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A Method to Partially Suppress ISI and MAI for DS SS CDMA Wireless Networks

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Abstract--- *We propose a method to partially suppress ISI and MAI for DS SS CDMA schemes in wireless LANs. The method can be regarded as an alternative approach to combat ISI and in particular MAI by the use of advanced multiuser detection. Instead of using very sophisticated detectors, we propose introduction of a simple modification to the carrier waveform which results in very substantial reduction in cross-correlation between users and an off-peak auto-correlation. The method can be applied to any DS SS CDMA scheme, but should be particularly useful in the case of short spreading signatures, as is the case of WLANs.*

I. INTRODUCTION

One of the major challenges faced by the telecommunication industry worldwide is development and commissioning of high capacity, wireless local area networks (WLANs). Current WLANs designed for high speed data transmission such as those considered by the IEEE 802.11 [1] and HYPERLAN [2] standards, mainly operate, or are going to operate, on industrial scientific medical (ISM) bands.

For data rates of several Mbps, as required for the future multimedia ATM WLANs [3], a severe BER degradation is caused by the channel dispersion due to multipath propagation. Additionally, there are strong jammers [4] such as microwave ovens, door sensors, medical appliances and, the most critical, other users of the same WLAN system utilizing the limited bandwidth of the ISM band.

Multipath problems can be successfully resolved if the direct sequence spread spectrum (DS SS) scheme is applied. However, only a small processing gain is achievable due to the total available bandwidth of tens of MHz and the high data rate of several Mbps. Consequently, in-band jammers, like other channels of the same WLAN acquired by means of code division multiple access (CDMA), may block the communication.

In theory, cancellation of that interference is possible if each of the users utilise orthogonal signals to transmit the data. If the delays between transmitters and receiver are anyhow different, as is generally the case of terminal to base station (BS) transmission, the signals received by the BS cannot be regarded as orthogonal [5]. Within the 50 m coverage area those differences may be in the order of a few code symbols (chips) depending on the data rate. This effect, referred to as Multiple Access Interference (MAI) [6], is particularly severe for very short spreading sequences, like 16-bits Walsh-Rademacher functions and 7-bits Gold codes studied in [5].

With short length spreading codes, also multipath propagation can cause severe problems. This effect is the main reason behind the Intersymbol Interference (ISI), and a good indicator of its severity is a normalized auto-correlation function within a channel. With the Walsh-Rademacher codes, the magnitude of the normalized auto-correlation function can in the worst case scenario reach the value of 1 for any delay caused by multipath [5], indicating that this code set does not give any protection against multipath ISI. If the Gold codes are used, the ISI is not as severe, but the magnitude of the auto-correlation function may, for some values of the delay, again reach the value of 0.7, which can create serious ISI as well [5].

Problems of ISI and in particular MAI can be fought by the use of advanced multiuser detection [6]. This, however, requires considerable complexity of receivers, and is rather unlikely to be implemented for such high data rates soon. In the paper we propose an alternative approach to suppress ISI and MAI by substantial cut in auto- and cross-correlation among the multipath signals and among different users [7]. This is done by introducing a modification to the carrier waveform. In the presented example the achieved reduction in ISI and MAI is at the order of 75%.

The paper is organised as follows. In Section II, we indicate the role of auto- and cross-correlation among signals corresponding to different users on the severity of ISI and MAI in DS SS CDMA systems. In Section III, we identify an auto-correlation of a carrier waveform as the major factor contributing to the value of auto- and cross-correlation among signals corresponding to different users and propose the method to reduce it significantly. Numerical results are given in Section IV and Section V concludes the paper.

II. MAI AND ISI IN DS SS CDMA

In conventional band-pass DS SS CDMA systems, like in other digital band-pass systems, the incoming sequence of data

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modulates a carrier $c(t)$. Usually, this is of the form $c(t) = A\cos(\omega_0 t)$ and the modulation is either BPSK or QPSK, but, there is no restriction placed on the type of neither the waveform nor the modulation [8].

In the case of an angular modulation, the modulated signal, $s_1(t)$, is expressed as:

$$s_1(t) = A\cos[\omega_0 t + \phi_1(t) + \phi_0] \tag{1}$$

where: A - the amplitude of modulated signal, $\omega_0 = 2\pi/T_0$ - angular carrier frequency, T_0 - period of the carrier, $\phi_1(t)$ - the information carrying phase function, ϕ_0 - initial value of the phase.

