Block Spreading for MUI/ISI-Resilient Generalized Multi-carrier CDMA with Multirate Capabilities

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***Abstract*— Potential increase in capacity along with the need to provide multimedia services and cope with multiuser interference (MUI) and intersymbol interference (ISI) arising due to wireless multipath propagation, motivate well multirate wideband code-division multiple-access (CDMA) systems. This paper develops an all-digital block-spread filterbank framework capable of encompassing single- or multi-rate transceivers for asynchronous or quasi-synchronous CDMA transmissions through multipath channels. Thanks to symbol blocking and through appropriate design of user codes, the resulting generalized multi-carrier (GMC) CDMA system guarantees symbol recovery irrespective of the (possibly unknown) FIR multipath channels in both downlink and uplink setups with low complexity FIR receivers. Simulations corroborate that the novel GMC-CDMA system outperforms existing multirate alternatives in the presence of asynchronism and multipath.**

I INTRODUCTION

Recently, there has been an increasing interest in providing multirate services, including text, images, data, and video, to wireless communicators. Future multirate systems should thus support multirate flexible Quality of Service (QoS) and rate-scalability, have low complexity, and exhibit resilience to MUI and ISI caused by multipath propagation.

Using direct-sequence (DS) CDMA, multirate services may be offered by choosing appropriately: chip rate, variable spreading length (vsl), number of multiple codes (mc[1]), and/or modulation format [6]. In the absence of multipath, performance of multirate DS-CDMA has been studied for both synchronous [5] and asynchronous systems [4]. Much of the existing multipath-free analysis focuses on asymptotic performance measures such as asymptotic multiuser efficiency.

MUI and ISI affect critically the capacity and performance of a CDMA system. MUI gives rise to near-far problems and although receiver designs (ZF, MMSE, or ML) can alleviate MUI, they often come at the price of noise enhancement and/or high complexity. Even worse, there may be cases where multiuser symbols are not even identifiable from the received signal when users experience asynchronous and/or (perhaps unknown) multipath channels that cause ISI. The recently proposed generalized multicarrier (GMC) CDMA (so called AMOUR) system in [1, 9, 10] addresses such problems for a *single-rate* system, where MUI/ISI-free transmissions are achieved in a quasi-synchronous multipath environment, while at the same time blind symbol recovery is guaranteed irrespective of frequency-selective multipath. In this paper, we develop an important *multirate* generalization to the AMOUR system, which preserves all its properties while being able to accommodate users of different rates.

First, we develop an all-digital filterbank-based multirate GMC-CDMA model which can describe both mc and vsl schemes in the general asynchronous multipath scenario (Section II). Next, we focus on quasi-synchronous GMC-CDMA transmissions in multipath to derive and evaluate a novel MUI/ISI-resilient multirate GMC-CDMA system, which has low complexity and fine rate resolution (Section III). Third, we evaluate performance of various linear receivers (MF, ZF, or MMSE) for two multirate CDMA schemes, namely mc and vsl, in the presence of multipath and compare them with that of our proposed system as well (Section IV).

II THE GMC-CDMA MULTIRATE MODEL

The symbol-periodic, single-rate, SC-CDMA filterbank of [7], is generalized here to a block-spread multirate GMC-CDMA system model.

We assume that: **as1)** the chip interval is common to all M users; i.e., $T_{c,\mu} = T_c, \forall \mu \in [0, M-1]$, where μ is the generic user index; i.e., all users spread their information symbols over the same bandwidth. Under as1), the composite received signal from all users can be filtered and sampled at the same rate, usually at the common chip rate. Here, we only consider chip rate sampling, but our formulation can be generalized to the oversampling case easily.

Fig. 1 depicts a discrete-time baseband equivalent chip rate filterbank multiple access block-transmission model, which generalizes the single rate filterbank model proposed in [1]. Each user μ groups the information symbols $s_\mu(n)$ in blocks of length K_μ, and then spreads each of the K_μ symbols using a distinct code of length P_μ denoted in Fig. 1 by the FIR filters $c_{\mu,k}(n)$, $k = 0, 1, \ldots, K_\mu - 1$, to produce the transmitted signal (chip rate[2]):

$$u_\mu(n) = \sum_{i=-\infty}^{\infty} \sum_{k=0}^{K_\mu - 1} s_\mu(iK_\mu + k) c_{\mu,k}(n - iP_\mu). \quad (1)$$

The sequence $u_\mu(n)$ goes through the Linear Time Invariant (LTI) channel represented in Fig. 1 by its impulse response

[1] We abbreviate multi-carrier as MC and multi-code as mc to avoid confusion.

