

Performance of Multicarrier CDMA with Dual Spreading in Nakagami-m Frequency Offset Fading Channels

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Abstract—In general, Multicarrier systems are very sensitive to carrier frequency offset (CFO) which generates intercarrier interference (ICI) resulting in performance degradation. However, by using frequency diversity in multicarrier DS-CDMA system, the effect of ICI caused by CFO can be significantly reduced. This can be achieved in Time-Frequency (TF) domain spreading MC DS-CDMA system which employs both time and frequency (TF) domain spreading or hybrid spreading. In this paper, the performance of TF-domain spread MC-DS-CDMA system over Nakagami-m fading channels is evaluated and investigated with varying CFO, number of users, number of subcarriers, and Signal-To-Noise-Ratio (SNR). The probability of bit error rate (BER) of TF-domain spread MC-DS-CDMA is derived using the standard Gaussian Approximation (SGA) approach for different values of m parameter. Numerical evaluation of the analytical expression of BER reveals that a high capacity and BER performance improvement are achieved for TF-domain spread MC-DS-CDMA system over the performance of multicarrier CDMA (MC-CDMA) system which spreads the signal in the frequency domain only. The simulation results show excellent agreement with the analysis.

Index Terms—multicarrier CDMA, carrier frequency offset, frequency-domain spreading, time-domain spreading, Nakagami fading channel.

I. INTRODUCTION

TODAY, multicarrier modulation is being selected as the transmission scheme for the majority of new broadband wireless communication systems [2]. Examples include digital subscriber line (DSL), European digital video broadcast (DVB), digital audio broadcast (DAB), and wireless local area network (WLAN) standards (IEEE 802.11 and 802.16). However, multicarrier systems are very sensitive to phase noise (PHN) and carrier frequency offset (CFO) caused by Doppler shift or by the oscillator instabilities [3-7]. The CFO in MC-DS-CDMA not only makes channels time-varying, but also destroys the orthogonality among sub-carriers, which causes inter-carrier interference (ICI) and multi-access

interference (MAI) [5, 6]. Even if orthogonal spreading codes are used, MC-DS-CDMA with CFO still suffers from MAI and ICI. As a result, MC-DS-CDMA is very sensitive to CFO, and is susceptible to CFO even more than conventional OFDM because multiple users are involved.

In the TF-domain spread MC-DS-CDMA system [1,8], users use two signature codes one for the T-domain spreading, while the other for the F-domain spreading instead of using solely T-domain spreading as in conventional MC-DS-CDMA system or solely F-domain spreading as in MC-CDMA system. The benefits of using F-domain spreading instead of F-domain repetition as in conventional MC-DS-CDMA is to mitigate the deficiency that the number of users decreases upon increasing the F-domain repetition depth. Thus, the total number of users supported by TF-domain spread MC-DS-CDMA is determined by the product of the T-domain spreading factor and the F-domain spreading factor. In addition, TF-domain spread MC-DS-CDMA system exhibits robustness against impairment channels and CFO in comparison with MC-CDMA system, as shown in this paper.

The objective of this paper is to investigate the effect of carrier frequency offsets on the performance of TF-domain spread MC-DS-CDMA system, and derive an expression of the probability of the BER over Nakagami-m fading channels. Nakagami distribution provides a more general and versatile way to model wireless channels [11-13], and has gained widespread application in the modeling of wireless fading channels. The probability of bit-error rate (BER) of the TF-domain spread MC-DS-CDMA scheme is evaluated in terms of the number of users, time and frequency spreading factors, normalized frequency offset, and SNR per bit by using the standard Gaussian approximation (SGA) approach [9]. The performance of TF-domain spread MC-DS-CDMA is compared with that obtained in [5] for MC-CDMA.

This paper is organized as follows; the proposed system model for TF-domain spread MC-DS-CDMA system is described in section II. The analysis and derivation of BER for TF-domain spread MC-DS-CDMA system is presented in section III. Our numerical and simulation results with comparisons are outlined in section IV. Finally, our conclusions and future work are discussed in section V.

