A MODIFIED PN CODE TRACKING LOOP FOR DIRECT-SEQUENCE SPREAD-SPECTRUM COMMUNICATION OVER ARBITRARILY CORRELATED MULTIPATH FADING CHANNELS

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ABSTRACT

A modified fully-digital PN code tracking loop is proposed for direct-sequence spread-spectrum communication. By taking advantage of the inherent diversity, a modified code tracking loop is embedded into a RAKE receiver to avoid problems caused by unstable locked points of error signals. Such unsteadiness of locked points often occurs with a conventional code tracking loop because the error signals may be randomly biased by multipath fading. Thus, a robust pull-in capability can be provided over a time-variant fading channel where multiple propagation paths are arbitrarily correlated. Very attractive behaviors obtained using the proposed technique are verified.

INTRODUCTION

Substantial efforts have focused on the tracking problem for spread-spectrum communication [1] though most of the analyses have been conducted in the context of analog implementation and AWGN channels. However, very often, frequency-selective fading in addition to AWGN can seriously harm the tracking capabilities of conventional code tracking loops [2]. The joint estimators for interference, multipath effects and code delay based on the extended Kalman filter (EKF) [3] can effectively deal with multipath effects in advance. However, since DS/SS wireless communication systems usually operate in very noisy environments, it has been found that the Kalman filter or recursive least-squares (RLS) algorithms, in practice, provide no superiority at all even after taking advantage of heavier computational loads (i.e., $O\left(N^2\right)$) and higher processing rates (i.e., twice the chip rate) [4]. Actually, any error in the estimate of the number of resolvable channel paths may completely change the functions of the EKF. In this paper, a fully-digital, noncoherent, modified code tracking loop is proposed, which can operate on bandlimited DS/SS systems over frequency-selective fading channels. The modified code tracking loop, assisted by central-branch correlation, is embedded into the RAKE receiver in the proposed technique. By taking advantage of the central-branch correlation, the error characteristic obtained on each RAKE finger can be kept within one chip duration; thus, the kind of self-interference that was encountered in previous works can be effectively reduced. By exploiting the inherent diversity using maximum ratio combining (MRC) and multipath interference cancellation (MPIC), the proposed technique can avoid unsteadiness in the locked points of the error signals and, thus, provides an improved error characteristic. It is proven that the error signals obtained using the proposed technique are definitely odd-symmetric with respect to the common locked point over arbitrarily correlated multipath fading channels.

SYSTEM DESCRIPTION

The modulator and demodulator schemes of a bandlimited DS/SS system have been thoroughly studied previously. To show in detail the operations involved in the modified code tracking loop proposed here, its complete block diagram is sketched in Fig.1. The complex representation of the baseband signal at the output of the chip-matched filter with the square-root raised-cosine transfer function $\sqrt{G_N\left(f\right)}$ is

$$r\left(t\right) = e^{j\theta(t)} \sum_{l=0}^{L} a_l\left(t\right) \sum_{m=-\infty}^{\infty} d_{\{m\}_M} c_{|m|_N} \cdot g\left[t - mT_c + lT_c\right] + n\left(t\right), \quad (1)$$

where $\{m\}_M$ and $|m|_N$ are the integer quotient (i.e., the integral part of $\frac{m}{M}$) and m modulus N, respectively; M is the processing gain; N is the PN code length; T_c is the chip duration; $\theta(t)$ denotes the phase error caused by the front-end noncoherent down-conversion process, where its effect can be absorbed into $a_{\,l}(t)$; $d_{\{m\}_M}$ is the $\{m\}_M$-th information-bearing QPSK complex symbol; c_k is the k-th chip value of the PN sequence; $g(t)$ is the overall chip shape with Fourier transform $G(f) = T_c G_N(f)$; and the PSD of the noise component $n(t)$ is $S_n(f) = N_0 G_N(f)/P$.