[2] Throughout this paper arguments n, k, i will denote respectively chip, symbol, block-of-symbols indices.

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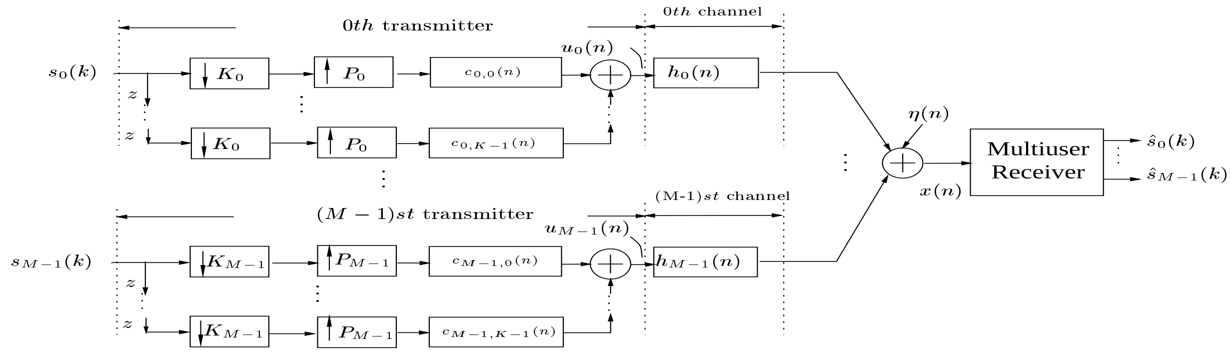

Figure 1: Multi-rate block-spread CDMA system

$h_\mu(n)$, which includes both multipath and the asynchronism among users as in [1] and [7], and is assumed to be FIR of order L_μ. Allowing for user-dependent channels covers the general uplink setup and subsumes the downlink where each user receives the superimposed transmissions through its own (but yet a single) channel $h_\mu(n) = h(n)$, $\forall\mu \in [0, M-1]$. With $\eta(n)$ denoting the filtered/sampled noise, the composite received signal from all M users is $x(n) = \sum_{\mu=0}^{M-1} x_\mu(n) + \eta(n)$, where

$$x_\mu(n) = \sum_{i=-\infty}^{\infty} \sum_{k=0}^{K_\mu-1} s_\mu(iK_\mu + k)\tilde{c}_{\mu,k}(n - iP_\mu), \quad (2)$$

and $\tilde{c}_{\mu,k}(n) := (c_{\mu,k} * h_\mu)(n)$, with '$*$' standing for convolution.

For user μ, a block of K_μ symbols is transmitted using P_μ chips. We thus define the information rate of user μ to be

$$R_\mu := \frac{K_\mu}{P_\mu T_c} \quad (3)$$

which has units of symbols/second. In order to incorporate different rate services, we have three options: i) fix $P_\mu = P$, $\forall\mu$, and vary K_μ; ii) fix $K_\mu = K$, $\forall\mu$, and vary P_μ; iii) vary both K_μ and P_μ.

In an mc-CDMA system (see e.g., [5]), high rate users are allocated a large number of codes (large K_μ) and each high rate symbol is spread by a different code but of the same code length P. This follows as a special case of our model corresponding to option i). In a vsl-CDMA system, the spreading code lengths P_μ for different rate users are different, but K_μ is kept the same ($K_\mu = 1, \forall\mu$), which corresponds to option ii). We have proved that with lcm denoting least common multiple and $P = lcm(P_0, \ldots, P_{M-1})$, one can view the vsl-CDMA (option ii) and the multirate option iii) as special cases of the mc-CDMA scheme, where each user spreads information symbols using multiple codes of length P, each being a time-shifted versions of a common shorter code [2].

