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A Multicarrier-CDMA Receiver with Full Interference Suppression and Carrier Frequency Offset Recovery

Besma Smida, Sofiène Affes, Kamal Jamaoui, and Paul Mermelstein
INRS-EMT, Université du Québec
Place Bonaventure, 800, de la Gauchetière Ouest, Suite 6900
Montréal, Québec, H5A 1K6, Canada

***Abstract*—A low-complexity multicarrier-CDMA space-time receiver with full interference suppression capabilities is developed and analyzed for high-rate transmissions over next-generation CDMA systems. First, we derive a complete model of the interference which takes into account MAI, ISI, and ICI. Based on this model, we introduce a new multicarrier interference subspace rejection (MC-ISR) receiver and analyze its performance in an unknown time-varying Rayleigh channel with multipath, carrier offset and cross-correlation between subcarrier channels. We also propose a realistic implementation of this receiver which includes an efficient strategy for carrier offset recovery in a multicarrier and multiuser detection scheme. Simulation results confirm the net advantage of the full interference suppression capabilities of MC-ISR.**

I. Introduction

The need to support great amounts of high-rate and burst-type traffic in wireless channels poses serious challenges to the current CDMA air interfaces. Technologies that could effectively enhance the overall bandwidth efficiency and the detection efficiently are hence required. Multi-carrier (MC)-CDMA systems in particular have received considerable attention, because they have the attractive feature of high spectral efficiency and because they can be easily implemented using the fast fourier transform (FFT) without significantly increasing the transmitter and receiver complexities [1]. Although MC-CDMA systems are promising, challenges remain before they can achieve their full potential.

One of the major obstacles in detecting MC-CDMA signals is interference. The multiple access interference (MAI) and the inter-symbol interference (ISI), which are inherited from conventional DS-CDMA, affect likewise the performance of MC-CDMA systems. In addition, MC-CDMA capacity is limited by the inter-carrier interference (ICI) due to the use of multicarrier modulation. Indeed, the imperfect frequency down-conversion due to the instability of local oscillators combined with the multipath effect disturbs the subcarriers orthogonality thereby causing ICI.

Since MC-CDMA systems also contain a DS-CDMA component, traditional multiuser detection can be performed on each carrier with some form of temporal adaptation. A variety of multi-user receivers have been investigated for MC-CDMA systems such as MMSE [2], successive interference cancellation (SIC) [3], parallel interference cancellation (PIC) [4], [5], MMSE/decorrellator [6], and subspace multiuser detection [7], [8]. Most of these receivers have focused on multiple access interference while ignoring the inter-carrier-interference. In addition, important system design issues such as carrier frequency offset recovery (CFOR) have often been neglected. In multiuser detection, the CFO of one user not only degrades the detection of that user itself, but also makes the receiver based on the ideal carrier frequency assumption no longer optimal, thus degrading the detection of the other users. An alternative multiuser detection technique, denoted interference subspace rejection (ISR), has been proposed for DS-CDMA [9]. This technique offers different modes. Each mode characterizes the interference vector in a different way and accordingly suppresses it. The flexibility and the robustness inherent to ISR make its exploitation in multicarrier systems of great interest.

In this paper, a low-complexity multicarrier space-time receiver is developed that mitigates the full interference effect while confronting wireless channel impairments. First, we derive a complete model of the interference which takes into account MAI, ISI, and ICI in a multipath fading channel with timing and frequency mismatch. Based on this model, we propose a new multicarrier interference subspace rejection (MC-ISR) receiver with full interference suppression capabilities. We incorporate the least complex and the more practical ISR interference rejection mode to simultaneously suppress MAI, ISI, and ICI at the signal combining step. We also propose a realistic implementation of the new MC-ISR receiver which includes an efficient strategy for carrier offset recovery in a multicarrier and multiuser detection scheme. Furthermore, the assessment of the new MC-ISR receiver is oriented toward an implementation in a future real-world wireless system. We hence assume correlated Rayleigh channels across subcarriers. Indeed, fading characteristics among subcarriers are highly correlated due to insufficient frequency separation between the subcarriers. Additionally, we analyze the performance of MC-ISR using very realistic link-level simulation setups that take into account time and frequency mismatch, imperfect power control, channel identification errors etc.