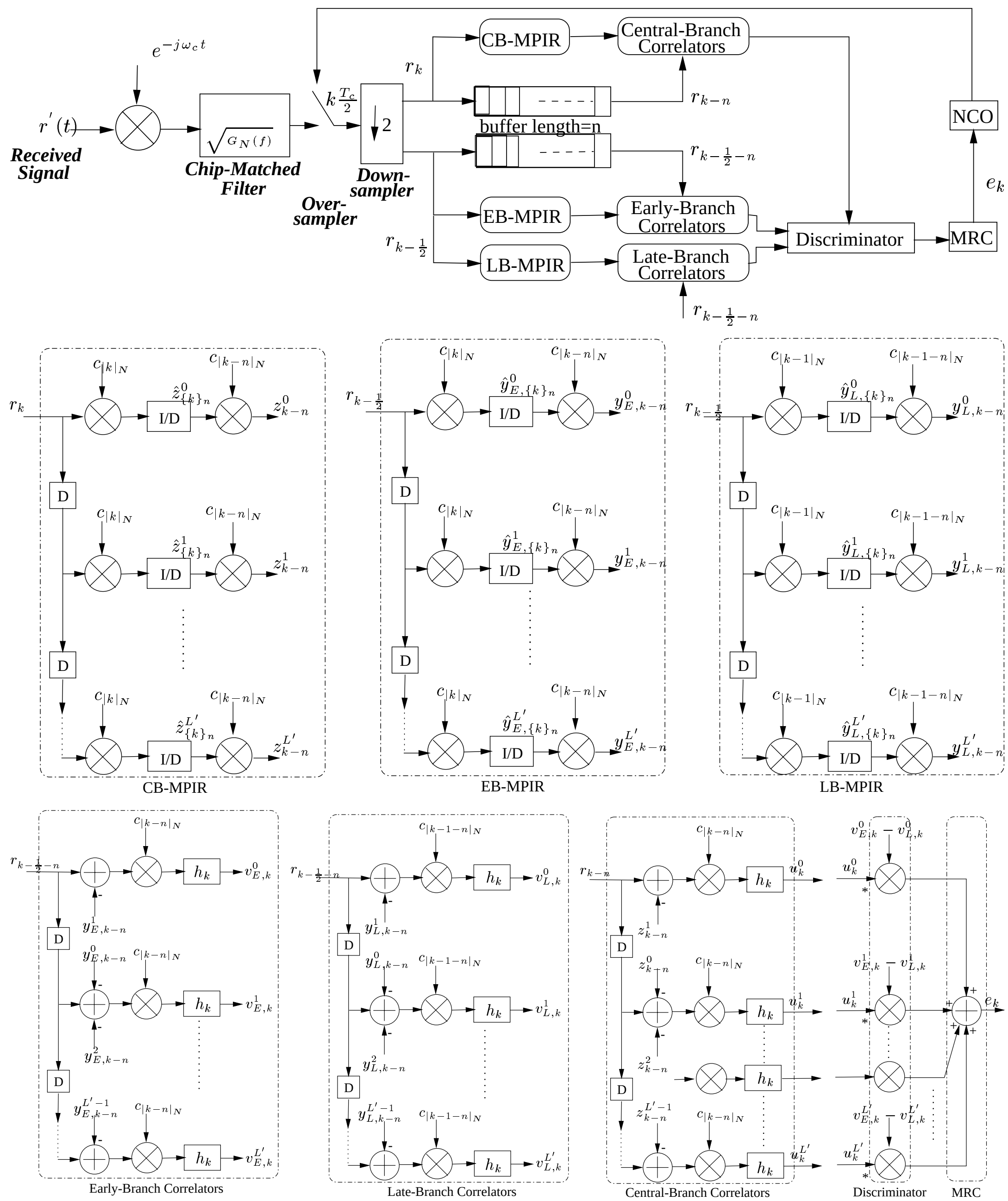

Figure 1: The proposed modified code tracking loop.