Next, we introduce the vector counterpart of (2) to facilitate the receiver design. We group the input sequences $s_\mu(n)$ into blocks of length K_μ (^{T} stands for transpose) $\boldsymbol{s}_\mu(i) := [s_\mu(iK_\mu), \ldots, s_\mu(iK_\mu + K_\mu - 1)]^T$, and the transmitted sequences $u_\mu(n)$ into blocks of length P_μ: $\boldsymbol{u}_\mu(i) := [u_\mu(iP_\mu), \ldots, u_\mu(iP_\mu + P_\mu - 1)]^T$. By setting $n = iP_\mu + p$, $0 \le p \le P_\mu - 1$ in (1) and taking into account the fact that $c_{\mu,k}(n) = 0$ for $n \notin [0, P_\mu - 1]$, we obtain $u_\mu(iP_\mu + p) = \sum_{k=0}^{K_\mu-1} s_\mu(iK_\mu + k)c_{\mu,k}(p)$. Therefore, the spreading operation of user μ can be described by the linear mapping

$$\boldsymbol{u}_\mu(i) = \boldsymbol{C}_\mu \boldsymbol{s}_\mu(i), \qquad \boldsymbol{C}_\mu := [\boldsymbol{c}_{\mu,0} \ldots \boldsymbol{c}_{\mu,K_\mu-1}], \quad (4)$$

where $\boldsymbol{c}_{\mu,k} := [c_{\mu,k}(0) \ldots c_{\mu,k}(P_\mu - 1)]^T$.

With $x(n)$ as their input, several receiver options are possible (see e.g., [8]): i) ML; ii) MF; iii) ZF; iv) MMSE ; v) variations of the above (e.g., adaptive and DF receivers). We will focus on the low-complexity linear receivers ii)-iv) only.

To allow for asynchronous multirate transmissions through multipath channels, we will consider N consecutive blocks of P received chips. Over the duration of NP chips, the μth user sends $NP/P_\mu = Q_\mu N$ blocks of K_μ symbols: $\bar{\boldsymbol{s}}_{\mu,N} := [\boldsymbol{s}_\mu^T(0) \cdots \boldsymbol{s}_\mu^T(Q_\mu N - 1)]^T$. These are spread first to produce $\bar{\boldsymbol{u}}_{\mu,N} := [\boldsymbol{u}_\mu^T(0) \cdots \boldsymbol{u}_\mu^T(Q_\mu N - 1)]^T = (\boldsymbol{I}_{Q_\mu N} \otimes \boldsymbol{C}_\mu)\bar{\boldsymbol{s}}_{\mu,N}$, where $\boldsymbol{I}_{Q_\mu N}$ denotes an identity matrix of dimension $Q_\mu N \times Q_\mu N$, and '$\otimes$' denotes the Kronecker product. The received signal $\tilde{\boldsymbol{x}}_N := [x(0) \ldots x(NP-1)]^T$ consists of NP chips and can be written as [c.f. (4)]

$$\tilde{\boldsymbol{x}}_N = \sum_{\mu=0}^{M-1} \mathbf{H}_{\mu,N}(\boldsymbol{I}_{Q_\mu N} \otimes \boldsymbol{C}_\mu)\bar{\boldsymbol{s}}_{\mu,N} + \tilde{\boldsymbol{\eta}}_N \quad (5)$$

where $\mathbf{H}_{\mu,N}$ is a channel-induced lower triangular Toeplitz convolution matrix of dimension $NP \times NP$ with first column $[h_\mu(0), \ldots, h_\mu(L_\mu), 0, \ldots, 0]$, and $\tilde{\boldsymbol{\eta}}_N$ is an $NP \times 1$ vector denoting AGN. To avoid Inter-Block Interference (IBI), we have discarded chips after NP, because their impact is negligible if one collects sufficient blocks to assure that $NP \gg L_\mu$, $\forall\mu$.