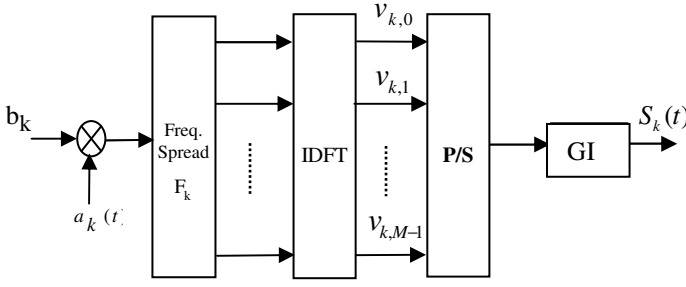


Fig.1 Transmitter of TF-domain spread MC-DS-CDMA scheme

II. SYSTEM MODEL

A. Transmitter Model

The transmitter block diagram of the TF-domain spread MC DS-CDMA system is shown in Fig.1 for a single user. The binary data symbols b_k of the k th user is first spread in time domain using the random signature sequence $a_k(t)$. The spread signal is then divided into M parallel branches, where M refers to the length of frequency spreading. Each branch of the signal is multiplied by the corresponding chip value of the F -domain spreading sequence F_k . Following, the F -domain spreading, each of the M branch signals modulates one of the M subcarrier frequencies using Inverse Discrete Fourier Transform IDFT block. We assume that the number of subcarriers is equal to the frequency spreading factor M . The m th IDFT output in the i th bit interval $[0, T_b)$ can be expressed as

$$v_{k,n} = \sqrt{A} \sum_{h=0}^{M-1} b_k^i a_k(t) F_{k,n} \frac{1}{M} e^{\frac{j2\pi}{M} nh} \quad n=0, \dots, M-1. \quad (1)$$

where A is the transmitted signal power. The time-frequency spreading sequences are assumed independent and identically distributed random variables. The time (T-domain) spreading waveform of the k th user is given as

$$a_k(t) = \sum_{l=0}^{\infty} a_{k,l} P(t - lT_c) \quad (2)$$

where $P(t)$ represents the rectangular T-domain chip waveform in chip interval $[0, T_c)$, and $a_{k,l} \in \{+1, -1\}$ generated at the rate of N chips. Assuming the transmitted power of each user is identical and equal to A . The transmitted signal after parallel-to-serial (P/S) conversion of user k and inserting the guard interval (GI) with length N_g is given as

$$S_k(t) = \sqrt{A} \sum_{n=-N_g}^{M-1} \sum_{h=0}^{M-1} b_k^i a_k(t) F_{k,n} \frac{1}{M} e^{\frac{j2\pi}{M} nh} \quad (3)$$

B. Channel Model

After the insertion of guard interval, the $S_k(t)$ signal is transmitted through a Nakagami- m [4] fading channel. The

parameter m in Nakagami distribution characterizes the severity of the fading channel, where $m=1$ represents Rayleigh fading, $m > 1$ can be approximated the Rician and lognormal distributions, while $m \rightarrow \infty$ corresponds to the Gaussian distribution. We assume the delay-spread of the channel is lower than chip-duration T_c , this can be achieved by employing high chip-duration spreading sequences. With the proper selection of the number of subcarriers, we can consider that, each subcarrier experiences independent flat fading. Assuming, there are K asynchronous TF-domain spread MC DS-CDMA users in the system with the same transmitted power. With perfect power control then, the received signal during the i th bit interval, impaired by the frequency offset is given as

$$r(t) = \sqrt{A} \sum_{k=1}^K \sum_{n=-N_g}^{M-1} \sum_{h=0}^{M-1} \alpha_{k,n} b_k^i(t - \tau_k) a_k(t - \tau_k) F_{k,n} \frac{1}{M} e^{\frac{j2\pi}{M} (n+\epsilon-g)h} \cdot e^{-j\psi_{k,n}} + \eta(t) \quad (4)$$

where the channel phases $\psi_{k,n}$ are i.i.d. random variable having uniform distribution in $[0, 2\pi)$, τ_k is the propagation delay for the k th user, ϵ is the normalized frequency offset, $\eta(t)$ is additive weight Gaussian noise (AWGN) with a double-sided power spectral density of value $(N_0/2)$ [9], while the fading amplitudes $\alpha_{k,n}$ are independent Nakagami random variables with a probability density function given by [4]

$$p(\alpha_{k,n}, \Omega_{k,n}) = \frac{2\alpha_{k,n}^{2m-1}}{\Gamma(m)} \left(\frac{m}{\Omega_{k,n}} \right)^m \exp\left(-\frac{m\alpha_{k,n}^2}{\Omega_{k,n}} \right) \quad (5)$$

where $\Omega_{k,n} = E(\alpha_{k,n}^2)$, $E[\cdot]$ refers to the expectation operator, $\Gamma(\cdot)$ is the Gamma function, and m is the Nakagami- m fading parameter, which is equal to $m = E^2[\alpha_{k,n}^2] / \text{var}[\alpha_{k,n}^2]$.