II. Data Model and Assumptions

A. Transmitter

We consider the uplink[1] of an asynchronous multi-cellular multicarrier CDMA system with U in-cell active users. For the sake of simplicity, we assume that all users use the same subcarriers and transmit with the same modulation at the same rate. The input information sequence of the u-th user is first converted into $N_c = 2K+1$ parallel[2] data sequences $b^u_{-K,n}, \dots, b^u_{0,n}, \dots, b^u_{K,n}$ where n is the time index. The data $b^u_{k,n} \in C_{\mathcal{M}}$ is $\mathcal{M}$-PSK modulated and differentially[3]

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[1] The proposed model and transceiver apply to both uplink and downlink transmissions.

[2] We selected an odd number of subcarriers to have a central frequency, but the model can easily be rearranged to operate with an even number of subcarriers.

[3] We can also use pilot symbols for coherent modulation and detection [11], but that is beyond the scope of this paper.

encoded at rate $1/T_{MC}$, where $T_{MC} = N_c \times T$ is the symbol duration after serial/parallel (S/P) conversion and $C_{\mathcal{M}} = \{\ldots, e^{\frac{j2\pi m}{\mathcal{M}}}, \ldots\}$, $m \in \{0, \ldots, \mathcal{M}-1\}$. The resulting S/P converter output is then spread with a spreading code $c^u(t)$ at a rate $1/T_c$. The spreading factor, defined as the ratio between the chip rate and the symbol rate is $L = \frac{T_{MC}}{T_c}$. Closed-loop power control is taken into account at the transmitter. All the data are then modulated in baseband by the inverse discrete Fourier transform (IDFT) and summed to obtain the multicarrier signal. No guard interval is inserted. Indeed, channel identification and equalization are achieved by MC-STAR (multicarrier spatio-temporal array-receiver) [10] and simulation results have shown that the guard interval length does not affect the link-level performance due to the multipath equalization capability of MC-STAR. Finally the signal is transmitted after pulse shaping and radio-frequency up-conversion.

The modulated subcarriers are orthogonal over the symbol duration T_{MC}. The frequency corresponding to the k-th subcarrier is $f_k = \lambda \times k/T_{MC}$. The transmitter belongs to the family of MT-CDMA if λ is set to 1, and to the class of MC-DS-CDMA if λ is set to L.

B. Channel Model

We consider transmission to M receiving antennas. The channel is assumed to be a slowly varying frequency selective Rayleigh channel with delay spread $\Delta\tau$. We note here that the large-scale path-loss that includes free-space path-loss and shadowing is the same for all subcarriers. Moreover the number of resolvable paths P and their propagation time-delays $\tau_1, \ldots, \tau_P$ depend on the reflecting objects and scatterers and therefore can be assumed equal for all subcarriers [12]. We assume correlated Rayleigh channels across subcarriers and adopt the approach proposed in [13] to generate it. We also assume that the received channel multipath components across the M antennas are independent.

C. Interference Analysis

The receiver implements down conversion, matched pulse filtering and chip-rate sampling followed by framing the observation into overlapping blocks of constant length of N_P chips. Hence, we obtain the MN_P vector-shaped matched-filter observation:

$$\underline{Y}_n = \sum_{u=1}^{U} \sum_{k=-K}^{K} \sum_{n'=n-1}^{n+1} s^u_{k,n'} e^{j2\pi\Delta f^u nT_{MC}} \underline{V}^u_{n',k,n} + \underline{N}_n, \quad (1)$$

where $s^u_{k,n'} = \psi^u_{k,n'} b^u_{k,n'}$, $\left(\psi^d_{k,n'}\right)^2$, and Δf^u are the n'-th signal component of the k-th carrier, the received power over carrier k, and the CFO of the user u, respectively. The symbol n' of carrier k of user u contributes its vector observation $s^u_{k,n'} \underline{Z}^u_{n',k,n} = s^u_{k,n'} e^{j2\pi\Delta f^u nT_{MC}} \underline{V}_{n',k,n}$, where $\underline{V}_{n',k,n}$ is the spread channel vector without CFO. Due asynchronism and multipath propagation, each user's observation vector carries information from current as well as from the previous and future symbols. Using Eq. (1), we can rewrite the observation vector for a desired user d with respect to its nth symbol of carrier k targeted for detection in the following simpler vector form:

$$\begin{aligned}
\underline{Y}_n &= \underbrace{s^d_{k,n} e^{j2\pi\Delta f^d nT_{MC}} \underline{V}^d_{n,k,n}}_{\text{desired signal}} \\
&+ \underbrace{\sum_{\substack{u=1\\u\neq d}}^{U} \sum_{k'=-K}^{K} \sum_{n'=n-1}^{n+1} s^u_{k',n'} e^{j2\pi\Delta f^u nT_{MC}} \underline{V}^u_{n',k',n}}_{\underline{I}^d_{\mathrm{MAI},k,n}} \\
&+ \underbrace{\sum_{\substack{k'=-K\\k'\neq k}}^{K} \sum_{n'=n-1}^{n+1} s^d_{k',n'} e^{j2\pi\Delta f^d nT_{MC}} \underline{V}^d_{n',k',n}}_{\underline{I}^d_{\mathrm{ICI},k,n}} \qquad (2) \\
&+ \underbrace{\sum_{\substack{n'=n-1\\n'\neq n}}^{n+1} s^d_{k,n'} e^{j2\pi\Delta f^d nT_{MC}} \underline{V}^d_{n',k,n}}_{\underline{I}^d_{\mathrm{ISI},k,n}} + \underline{N}_n, \\
&= s^d_{k,n} \underline{Z}^d_{n,k,n} + \underline{I}^d_{k,n} + \underline{N}_n.
\end{aligned}$$

The total interference $\underline{I}^d_{k,n}$ includes three types of interference: 1) The multiple access interference $\underline{I}^d_{\mathrm{MAI},k,n}$ is due to the N_c carriers from the other users $u \neq d$. 2) The inter-carrier interference $\underline{I}^d_{\mathrm{ICI},k,n}$ is due to the other carriers, $k' \neq k$, from the same user d. 3) The inter-symbol interference $\underline{I}^{d,k}_{\mathrm{ISI},k,n}$ is due to the same carrier k from the same user d. The noise vector $\underline{N}_n$, which comprises the preprocessed thermal noise and the out-cell users, is assumed to be uncorrelated both in space and time with variance σ^2_N.

In previous work [10] we have assumed the interference $\underline{I}^d_{k,n}$ as another contribution to the noise $\underline{N}_n$. Hence, the signal component of the desired user's carrier was extracted there by spatio-temporal maximum ratio combining (MRC) as follows:

$$\hat{s}^d_{k,n} = \underline{W}^{d^H}_{MRC,k,n} \underline{Y}_n = \frac{\hat{\underline{Z}}^{d^H}_{n,k,n} \underline{Y}_n}{\| \hat{\underline{Z}}^d_{n,k,n} \|^2}. \quad (3)$$

Eq. (2) shows that the net interference increases with the number of interferers and subcarriers, which severely limits the capacity of the MC-CDMA system with simple MRC receivers. Therefore, in the next section, we shall use the data decomposition of Eq. (2) to formulate the interference suppression problem and propose a new MC-CDMA receiver with full interference suppression capabilities.

III. Proposed Multicarrier CDMA Receiver

A. Multicarrier Interference Subspace Rejection (MC-ISR)

Provided that an estimate of the total interference $\hat{\underline{I}}^d_{k,n} = \hat{\underline{I}}^d_{\mathrm{MAI},k,n} + \hat{\underline{I}}^d_{\mathrm{ICI},k,n} + \hat{\underline{I}}^d_{\mathrm{ISI},k,n}$ is made available at the receiver, we can eliminate it and yet achieve distortionless response to the desired signal by imposing the following simple constraints to the combiner:

$$\begin{cases} \underline{W}^{d\ H}_{k,n} \hat{\underline{Z}}^d_{n,k,n} &= 1, \\ \underline{W}^{d\ H}_{k,n} \hat{\underline{I}}^d_{k,n} &= 0. \end{cases} \quad (4)$$

The first constraint guarantees a distortionless response to the desired signal while the second directs a null to total interference realization and thereby cancels it (i.e. the simplest mode of ISR). Exploiting the general framework developed in