Letting $\bar{\boldsymbol{C}}_{\mu,N} := \mathbf{H}_\mu(\boldsymbol{I}_{Q_\mu N} \otimes \boldsymbol{C}_\mu)$ and $\tilde{\boldsymbol{s}}_N := [\bar{\boldsymbol{s}}_{0,N}^T, \ldots, \bar{\boldsymbol{s}}_{M-1,N}^T]^T$, we can also write (5) as

$$\tilde{\boldsymbol{x}}_N = [\bar{\boldsymbol{C}}_{0,N} \ldots \bar{\boldsymbol{C}}_{M-1,N}]\tilde{\boldsymbol{s}}_N + \tilde{\boldsymbol{\eta}}_N := \tilde{\boldsymbol{C}}_N \tilde{\boldsymbol{s}}_N + \tilde{\boldsymbol{\eta}}_N. \quad (6)$$

Based on (6), a general linear FIR receiver can be described by the matrix $\boldsymbol{G}_N$ of dimension $(N \cdot \sum_{\mu=0}^{M-1} Q_\mu K_\mu) \times NP$ as follows:

$$\hat{\tilde{\boldsymbol{s}}}_N := \boldsymbol{G}_N \tilde{\boldsymbol{x}}_N = \boldsymbol{G}_N \tilde{\boldsymbol{C}}_N \tilde{\boldsymbol{s}}_N + \boldsymbol{G}_N \boldsymbol{\eta}_N, \quad (7)$$

where $\hat{\tilde{\boldsymbol{s}}}_N$ is the estimated symbol vector defined similar to $\tilde{\boldsymbol{s}}_N$. Note that all elements of $\hat{\tilde{\boldsymbol{s}}}_N$ are not equally reliable; those on either end of $\tilde{\boldsymbol{s}}_N$ may not be as accurately estimated as those in the middle, because the symbols in the middle part are more correlated with the remaining symbols in the $\tilde{\boldsymbol{s}}_N$ vector due to the channel memory. Without knowing which input block yields the best estimate, we can choose the middle block.

Depending on how we select $\boldsymbol{G}_N$ in (7), we obtain different linear receivers. Possible choices are the MF and ZF receivers given by ($^{\mathcal{H}}$ stands for Hermitian transpose and † denotes pseudoinverse): $\boldsymbol{G}_N^{mf} = \tilde{\boldsymbol{C}}_N^{\mathcal{H}}$, $\boldsymbol{G}_N^{zf} = \tilde{\boldsymbol{C}}_N^{\dagger}$; and with $\boldsymbol{R}_s := E[\tilde{\boldsymbol{s}}_N(i)\tilde{\boldsymbol{s}}_N^{\mathcal{H}}(i)]$ and $\boldsymbol{R}_\eta := E[\tilde{\boldsymbol{\eta}}_N(i)\tilde{\boldsymbol{\eta}}_N^{\mathcal{H}}(i)]$, the MMSE receiver $\boldsymbol{G}_N^{mmse} = \boldsymbol{R}_s\tilde{\boldsymbol{C}}_N^{\mathcal{H}}(\boldsymbol{R}_\eta + \tilde{\boldsymbol{C}}_N\boldsymbol{R}_s\tilde{\boldsymbol{C}}_N^{\mathcal{H}})^{-1}$.

III MULTIRATE MUI/ISI-FREE GMC-CDMA

Our derivation of the different receivers in the previous section assumed that the matrix inverse $\boldsymbol{G}_N^{zf}$ exists. Unlike CDMA systems relying on symbol-periodic codes, the AMOUR system proposed in [1, 10] guarantees identifiability and blind recovery of the user symbols irrespective of the (possibly unknown) Lth-order multipath channels, by specially designing long spreading sequences $c_{\mu,k}(n)$. Moreover, MUI is eliminated deterministically by applying a simple linear transformation on the received signal. It is practically important to carry these desirable MUI/ISI-elimination features over to a multirate CDMA system.

The basic idea behind GMC-CDMA is to build user code polynomials specified by distinct sets of what we term *signature points* on the complex plane. Users' codes are constructed such that their $\mathcal{Z}$-transforms are zero at other users' signature points and non-zero at each user's own signature points. Specifically, define the code polynomial $C_{\mu,k}(z) := \sum_{n=0}^{P_\mu} c_{\mu,k}(n)z^{-n}$ and let each user be given distinct signature points $\{\rho_{\mu,j}\}_{j=0}^{J-1}$, where J is a design parameter. It is then possible to construct codes such that [1]

$$C_{\mu,k}(\rho_{m,j}) = A_\mu f_{\mu,k,j}\delta(\mu - m),\ \forall m, \forall\mu, \forall k, \forall j, \qquad (8)$$