The signal $r(t)$ is sampled at the instants $t_k = (k + \varepsilon_k)T_c$ and $t_{k-\frac{1}{2}} = \left(k + \varepsilon_k - \frac{1}{2}\right)T_c$ (i.e., a sampling rate of $\frac{2}{T_c}$), where ε_k is the k-th normalized chip timing error, in order to produce two parallel sequences: an integer-instant stream $\{r_k = r(t_k)\}$ and a half-integer-instant stream $\left\{r_{k-\frac{1}{2}} = r\left(t_{k-\frac{1}{2}}\right)\right\}$.

Multipath Interference Regeneration

The integer-instant samples r_k are first fed into the central-branch multipath interference regenerator (CB-MPIR), and they are also delayed for the sake of the I/D latency n by means of a buffer before entering the following central-branch correlators; meanwhile, the half-integer-instant samples $r_{k-\frac{1}{2}}$ are sent into both the early-branch multipath interference regenerator (EB-MPIR) and the late-branch multipath interference regenerator (LB-MPIR), and they are also delayed for the sake of the I/D latency n before entering the early- and late-branch correlators. In CB-MPIR, r_k is first despread by means of $c_{|k|_N}$ for each of the $L+1$ paths, and then the signal propagated through each path can be reproduced by multiplying the output of the I/D filter $\hat{z}^{p}_{\{k\}_n}$ by the delayed spreading sequence $c_{|k-n|_N}$. Thus, the cross-correlation extracted from the integer-instant stream on the p-th finger of the RAKE structure can be expressed as $\hat{z}^{p}_{\{k\}_n} = ID\left\{r_{k-p} \times c_{|k|_N}\right\}$, where $ID\left\{\cdot\right\}$ denotes the I/D filtering operation (i.e., $ID\left\{\cdot\right\} = \frac{1}{n}\sum_{i=0}^{n-1}\left\{\cdot\right\}$).

Similar operations are also applied to $r_{k-\frac{1}{2}}$ in both EB-MPIR and LB-MPIR. The cross-correlation extracted from the half-integer-instant stream on the p-th finger of the RAKE receiver can be expressed as $\hat{y}^{p}_{E,\{k\}_n} = ID\left\{r_{k-\frac{1}{2}-p} \times c_{|k|_N}\right\}$ and $\hat{y}^{p}_{L,\{k\}_n} = ID\left\{r_{k-\frac{1}{2}-p} \times c_{|k-1|_N}\right\}$.

Error Signal and S-Curve of MCTL/MPIC

In the early-, late- and central-branch correlators, the corresponding MPI from adjacent paths is first subtracted out from the delayed integer-instant and the delayed half-integer-instant streams (i.e., $\left\{r_{k-n}\right\}$ and $\left\{r_{k-\frac{1}{2}-n}\right\}$) before they are cross-correlated with the local PN sequence. As a result, the cross-correlations on the p-th central-, early- and late-branch correlators, i.e., u^p_k, $v^p_{E,k}$ and $v^p_{L,k}$, can be expressed as

$$\begin{aligned}
u^p_k &= \left\{\left[r_{k-p-n} - \left(\hat{z}^{p-1}_{\{k-n\}_n} + \hat{z}^{p+1}_{\{k-n\}_n}\right) \times c_{|k-n|_N}\right] \times c_{|k-n|_N}\right\} \otimes h_k, \\
v^p_{E,k} &= \left\{\left[r_{k-\frac{1}{2}-p-n} - \left(\hat{y}^{p-1}_{E,\{k-n\}_n} + \hat{y}^{p+1}_{E,\{k-n\}_n}\right) \times c_{|k-n|_N}\right] \times c_{|k-n|_N}\right\} \otimes h_k \\
v^p_{L,k} &= \left\{\left[r_{k-\frac{1}{2}-p-n} - \left(\hat{y}^{p-1}_{L,\{k-n\}_n} + \hat{y}^{p+1}_{L,\{k-n\}_n}\right) \times c_{|k-1-n|_N}\right] \times c_{|k-1-n|_N}\right\} \otimes h_k,
\end{aligned}$$

