REDUCTION OF MULTIPLE ACCESS INTERFERENCE IN MC-CDMA IN THE PRESENCE OF RAYLEIGH FADING

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ABSTRACT

A new technique is proposed that offers significant reduction of multiple access interference (MAI) encountered in asynchronous multicarrier code division multiple access (MC-CD MA) detection. Using a dual frequency switching component at the transmitter enables the removal of a portion of unwanted interference signals from the decision variable. Bit-error rate (BER) comparisons are shown for the use of both Gold and Walsh-Hadamard (WH) spreading sequences. The proposed switching technique clearly outperforms the existing MC-CDMA technique, however, additional bandwidth is required.

1. INTRODUCTION

Multicarrier code division multiple access (MC-CDMA) [1] has recently received a great deal of attention, investigating its potential benefits over the direct-sequence CDMA (DS-CDMA) technique featuring prodominantly in third generation (3G) cellular technologies such as UMTS, W-CDMA and cdma2000. Over asynchronous channels, where multiple access interference (MAI) is significantly degrading, the use of MC-CDMA has been demonstrated to outperform the single carrier DS-CDMA technique [2][3][4]. The multicarrier modulation format of the MC-CDMA technique allows the number of subcarriers to be designed such that each subchannel is subject to frequency nonselective fading [3] and furthermore, the insertion of a cyclic prefix has been shown to mitigate intersymbol interference in the presence of multipath [5]. MAI remains a destructive presence and a major limitation in CDMA detection and here we propose a dual frequency switching technique that reduces the amount of MAI incurred during asynchronous transmission.

The proposed scheme is named dual frequency MC-CDMA (DF/MC-CDMA) and involves periodic switching of the carrier frequency between two selected frequencies, which induces a Doppler separation between a portion of the unwanted MAI and the desired data. Such Doppler separation alleviates the decision variable of the MAI emanating from lagging data symbols in a symbol-by-symbol recovery method.

This paper is organized as follows: section 2 details the considered cellular scenario, specifying the asynchronous channel model. The signal models of the existing MC-CDMA and proposed DF/MC-CDMA systems are established in sections 3 and 4 respectively. In these sections the MAI is formulated and the partial reduction of MAI achieved by the DF/MC-CDMA technique is deduced in section 4. Section 5 defines the bit-error rate (BER) performance metric and simulation results are given in section 6 showing a comparison between the MC-CDMA and DF/MC-CDMA performances for the use of both Gold and Walsh Hadamard (WH) codes. Finally, section 7 concludes the paper.

2. SYSTEM DESCRIPTION

A single cell consisting of K users $(k = 1, ..., K)$ transmitting asynchronously over the uplink channel is considered. The ith data symbol of user k is denoted as b_{ki} for which all data is BPSK modulated and $i.i.d$ such that $Pr\{b_{ki} = -1\} = Pr\{b_{ki} = 1\} = 0.5$. The spreading factor of each code is given as $N = T_s/T_c$ where T_s and T_c denote the symbol and chip durations respectively. The data stream and assigned spreading code of the kth user are respectively expressed as

$$b_k(t) = \sum_{i=-\infty}^{\infty} b_{ki} \cdot u_{T_s}(t - iT_s) \tag{1}$$

and

$$c_k(t) = \sum_{n=1}^{N} c_{kn} \cdot u_{T_c}(t - nT_c + T_c) \tag{2}$$

where c_{kn} is the nth chip of the kth code and

$$u_T(t) = \begin{cases} 1, & 0 \le t < T \\ 0, & \text{elsewhere} \end{cases} \tag{3}$$

is the rectangular pulse shaping waveform.

We consider an asynchronous slow varying Rayleigh fading uplink channel in which τ_k denotes the timing offset of the kth user. We model the channel attenuation experienced by the nth subchannel of the kth user as a zero-mean Gaussian random variable $\beta_{kn} \exp(j\varphi_{kn})$ for which β_{kn} is Rayleigh distributed with $E\left[\beta_{kn}^2\right] = 1$ and φ_{kn} is equally distributed over the interval $\left[0,\ 2\pi\right)$. Moreover, we consider slow varying Rayleigh fading and hence we assume the gain is constant over two symbol durations, $2T_s$.