where $f_{m,k,j}$ are non-zero constants up to the designer's choice and A_μ controls the μth user's transmitted power. The code polynomials $C_{\mu,k}(z)$ in [1] have order $MJ - 1$. With L denoting an upper bound on all channel orders ($L \geq L_\mu$, $\forall\mu$), we append L trailing zeros (guard chips) at the end of codes $c_{\mu,k}(n)$ thereby augmenting their length to $P = MJ + L$. In addition to as1), we now also assume that: **as2)** the system is quasi-synchronous, and the underlying FIR channels have maximum order $L = \tilde{L} + D$ which incorporates the maximum number of discrete-time equivalent paths $\tilde{L}$, and the maximum delay $D \ll P = MJ + L$ that arises due to asynchronism among users. Our P-long codes $c_{\mu,k}(n)$ have L trailing zeros; i.e., $c_{\mu,k}(n) = 0$ for $n \notin [0, MJ - 1]$.

It is shown in [1, 10] that under as1), as2) and with $J = K + L$ and appropriately chosen $f_{\mu,k,j}$, code design (8) guarantees blind channel identifiability and MUI/ISI-free symbol recovery irrespective of the multipath channels and independent of the symbol constellation.

Because each of the M users in the single-rate system of [1] transmits K information symbols with P-long codes, the system's bandwidth efficiency is $\mathcal{E} := MK/P$ and approaches 1, provided that one selects $J = K+L$ and block lengths $K \gg L$. Actually, due to as2) the channels are of the form $H_\mu(z) := \sum_{l=0}^{L} h_\mu(l)z^{-l} = z^{-d}\sum_{l=0}^{\tilde{L}} h(l+d)z^{-l}$, where $0 \leq d \leq D$. Therefore, they can have at most $\tilde{L}$ finite roots per channel. As a result, the condition $J = K + L > L$ in [1, 10] for guaranteeing blind channel identifiability and symbol recovery can be relaxed to $J = K + \tilde{L} > \tilde{L}$. Note that in this latter case, each user can transmit $K_\mu = K = J - \tilde{L}$ symbols per $P_\mu = P$ chips, and therefore has rate $R_\mu = R = K/(PT_c)$, $\forall\mu$. The total rate is thus

$$R_T := \sum_{\mu=0}^{M-1} R_\mu = \frac{MK}{T_cP} = \frac{M(J-\tilde{L})}{T_c(MJ+L)}, \qquad (9)$$

which can be made as close to $1/T_c$ as one chooses by sufficiently increasing J.

To accommodate different rates, the multicode approach was alluded to in [1]. Specifically, it was recommended in [1] to split each high rate user's symbol stream into several low rate substreams, so that each spread substream is treated as if it corresponded to a virtual user. But in this way, the rate can take only multiple values of $R = K/(PT_c)$, i.e., one of $\{R, 2R, \ldots, MR\}$. We say that the rate resolution in this case is R.

To achieve finer resolution, we can allocate different numbers J_μ of signature points to different users instead of the same number J used in [1]. Suppose there are a *total number* of J_T signature points, where J_T is a design parameter. We can allocate J_μ signature points to user μ, subject to the constraints **c1)** $J_\mu > \tilde{L}$; **c2)** $\sum_{\mu=0}^{M-1} J_\mu = J_T$. Constraint c1) guarantees symbol recovery irrespective of frequency-selective multipath.

With J_μ signature points, the μth user can transmit $K_\mu = J_\mu - \tilde{L}$ symbols with $P = J_T + L$ chips; therefore, the rate of user μ now becomes $R_\mu = (J_\mu - \tilde{L})/(PT_c)$, and as before, the total rate

$$R_T = \frac{J_T - M\tilde{L}}{PT_c} = \frac{J_T - M\tilde{L}}{(J_T + L)T_c} \qquad (10)$$

can be made as close to $1/T_c$ as one wishes by simply increasing J_T. There are tradeoffs in selecting J_T though: larger J_T implies higher total rate but also longer decoding delay. Other tradeoffs such as peak-to-average power ratio that were discussed in [1] for the single-rate ($J_\mu = J$) AMOUR system apply here as well.