C. Receiver Model

The receiver model of the proposed scheme for single user detection is shown in Fig.2. Before the discrete Fourier transform (DFT) process, the guard intervals are removed from the received signal, then it is converted into M parallel branches by using (S/P) converter. The g th output of the DFT is given as follows

$$y_g = \sqrt{A} \sum_{n=0}^{M-1} \sum_{k=1}^K \sum_{h=0}^{M-1} \alpha_{k,n} b_k^i(t) a_k(t) F_{k,n} \frac{1}{M} e^{\frac{j2\pi}{M} (n+\epsilon-g)h} \cdot e^{-j\psi_{k,n}} + \eta_g \quad g=0, 1, \dots, M-1. \quad (6)$$

where η_g is the DFT of Weight Gaussian Noise (WGN) $\eta(t)$, which is still Gaussian, since the phase variation does not

change the characteristic of a complex Gaussian process [9].

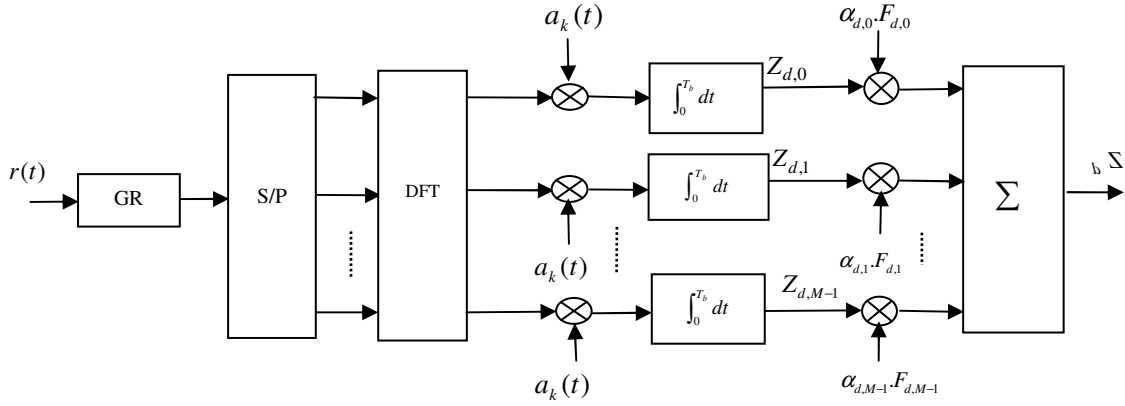


Fig.2 Receiver model of TF-domain spread MC DS-CDMA system

The above equation can be rewritten as

$$y_g = \sqrt{A} \sum_{n=0}^{M-1} \sum_{h=0}^{M-1} \{ b_d^j(t-\tau) a_d(t-\tau) F_{d,n} + \sum_{\substack{k=1 \\ k \neq d}}^K b_k^j(t-\tau_k) a_k(t-\tau_k) F_{k,n} \} \cdot \frac{\alpha_{k,n}}{M} e^{\frac{j2\pi}{M}(n+\varepsilon-g)h} \cdot e^{-j\psi_{k,n}} + \eta_g. \quad (7)$$

where $b_d^j(t)$, $a_d(t)$, $F_{d,n}$, τ are the data bit, time spreading, frequency spreading sequences, and time delay of the d th user respectively. Let us consider the downlink detection strategy and the d th user is the reference user. After the DFT block, each branch is correlated with the signature sequence of the reference user, the output of the correlator as shown in Fig. 2 is given as

$$Z_{d,g} = \frac{1}{T_b} \int_{\tau}^{T_b+\tau} y_g a_d(t-\tau) dt \quad (8)$$

without loss of generality, we assume that $\tau=0$ for simplicity, the above equation can be written as

$$Z_{d,g} = \sqrt{A} \sum_{n=0}^{M-1} \sum_{h=0}^{M-1} \left(\alpha_{d,n} b_d^j F_{d,n} + \sum_{\substack{k=1 \\ k \neq d}}^K \alpha_{k,n} \Re_k F_{k,n} e^{-j\psi_{k,n}} \right) \cdot \frac{1}{M} e^{\frac{j2\pi}{M}(n+\varepsilon-g)h} + \eta_g. \quad (9)$$

where $\Re_k$ in (9) is given as in [5]

$$\Re_k = [b_k[-1]R_k(\tau_k) + b_k[0]\hat{R}_k(\tau_k)] \quad (10)$$

where R_k , $\hat{R}_k$ are the cross-correlation between the T-domain spreading sequences of the d th user and k th user, which are given as