Next the signal $s_1(t)$ is multiplied by the spreading signal $g_1(t)$ belonging to user 1, and the resulting signal $g_1(t)s_1(t)$ is transmitted over the radio channel. Simultaneously, all other users 2 through N multiply their signals by their own code functions. The signal $R(t)$ intercepted in the receiver antenna, neglecting the different path losses is given by:

$$\begin{aligned} R(t) = {} & g_1(t-\tau_1)s_1(t-\tau_1) + \\ & g_2(t-\tau_2)s_2(t-\tau_2) + \\ & \dots + \\ & g_N(t-\tau_N)s_N(t-\tau_N) \end{aligned} \tag{2}$$

where τ_i; i =1, 2, ... ,N denote delays corresponding to different transmission paths associated with the user i.

Assuming the receiver configured to receive messages from user 1, which means the receiver being perfectly synchronised with the user 1, the despread signal r(t) is given by:

$$\begin{aligned} r(t) = {} & g_1^2(t-\tau_1)s_1(t-\tau_1) + \dots \\ & + g_1(t-\tau_1)g_N(t-\tau_N)s_N(t-\tau_N) \end{aligned} \tag{3}$$

where the term $g_1^2(t-\tau_1)s_1(t-\tau_1)$ is the desired signal and the other terms $g_1(t-\tau_1)g_i(t-\tau_N)s_i(t-\tau_N)$; $(i \neq 1)$ are the interfering signals responsible for the MAI. Because finally the signal is demodulated using the matched filter or correlative detectors, an increase in the value of cross-correlation between the code $g_1(t-\tau_1)$ and other codes $g_i(t-\tau_i)$ is followed by the more severe MAI.

The similar findings can be drawn if detection without previous despreading is concerned. For example, in the case of BPSK, to obtain the received data bit $\widehat{d}_1$ the received signal $R(t)$ can be correlated either with $g_1(t-\tau_1)$:

$$\widehat{d_1} = \begin{cases} 1, & \int_T R(t)g_1(t-\tau_1)dt > 0 \\ -1, & \int_T R(t)g_1(t-\tau_1)dt < 0 \end{cases} \tag{4}$$

or with $g_1(t-\tau_1)s_1^{(1)}(t-\tau_1)$:

$$\widehat{d_1} = \begin{cases} 1, & \int_T R(t)g_1(t-\tau_1)s_1^{(1)}(t-\tau_1)dt > 0 \\ -1, & \int_T R(t)g_1(t-\tau_1)s_1^{(1)}(t-\tau_1)dt < 0 \end{cases} \tag{5}$$

where $s_1^{(1)}(t-\tau_1)$ is the band-pass signal waveform bearing“1”.

One of the features of mobile or indoor microwave systems is multipath propagation where the receiver antenna, even with only a single transmitter, intercepts signals coming through different paths and thus exhibiting different delays. Therefore the received signal $R(t)$ is in such a case equal to:

$$\begin{aligned} R(t) = {} & A_1 g_1(t-\tau_1)s_1(t-\tau_1) + \\ & A_2 g_1(t-\tau_2)s_1(t-\tau_2) + \\ & \dots + \\ & A_M g_1(t-\tau_M)s_1(t-\tau_M) \end{aligned} \tag{6}$$

where the coefficients $A_1 > A_2 > \dots > A_M$ represent amplitudes of signals having different propagation paths. Usually a receiver is synchronized with the strongest signal component $A_1 g_1(t-\tau_1)s_1(t-\tau_1)$ corresponding to the direct line of sight, if such a one exists. Hence, the other terms, independently of the detection method, are sources of the ISI, since their delays τ_i; $(i \neq 1)$, are not equal to τ_1.

In order to minimise the ISI, the codes $g_1(t), \dots, g_N(t)$ are optimized to have low auto-correlation for delays greater than a single chip. An example of such optimized codes is a set of Gold codes. For the short length codes, however, even Gold codes exhibit quite significant auto-correlation which for some values of the delay can reach very substantial magnitudes of 0.71 [9].