In summary, to equip our GMC-CDMA system with multirate capabilities, we follow these design steps:

S1) Choose $J_T \gg L$ so that $\sum_{\mu=0}^{M-1} R_\mu$ comes close to the available bandwidth $1/T_c$, while respecting a prescribed decoding delay.

S2) For each user μ, allocate J_μ of the J_T signature points so that R_μ is close to the μth user's desired rate.

S3) Design user codes $c_{\mu,k}(n)$ so that their polynomials $C_{\mu,k}(z)$ satisfy (8). Specifically, we start with points $\rho_{m,j}$ on the complex plane, and using Lagrange interpolation, we obtain the user code polynomials

$$C_{\mu,k}(z) = A_\mu \sum_{\lambda=0}^{J_\mu-1} \rho_{\mu,\lambda}^{-k} \prod_{\substack{m=0\\(m,j)\neq(\mu,\lambda)}}^{M-1} \prod_{j=0}^{J_m-1} \frac{1-\rho_{m,j}z^{-1}}{1-\rho_{m,j}\rho_{\mu,\lambda}^{-1}}\ , \quad (11)$$

that can be readily checked to obey (8).

S4) Design the receiver using any of the structures in Section II with $N = 1$. □

Thanks to the L guard chips that we appended in our user codes (as per as2), there is no IBI between the P-long blocks. If the AGN is white and the transmitted symbols are blockwise uncorrelated, the received P-long blocks will be statistically independent, which explains why designing a receiver with memory $N = 1$ incurs no loss of optimality in S4).

We now proceed to show that the so designed multirate system inherits the MUI/ISI-free properties of [1, 10] and guarantees the identifiability of user symbols irrespective of multipath. Since $P_\mu = P$, $\forall\mu$, (6) simplifies to

$$\tilde{\boldsymbol{x}} = [\mathbf{H}_0\boldsymbol{C}_0 \ldots \mathbf{H}_{M-1}\boldsymbol{C}_{M-1}]\tilde{\boldsymbol{s}} + \tilde{\boldsymbol{\eta}}, \quad (12)$$

where we have omitted the subscript N for simplicity. Only the symbols in the first ($i = 0$) block are involved in $\tilde{\boldsymbol{s}}$.

Defining $\boldsymbol{v}_P(\rho_{\mu,k}) := [1\, \rho_{\mu,k}^{-1} \ldots \rho_{\mu,k}^{1-P}]^T$ and $S_\mu(z) := \sum_{n=0}^{K_\mu-1} s_\mu(n)z^{-n}$, it can be readily verified, with codes as in S3), that $\forall\mu$, $\forall k$,

$$\tilde{y}_{\mu,k} := \boldsymbol{v}_P^T(\rho_{\mu,k})\tilde{\boldsymbol{x}} = H_\mu(\rho_{\mu,k})S_\mu(\rho_{\mu,k}) + \boldsymbol{v}_P^T(\rho_{\mu,k})\tilde{\boldsymbol{\eta}}, \quad (13)$$

which proves that our multirate GMC-CDMA code design has achieved user separation at the signature points. For the μth user, $S_\mu(z)$ is of degree $K_\mu - 1$ unless $S_\mu(z) \equiv 0$; therefore, $S_\mu(z)$ has at most $K_\mu - 1$ finite roots. We know from as2) that $H_\mu(z)$ can have at most $\tilde{L}$ finite roots. Therefore, $H_\mu(z)S_\mu(z)$ can have at most $K_\mu - 1 + \tilde{L} := J_\mu - 1$ roots. It follows that if $S_\mu(z) \not\equiv 0$, at least one of $H_\mu(\rho_{\mu,j})S_\mu(\rho_{\mu,j})$ must be nonzero for $j = 0, 1, \ldots, J_\mu - 1$. To establish identifiability of users' symbols from $\tilde{\boldsymbol{x}}$ in the absence of noise, we argue by contradiction supposing that there exist two distinct symbol sets $\tilde{\boldsymbol{s}}^{(1)} \not\equiv \tilde{\boldsymbol{s}}^{(2)}$ that yield $\tilde{\boldsymbol{x}}^{(1)} \equiv \tilde{\boldsymbol{x}}^{(2)}$. But (13) implies that $H_\mu(\rho_{\mu,j})[S_\mu^{(1)}(\rho_{\mu,j}) - S_\mu^{(2)}(\rho_{\mu,j})] \equiv 0, \forall\mu \in [0, M-1]$ and $j \in [0, J_\mu - 1]$, which is impossible because the $S_\mu(z) := S_\mu^{(1)}(z) - S_\mu^{(2)}(z) \not\equiv 0$.

