distance of adjacent spectral peaks equals the bit rate divided by the sequence length. The measurement exhibits the correct spectral distance of 157.5MHz.

Conclusions: A completely integrated silicon PRBS generator providing adjustable bit rates up to 25Gbit/s is presented; 26Gbit/s are also available with a slightly degraded performance. For the first time, this bit rate is achieved by on-chip multiplexing using only one shift register and one additional Boolean operation. Furthermore, this work demonstrates the ability to realise complex integrated high-speed devices using an advanced implanted base silicon bipolar technology.

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Symbol-by-symbol based adaptive interference canceller for asynchronous DS/CDMA systems in multipath fading channels

Jeong Hoon Ko, Jung Suk Joo and Yong Hoon Lee

Indexing terms: Intersymbol interference, Multipath channels, Fading

The authors propose a new interference cancellation scheme called the symbol-by-symbol based adaptive interference canceller (SAIC), whichadaptively estimates and removes both multiple access interference (MAI) and intersymbol interference (ISI) at the output of the Rake receiver. The SAIC is considerably simpler to implement than existing techniques; computer simulation results demonstrate that it can perform much better than conventional Rake receivers.

Introduction: Although the interference cancellation schemes in [1 – 5] can effectively reduce the multiple access interference (MAI) in asynchronous DS/CDMA communications, their application to practical systems is rather difficult mainly because of their complexity in implementation. These interference cancellers require either a sophisticated respreading technique or the evaluation of partial cross-correlation, which is computationally expensive. Furthermore, when a Rake receiver is employed in a multipath fading environment, use of several interference cancellers, one canceller for each finger of the Rake receiver, is usually required. Therefore, the complexity tends to increase as the number of fingers is increased.

In this Letter, we propose a new interference cancellation scheme that adaptively estimates and removes interference from the output of the Rake receiver on a symbol-by-symbol basis. This scheme, called the symbol-by-symbol based adaptive interference canceller (SAIC), estimates interferences by using a simple least-mean-square (LMS) algorithm and is particularly useful for eliminating interference under a slow fading channel environment. The SAIC requires neither respreading nor partial cross-correlation values and its complexity is independent of the number of fingers, since it is located following the Rake receiver. Therefore, it is considerably simpler to implement than existing methods. It will be shown through computer simulation that the receiver performance can be significantly improved by employing the SAIC.

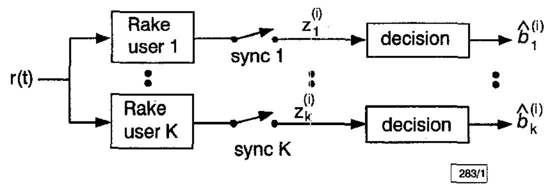

Fig. 1 *Conventional detector employing Rake receiver for each user*

System model: We consider BPSK transmission through multipath channel shared by K users employing a direct sequence spread spectrum modulation. Using the notations and the channel model in [2], the communication signals are expressed as follows: The kth user's data signal $b_k(t)$ is given by $b_k(t) = \Sigma_{i=-\infty}^{\infty} b_k^{(i)} P_{Tb}(t - iT_b)$ where $P_{Tb}(t) = 1$ for $0 \le t < T_b$ and $P_{Tb}(t) = 0$, otherwise; $b_k(i) \in \{\pm1\}$ denotes the ith transmitted bit of the kth user. The kth user's spreading signal is expressed as $a_k(t) = \Sigma_{i=-\infty}^{\infty} a_k^{(i)} P_{Tc}(t - iT_c)$, where $a_k^{(i)} \in \{\pm1\}$ is the spreading sequence of period N and $P_{Tc}(t)$ is the spreading chip waveform with duration $T_c = T_b/N$. The transmitted signal is a carrier modulated version of $b_k(t)a_k(t)$.

The signal received over a multipath fading channel can be written in the form:

$$r(t) = \sum_{k=1}^{K}\sum_{\lambda=1}^{L_k} \sqrt{2P_k}\, g_{k,\lambda} u_k(t - \tau_{k,\lambda}) \cos(w_c t + \phi_{k,\lambda}) + n(t) \quad (1)$$

where L_k is the number of paths in the kth user's link, P_k is the transmission power, $g_{k,\lambda}$ is the path amplitude having a Rayleigh distribution, $u_k(t) = b_k(t)a_k(t)$, $\tau_{k\lambda}$ and $\phi_{k,\lambda}$ denote the time delay and the phase offset associated with the kth user's λth path, respectively, and $n(t)$ is zero-mean white Gaussian noise. It is assumed that $\tau_{k,\lambda}$ and $\phi_{k,\lambda}$ are uniformly distributed over $[0, T_b)$ and $[0, 2\pi)$, respectively.