$$R_k(\tau_k) = \int_{nT_c}^{nT_c+\tau_k} a_d(t) a_k(t-\tau_k) dt$$

$$\hat{R}_k(\tau_k) = \int_{nT_c+\tau_k}^{(n+1)T_c} a_d(t) a_k(t-\tau_k) dt$$

In the final stage of the receiver in Fig.2, the subcarrier signals conveying the same data bit are de-spread using the F-domain spreading sequence of the desired user ($F_{d,g}$ $g=0,1,...,M-1$.) and are combined by using MRC scheme. In this model, we assume that the channel fading parameters ($\alpha_{d,g}$ $g=0,1,...,M-1$.) are perfectly estimated by employing the approach in [6]. Consequently, referring to Fig.2 the decision variable Z_d of the i th bit interval can be expressed as

$$Z_{d,g} = \sqrt{A} \alpha_{d,g}^2 b_d^j \sum_{h=0}^{M-1} \frac{1}{M} e^{\frac{j2\pi}{M}gh} + \sqrt{A} \sum_{\substack{n=0 \\ n \neq g}}^{M-1} \sum_{h=0}^{M-1} \alpha_{d,g} \alpha_{d,n} b_d^j F_{d,n} F_{d,g} \frac{1}{M} e^{\frac{j2\pi}{M}(n+\varepsilon-g)h} + \sqrt{A} \sum_{\substack{g=0 \\ n \neq g}}^{M-1} \sum_{\substack{n=0 \\ k \neq d}}^{M-1} \sum_{h=0}^{M-1} \alpha_{d,g} \alpha_{k,n} \Re_k F_{d,g} F_{k,n} \frac{1}{M} e^{\frac{j2\pi}{M}(n+\varepsilon-g)h} e^{-j\psi_{k,n}} + \sqrt{A} \sum_{g=0}^{M-1} \sum_{\substack{k=1 \\ k \neq d}}^K \sum_{h=0}^{M-1} \alpha_{d,g} \alpha_{k,g} \Re_k F_{d,g} F_{k,g} \frac{1}{M} e^{\frac{j2\pi}{M}gh} e^{-j\psi_{k,g}} + \sum_{g=0}^{M-1} \alpha_{d,g} F_{d,g} N_{d,g}. \quad (11)$$

The above equation can be expressed as

$$Z_d = D_d + I_s + I_{ICI} + I_{MAI} + N. \quad (12)$$

where the first term in (12) D_d is the desired signal of the d th user, the second term (I_s) is the self interference which is the

interference from the desired user's data in other chip intervals due to non zero frequency offset., the third term (I_{ICI}) is the intercarrier interference which is due to the interference from other users in other chip intervals, the fourth term (I_{MAI}) is multiple access interference due to the nonorthogonal spreading sequences, and the final (N_d) is the noise signal. The noise component shown in (12) is still Gaussian since a phase rotation due to frequency offset does not change its characteristics.

III. BIT ERROR RATE ANALYSIS

In this section, we derive the downlink BER of the TF-domain spread MC DS-CDMA system, which communicating over Nakagami-m fading channel and in the presence of carrier frequency offset. The channel fading and phase shift variables are assumed to be constant within the symbol-duration. Based on the Gaussian approximation [7], the decision variable Z_d in (11) can be approximated as a Gaussian random variable having a mean given by

$$\begin{aligned} E[Z_d] &= E\left[\sqrt{A} \sum_{g=0}^{M-1} \frac{\alpha_{d,g}^2}{M} b_d^i \sum_{h=0}^{M-1} \frac{1}{M} e^{\frac{j2\pi\epsilon h}{M}}\right] \\ &= \sqrt{A} \sum_{g=0}^{M-1} \frac{E(\alpha_{d,g}^2)}{M} b_d^i S_0 \end{aligned} \quad (13)$$

where the variable S_0 ($S_0 = S_n|_{n=0}$) can be obtained from [10], as

$$\begin{aligned} S_n &= \frac{1}{M} \sum_{h=0}^{M-1} e^{\frac{j2\pi}{M}(n+\epsilon)h} \\ &= \frac{\sin(\pi(n+\epsilon))}{M \sin(\frac{\pi}{M}(n+\epsilon))} e^{\left\{j\left\{\pi\left(1-\frac{1}{M}\right)(n+\epsilon)\right\}\right\}} \end{aligned} \quad (14)$$

