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

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ABSTRACT

This paper proposes an alternative transmission structure to the existing direct-sequence code division multiple access (DS-CDMA) technique in order to alleviate the decision variable from a substantial portion of the multiple access interference (MAI) incurred over an asynchronous slow varying Rayleigh fading channel. The proposed technique uses a dual frequency switching system that shifts lagging interference components to an alternative frequency band thus reducing the degree of MAI incurred in the considered symbol-by-symbol matched filter recovery. Bit-error rate (BER) performance comparisons are offered for the use of both Gold and Walsh-Hadamard (WH) codes. The proposed technique successfully reduces the amount of MAI experienced, however, this reduction comes at the cost of an increased bandwidth.

1. INTRODUCTION

Direct-sequence code division multiple access (DS-CDMA) has been incorporated as the multiple access scheme for the air interface in a number of 3G cellular technologies including UMTS, W-CDMA and cdma2000. Despite the capacity and frequency reuse benefits of DS-CDMA, existing phenomenon such as the near-far effect, frequency-selective fading, intersymbol interference (ISI) and multiple access interference (MAI) degrade the performance of DS-CDMA detection. Multicarrier CDMA systems [1] have been established to combat frequency-selective fading, combining the use of multicarrier modulation, as seen in orthogonal frequency division multiplexing (OFDM), with the CDMA concept. Of these hybrid systems, the MC-CDMA technique offers the best performance [2][3] and furthermore, the use of a cyclic prefix in the MC-CDMA technique has been shown to mitigate the problem of ISI [4]. The occurrence of MAI remains a limiting factor in CDMA detection, degrading the bit-error rate (BER) performance over asynchronous channels (such as the uplink channel). Here we propose an alternative technique that reduces the degree of MAI inflicted during asynchronous transmission. The proposed scheme is named dual frequency DS-CDMA (DF/DS-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, characterizing the channel and modulation models. The existing DS-CDMA detection model is detailed in section 3 and the proposed DF/DS-CDMA signal and detection models are derived in sections 4 and 4.1 respectively. Section 5 defines the BER performance metric and section 6 illustrates the MAI reduction and the corresponding BER improvement offered by the DF/DS-CDMA technique in comparison to the existing DS-CDMA technique. The results for the use of both WH and Gold codes are displayed in section 6. Finally, section 7 concludes the paper.

2. SYSTEM DESCRIPTION & SIGNAL MODELS

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 $u_T(t)$ is the rectangular pulse shaping waveform equal to unity over the interval $0 \le t < T$ and zero elsewhere.

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 kth user as a zero-mean Gaussian random variable $\beta_k \exp(j\varphi_k)$ for which β_k is Rayleigh distributed with $E\left[\beta_k^2\right] = 1$ and φ_k 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 $\tau_k \ge 0, \forall k$. We assume perfect power control at the base station and the signal power of each user is normalized to unity in all systems.

3. EXISTING DS-CDMA DETECTION

The DS-CDMA signal received at the base station comprises of delayed and attenuated versions of the signals transmitted by the K active users such that

$$r(t) = \sum_{k=1}^{K} \beta_k b_k(t-\tau_k) c_k(t-\tau_k) \exp\left(j\left[2\pi f_c t - \phi_k + \varphi_k\right]\right) \quad (3)$$

where f_c denotes the carrier frequency, β_k and φ_k are the gain and phase channel distortions experienced by the kth user and $\phi_k = 2\pi f_c \tau_k$. Upon reception the received signal in (3) is demodulated, despread by $c_x(t)$ and passed through a matched filter shaped to the rectangular pulse waveform. Recovering the desired data b_{xi} via a symbol-by-symbol recovery method yields the following matched filter output

$$y_{xi}^{ds} = \frac{1}{T_s}\int_{iT_s}^{(i+1)T_s} \alpha_x r(t) c_x(t) \exp\left(-j\left[2\pi f_c t + \varphi_x\right]\right) dt \quad (4)$$