The timing offset of each user is assumed to be distributed over one symbol duration, T_s, with equal probability. Timing offsets are quantized to integer multiples of the chip duration, T_c, making $\tau_k \in [0, (N-1)\,T_c]$. Note that timing offsets τ_k account for the propagation delay and the timing misalignment amongst users. All timing offsets are made with respect to the reference user, denoted as user x, for which $\tau_x = 0$ and for simplicity purposes, all interferers are temporally offset such that $\tau_k \geq 0,\ \forall k$. This offset condition of the asynchronous channel is depicted in Fig.1.

We assume perfect power control at the base station and the signal power of each user is normalized to unity in both systems. Moreover, the assumption of perfect carrier and symbol recovery is made for both the MC-CDMA and DF/MC-CDMA systems.

3. EXISTING MC-CDMA DETECTION

The transmitted MC-CDMA signal of the kth user, ignoring any random phase offset, is expressed as

$$s_k^{mc}(t) = \sum_{n=1}^{N} b_k(t)\, c_{kn} \exp(j\omega_n t) \qquad (4)$$

where $b_k(t)$ is defined in (1) and $\omega_n = \omega_c + \frac{2\pi n}{T_s}$ is the nth subcarrier frequency, neighbouring subcarriers being orthogonal and separated by $\Delta\omega = \frac{2\pi}{T_s}$. The MC-CDMA received signal at the base station is written as [4]

$$r(t) = \sum_{k=1}^{K}\sum_{n=1}^{N} \beta_{kn} b_k(t-\tau_k)\, c_{kn} \exp(j[\omega_n t - \phi_k + \varphi_{kn}]) \qquad (5)$$

where $\phi_k = \omega_n \tau_k$ and φ_{kn} is the phase offset experienced over the nth subcarrier of user k. Following subcarrier demodulation and despreading, the matched filter output of the MC-CDMA system is given as [6]

$$\begin{aligned} y_{xi}^{mc} &= \frac{1}{T_s}\int_{iT_s}^{(i+1)T_s} r(t) \sum_{n'=1}^{N} \alpha_{xn'} c_{xn'} \\ &\cdot \exp(-j[\omega_{n'} t + \varphi_{xn'}])\, dt \end{aligned} \qquad (6)$$

where $\alpha_{xn'}$ is dependent on the combining strategy used. Applying equal gain combining (EGC) [7], making $\alpha_{xn'} = 1$,

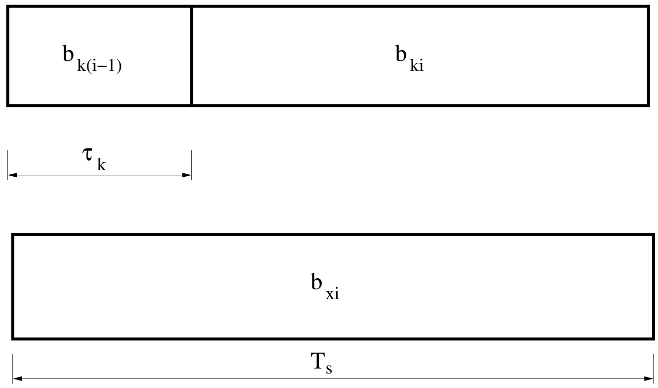

Fig. 1. Misalignment of Data Symbols Due to Asynchronous Channel

the matched filter output in (6) becomes [6]

$$\begin{aligned} y_{xi}^{mc} &= \frac{1}{T_s}\int_{iT_s}^{(i+1)T_s} r(t) \sum_{n'=1}^{N} c_{xn'} \\ &\cdot \exp(-j[\omega_{n'} t + \varphi_{xn'}])\, dt \qquad (7) \\ &= \frac{1}{T_s}\int_{iT_s}^{(i+1)T_s} \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{n'=1}^{N} \beta_{kn} b_k(t-\tau_k) \\ &\cdot c_{kn} c_{xn'} \exp(j[\{\omega_n - \omega_{n'}\}t - \xi_{knn'}])\, dt \qquad (8) \end{aligned}$$