III. OPTIMIZATION OF CARRIER WAVEFORM

A covariance $\xi_{ij}(\tau)$ of the two CDMA signals $g_i(t)s_i(t)$ and $g_j(t)s_j(t)$ is given by:

$$\xi_{ij}(\tau) = \int_T g_i(t)s_i(t)g_j(t-\tau)s_j(t-\tau)dt, \tag{7}$$

where T is the data interval, and τ is a relative delay between the two signals, $0 \le \tau < T$.

For binary sets of spreading signatures, codes $g_i(t)$ and $g_j(t)$ can only take values of “1” and “-1”. Hence, the integral (7) can be rewritten as:

$$\xi_{ij}(\tau) = \int_{\theta_{ij}^+(\tau)} s_i(t)s_j(t-\tau)dt - \int_{\theta_{ij}^-(\tau)} s_i(t)s_j(t-\tau)dt, \tag{8}$$

where:

$\theta_{ij}^+(\tau)$ - set of all those intervals where:

$$g_i(t) = g_j(t-\tau)$$

$\theta_{ij}^-(\tau)$ - set of all those intervals where:

$$g_i(t) = -g_j(t-\tau)$$

Note here that:

$$\theta_{ij}^+(\tau) \cup \theta_{ij}^-(\tau) = \langle 0,\ T\rangle . \qquad (9)$$

Assuming the cosinusoidal carrier, BPSK modulation, and carrier frequency being much greater than a chip rate; $T_0 \ll T_c$, the equation (8) can be simplified to the form:

$$\xi_{ij}(\tau) \approx [\|\theta_{ij}^+(\tau)\| - \|\theta_{ij}^-(\tau)\|] \cdot \int_{T_0} s_i(t) s_j(t-\tau)dt; \qquad (10)$$

where $\|\theta_{ij}^+(\tau)\|$ and $\|\theta_{ij}^-(\tau)\|$ denote the cumulative lengths of the intervals where $g_i(t) = g_j(t-\tau)$ and $g_i(t) = -g_j(t-\tau)$, respectively. Furthermore, the covariance $\gamma_{ij}(\tau)$ between the code sequences $g_i(t)$ and $g_j(t)$, defined as:

$$\gamma_{ij}(\tau) = \int_T g_i(t) g_j(t-\tau)dt, \qquad (11)$$

can be expressed as:

$$\gamma_{ij}(\tau) = \|\theta_{ij}^+(\tau)\| - \|\theta_{ij}^-(\tau)\|, \qquad (12)$$

Substituting (12) for $\gamma_{ij}(\tau)$ in (10) yields:

$$\xi_{ij}(\tau) = \gamma_{ij}(\tau) \cdot \int_{T_0} s_i(t) s_j(t-\tau)dt\ . \qquad (13)$$

It is clearly visible from (8) and particularly from (13) that the value of the covariance $\xi_{ij}(\tau)$ depends not only on the covariance $\gamma_{ij}(\tau)$ between the code sequences $g_i(t)$ and $g_j(t)$ but also on the carrier auto-correlation $\kappa_c(\tau)$.

Generally, the auto-correlation of a periodic signal is also periodic function of the same period as the signal. The normalized to energy per bit auto-correlation $\kappa_c(\tau)$ of the cosinusoidal carrier, if $T_0 \ll T$:

$$\kappa_c(\tau) = \frac{\int_T \cos(\omega_0 t)\cos(\omega_0 t - \omega_0 \tau)dt}{0.5T} \approx \cos(\omega_0 \tau), \qquad (14)$$

is a periodic function of τ with the period equal to T_0.

Since there is no restriction placed on the carrier as far as the principles of DS-CDMA are concerned, the decrease in the magnitude of the covariance $\xi_{ij}(\tau)$ between the signals of the channel i and the channel j can be achieved with such a modification of the carrier waveform that its normalized to energy per bit auto-correlation function $\kappa_M(\tau)$ will be a periodic function of a period T_M. The period T_M should be chosen to be greater than the maximum relative delay between any two channels or between any non-negligible multipath signals and that the magnitude of this auto-correlation function never reaches the value of 1 apart from the delay τ being an integer multiple of T_M. Certainly, it is desired that for delays $T_c < \tau < T_M - T_c$ the magnitude of the auto-correlation $|\kappa_M(\tau)|$ be as low as possible.