where $\otimes$ denotes the convolution operator; h_k is the impulse response function of the first-order lowpass filter, the transfer function of which is $H\left(Z\right) = \frac{1-b}{1-bZ^{-1}}$, $b = \exp\left(-2\pi B_b T_c\right)$, which has bandwidth B_b comparable with the symbol rate $\frac{1}{T}$. The data modulation effect and the channel fading effect on $v^p_{E,k}$ and $v^p_{L,k}$ need to be compensated for by multiplying them with the complex conjugate of u^p_k. In addition, u^p_k can effectively keep the error characteristic on each RAKE finger within the range $\left[-T_c, T_c\right]$ in order to reduce the self-interference effect. Therefore, the resultant error signal of the proposed technique, which is called the modified code tracking loop with multipath interference cancellation (MCTL/MPIC) for simplicity, can be obtained by means of maximum ratio combining (MRC) criterion and expressed as $e^{MCTL/MPIC}_k = Re\left\{\sum_{\forall p}\left(u^p_k\right)^* \cdot \left(v^p_{E,k} - v^p_{L,k}\right)\right\}$, where $\left(\cdot\right)^*$ denotes the operation of taking the complex conjugate.

After some manipulations, the error signal of MCTL/MPIC for $\varepsilon_k = \varepsilon$ can be rewritten as

$$\begin{aligned}
e^{MCTL/MPIC}_k &= \left(5\Gamma_0 - 8\Gamma_1 + 4\Gamma_2 - \Gamma_3\right) S_1\left(\varepsilon\right) + \left(3\Gamma_0 - 6\Gamma_1 + 5\Gamma_2 - 3\Gamma_3 + \Gamma_4\right) S_2\left(\varepsilon\right) \\
&+ \left(5\Gamma_0 - 8\Gamma_1 + 4\Gamma_2 - \Gamma_3\right) S_3\left(\varepsilon\right),
\end{aligned} \tag{2}$$

where $S_1\left(\varepsilon\right) = g\left(\varepsilon T_c\right)\left\{g\left[\left(\varepsilon - \frac{1}{2}\right)T_c\right] - g\left[\left(\varepsilon + \frac{1}{2}\right)T_c\right]\right\}$, $S_2\left(\varepsilon\right) = g\left[\left(\varepsilon-1\right)T_c\right] g\left[\left(\varepsilon + \frac{1}{2}\right)T_c\right] - g\left[\left(\varepsilon+1\right)T_c\right] g\left[\left(\varepsilon - \frac{1}{2}\right)T_c\right]$, $S_3\left(\varepsilon\right) = g\left[\left(\varepsilon+1\right)T_c\right] g\left[\left(\varepsilon + \frac{1}{2}\right)T_c\right] - g\left[\left(\varepsilon-1\right)T_c\right] g\left[\left(\varepsilon - \frac{1}{2}\right)T_c\right]$, $\Gamma_0 = \sum_{\forall p}\|a_p\|^2$, $\Gamma_1 = \sum_{\forall p} Re\left\{a_p a^*_{p+1}\right\}$, $\Gamma_2 = \sum_{\forall p} Re\left\{a_p a^*_{p+2}\right\}$, $\Gamma_3 = \sum_{\forall p} Re\left\{a_p a^*_{p+3}\right\}$ and $\Gamma_4 = \sum_{\forall p} Re\left\{a_p a^*_{p+4}\right\}$. It needs to be noted that Γ_0, Γ_1, Γ_2, Γ_3 and Γ_4 all vary over time with the variation of the channel effects, though no apparent symbol, k or t, is employed here. If a_l, $\forall l$ are independent complex Gaussian random variables with zero means, then the error characteristic (i.e., the so-called S-curve) can be further formulated as $S^{MCTL/MPIC}\left(\varepsilon\right) = < E\left\{\Gamma_0\right\} > \left[5S_1\left(\varepsilon\right) + 3S_2\left(\varepsilon\right) + 5S_3\left(\varepsilon\right)\right]$, where $< \cdot >$ and $E\left\{\cdot\right\}$ denote the time-average and expectation operations, respectively. No matter what kind of combination of the channel tap weights, a_l, $\forall l$ (say, uncorrelated, correlated or arbitrarily correlated with time-varying cross-correlations among multiple propagation paths), is considered, both the error signal and S-curve of MCTL/MPIC have been proven to be definitely odd-symmetric with respect to their common locked point at $\varepsilon = 0$ because $S_1(\varepsilon)$, $S_2(\varepsilon)$ and $S_3(\varepsilon)$ all have this property. Note that the shapes of $S_1(\varepsilon)$, $S_2(\varepsilon)$ and $S_3(\varepsilon)$ are plotted in Fig.2.