Symbol-by-symbol based adaptive interference canceller: Fig. 1 shows the conventional detector employing a Rake receiver for each user. The Rake receiver with F fingers consists of F correlators, which operate with proper delays, followed by a combiner. We assume equal gain combining for the sake of simplicity. Since the time delay $\tau_{k,\lambda} \in [0, T_b)$, the ith output of the kth Rake receiver can be written as

$$\begin{aligned} z_k^{(i)} = {} & \alpha_{k,k}^{(i)}(0) b_k^{(i)} + \alpha_{k,k}^{(i)}(-1) b_k^{(i-1)} + \alpha_{k,k}^{(i)}(1) b_k^{(i+1)} \\ & + \sum_{l \neq k} \left(\alpha_{k,l}^{(i)}(-1) b_l^{(i-1)} + \alpha_{k,l}^{(i)}(0) b_l^{(i)} + \alpha_{k,l}^{(i)}(1) b_l^{(i+1)} \right) \\ & + \sum_{m=1}^{F} \eta_{k,m}^{(i)} \end{aligned} \quad (2)$$

where $\eta_{k,m}^{(i)}$ is the sampled Gaussian noise associated with each finger and $\alpha_{k,l}^{(i)}(j), j \in \{-1, 0, 1\}$ represents the amount of interference caused by the lth user's $(i + j)$th data. Specifically, $\alpha_{k,k}^{(i)}(-1)\, b_k^{(i-1)}$ and $\alpha_{k,k}^{(i)}(1) b_k^{(i+1)}$ are each intersymbol interference (ISI) caused by multipath transmission and $\alpha_{k,l}^{(i)}(j) b_l^{(i+j)}$, $l \neq k$, $j \in \{-1, 0, 1\}$, are MAI terms ($\alpha_{k,l}^{(i)}(j)$ is expressed in terms of the path amplitude and the partial cross-correlations; the expression for $\alpha_{k,l}^{(i)}(j)$ is rather lengthy and is thus omitted). Note that the MAI caused by the lth user consists of only three terms corresponding to $b_l^{(i-1)}$, $b_l^{(i)}$, and $b_l^{(i+1)}$. To simplify notations, eqn. 2 is rewritten as

$$z_k^{(i)} = \alpha_{k,k}^{(i)}(0) b_k^{(i)} + I_k^{(i)} + \sum_{l \neq k} M_{k,l}^{(i)} + \sum_{m=1}^{F} \eta_{k,m}^{(i)} \quad (3)$$

where $I_k^{(i)} = \alpha_{k,k}^{(i)}(-1)b_k^{(i-1)} + \alpha_{k,k}^{(i)}(1)b_k^{(i+1)}$ and $M_{k,l}^{(i)} = \alpha_{k,l}^{(i)}(-1)b_l^{(i-1)} + \alpha_{k,l}^{(i)}(0)b_l^{(i)} + \alpha_{k,l}^{(i)}(1)b_l^{(i+1)}$. The design of an interference cancellation scheme can be formulated as a problem for minimising $E[|(z_k^{(i)} - I_k^{(i)} - \Sigma_{l\neq k} M_{k,l}^{(i)}) - \alpha_{k,k}^{(i)}(0)b_k^{(i)}|^2]$ with respect to $\alpha_{k,l}^{(i)}(j)$. When $\alpha_{k,l}^{(i)}(j)$ are slowly varying, this problem may be solved by the LMS algorithm, which results in the following update equations:

$$e_k^{(i)} = z_k^{(i)} - \hat{I}_k^{(i)} - \sum_{l\neq k} \hat{M}_{k,l}^{(i)} - \hat{\alpha}_{k,k}^{(i)}(0)b_k^{(i)} \quad (4)$$

$$\hat{\alpha}_{k,k}^{(i+1)}(0) = \hat{\alpha}_{k,k}^{(i)}(0) + \mu_1 e_k^{(i)} b_k^{(i)} \quad (5)$$

$$\hat{\alpha}_{k,l}^{(i+1)}(j) = \hat{\alpha}_{k,l}^{(i)}(j) + \mu_2 e_k^{(i)} b_l^{(i+j)} \quad \text{for } (l,j) \neq (k,0) \quad (6)$$

where $\hat{I}_k^{(i)} = \hat{\alpha}_{k,k}^{(i)}(-1)b_k^{(i-1)} + \hat{\alpha}_{k,k}^{(i)}(1)b_k^{(i+1)}$ and $\hat{M}_{k,l}^{(i)} = \hat{\alpha}_{k,l}^{(i)}(-1)b_l^{(i-1)} + \hat{\alpha}_{k,l}^{(i)}(0)b_l^{(i)} + \hat{\alpha}_{k,l}^{(i)}(1)b_l^{(i+1)}$. In practice, the symbol values $b_l^{(i+j)}$ in these equations should be replaced with tentative decision values; we may employ a training sequence for $\hat{\alpha}_{k,k}^{(i)}(j)$, but this is not possible for the other cases.