where $\xi_{knn'} = -\phi_k + \varphi_{kn} - \varphi_{xn'}$. Due to the symbol boundary misalignments caused by τ_k, the matched filter output is conditioned on b_{ki} as well as the previous lagging symbol $b_{k(i-1)}$ of each interfering signal, which is expressed as [4]

$$\begin{aligned} y_{xi}^{mc} &= \frac{1}{T_s}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{n'=1}^{N} \beta_{kn} c_{kn} c_{xn'} \exp(j\xi_{knn'}) \\ &\cdot \left[b_{k(i-1)} \int_{iT_s}^{iT_s+\tau_k} \exp(j\{\omega_n - \omega_{n'}\}t)\, dt \right. \\ &+ \left. b_{ki} \int_{iT_s+\tau_k}^{(i+1)T_s} \exp(j\{\omega_n - \omega_{n'}\}t)\, dt \right] \end{aligned} \qquad (9)$$

This expression in (9) is simplified as

$$y_{xi}^{mc} = \frac{1}{T_s}\sum_{k=1}^{K}\left[b_{k(i-1)} V_{kx}(\tau_k) + b_{ki}\hat{V}_{kx}(\tau_k)\right] \qquad (10)$$

where the partial spectral correlation functions [8], $V_{kx}(\tau_k)$ and $\hat{V}_{kx}(\tau_k)$, are given by

$$\begin{aligned} V_{kx}(\tau_k) &= \sum_{n=1}^{N}\sum_{n'=1}^{N} \beta_{kn} c_{kn} c_{xn'} \exp(j\xi_{knn'}) \\ &\int_{0}^{\tau_k} \exp(j\{\omega_n - \omega_{n'}\}t)\, dt \end{aligned} \qquad (11)$$

$$\hat{V}_{kx}(\tau_k) = \sum_{n=1}^{N}\sum_{n'=1}^{N} \beta_{kn} c_{kn} c_{xn'} \exp(j\xi_{knn'}) \int_{\tau_k}^{T_s} \exp(j\{\omega_n - \omega_{n'}\} t)\, dt \quad (12)$$

The decision variable in (10) can finally be expressed as

$$y_{xi}^{mc} = \beta_x b_{xi} \sum_{n=1}^{N} c_{xn}^2 + \sum_{k \neq x}^{K} M_{kxi}^{mc} \quad (13)$$

where

$$M_{kxi}^{mc} = \frac{1}{T_s}\left[b_{k(i-1)} V_{kx}(\tau_k) + b_{ki}\hat{V}_{kx}(\tau_k)\right] \quad (14)$$

is the MAI incurred by user x from user k in the recovery of b_{xi}.

4. PROPOSED DF/MC-CDMA DETECTION

Excluding channel fading, the distinguishing attribute separating the desired information signal from the multiple interference signals is the absence of timing misalignment between the desired symbols and the detection interval $iT_s \leq t \leq (i+1)T_s$. To exploit this condition, a controlled frequency separation is inserted between consecutive symbols of each transmission signal $s_k(t)$. Such frequency separation is facilitated by a periodic switching component at the transmitter which is driven by a fixed switching pattern common to all K users in the considered system. This switching pattern periodically shifts the already modulated MC-CDMA signals between two selected frequency bands.

The time-variant switching pattern, denoted by $\omega_d(t)$, of period T_s is represented by

$$\omega_d(t) = \omega_d^i, \quad iT_s \leq t \leq (i+1)T_s \quad (15)$$

where $\omega_d^i \in \{\omega_d^1, \omega_d^2\}$ denotes the switching frequency that alternates every T_s such that $\omega_d^i \neq \omega_d^{(i\pm1)}$. Applying this switching component to the previously defined MC-CDMA format yields the transmitted DF/MC-CDMA signal of the kth user (depicted in Fig.2), expressed as

$$s_k^{df}(t) = \sum_{n=1}^{N} b_k(t) c_{kn} \exp(j\{\omega_n + \omega_d(t)\} t) \quad (16)$$

which is of similar format to frequency hopping modulated signals as in [9]. Choosing the switching period as T_s enables one frequency shift every symbol duration making ω_d^i the switching frequency constant over the ith symbol and all frequency switching is assumed time-synchronous with the symbol boundaries.

