G. Gulak, "Joint data and kalman estimation of fading channel using a generalized viterbi algorithm," *International Conference on Communications*, vol. 2, pp. 1198–1203, May 1996.

[11] H. Kubo, K. Murakami, and T. Fujino, "Adaptive maximum-likelihood sequence estimation by means of combined equalization and decoding in fading environments," *IEEE J. Select. Areas Commun.*, vol. 13, pp. 102–109, Jan. 1995.

[12] Mark E. Rollins and Stanley J. Simmons, "Simplified per-survivor kalman processing in fast frequency-selective fading channels," *IEEE Trans. Commun.*, vol. 45, pp. 544–553, May 1997.

[13] Electronic Industries Association, *EIA/TIA IS-136: dual-mode mobile station-base station compatibility standard*, TIA, Washington D.C., 1994.