The variance of the decision variable Z_d can be evaluated as

$$Var[Z_d] = Var[I_s] + Var[I_{ICI}] + Var[I_{MAI}] + Var[N_d]. \quad (15)$$

where as stated in [6], we assume a negative exponentially decaying multipath intensity profile (MIP) distribution given by $\Omega = E(\alpha_{k,n}^2) = \Omega_0 \exp(-\zeta l)$, $\zeta \geq 0$, l is tap number, Ω_0 is the average signal strength corresponding to the first resolvable path and ζ is the rate of average power decay. We assume that all the subcarrier signals of the different users have the same MIP distribution. The variance of self interference can be calculated as follows

$$I_s = \sum_{g=0}^{M-1} \alpha_{d,g} I_g^s \quad (16)$$

where the variance of I_g^s is given as

$$\begin{aligned} var(I_g^s) &= E \left[\left(\sqrt{A} \sum_{\substack{n=0 \\ n \neq g}}^{M-1} \sum_{h=0}^{M-1} \alpha_{d,n} F_{d,g} F_{d,n} S_{n-g} \right)^2 \right] \\ &= \frac{A}{M^2} \sum_{\substack{n=0 \\ n \neq g}}^{M-1} E(\alpha_{d,n}^2) S_{n-g}^2 = \frac{A\Omega}{M^2} \sum_{\substack{n=0 \\ n \neq g}}^{M-1} S_{n-g}^2 \end{aligned} \quad (17)$$

For simplicity, we take the average of the variance of I_s in (17) so, we can express the variance of I_s as follow

$$\begin{aligned} var(I_s) &= \frac{1}{M} \sum_{g=0}^{M-1} \alpha_{d,g}^2 var(I_g^s) \\ &= \frac{A\Omega}{M^2} W \sum_{g=0}^{M-1} \alpha_{d,g}^2 \end{aligned} \quad (18)$$

where it can be stated that

$$\begin{aligned} W &= \frac{1}{M} \sum_{\substack{n=0 \\ n \neq g}}^{M-1} S_{n-g}^2 \\ &= \sum_{n=1}^{M-1} (S_n^2 + S_{-n}^2) (1 - n/M) \end{aligned} \quad (19)$$

By following the same steps above, we can evaluate the variance of both intercarrier interference and multiple access interference, which are given as

$$Var[I_{ICI}] = \frac{A(K-1)\Omega}{3NM^2} W \sum_{g=0}^{M-1} \alpha_{d,g}^2 \quad (20)$$

and

$$Var[I_{MAI}] = \frac{A(K-1)\Omega}{3NM^2} S_0^2 \sum_{g=0}^{M-1} \alpha_{d,g}^2 \quad (21)$$

since $E[\Re_k^2] = (2/3N)$ and $E[real(e^{-j\psi_{k,n}})^2] = (1/2)$ as given in [6]. Finally, the variance of the complex Gaussian random process shown in (11) can be obtained as follows, the variance of the noise term N_d is given by

$$Var[\eta] = \frac{(N_0/2)}{M} \sum_{g=0}^{M-1} \alpha_{d,g}^2 \quad (22)$$

Then from the above derivation, we can obtain the variance of the decision variable Z_d , which can be written as

$$Var[I_{ICI}] = A \left[\left(1 + \frac{(K-1)}{3N} \right) \frac{W}{M^2} + \frac{(K-1)}{3NM^2} + \frac{(N_0/2A)}{M\Omega} \right] \sum_{g=0}^{M-1} \alpha_{d,g}^2 \quad (23)$$

From the mean and the variance shown in (13) and (21) respectively, we can express the average BER of the TF-domain spread MC DS-CDMA system over Nakagami-m fading channel as

$$P_b(\gamma) = Q \left(\sqrt{\frac{(E [Z_d])^2}{\text{Var} [Z_d]}} \right) = Q \left(\sqrt{\gamma_d \sum_{g=0}^{M-1} \frac{\alpha_{d,g}^2}{\Omega}} \right) \quad (24)$$

where

$$\gamma_d = S_0^2 \left[\left(\Omega_0 \frac{(2E_b / N_0)}{M} \right)^{-1} + \left(1 + \frac{K-1}{3N} \right) W + \frac{K-1}{3N} S_0^2 \right]^{-1} \quad (25)$$

for BPSK signal modulation, E_b is the energy during the bit interval. The Gaussian Q-function can be represented in the form of $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-(t^2/2)} dt$ as in [7], but for a convenient analytical expression of the average BER, we use the alternative expression of the Q-function, which was presented in [8] and is given as

$$Q(x) = \frac{1}{\pi} \int_0^{\pi/2} \exp \left(-\frac{x^2}{2 \sin^2 \theta} \right) d\theta \quad x \geq 0 \quad (26)$$

To compute the average BER, we must statistically average (24) over the joint probability density function of fading attenuations $p_\alpha(\alpha_{d,0}, \dots, \alpha_{d,M-1})$. For the assumption of independent fading channels at different subcarriers, the average BER can be expressed as

$$P_b = \frac{1}{\pi} \int_0^{\pi/2} \left(\frac{m \sin^2 \theta}{\gamma_d + m \sin^2 \theta} \right)^{mM} d\theta \quad (27)$$

Next, we investigate the achievable performance of the proposed system based on the probability of bit error rate shown in (27).