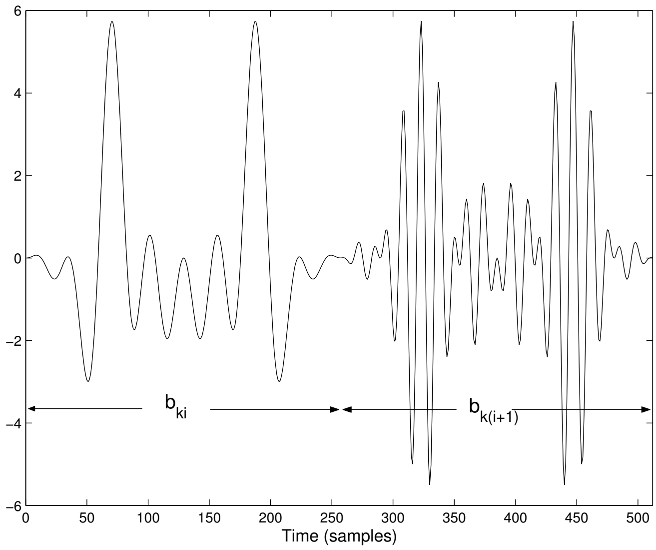

Fig. 2. DF/MC-CDMA Transmission Signal $s_k^{df}(t)$

The asynchronous DF/MC-CDMA received signal at the base station is written as

$$r(t) = \sum_{k=1}^{K}\sum_{n=1}^{N} \beta_{kn} b_k(t-\tau_k) c_{kn} \cdot \exp(j[\{\omega_n + \omega_d(t-\tau_k)\}\{t-\tau_k\} + \varphi_{kn}]) \quad (17)$$

For the detection of b_{xi}, the signal received at the BS is first deswitched by the appropriate frequency, ω_d^i, corresponding to the detection interval $iT_s \leq t \leq (i+1)T_s$, by $\exp(-j\omega_d^i t)$. Subcarrier demodulation and despreading follows through the application of $c_{xn'} \exp(-j\omega_{n'} t)$ for $n' = 1, \ldots, N$. At this stage of the detection process we are dealing with baseband signal components (following the deswitching and subcarrier demodulation operations). Here a low-pass filter is applied to retain the signal components associated with ω_d^i and remove those associated with $\omega_d^{(i-1)}$. The output of the matched filter is then expressed as

$$y_{xi}^{df} = \frac{1}{T_s}\int_{iT_s}^{(i+1)T_s} r(t) \sum_{n'=1}^{N} \alpha_{xn'} c_{xn'} \cdot \exp\left(-j\left[\{\omega_{n'} + \omega_d^i\} t + \varphi_{xn'}\right]\right) dt \quad (18)$$

Employing EGC such that $\alpha_{xn'} = 1$ and substituting the received signal in (17) into (18) yields

$$y_{xi}^{df} = \frac{1}{T_s}\int_{iT_s}^{(i+1)T_s} \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{n'=1}^{N} \beta_{kn} b_k(t-\tau_k) c_{kn} c_{xn'} \exp\Big(j\big[\{\omega_n - \omega_{n'} + \omega_d(t-\tau_k) - \omega_d^i\} t - \{\omega_d(t-\tau_k) + \omega_n\}\tau_k + \varphi_{kn} - \varphi_{xn'}\big]\Big) dt \quad (19)$$

Expanding this expression into distinct symbol components yields

$$= \frac{1}{T_s}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{n'=1}^{N}\beta_{kn}c_{kn}c_{xn'}$$
$$\Bigg[\quad b_{k(i-1)}\int_{iT_s}^{iT_s+\tau_k}\exp\left(j\Big[\{\omega_n-\omega_{n'}+\nu_i\}t + \Psi_{knn'}^{(i-1)}\Big]\right)dt$$
$$+ \quad b_{ki}\int_{iT_s+\tau_k}^{(i+1)T_s}\exp\left(j\left[\{\omega_n-\omega_{n'}\}t+\Psi_{knn'}^{i}\right]\right)dt\Bigg] \tag{20}$$