[9], the solution to the specific optimization problem in Eq. (4) is the MC-ISR combiner $\underline{W}^d_{k,n}$ given as follows:

$$Q_n = 1/(\widehat{\underline{I}}^{d\,H}_{k,n}\widehat{\underline{I}}^d_{k,n}) = 1/\parallel \widehat{\underline{I}}^d_{k,n}\parallel^2, \quad (5)$$

$$\mathbf{\Pi}^d_{k,n} = \mathbf{I}_{N_T} - \widehat{\underline{I}}^d_{k,n}\widehat{\underline{I}}^{dH}_{k,n} \times Q_n\ , \quad (6)$$

$$\underline{W}^d_{k,n} = \frac{\mathbf{\Pi}^d_{k,n}\widehat{\underline{Z}}^d_{n,k,n}}{\widehat{\underline{Z}}^{d^H}_{n,k,n}\mathbf{\Pi}^d_{k,n}\widehat{\underline{Z}}^d_{n,k,n}}\ , \quad (7)$$

where $N_T = M \times N_P$ is the total space dimension and $\mathbf{I}_{N_T}$ denotes an $N_T \times N_T$ identity matrix. First, we form the projector $\mathbf{\Pi}^d_{k,n}$ orthogonal to the total interference realization. Second, we project the estimated response vector $\widehat{\underline{Z}}^d_{n,k,n}$ and normalize it to derive the combiner. We use this combiner instead of MRC to extract the n-th signal component of the k-th carrier of the desired user as:

$$\hat{s}^d_{k,n} = \underline{W}^{d^H}_{k,n}\underline{Y}_n\ . \quad (8)$$

Unlike most of the multi-user receivers proposed for MC-CDMA which focus on multiple access interference while ignoring the inter-carrier-interference, MC-ISR fully suppresses the total interference resulting from MAI, ISI, and ICI by simple yet efficient nulling. Simulation results will later show that ICI is not negligible and that full interference suppression is required to improve the MC-CDMA system performance.

B. MC-ISR Receiver Implementation

As mentioned in section III-A, the proposed MC-ISR receiver requires accurate channel parameter estimates and data decisions to reconstruct the total interference $\widehat{\underline{I}}^d_{k,n}$ and null it reliably. Unlike previous works on interference suppression or multi-user detection [2], [5] which assume perfect knowledge of the channel, we propose here a full space-time receiver solution that jointly implements channel identification and synchronization both in time and frequency using MC-STAR [10] as well as signal combining with full interference suppression capabilities.

The implementation of closed-loop CFOR[4] jointly with multicarrier and multi-user detection (here by MC-ISR) requires careful attention regarding the order in which these two tasks should be processed. Indeed, conventional operation of CFOR at an early processing stage[5] prior to interference suppression would require (on the uplink only) independently CFO-compensated observations and interference null constraints as many as the received incell users, thereby resulting in a tremendous complexity increase. Here we develop an efficient post-interference-suppression CFOR scheme by splitting the MC-ISR combining operation of Eq. (8) in two steps, an observation-cleaning projection and an MRC combining, and insertion of CFO compensation between the two as follows:

$$\underline{Y}^d_{\Pi,k,n} = \mathbf{\Pi}^d_{k,n}\underline{Y}_n, \quad (9)$$

$$\widehat{\Delta f}^d_n = \widehat{\Delta f}^d_{n-1} + \widehat{\delta f}^d_n, \quad (10)$$

$$\dot{\underline{Y}}^d_{\Pi,k,n} = \underline{Y}^d_{\Pi,k,n}e^{-j2\pi\widehat{\Delta f}^d_n nT}, \quad (11)$$

$$\widehat{\underline{V}}^d_{\Pi,k,n} = \mathbf{\Pi}^d_{k,n}\widehat{\underline{V}}^d_{k,n}, \quad (12)$$

$$\hat{s}^d_{k,n} = \frac{\widehat{\underline{V}}^{d\,H}_{\Pi,k,n}\dot{\underline{Y}}^d_{\Pi,k,n}}{\parallel \widehat{\underline{V}}^d_{\Pi,k,n}\parallel^2}. \quad (13)$$

The cleaning projection of Eq. (9) results in an "almost interference-free" observation $\underline{Y}^d_{\Pi,k,n}$ and allows for CFO estimation and compensation in Eqs. (10) and (11), respectively, using the CFOR module of the single-user MC-STAR (please refer to [10],[14] for details on how to estimate the CFO adjustment term in Eq. (11)), and for MRC combining in Eq. (13) using the projected estimate of the spread channel vector without CFO $\widehat{\underline{V}}^d_{\Pi,k,n}$. To the best of our knowledge, we are the first to report on and address this issue and to propose an efficient scheme for closed-loop CFOR in a multi-user detection context. It is important to mention here that if $\Delta f^u = \Delta f\ \forall\ u \in \{1,\ldots,U\}$ (i.e., downlink), then there is no need to estimate the CFO for the MC-ISR to null the in-cell interference. Indeed the MC-ISR combiner $\underline{W}^d_{k,n}$ satisfies the optimization property in Eq. (4). Thus, it is not affected by the CFO of other users, i.e.,