Equations (10) to (14) has been derived under the assumption that BPSK modulation is used. Similar findings can be obtained for QPSK modulation as well.

In addition, an influence of the carrier modification on the bandwidth occupied by the DS SS CDMA signals always requires examination while optimizing parameters of the modified carrier. For some classes of the modifications, smoothing of the spectral characteristics can be achieved as an extra benefit.

IV. NUMERICAL EXAMPLE

To illustrate the efficiency of the proposed method, let consider two BPSK signals spread by the use of two 16-bit Walsh-Rademacher signatures:

$$\{1\ 1\ -1\ -1\ -1\ -1\ 1\ 1\ 1\ 1\ -1\ -1\ -1\ -1\ 1\ 1\}$$

$$\{1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\ 1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\}.$$

The auto- and cross-correlation profiles of the spread signals are presented in Figure 1, Figure 2, and Figure 3.

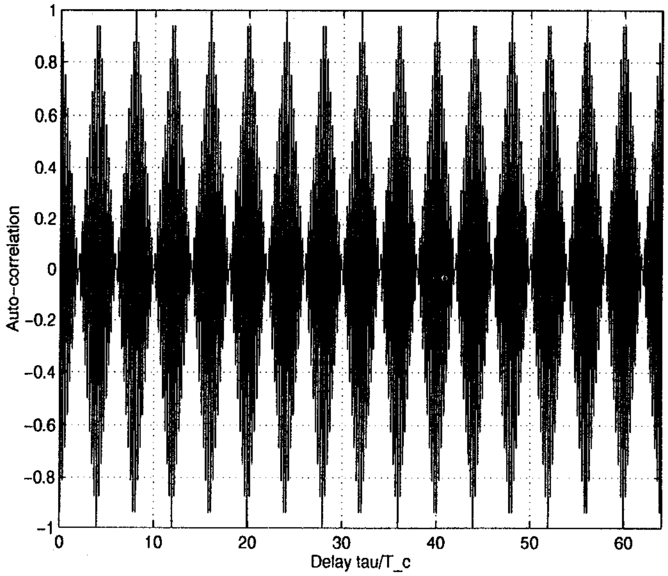

Figure 1: Auto-correlation profile of a BPSK signal spread by signature: $\{1\ 1\ -1\ -1\ -1\ -1\ 1\ 1\ 1\ 1\ -1\ -1\ -1\ -1\ 1\ 1\}$.

The desired modification of the carrier waveform can be achieved by an auxiliary frequency modulation of the carriers by two triangular waves $w_1(t)$ and $w_2(t)$:

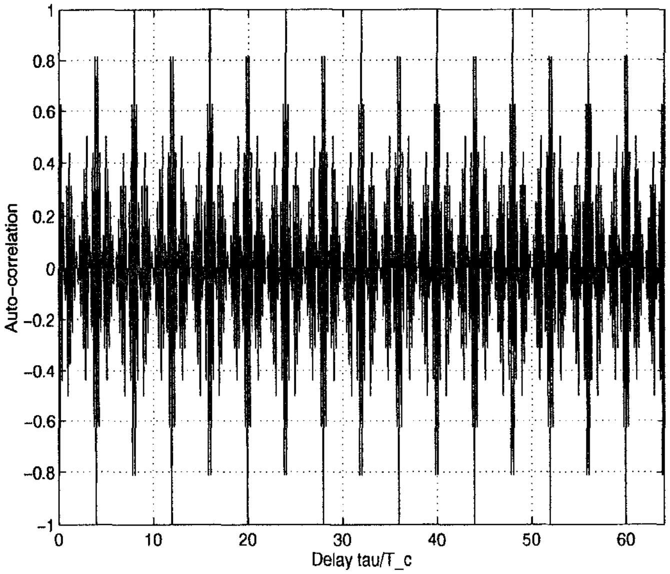

Figure 2: Auto-correlation profile of a BPSK signal spread by signature: $\{1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\ 1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\}$.