where $\Psi_{knn'}^{i} = -\left\{\omega_n+\omega_d^i\right\}\tau_k + \varphi_{kn} - \varphi_{xn'}$ and $\nu_i = \omega_d^{(i-1)} - \omega_d^i$. Separating the expression in (20) into the desired information and MAI components gives, leaves

$$y_{xi}^{df} = b_{xi}\sum_{n=1}^{N}\beta_{xn}c_{xn}^2 + \sum_{k\neq x}^{K}M_{kxi}^{df} \tag{21}$$

which comprises of the desired information component and a sum of MAI contributions from the $K-1$ interfering users. The MAI contribution from a single interferer consists of two components such that

$$M_{kxi}^{df} = \check{M}_{kxi}^{df} + \hat{M}_{kxi}^{df} \tag{22}$$

where $\check{M}_{kxi}^{df}$ and $\hat{M}_{kxi}^{df}$ are the MAI components over the temporal intervals $iT_s \leq t \leq iT_s+\tau_k$ and $iT_s+\tau_k \leq t \leq (i+1)T_s$ respectively. The first MAI component is expressed as

$$\check{M}_{kxi}^{df} = \frac{1}{T_s}\int_{iT_s}^{iT_s+\tau_k}\sum_{n=1}^{N}\sum_{n'=1}^{N}\beta_{kn}b_{k(i-1)}c_{kn}c_{xn'} \cdot \exp\left(j\left[\{\omega_n-\omega_{n'}+\nu_i\}t+\Psi_{knn'}^{(i-1)}\right]\right)dt \tag{23}$$

and represents the MAI incurred over the interval $iT_s \leq t \leq iT_s+\tau_k$. It is seen that all interfering signal components are successfully removed by the low-pass filter due to the presence of ν_i over the interval $iT_s \leq t \leq iT_s+\tau_k$ (23). It can therefore be written that

$$\check{M}_{kxi}^{df} = 0 \quad \forall k\neq x \quad \text{iff} \quad \nu_i \geq \frac{N}{T_s} \tag{24}$$

and it follows that no MAI is incurred over this portion of the symbol detection interval.

The second MAI component (representing MAI incurred over the detection interval $iT_s+\tau_k \leq t \leq (i+1)T_s$) is not a function of the Doppler offset ν_i and is expressed as

$$\hat{M}_{kxi}^{df} = \frac{1}{T_s}\int_{iT_s+\tau_k}^{(i+1)T_s}\sum_{n=1}^{N}\sum_{n'=1}^{N}\beta_{kn}b_{ki}c_{kn}c_{xn'} \cdot \exp\left(j\left[\{\omega_n-\omega_{n'}\}t+\Psi_{knn'}^{i}\right]\right)dt \tag{25}$$

or alternatively as

$$\hat{M}_{kxi}^{df} = \frac{b_{ki}}{T_s}\hat{V}_{kx}(\tau_k)\exp\left(-j\omega_d^i\tau_k\right) \tag{26}$$

where $\hat{V}_{kx}(\tau_k)$ was defined in (12).

5. PERFORMANCE

To assess the benefits of the proposed DF technique it is desirable to compare the BER performance against that of the existing DS-CDMA technique. With all MAI being zero-mean, the total MAI power inflicted by each interferer during detection is M_{kxi}^2. For a given offset, the MAI power can take different values depending on $b_{k(i-1)}$ and b_{ki} and therefore we consider the conditional MAI power in our system performance analysis which is the conditional expectation of the MAI power for a given offset value, defined as

$$\sigma_x^2(\underline{\tau}) = \sum_{k\neq x}^{K}E\left[M_{kxi}^2\left(\underline{\beta}_k, b_{ki}, b_{k(i-1)}, \tau_k\right)|\tau_k\right] \tag{27}$$

where $E[a|b]$ denotes the expectation of a given b, $\underline{\beta}_k = \left[\begin{array}{ccc}\beta_{k1} & \ldots & \beta_{kN}\end{array}\right]$ and $\underline{\tau}$ denotes the vector of offsets defining the asynchronous channel for which $\tau_x = 0\,\forall\underline{\tau}$. In the absence of additive noise, the signal-to-interference ratio (SIR) is given by

$$\gamma = \left(\frac{\beta_x}{\sigma_x}\right)^2 \tag{28}$$

and the resulting probability of error for BPSK modulated data is given by [10]

$$P_e = Q(\sqrt{\gamma}) = Q\left(\frac{\beta_x}{\sigma_x}\right) \tag{29}$$

where

$$Q(x) = \int_x^{\infty}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{t^2}{2}\right)dt \tag{30}$$

is the complementary Gaussian cumulative distribution function.