$$\underline{W}^{d,k^H}_n\widehat{\underline{I}}^d_{k,n} = 0 \implies e^{j2\pi\Delta f nT_{MC}}[\underline{W}^{d,k^H}_n\widehat{\underline{I}}^d_{k,n}] = 0. \quad (14)$$

Once the MC-ISR projection is performed in Eq. (9) after reconstruction of $\widehat{\underline{I}}^d_{k,n}$ without CFO, we implement the same CFOR scheme implemented in part by Eqs. (10) and (11). Hence, like the near-far resistant detector proposed in [15], the multiuser CFOR problem can be transformed on the downlink into a single-user CFOR problem and conventional single-user methods can therefore be used to estimate the frequency offset.

IV. Simulation Results

A. Simulation Setup

We consider an MC-CDMA system operating at a carrier of 1.9 GHz with maximum bandwidth of 5 MHz. We select a frequency offset Δf of 200 Hz, the maximum error tolerated by 3G standards[6] ($\equiv$ 0.1 ppm) for the frequency mismatch between the mobile and the base station [16]. We assume a frequency selective Rayleigh fading channel with P propagation paths with exponentially decreasing powers and delay spread $\Delta\tau = 4$ chips. The channel is correlated across subcarriers and varying in time with Doppler shift f_D. We consider that time-delays vary linearly in time with a delay drift of 0.049 ppm. The receiver has $M = 1$ or 2 antennas. We implement closed-loop power control operating at 1600 Hz and adjusting the power in steps of ± 0.25 dB. An error rate on the power control bit of 5% and a feedback delay of 0.625 ms are simulated.

B. Validation of the CFOR strategy

To validate the efficiency of the proposed CFOR strategy in a multicarrier and multiuser detection scheme on the uplink,

[4] In contrast to open-loop structures, closed-loop CFOR reduces the channel time-variations and greatly improves their tracking.

[5] Usually CFOR is embedded in the RF chain or plugged to the preprocessor output.

[6] We select $\Delta f = 200$ Hz to show that even CFO residuals below the maximum value tolerated by 3G standards result in significant losses in performance.

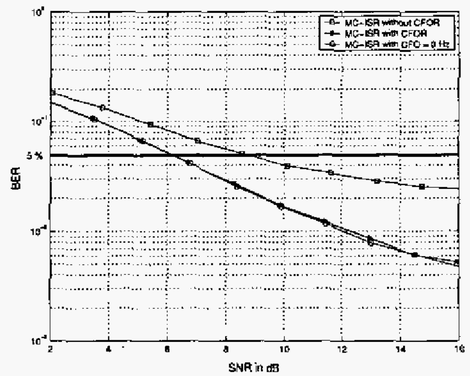

Fig. 1. BER vs. SNR for MT-CDMA MC-ISR, $L = 96$, $N_c = 7$, $U = 5$, with and without CFOR.

we consider a multiuser DBPSK MT-CDMA system with seven subcarriers, a spreading factor of 96, and 5 incell users ($N_c = 7$, $L = 96$, $U = 5$). The frequency offset normalized by the subcarrier separation ($\Delta f \times T_{MC}$) is set[7] to 0.005. Fig. 1 shows the link-level results of MC-ISR with and without CFOR. Results suggest that a CFO of 200 Hz has a serious impact on the performance of MC-CDMA and that the link-level gain with the proposed CFOR is in the range of 2 dB at a BER of 5% before channel decoding. By comparing the link-level curves of MC-ISR with CFOR and MC-ISR without a frequency offset (i.e., CFO = 0 Hz), we notice that CFOR compensates almost completely the performance loss due to the frequency offset. These results confirm the need for and the efficiency of the proposed CFOR in a multicarrier and multiuser detection context.