where α_x is dependent on the combining strategy used. Applying equal gain combining (EGC) [5], making $\alpha_{xn'} = 1$, and substituting (3) into (4), this matched filter output becomes

$$\begin{aligned} y_{xi}^{ds} &= \frac{1}{T_s}\sum_{k=1}^{K} \beta_k \exp(j\xi_{kx}) \\ &\cdot \left[b_{k(i-1)}\int_{iT_s}^{iT_s+\tau_k} c_k(t-\tau_k) c_x(t)\, dt \right. \\ &+ \left. b_{ki}\int_{iT_s+\tau_k}^{(i+1)T_s} c_k(t-\tau_k) c_x(t)\, dt\right] \end{aligned} \quad (5)$$

where $\xi_{kx} = \varphi_k - \varphi_x - \phi_k$. Following the carrier demodulation, despreading and matched filter operations, the desired data b_{xi} is retrieved, however, it is corrupted by the presence of MAI. Separating the desired data component from the MAI gives a matched filter output of

$$y_{xi}^{ds} = \beta_x b_{xi} + \sum_{k\neq x}^{K} M_{kxi} \quad (6)$$

where M_{kxi} denotes the MAI contribution of the kth user in the symbol-by-symbol recovery of b_{xi} and is expressed as [6][7]

$$M_{kxi} = \frac{\beta_k \cos(\xi_{kn})}{T_s}\left[b_{k(i-1)} R_{kx}(\tau_k) + b_{ki}\hat{R}(\tau_k)\right] \quad (7)$$

where the partial cross-correlation functions, $R_{kx}(\tau_k)$ and $\hat{R}_{kx}(\tau_k)$, are defined in [7] as

$$R_{kx}(\tau_k) = \int_0^{\tau_k} c_x(t) c_k(t-\tau_k)\, dt \quad (8)$$

and

$$\hat{R}_{kx}(\tau_k) = \int_{\tau_k}^{T_s} c_x(t) c_k(t-\tau_k)\, dt \quad (9)$$

4. PROPOSED DF/DS-CDMA SIGNAL MODEL

It is desired to insert a controlled frequency separation between consecutive symbols of the transmission signal, $s_k(t)$, of each user. This is enabled by the DF switching component depicted in Fig. 1, periodically switching between the dual frequencies employed. This periodic switching is controlled by a fixed switching pattern, termed the dual band switching pattern (DBSP), common to all K subscribers in the cell. The DBSP is analogous to the frequency hopping pattern seen in frequency hopping systems [8]. At the transmitter the DBSP activates the switching circuit which in turn shifts the frequency of the DS-CDMA modulated signal. The time-variant DBSP, $f_d(t)$, of period T_s is represented by

$$f_d(t) = f_d^i, \quad iT_s \le t \le (i+1)T_s \quad (10)$$

where $f_d^i \in \left\{f_d^1, f_d^2\right\}$ denotes the switching frequency that alternates every T_s such that $f_d^i \neq f_d^{(i\pm1)}$.