6. SIMULATIONS

Monte Carlo simulations were performed to verify the MAI reduction capability of the proposed DF/MC-CDMA technique. The MAI reduction achieved by the proposed method can be experienced using any set of spreading sequences, however, only the results for the use of Gold and WH codes are presented here. Both the MC-CDMA and DF/MC-CDMA systems considered were simulated, running $10,000$ realizations and randomly generating a different offset vector $\underline{\tau}$ in each realization. To ensure a fair performance comparison, the same channel and offset vector were applied in each system. The bandwidth expansion in the proposed DF/MC-CDMA

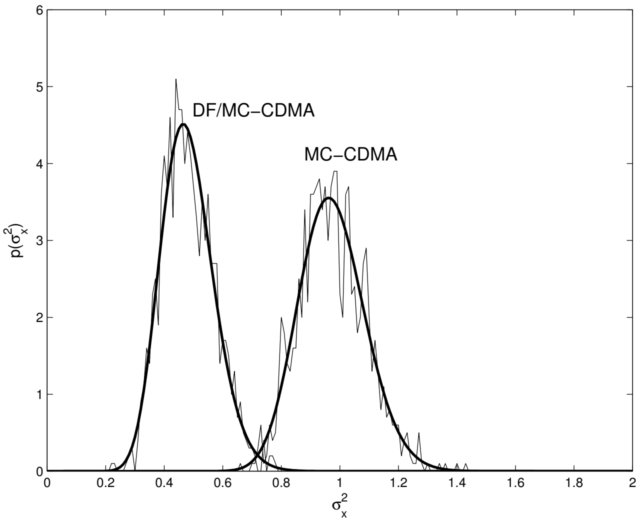

Fig. 3. Total MAI Power Histograms: Gold codes $N = 63$

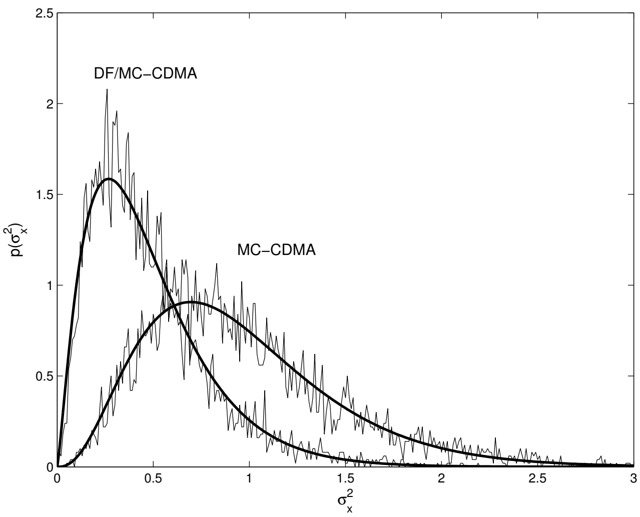

Fig. 4. Total MAI Power Histograms: WH codes $N = 64$

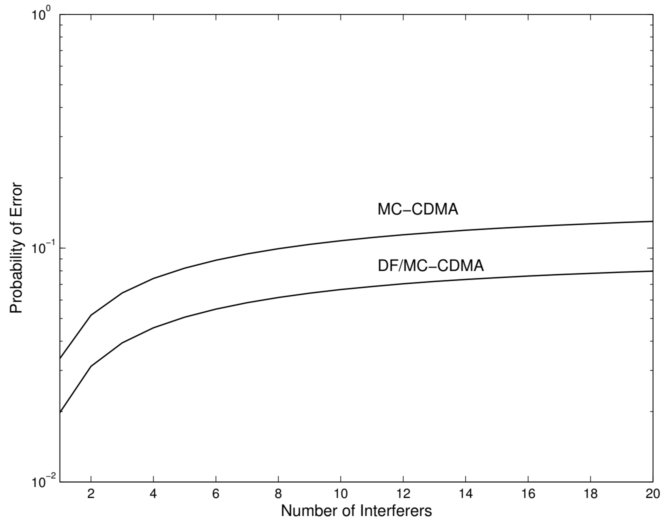

Fig. 5. BER Performance: Gold codes $N = 63$

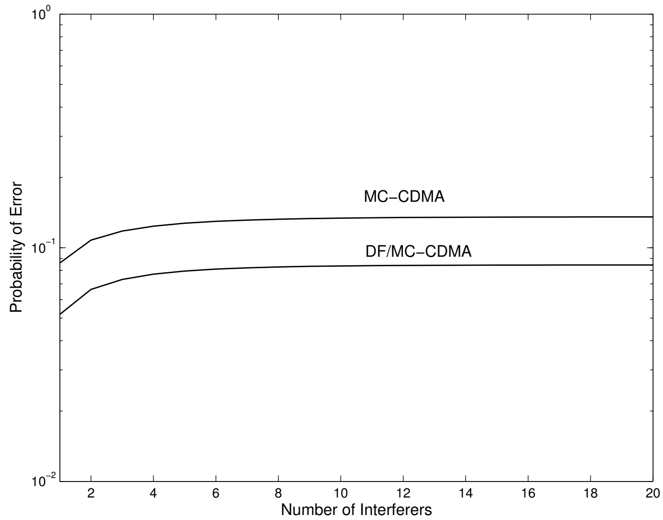

Fig. 6. BER Performance: WH codes $N = 64$

is minimized by taking the separation between the dual frequencies as N/T_s.

To demonstrate the reduction of MAI incurred by the reference user, the observed total MAI power, σ_x^2, was recorded for each realization and the corresponding histograms are displayed in Figs.3 and 4 for a $K = 64$ loaded system using Gold codes of $N = 63$ amd WH codes of $N = 64$ respectively. These histograms are successfully fitted by the Nakagami-m distribution [11] as shown by the smooth curves in Figs.3 and 4; the details of this fitting form the topic of a previous study [12]. It can be seen that these histograms follow the Nakagami-m power distribution given by [12]

$$p\left(\sigma_x^2\right) = \left(\frac{m}{\zeta}\right)^m \frac{\left(\sigma_x^2\right)^{m-1}}{\Gamma\left(m\right)} exp\left(-\frac{m\sigma_x^2}{\zeta}\right) \qquad (31)$$