IV. PERFORMANCE RESULTS

In this section, we evaluate the performance of TF-domain spread MC DS-CDMA system. In the following, we assume random time and frequency spreading sequences, unless otherwise specified. Fig.3 compares the simulation results of TF-domain spread MC DS-CDMA system with the theoretical performance shown in (27) in Rayleigh fading channel ($m=1$), using random spreading sequences, and one interferer at different values of frequency offset. We can observe that, the simulation results agree with the numerical results, but there is some difference at high SNR. The simulation results in Fig.3, show that the SGA method becomes slightly poorer at large frequency offset and at high SNR.

In Fig.4, we compare the performance of the TF-domain spread MC DS-CDMA system and MC-CDMA system [9] versus the number of users and with different values of frequency offsets. The results in Fig.4 are obtained using the parameters of $M=16$, $N=32$, and $E_b/N_0 = 15$ dB. We note from the results in Fig.4, that the BER performance of MC-CDMA system degrades quickly and saturates, where the effect of frequency offset becomes less significant when the number of users increased upon ten ($K > 10$). This is due to the increase in

the ICI and MAI, while the TF-domain spread MC DS-CDMA system can achieve better BER with increasing number of users at $\epsilon=0$, and 0.1, but the performance saturates at $\epsilon=0.2$.

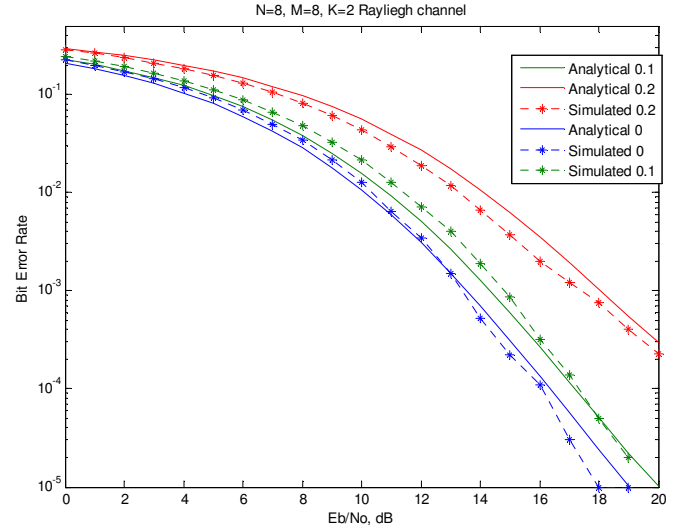


Fig.3 Simulated BER performance of TF-domain spread MC DS-CDMA, using random spreading sequences in Rayleigh channel ($m=1$).

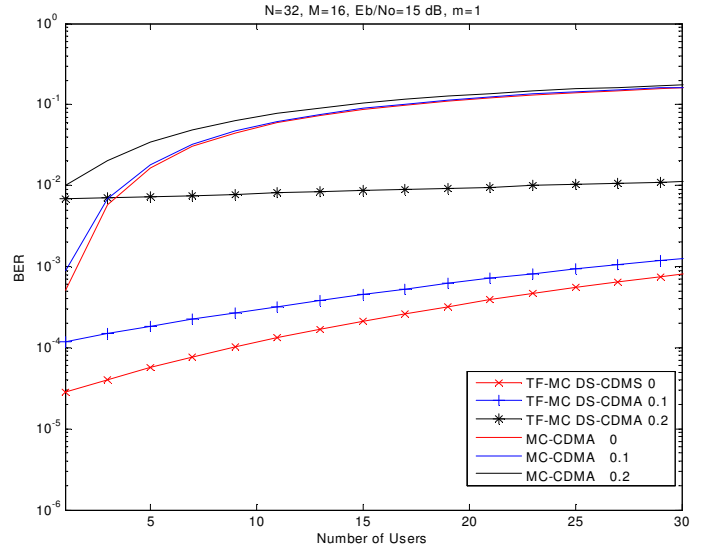


Fig.4 BER of TF-domain spread MC DS-CDMA and MC-CDMA system with different frequency offset versus number of users.