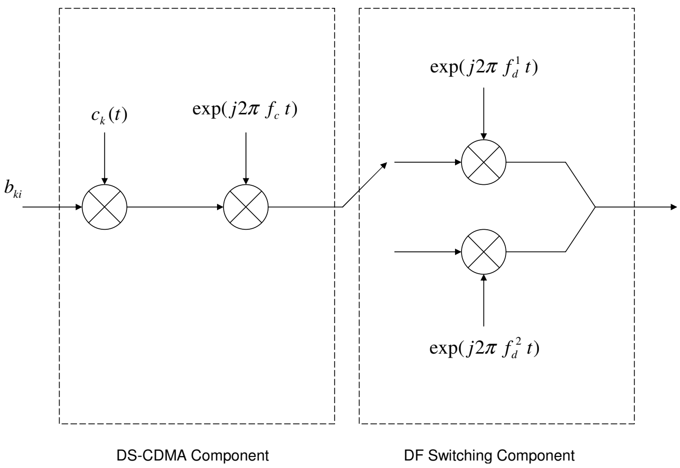

Fig. 1. DF/DS-CDMA Transmission Structure

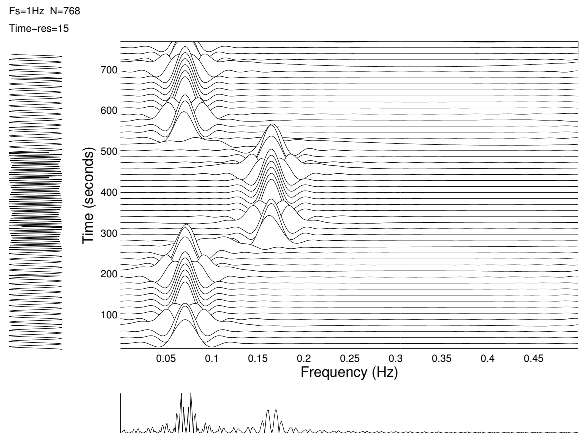

Fig. 2. Time-Frequency Distribution of DF/DS-CDMA Transmission Signal $s_k(t)$

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

$$s_k(t) = b_k(t)\, c_k(t) \exp\left(j2\pi \left\{f_c + f_d(t)\right\} t\right) \tag{11}$$

which is of similar format to that in [8]. Choosing the switching period as T_s enables one frequency shift every symbol duration making the transmitted signal

$$s_k(t) = \sum_{i=-\infty}^{\infty} b_{ki} \cdot u_{T_s}(t - iT_s)\, c_k(t) \exp\left(j2\pi \left\{f_c + f_d^i\right\} t\right) \tag{12}$$

where f_d^i is the shifting frequency, constant over the ith symbol and all frequency shifting is assumed time-synchronous with the symbol boundaries. The periodic shifting of the carrier frequency is seen more clearly in the time-frequency plane as in Fig. 2. Here the shifting of the DS-CDMA signal spectrum between DF bands can be viewed as a function of time.

The rationale behind the combination of the DF technique with the CDMA system presented here is the possible reduction of the MAI component dependent on the previous symbols $b_{k(i-1)}$ (see (7)). This is achieved by shifting consecutive symbols to altering frequencies and hence it is necessary for $f_d^i \neq f_d^{(i\pm1)}$ throughout the transmission signal. Moreover, it is assumed that f_d^i is taken as the same for all K users in the system.

4.1. Proposed DF/DS-CDMA Detection

Following transmission over a slow varying Rayleigh fading asynchronous channel, the received DF/DS-CDMA signal is expressed as

$$\begin{aligned} r^{df}(t) &= \sum_{k=1}^{K} \beta_k b_k(t-\tau_k)\, c_k(t-\tau_k) \\ &\cdot \exp\left(j\left[2\pi\left\{f_c + f_d(t-\tau_k)\right\}\left\{t-\tau_k\right\} + \varphi_k\right]\right) \end{aligned} \tag{13}$$

Using a symbol-by-symbol recovery method, the desired data b_{xi} is retrived by first deswitching the received signal with $\exp\left(-j2\pi f_d^i t\right)$, demodulating with $\exp\left(-j2\pi f_c t\right)$, depreading by applying $c_x(t)$ and applying the matched filter. The output following these operations is expressed as

$$\begin{aligned} y_{xi}^{df} &= \frac{1}{T_s}\int_{iT_s}^{(i+1)T_s} \alpha_x r^{df}(t)\, c_x(t) \\ &\qquad \exp\left(-j\left[2\pi\left\{f_c + f_d^i\right\} t + \varphi_x\right]\right) dt \qquad (14) \\ &= \frac{1}{T_s}\sum_{k=1}^{K} \beta_k \Bigg[b_{k(i-1)} \exp\left(j\xi_{kx}^{(i-1)}\right) \\ &\qquad \int_{iT_s}^{iT_s+\tau_k} c_k(t-\tau_k)\, c_x(t) \exp\left(j2\pi\nu_i t\right) dt \\ &+ b_{ki}\exp\left(j\xi_{kx}^{i}\right)\int_{iT_s+\tau_k}^{(i+1)T_s} c_k(t-\tau_k)\, c_x(t)\, dt \Bigg] \qquad (15) \end{aligned}$$