C. Advantage of Full Interference Suppression

The imperfect frequency down-conversion due to the instability of local oscillators combined with the multipath effect disturbs the orthogonality of the subcarriers and hence causes ICI. In this section we evaluate the advantage of full interference suppression on the link-level performance of MC-CDMA. We assume one receiving antenna only ($M = 1$). We plot the link-level performance of MT-CDMA ($L = 32, N_c = 3, U = 8$) and MC-DS-CDMA ($L = 64, N_c = 3, U = 8$) with both MC-MRC (i.e., multicarrier receiver with MRC combining) and MC-ISR in Fig. 2. It is clear that MC-ISR performs better than MC-MRC. Indeed, we observe gains of 5 dB and more than 7 dB in SNR for MT-CDMA and MC-DS-CDMA, respectively. MC-DS-CDMA gains are higher than MT-CDMA with MC-ISR vs. MC-MRC because it uses smaller processing gains.

In order to evaluate the specific impact of ICI on the link-level performance, we compare the BER curves of MT-CDMA ($L = 32, N_c = 3, U = 8$) MC-ISR with and without full interference suppression (i.e., with and without ICI suppression). Fig. 3 shows that MC-ISR with full interference rejection is required to improve the system performance. Indeed, at a bit error rate of 5%, MC-ISR with full interference suppression performs 2 dB better than MC-ISR with MAI suppression only. In order to capture in more details the gains achieved by ICI suppression in MC-CMDA, we proceed in Fig. 4 to additional

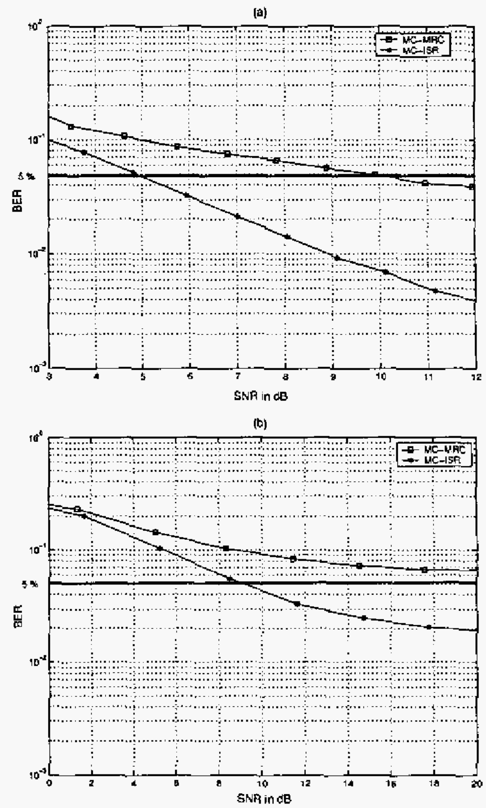

Fig. 2. BER vs. SNR in dB of MC-MRC and MC-ISR with (a): MT-CDMA, $L = 64$, $N_c = 3$, $U = 8$, DBPSK and (b): MC-DS-CDMA, $L = 32$, $N_c = 3$, $U = 8$, DBPSK.

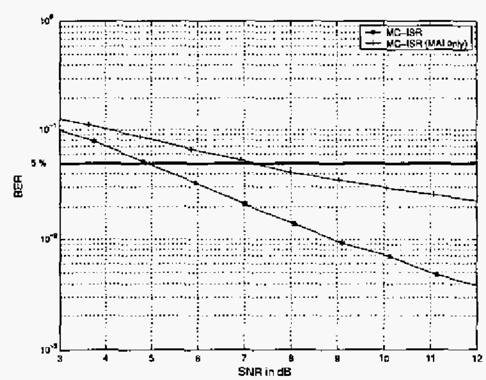

Fig. 3. BER vs. SNR in dB of MT-CDMA MC-ISR, $L = 64$, $N_c = 3$, $U = 8$, with and without full interference suppression (i.e., with and without ICI suppression).

comparisons between the link-level BER performances of MC-ISR and MC-MRC in a single-user context (i.e., $U = 1$, no MAI, only ICI and negligible ISI). Starting from the reference situation of Fig. 4-a with $L = 96$, $N_c = 7$ and DBSPK where the reported SNR gain due to ICI suppression is about 0.5 dB, the results suggest that ICI suppression is even more advantageous at higher-rate transmissions, more so increasingly when we move to the scenarios of Figs. 4-b, 4-c and 4-d; i.e., when we increase the number of carriers to $N_c = 11$ (SNR gain is about 1 dB), reduce the processing gain to $L = 32$ (SNR gain is about 3 dB), or increase the modulation order to D8PSK (SNR gain far exceeds 10 dB if not infinite), respectively. These results further confirm the benefits of ICI rejection in a full interference suppression