Figures 5 and 6 illustrate the probability of BER shown in (27) versus E_b/N_0 with increasing the numbers of subcarriers (M) at $\epsilon=0.1$ and 0.2, respectively. The plot in Fig.5 shows that, at $E_b/N_0 < 10$ dB the BER of all cases are comparable, otherwise the BER becomes better with increasing the number of subcarriers. While in Fig.6, there is a crossover of all curves at $E_b/N_0 < 15$ dB, otherwise, the performance improves with increasing the number of subcarriers.

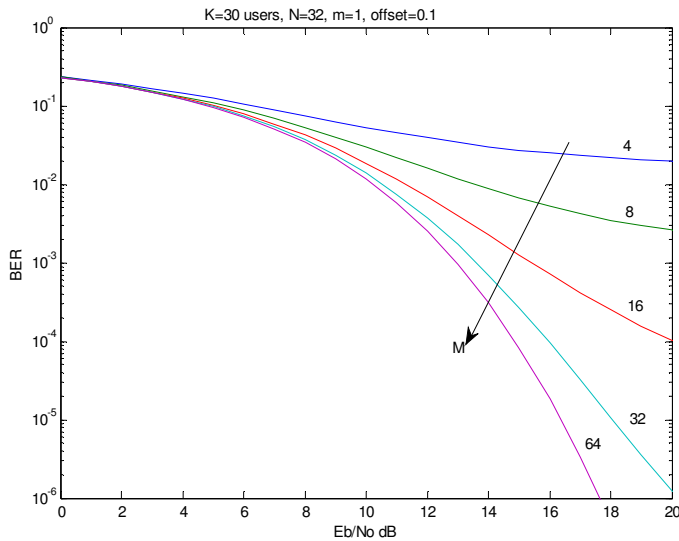


Fig.5 BER of TF-domain spread MC DS-CDMA system at $\epsilon=0.1$, and with different values of subcarriers

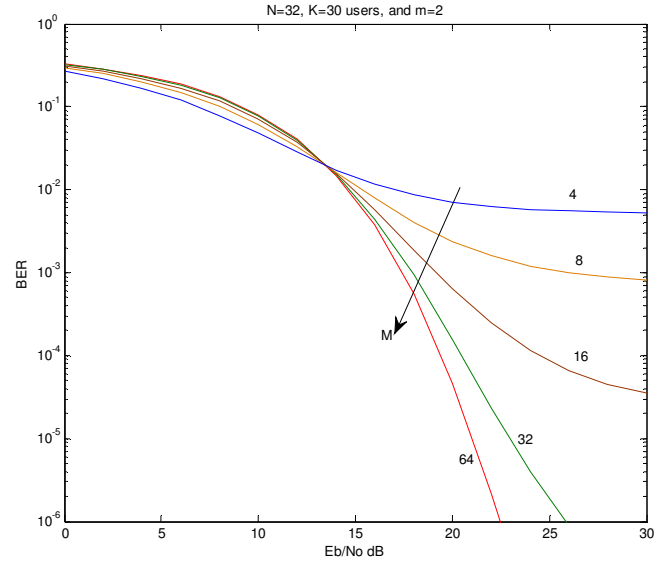


Fig.7 Performance of TF-domain spread MC DS-CDMA system in Nakagami channel ($m=2$) at $\epsilon=0.2$, and different values of subcarriers .

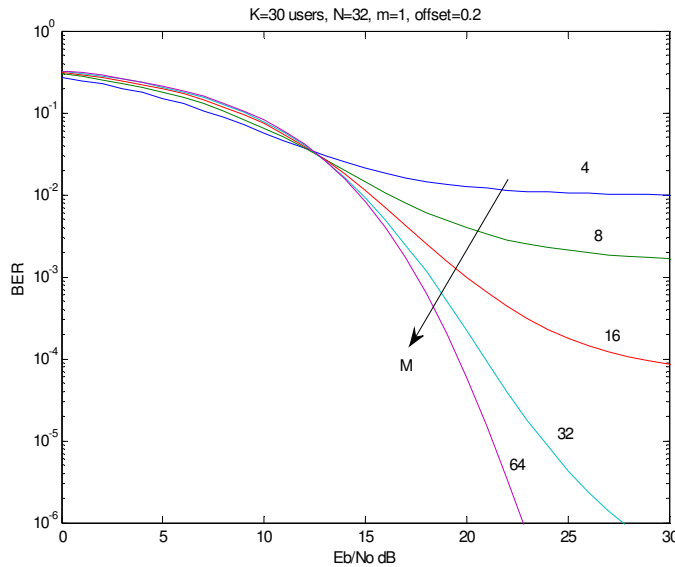


Fig.6 BER of TF-domain spread MC DS-CDMA system at $\epsilon=0.2$, and with different values of subcarriers

Fig.7 shows the performance of the system in Nakagami fading channel with ($m=2$). As we note in Fig.7, there is some improvement in performance compared to Fig.6. The Figure 8 illustrates the effects of channel fading parameter m on the performance of the system with different values of offset. As expected, the system performance improves as the amount of fading decreases, more specifically, as m increases. For orthogonal spreading sequences, the results have been obtained previously not changed, because the inter-carrier interference and also the multiple access interference still exist.