Actually, using the same technique as in [1, 10] one can establish that the multirate users can be isolated not only at their signature points of the received data polynomial but also on the entire $\mathcal{Z}$-plane; i.e., our code design in (11) allows multiple users to transmit through their own single user equivalent channels. Furthermore, the channels can be estimated even blindly (up to a scalar) by applying signal/noise subspace decomposition techniques [1].

We summarize our results on multirate MUI/ISI-resilient GMC-CDMA transceiver design in the following theorem.

Theorem 1 (multirate GMC-CDMA): *Given channel parameters $\tilde{L}$, D, and users of prescribed rates $R_0, \ldots, R_{M-1}$ that satisfy $R_T = \sum_{\mu=0}^{M-1} R_\mu < 1/T_c$, choose $J_T > (LT_cR_T + M\tilde{L})/(1 - T_cR_T)$ such that: $J_T = \sum_{\mu=0}^{M-1} J_\mu$, $(J_\mu - \tilde{L})/PT_c > R_\mu$, and select $P = J_T + L$. Under as1) and as2), MUI/ISI-free transmissions at or above the specified rates are then possible irrespective of multipath channels up to order $L = \tilde{L} + D$ with guaranteed (even blind) channel identifiability and symbol recovery.*

Because $P_\mu = P, \forall\mu$, we note that $R_\mu = K/(PT_c)$ in (3), and from constraint c1) we infer that in order to guarantee MUI/ISI-free symbol recovery, we must have $J_\mu \in [K_\mu + \tilde{L}, J_T]$; i.e., since $K_\mu \geq 1$, a specific user can be allocated from $1 + \tilde{L}$ to J_T signature points. Therefore, each user's rate can be any one of $\{\frac{1}{PT_c}, \frac{2}{PT_c}, \ldots, \frac{J_T-\tilde{L}}{PT_c}\}$. The rate resolution in this case is $1/(PT_c)$, which is K times finer than the virtual user scheme of [1] and can be made small if we choose P large, or equivalently J_T large.

IV Performance Comparisons

In this section, we compare mc with vsl schemes for different receivers in the asynchronous multipath scenario. We also compare their performance with that of the proposed multirate GMC-CDMA system of Section III.

Test case 1 (mc versus vsl comparisons) We use random spreading codes to remove code-dependent effects. The spreading length P is chosen to be 16, and the simulation includes $M = P/2 = 8$ users, four of which are single rate users with $R_L = 1/(16T_c)$ symbols/second, and the other four users are double rate users with $R_H = 2R_L$. The system is assumed to be asynchronous. The channels we adopt are of order $\tilde{L} = 5$ with uncorrelated taps of equal variance zero-mean complex Gaussian random variables (Rayleigh fading). BPSK symbol modulation is used, and the performance measure is BER versus E_b/N_0, where E_b denotes energy per bit (assumed to be the same for all users). The BERs are averaged over 500 channel realizations and also across the users of the same rate that results in: BER for mc high rate users, mc low rate users, vsl high rate users, and vsl low rate users. We focus on the FIR multichannel receivers defined in Section II. It is shown in [3] that with moderate memory-length ($N = 11$ here), the FIR decorrelator provides the performance of an IIR decorrelator. From Fig. 2, we can see that mc- and vsl-CDMA perform similarly for all three equalizers. Interestingly, similar observations were drawn in [4] in the absence of multipath. One can thus conclude that on the average (depending on the code used), mc- and vsl-CDMA do not differ from each other in the presence of multipath fading channels whether or not the transmission is synchronous or asynchronous.