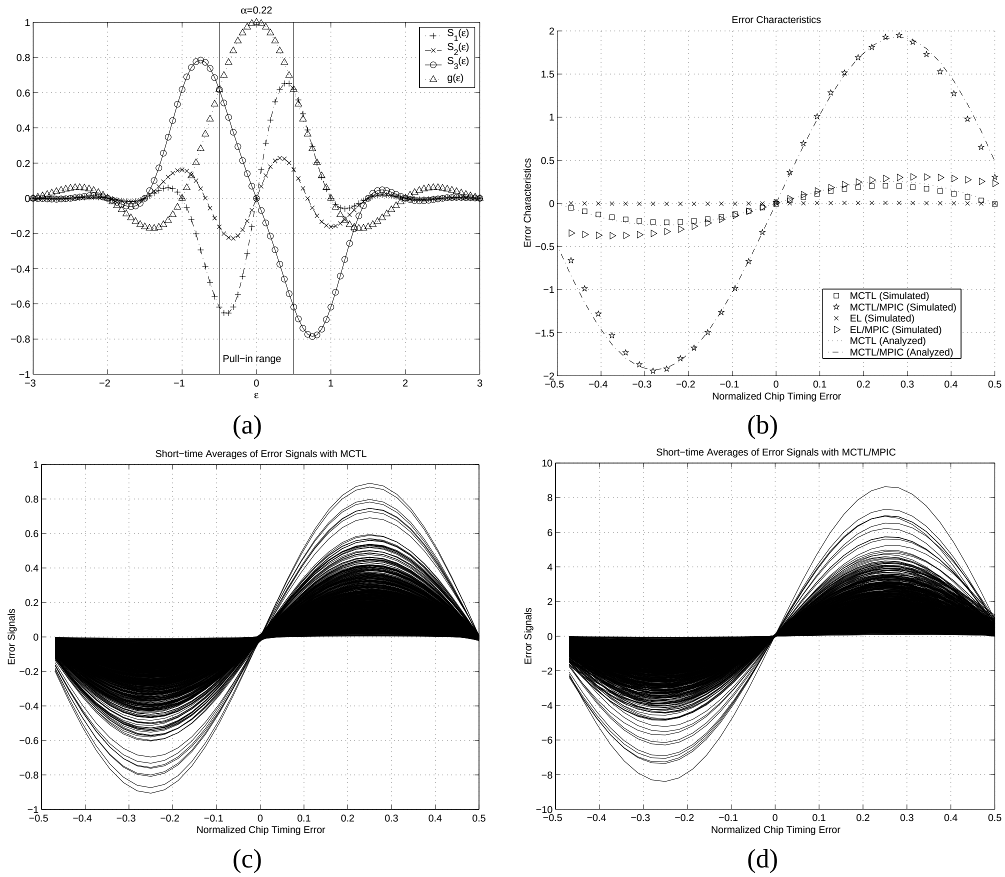

Figure 2: (a) The shapes of $S_1(\varepsilon)$, $S_2(\varepsilon)$ and $S_3(\varepsilon)$. (b) Comparison of the error characteristics (i.e., long-time averages of the expected error signals) of PN code tracking loops. (c) Short-time averages of the error signals of MCTL. (d) Short-time averages of the error signals of MCTL/MPIC.

CONCLUSTION

In this paper, a novel modified code tracking loop has been proposed for direct-sequence spread-spectrum communication over a frequency-selective fading channel. By taking advantage of the inherent diversity and multipath interference cancellation schemes, the proposed technique can provide better pull-in capability. Analytical results of S-curves have been derived.

References

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