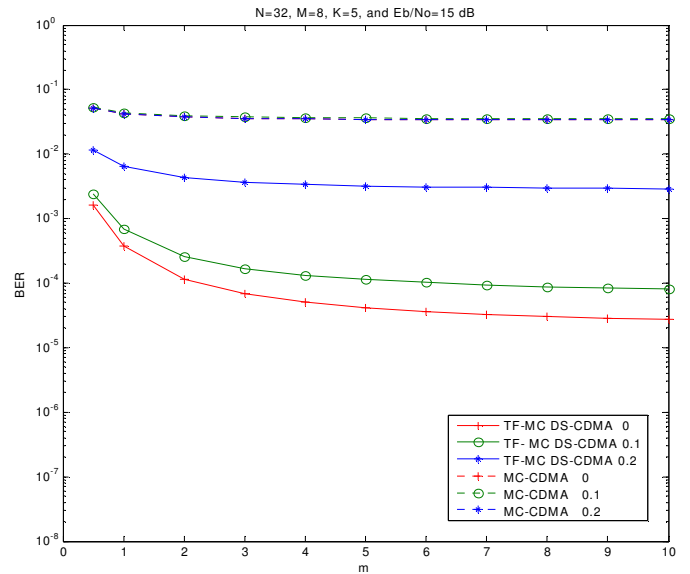


Fig.8 BER versus the fading parameter m with different frequency offset for TF-domain spread MC DS-CDMA system, and MC-CDMA system .

Finally, in order to evaluate the BER performance of the system in AWGN channel, we put $\alpha_{d,g} = 1$ and $\Omega = 1$ in (24) this is shown in Fig.9. We observe from Fig.9, that the BER performance of the system degrades as the normalized frequency offset increases.

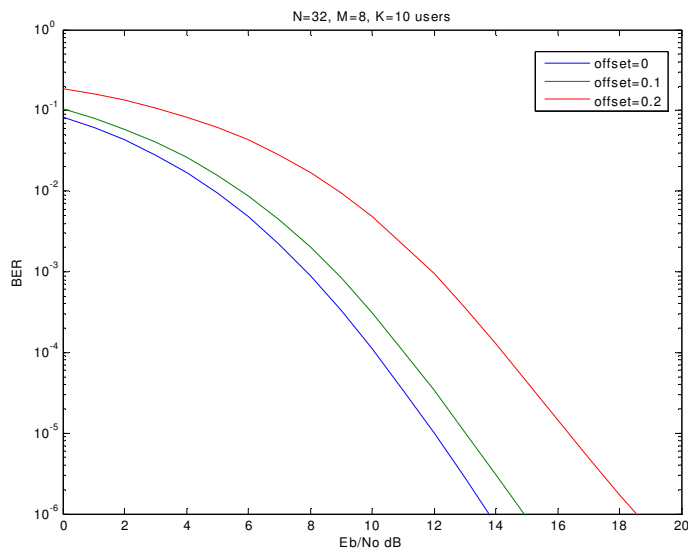


Fig.9 BER of TF-domain spread MC DS-CDMA system in AWGN

V. CONCLUSION

In this contribution, we have investigated the effect of the carrier frequency offset on the BER performance of MC DS-CDMA using both the time and frequency domain spreading. The probability of BER of TF-domain spread MC DS-CDMA system has been evaluated analytically when communicating over Nakagami-m fading channel in terms of the number of users, the spreading sequences, and frequency offset using the approach of standard Gaussian approximation (SGA) which reduces the computational complexity. The simulation results using random spreading sequences verified our numerical results. The performance of the proposed system was compared with that for MC-CDMA system for random spreading sequences. Our numerical results show that the TF-domain spread MC DS-CDMA system is capable of achieving a high BER performance and capacity improvement compared with the performance of MC-CDMA system. Also, as we show in the pervious section that, the TF-domain spread MC DS-CDMA system can mitigate the low frequency offset ($\epsilon < 0.2$), but at high frequency offset, its performance can be improved by increasing number of subcarriers and energy per bit. Therefore, the TF-domain spread MC DS-CDMA can achieve the requirements of broadband wireless communications.

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