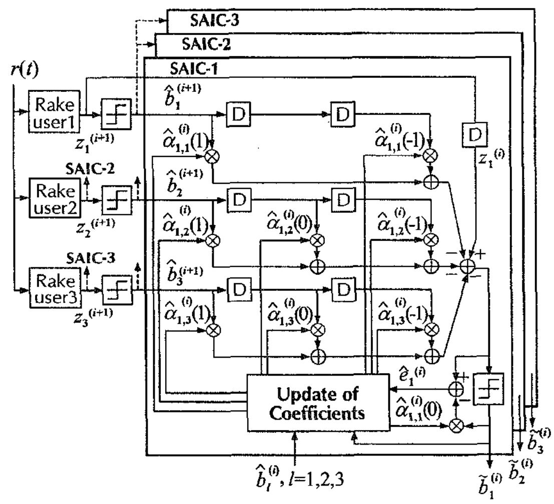

Fig. 2 *Structure of SAIC-1 (SAIC for user 1) when number of users K = 3*

D represents delay by T_b

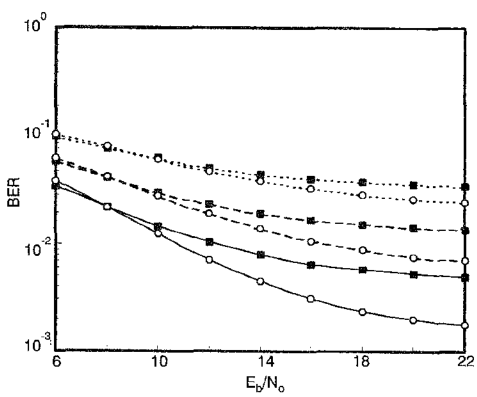

Fig. 3 *Comparison of BER values between conventional receiver in Fig. 1 and SAIC in multipath Rayleigh fading channels*

F is number of fingers
■ conventional receiver
O SAIC
.... $F = 2$
– – – – $F = 3$
——— $F = 4$

The SAIC, illustrated in Fig. 2 for $K = 3$, is proposed, based on the above discussions. For each user, it requires tentative decisions of all K users, and the number of $\hat{\alpha}_{k,l}^{(i)}(j)$ to be updated for each time index i is $3K$. Since the interferences are estimated and eliminated on a symbol-by-symbol basis, the SAIC requires neither respreading nor partial cross-correlation values. In addition, its complexity is independent of the number of fingers of the Rake receiver, since it is located following the Rake receiver. As a consequence, the SAIC is considerably simpler to implement than existing interference cancellation schemes. Its performance, however, may be degraded if the tentative decisions are unreliable due to low SNR, and if $\alpha_{k,l}^{(i)}(j)$ varies rapidly due to fast time-varying fading.

Simulation: The performance of the Rake receiver followed by the proposed SAIC is compared with the conventional Rake receiver by simulating a 10 user ($K = 10$) asynchronous DS/CDMA system. Each user was assigned a unique spreading sequence from a set of Gold codes of length 63, and the data rate $1/T_b$ was 64kbit/s. We consider a multipath channel with slowly time-varying Rayleigh fading in which a 900MHz carrier frequency and 50km/h travelling speed were assumed. The number of multipaths was assumed to be four ($L_k = 4$, for each k). The path amplitudes, $g_{k,\lambda}$ were normalised so that the signal power levels at the input and output of the channel are the same, i.e. $\Sigma_{\lambda=1}^{4} E\{g_{k,\lambda}^2\} = 1$, for each k. The BER values were estimated through 100 simulation runs. For each run, we generated random binary input sequences $b_k^{(i)}$ of length 51,000 for $k = 1, ..., 10$. The first 1000 symbol period of each sequence was considered as a preamble period, in which training sequences were used for $\alpha_{k,k}^{(i)}(j)$ and the errors which occured in this period were ignored. For each SNR, several values of μ_1 and μ_2 were tried and the ones exhibiting best performance were selected. This resulted in $\mu_1 \in [0.05, 0.06]$ and $\mu_2 \in [0.005, 0.025]$. Fig. 3 shows the BER values of the SAIC and the conventional receiver in Fig. 1. As expected, the performance of the two receivers is improved as the number of fingers of their Rake receiver approaches the number of multipaths. The performance of the SAIC is comparable to that of the conventional receiver when E_b/N_0 is < 10dB, but the former becomes considerably better than the latter as E_b/N_0 is increased. This is because more accurate $\hat{\alpha}_{k,l}^{(i)}(j)$ can be obtained for high E_b/N_0.

Conclusion: A new interference cancellation scheme that can easily be implemented for asynchronous DS/CDMA systems in multipath fading channels was proposed. The performance of this scheme, called the SAIC, is improved as the channel becomes slowly time-varying and as the number of resolvable paths is increased. Therefore, the SAIC is particulary useful for future wideband DS/CDMA systems with a high data rate.

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