where $\xi_{kx}^i = \varphi_k - \varphi_x - 2\pi\left\{f_c + f_d^i\right\}\tau_k$ and $\nu_i = f_d^{(i-1)} - f_d^i$ denotes the induced Doppler shift between consecutive symbols.

The matched filter output can further be expanded as

$$y_{xi}^{df} = \beta_x b_{xi} + \sum_{k\neq x}^{K} M_{kxi}^{df} \tag{16}$$

where M_{kxi}^{df} is the MAI produced by the kth user in the detection of b_{xi}. This expression illustrates the superposition of the desired data, b_{xi}, with the MAI contributions for each of the $K-1$ interferers in the system. The total MAI incurred over the symbol recovery duration is segmented into two components such that

$$M_{kxi}^{df} = \check{M}_{kxi}^{df} + \hat{M}_{kxi}^{df} \quad (17)$$

where $\check{M}_{kxi}^{df}$ is the first MAI component that represents the MAI produced over the interval $iT_s \le t \le iT_s + \tau_k$ while the second component, $\hat{M}_{kxi}^{df}$, represents the MAI produced over the interval $iT_s + \tau_k \le t \le (i+1)T_s$. The first MAI component is given as

$$\begin{aligned} \check{M}_{kxi}^{df} &= \frac{\beta_k b_{k(i-1)} \exp\left(j\xi_{kx}^{(i-1)}\right)}{T_s} \\ &\cdot \int_{iT_s}^{iT_s+\tau_k} c_k(t-\tau_k)\, c_x(t) \\ &\cdot \exp\left(j2\pi\Big\{\underbrace{f_d^{(i-1)} - f_d^i}_{\nu_i}\Big\}t\right) dt \quad (18) \\ &= \frac{\beta_k b_{k(i-1)} \exp\left(j\xi_{kx}^{(i-1)}\right)}{T_s} I(\tau_k) \quad (19) \end{aligned}$$

where

$$I(\tau_k) = \int_{iT_s}^{iT_s+\tau_k} c_k(t-\tau_k)\, c_x(t) \exp(j2\pi\nu_i t)\, dt \quad (20)$$

and the second component is given as

$$\begin{aligned} \hat{M}_{kxi}^{df} &= \frac{\beta_k b_{ki} \exp\left(j\xi_{kx}^{i}\right)}{T_s} \\ &\quad \int_{iT_s+\tau_k}^{(i+1)T_s} c_k(t-\tau_k)\, c_x(t)\, dt \quad (21) \\ &= \frac{\beta_k b_{ki} \exp\left(j\xi_{kx}^{i}\right)}{T_s} \hat{R}_{kx}(\tau_k) \quad (22) \end{aligned}$$

where $\hat{R}_{kx}(\tau_k)$ is a partial cross-correlation function defined in [7]. Due to the introduced Doppler shift $\nu_i = f_d^{(i-1)} - f_d^i$, the first MAI component in (17) can be shown to equate to zero for specific values of ν_i. All offsets have been assumed integer multiples of T_c and due to this assumed chip alignment the integral in (20) is evaluated as

$$\begin{aligned} I(\tau_k) &= \sum_{n=0}^{\tau_k-1} \int_{nT_c}^{(n+1)T_c} \delta_n \exp(j2\pi\nu_i t)\, dt \quad (23) \\ &= \sum_{n=0}^{\tau_k-1} \frac{\delta_n}{j2\pi\nu_i} \Big[\exp(j2\pi\nu_i t) \Big]_{nT_c}^{(n+1)T_c} \quad (24) \\ &= 0 \quad \text{iff} \quad \nu_i = \frac{m}{T_c} \quad (25) \end{aligned}$$

where m is an integer and $\delta_n = \pm 1$. It can be noted that this frequency separation condition corresponds to the use of orthogonal dual switching frequencies.