where $m = E\left[\sigma_x^2\right]^2 / \mathrm{var}\left(\sigma_x^2\right)$, $\zeta = E\left[\sigma_x^2\right]$ and $\Gamma\left(m\right)$ is the Gamma function given by

$$\Gamma\left(m\right) = \int_0^\infty x^{m-1} exp\left(-x\right) dx \qquad (32)$$

As is evident from these histograms, the DF/MC-CDMA scheme offers significant MAI reduction and the range of total MAI power values is considerably lower than those of the MC-CDMA scheme.

Figure 5 shows the BER performance for an increasing number of interferers, of both systems for the use of Gold codes of $N = 63$ while Fig. 6 illustrates the corresponding BER performance using WH codes of $N = 64$. It can clearly be observed in both figures that the proposed dual frequency technique offers an improved BER performance as a result of the partial MAI reduction. The major drawback of this reduction technique however, is the bandwidth increase associated with the addition of the dual frequency switching component. From a design point of view, a decision on whether additional bandwidth is expendable to achieve more attractive BERs needs to be made when considering the proposed dual frequency system described here; with $\nu_i = N/T_s$ the bandwidth is increased to approximately twice that of the MC-CDMA system.

7. CONCLUSION

A method for the partial reduction of MAI incurred by an MC-CDMA system over an asynchronous Rayleigh fading channel has been proposed. Applying a periodic switching component to the MC-CDMA technique shifts a portion of the unwanted interference signals to an alternative frequency band. The proposed DF/MC-CDMA technique offers an improved BER performance over its MC-CDMA counterpart, however, this improvement comes at the cost of bandwidth sacrifice.

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