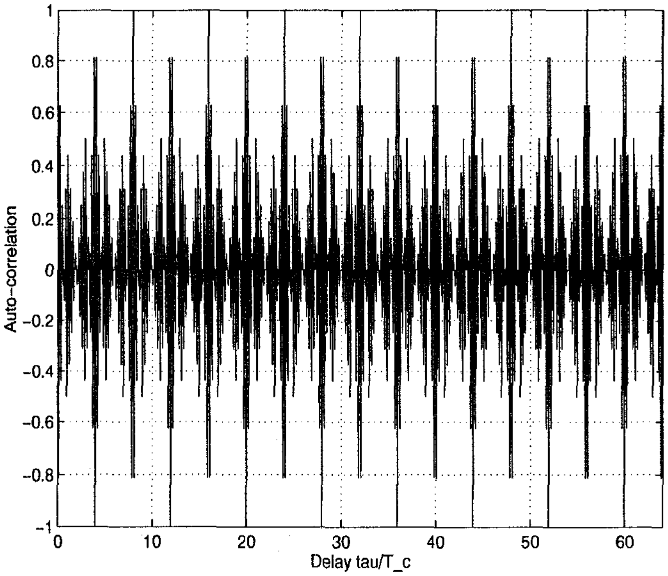

Figure 3: Cross-correlation between two BPSK signals spread with by signatures: $\{1\ 1\ -1\ -1\ -1\ -1\ 1\ 1\ 1\ 1\ -1\ -1\ -1\ -1\ 1\ 1\}$ **and** $\{1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\ 1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\}$.

$$w_1(t) = \alpha_1 \cdot Tr\left(\frac{t}{16T_c}\right), \tag{15}$$

$$w_2(t) = \alpha_2 \cdot Tr\left(\frac{t}{32T_c}\right), \tag{16}$$

where

$$Tr(t) = \begin{cases} -0.25(t-0.5), & (0 \le t < 1) \\ 0.25(t-1.5), & (1 \le t < 2) \end{cases} \tag{17}$$

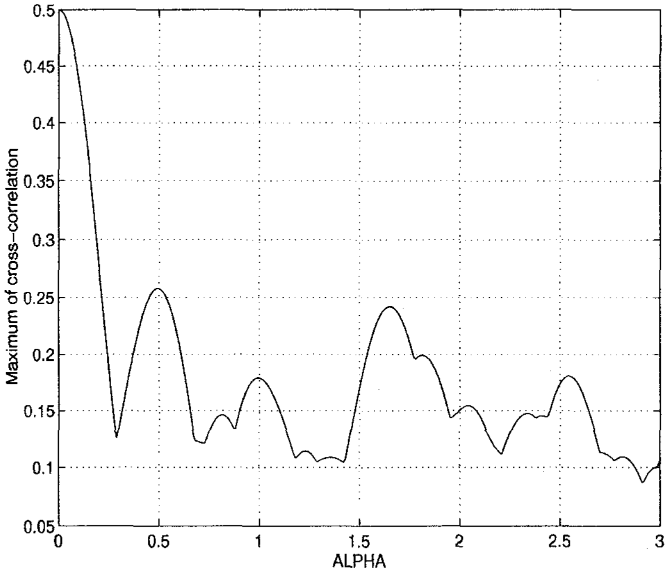

Figure 4: Maximum value of cross-correlation magnitude between the two signals as function of parameter α.

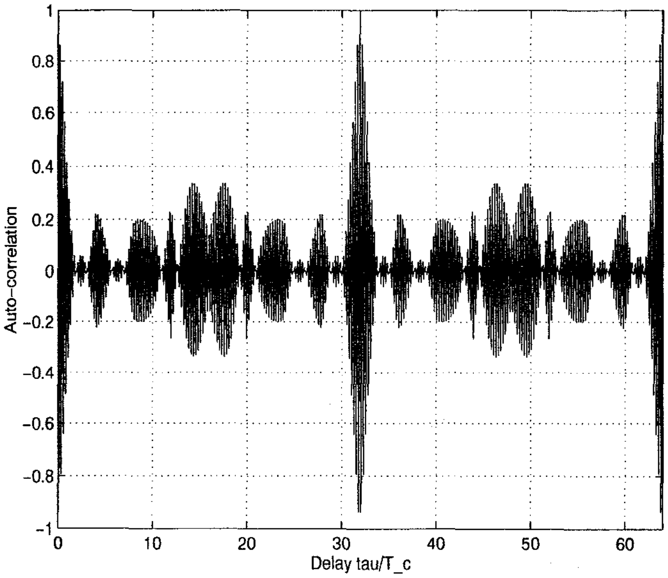

Figure 5: Auto-correlation for signal spread by the signature: $\{1\ 1\ -1\ -1\ -1\ -1\ 1\ 1\ 1\ 1\ -1\ -1\ -1\ -1\ 1\ 1\}$ **and with a modified carrier,** $\alpha = 1.3$.