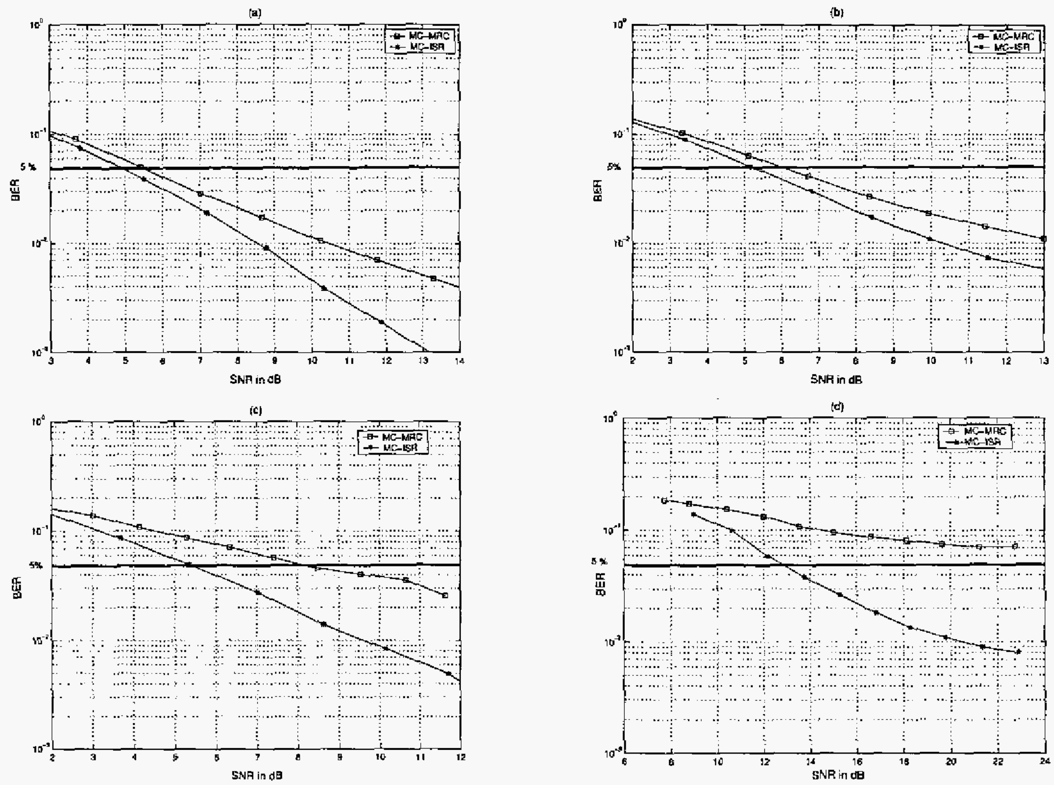

Fig. 4. BER vs. SNR in dB of MC-ISR and MC-MRC with single-user MT-CDMA and (a): $L = 96,\ N_c = 7$, DBPSK, (b): $L = 96,\ N_c = 11$, DBPSK, (c): $L = 32,\ N_c = 7$, DBPSK, and (d): $L = 96,\ N_c = 7$, D8PSK.

scheme using MC-ISR.

V. Conclusions

In this contribution we proposed a spectrum-efficient, low-complexity multicarrier-CDMA space-time receiver with full interference suppression capabilities named MC-ISR. First, we derived a complete model of the interference which takes into account MAI, ISI and ICI in a multipath fading channel with timing and frequency mismatch. Based on this model, we proposed a new multicarrier interference subspace rejection receiver. We also proposed a realistic implementation of the new MC-ISR receiver which includes an efficient strategy for carrier offset recovery in a multicarrier and multiuser detection scheme. MC-ISR supports both the MT-CDMA and MC-DS-CDMA air interfaces. Furthermore, we analyzed the performance of MC-ISR in an unknown time-varying Rayleigh channel with multipath, carrier offset and cross-correlation between subcarrier channels and took into account all channel estimation errors. Simulation results confirm the net advantage of the full interference suppression capabilities of MC-ISR. With three subcarriers and DBPSK modulation, we observe gains of 5 dB and more than 7 dB in SNR for MT-CDMA and MC-DS-CDMA, respectively.

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