With the first MAI component equating to zero, the real component of the matched filter output can be simplified to show the recovered information and the sum of MAI terms in (22) as

$$y_{xi}^{df} = \beta_x b_{xi} + \frac{1}{T_s} \sum_{k \ne x}^{K} \beta_k b_{ki} \hat{R}_{kx}(\tau_k) \cos\left(\xi_{kx}^i\right) \quad (26)$$

Here only the real component of the MAI in (22) is considered as is done in the decision process.

5. PERFORMANCE EVALUATION

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 incurred during detection is defined as

$$M_{xi}^2(\underline{\tau}) = \sum_{k \ne x}^{K} M_{kxi}^2\left(\beta_k, b_{ki}, b_{k(i-1)}, \tau_k\right) \quad (27)$$

where $\underline{\tau}$ denotes the vector of offsets defining the asynchronous channel for which $\tau_x = 0\ \forall \underline{\tau}$. To obtain a single valued MAI power for each possible offset value, we define our interference metric as the total conditional MAI power given by

$$\sigma_x^2(\underline{\tau}) = \sum_{k \ne x}^{K} E\left[M_{kxi}^2\left(\beta_k, b_{ki}, b_{k(i-1)}, \tau_k\right) | \tau_k\right] \quad (28)$$

where $E[a|b]$ denotes the expectation of a given b. In the absence of channel fading and additive noise, the signal-to-interference ratio (SIR) is given by

$$\gamma = \left(\frac{\beta_x}{\sigma_x}\right)^2 \quad (29)$$

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

$$P_e = Q\left(\sqrt{\gamma}\right) = Q\left(\frac{\beta_x}{\sigma_x}\right) \quad (30)$$

where

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{t^2}{2}\right) dt \quad (31)$$

is the complementary Gaussian cumulative distribution function.

6. SIMULATION RESULTS

Monte Carlo simulations were performed to validate the MAI reduction capabilities of the proposed DF technique. A $K = 64$ user system employing Gold codes of $N = 63$ and WH codes of $N = 64$ was simulated for both the DS-CDMA and DF/DS-CDMA techniques, normalizing all transmission powers to unity, and $10,000$ realizations were run randomly generating a new offset vector $\underline{\tau}$ for each realization. To minimize the bandwidth increase resulting from the addition of the switching component, the minimum Doppler shift is used which corresponds to $m = 1$ in (25).

From the DF/DS-CDMA detection model derived in section 4.1 the degree of MAI incurred by the proposed system during asynchronous transmission is expected to be less than that of the existing DS-CDMA system. To visualize this MAI reduction, the observed total MAI power, σ_x^2, was recorded for each realization and the resulting histograms are depicted in Figs.3 and 4 for the use of Gold codes of $N = 63$ and WH codes of $N = 64$ respectively. These histograms are successfully fitted by the Nakagami-m distribution [9] as shown by the smooth curves in Figs.3 and 4; the details of this fitting form the topic of a previous study [6]. It can be seen that these histograms follow the Nakagami-m power distribution given by [6]

$$p\left(\sigma_x^2\right) = \left(\frac{m}{\zeta}\right)^m \frac{\left(\sigma_x^2\right)^{m-1}}{\Gamma\left(m\right)} exp\left(-\frac{m\sigma_x^2}{\zeta}\right) \qquad (32)$$

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

$$\Gamma\left(m\right) = \int_0^\infty x^{m-1} exp\left(-x\right) dx \qquad (33)$$