Test case 2 (Performance of the multirate GMC-CDMA) To allow for maximum asynchronism between GMC-CDMA users we choose $D = 15$, and the number of paths $\tilde{L} = 5$, the same as in the previous simulation. To maintain the same bandwidth occupied by GMC- and mc/vsl-CDMA, we select $P = 240$ in the GMC-CDMA system, which offers a total of $J_T = P - D - \tilde{L} = 220$ signature points. These signature points are chosen equispaced around the unit circle. Slow users of rate R_L are allocated $J_L = 20$ signature points each, while fast (high rate) users are given $J_H = 35$ signature points. Fig. 3 shows the averaged BER for a multirate GMC-CDMA system of $M = 8$ users (4 users with rate R_L and 4 users with double rate $R_H = 2R_L$). We observe that the low rate users exhibit better performance than that of high rate users, because each low rate user is allocated more bandwidth per symbol since $(J_L - \tilde{L})/J_L > (J_H - \tilde{L})/J_H$. As we will illustrate in the next test case, the multirate GMC-CDMA system outperforms mc/vsl-CDMA. Therefore, on the average, users in the GMC-CDMA system require less power to achieve the same performance.

Test case 3 (GMC-CDMA versus mc/vsl-CDMA) The system parameters are the same as those in test cases 1 and 2. Figs. 4 reports MMSE equalization performance for the three systems in the cases of $\tilde{L} = 1$. The BER for each system is also averaged over high rate users and low rate users. We observe that for all SNR values, the GMC-CDMA system is consistently better than averaged mc/vsl-CDMA systems.

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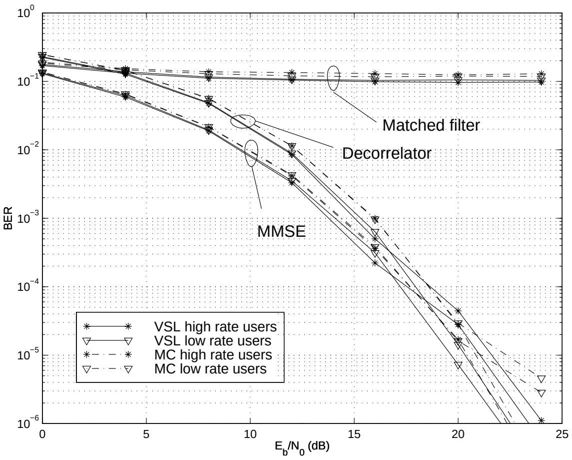

Figure 2: Performance of mc and vsl

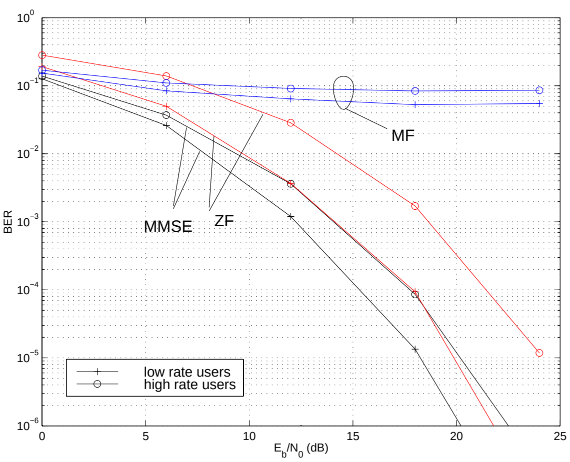

Figure 3: Performance of multirate GMC-CDMA

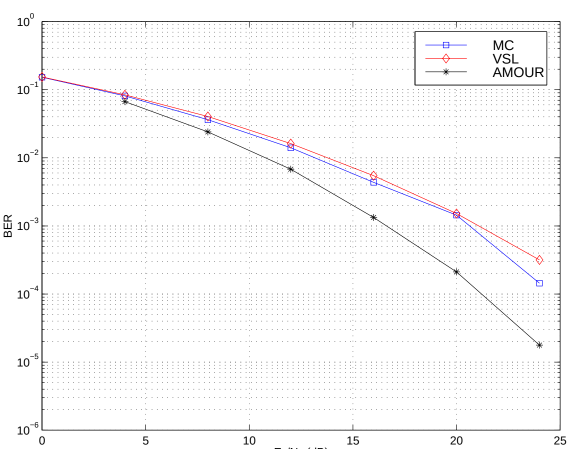

Figure 4: GMC-CDMA versus mc/vsl: $\tilde{L} = 1$