The amplitudes of these triangular waves can be optimized to achieve the lowest cross-correlation between the BPSK signals or to achieve the lowest values of the off-peak auto-correlations. In Figure 4, the plot of the maximum value of the cross-correlation magnitude versus the parameter $\alpha = \alpha_1 = \alpha_2$ is presented. It is visible that even for quite low values of α a significant reduction in the maximum value of the cross-correlation is possible. To better assess the possible gain, plots equivalent to those of Figure 1, Figure 2, and Figure 3 are given in Figure 5, Figure 6 and Figure 7 for $\alpha = 1.3$. Additional improvement of the results can be achieved if the amplitudes of $w_1(t)$ and $w_2(t)$ are optimized separately.

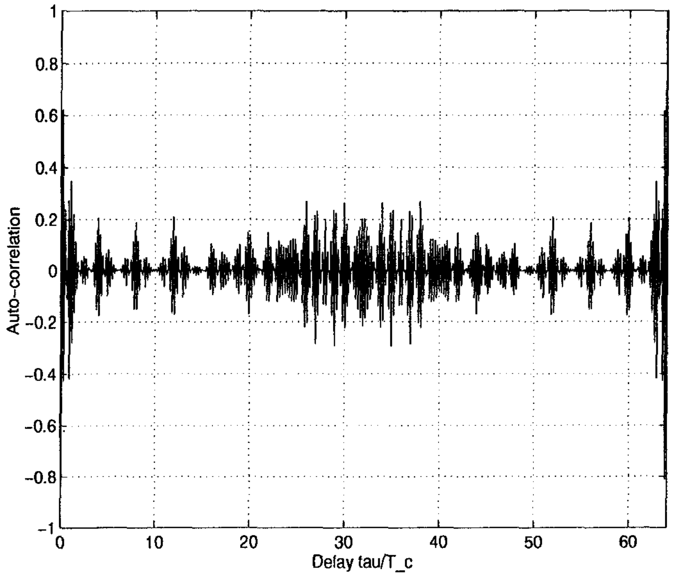

Figure 6: Auto-correlation for signal spread by the signature: $\{1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\ 1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\}$ and with a modified carrier, $\alpha = 1.3$.

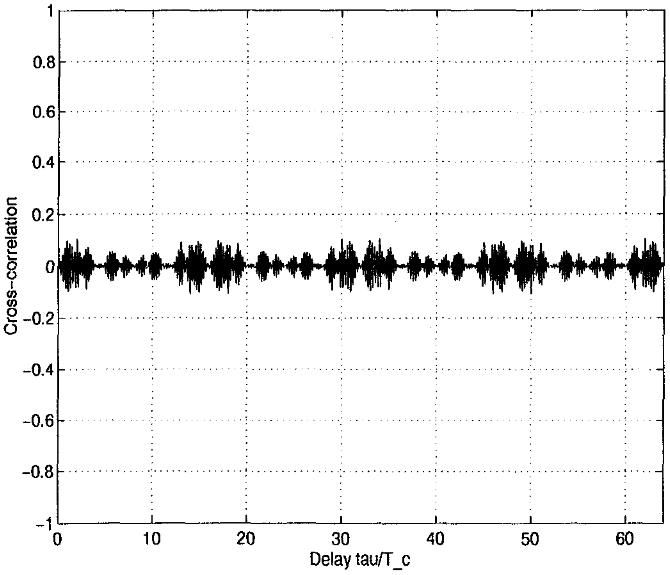

Figure 7: Cross-correlation between the signals for $\alpha = 1.3$.

V. CONCLUSIONS

In the paper we have presented a method to substantially suppress MAI for asynchronous DS SS CDMA systems. The method can also be used to significantly reduce ISI for systems operating in severe multipath environments. The proposed method can be used as an alternate to multiuser detection, particularly for high data rates, as those of ATM WLANs.

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