The MAI reduction offered by the DF/DS-CDMA technique is clear from these results for the use of both spreading code sets. This reduction of MAI is evident as the histograms of the dual frequency technique are distributed over the lower end of the interference power scale in comparison to that of the DS-CDMA technique. The corresponding BER performances obtained from the Monte Carlo simulations are displayed in Fig. 5 and 6 for a $K = 64$ loaded system using Gold and WH codes respectively. With the proposed DF/DS-CDMA system offering a reduction of the incurred MAI in comparison to the DS-CDMA system, the resulting BER is naturally improved as is shown in Figs. 5 and 6 for an increasing number of interferers. The addition of the DF component to the DS-CDMA scheme offers a significant BER improvement, however, this improvement comes at the expensive of bandwidth; the overall bandwidth of the DF/DS-CDMA system is 1.5 times larger than the DS-CDMA bandwidth.

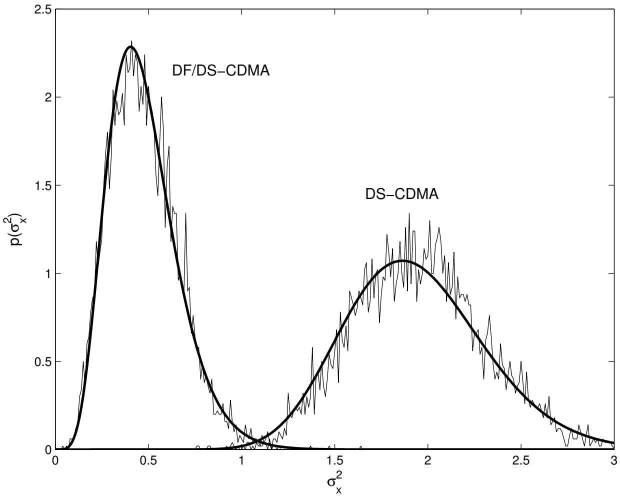

Fig. 3. Total MAI Power Histograms: Gold $N = 63$

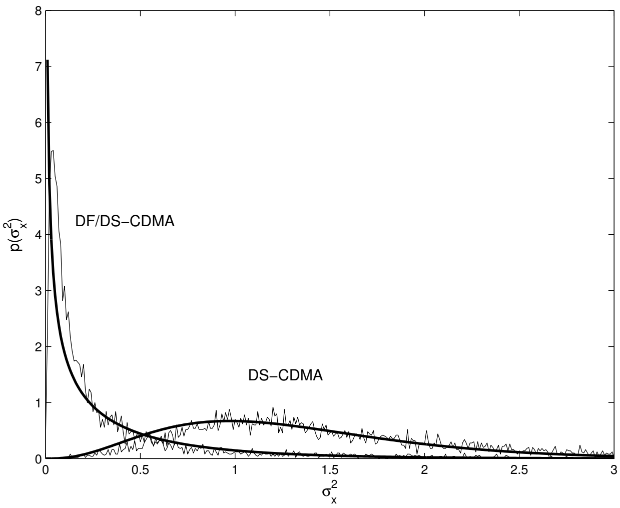

Fig. 4. Total MAI Power Histograms: WH $N = 64$

7. CONCLUSION

A hybrid multiple access scheme has been proposed that partially reduces MAI caused by asynchronous transmission. The proposed technique offers improved BER performance, however, this comes at the cost of an increased bandwidth. In a system motivated by achievable BER, the DF technique is the better multiple access scheme as it outperforms its DS-CDMA counterpart. On the other hand, in a system with tight bandwidth restrictions, the bandwidth sacrificed to achieve the improved BER may not be expendable, in which case the DF technique may hold little appeal.

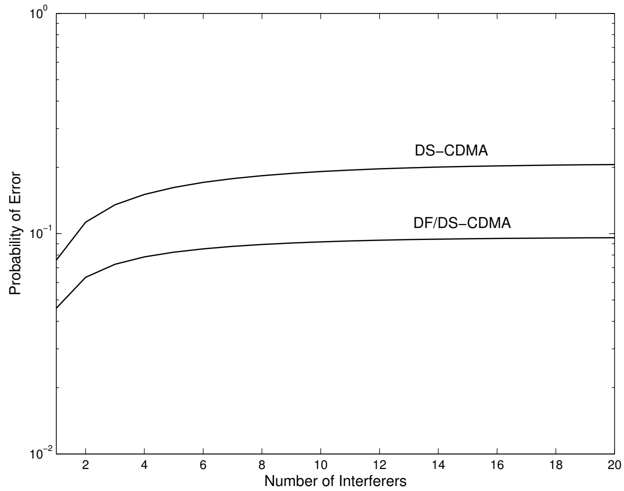

Fig. 5. BER Performance: Gold codes $N = 63$

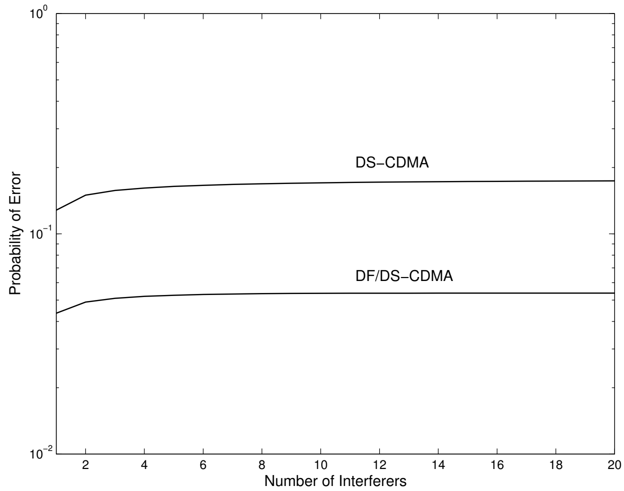

Fig. 6. BER Performance: WH codes $N = 64$

8. REFERENCES

[1] S. Hara and R. Prasad, "Overview of multicarrier CDMA," *IEEE Communications Magazine*, vol. 36, pp. 126–133, December 1997.

[2] X. Gui and T. Ng, "Performance of asynchronous orthogonal multicarrier CDMA system in frequency selective fading channel," *IEEE Trans. Communications*, vol. 47, no. 7, pp. 1084–1091, July 1999.

[3] S. Hara and R. Prasad, "Design and performance of multicarrier CDMA system in frequency-selective Rayleigh fading channels," *IEEE Trans. Vehicular Technology*, vol. 48, no. 5, pp. 1584–1595, September 1999.

[4] K. Ko, T. Kim, S. Choi, and D. Hong, "Semi-analytical approach of asynchronous MC-CDMA systems with a cyclic prefix," *IEEE Communications Letters*, vol. 9, no. 2, pp. 142–144, February 2005.

[5] M. Schwartz, W. R. Bennett, and S. Stein, *Communication Systems and Techniques*. IEEE Press, 1996.

[6] D. Carey, B. Senadji, and D. Roviras, "Statistical modeling of multiple access interference power: a Nakagami-m random variable," in *Proc. (WITSP-04)*, December 2004, pp. 219–224.

[7] M. B. Pursley, D. V. Sarwate, and W. E. Stark, "Performance evaluation for phase-coded spread-spectrum multiple-access communication-Part I: system analysis," *IEEE Trans. Communications*, vol. COM-25, no. 8, pp. 795–799, August 1977.

[8] E. A. Geraniotis, "Coherent hybrid DS-SFH spread-spectrum multiple-acess communications," *IEEE J. on Selected Areas in Communications*, vol. 3, no. 5, pp. 695–705, September 1985.

[9] M. D. Yacoub, J. E. V. Bautista, and L. Guerra de Rezende Guedes, "On higher order statistics of the Nakagami-m distribution," *IEEE Trans. Vehicular Technology*, vol. 48, no. 3, pp. 790–794, May 1999.