IMPULSE RADIO MULTIPLE ACCESS THROUGH ISI CHANNELS WITH MULTI-STAGE BLOCK-SPREADING

Liuqing Yang and Georgios B. Giannakis

Dept. of ECE, Univ. of Minnesota, 200 Union Street SE, Minneapolis, MN 55455

ABSTRACT

Impulse Radio (IR) has received increasing interest for Multiple Access (MA). Operating in dense multipath environments, IRMA systems are affected by the Multiple User Interference (MUI) and Intersymbol Interference (ISI). Analog IRMA utilizes random time-hopping codes to mitigate such adverse effects statistically. In this paper, we develop an all-digital IRMA scheme that relies on multi-stage block-spreading (MS-BS) to eliminate MUI deterministically, regardless of ISI multipath effects. Unlike conventional IRMA systems, our proposed MS-BS-IRMA system exhibits no degradation in performance when accommodating a large number of users.

1. INTRODUCTION

Impulse Radio (IR) or Ultra-wideband (UWB) communication systems receive increasing attention thanks to their attractive features for baseband multiple access, low-power consumption, convenience to overlay existing infrastructure, and multimedia services. IR technology equipped with random time hopping (TH) codes and pulse position modulation (PPM) was proposed in [8, 5], where it is referred to as Impulse Radio Multiple Access (IRMA). The random shifts together with the ultra-short pulse shaper, and the data modulation result in a transmitted signal with low power spectral density spread across the ultra-wide bandwidth.

IRMA systems often have to operate in dense multipath environments. As a result, the Multi-User Interference (MUI) and Inter-Symbol Interference (ISI) affect system capacity and performance severely [1, 2]. In the analog IRMA schemes proposed so far, the MUI is treated as Gaussian noise, and suppressed statistically. Such schemes require successful application of (strict) power control, and rely on the Gaussian approximation of the MUI [7], which is not valid when the number of users is not large enough. On the other hand, as the number of users increases, additional power becomes a must for a given BER [7]. As to the IR system performance over ISI multipath channels, only the single-user case has been tested in [1, 2]. Recently, a digital IRMA model was developed in [3]. This scheme is tailored to a *downlink* scenario, and invokes multiuser detection (MUD) to improve upon the statistical MUI cancellation. However, [3] is not suitable for the uplink operation; even in the downlink, the maximum number of users the system can accommodate is quite limited compared to the conventional IRMA system [7].

In this paper, we develop an all-digital IRMA that relies on multi-stage block-spreading (MS-BS) operations to gain resilience to MUI and ISI. Chip-Interleaved Block-Spread CDMA (CIBS-CDMA) was developed in [10] to eliminate MUI *deterministically* at the receiver by parsing the information stream into blocks, on which block-spreading and chip-interleaving are performed prior to transmission. CIBS-CDMA relies on linear modulation, and has been shown to be suitable for a bandwidth-efficient setup. Here, we show that in power-efficient IRMA systems using orthogonal M-ary PPM modulation, the features of CIBS in MUI elimination still hold by employing our novel MS-BS designs. Those render the multiple access channel equivalent to a set of independent parallel single-user frequency-selective channels with AWGN, on which any single-user equalizer can then be employed. Our MS-BS-IRMA transceivers have low-complexity, and are applicable to both *uplink* and *downlink* setups. Furthermore, thanks to the two stages of BS, the proposed system can accommodate a large number of users without sacrificing performance, in contrast to conventional IRMA systems.

In Section 2, we develop a digital M-ary PPM-IRMA model starting from the conventional continuous-time model [6]. The digital equivalent model of the ISI multipath channel is also introduced in this section. Based on the signal and channel models, the MS-BS-IRMA transceiver designs are proposed in Section 3. As a result, mutual orthogonality between different users' addresses is preserved even after multipath propagation, which enables deterministic multiuser separation. Simulation results are presented in Section 4.

Notation: Bold upper (lower) letters denote matrices (column vectors); $(\cdot)^T$ and $(\cdot)^{\mathcal{H}}$ denote transpose and Hermitian transpose, respectively; $\delta(\cdot)$ and $\otimes$ stand for Kronecker's delta and Kronecker product, respectively. $\mathrm{E}\{\cdot\}$ for expectation, $\lfloor\cdot\rfloor$ for integer floor, and $\lceil\cdot\rceil$ for integer ceiling; $\mathbf{I}_K$ denotes the identity matrix of size K; and $\mathbf{0}_{M\times N}$ denotes an all-zero matrix with size $M \times N$.

2. M-ARY PPM-IRMA MODELING

In this section, we develop a digital M-ary PPM-IRMA model starting from the conventional continuous-time model [6]. We also introduce the ISI multipath channel, and present the discrete-time equivalent model.

2.1. Signal Model with Time-Hopping

To facilitate the transition from the continuous-time PPM to our block-spreading model, we first briefly review the PPM-IRMA setup in [3].

In M-ary PPM-IRMA, for each, e.g., the u-th user, every transmitted M-ary PPM symbol is repeated over N_f frames each having duration T_f. Each frame comprises N_c chips. With T_c denoting chip duration, we have $T_f = N_cT_c + T_g$, where T_g is a guard time introduced to account for processing delay at the receiver between two successively received frames. Hereafter, we will assume $T_g = 0$ for simplicity. We denote the u-th user's information bearing symbol transmitted during the k-th frame as $I_u(\lfloor k/N_f\rfloor)$, where $I_u(\lfloor k/N_f\rfloor) \in [0, M-1]$.

Each segment of duration N_fT_f contains N_f copies of a single symbol (one per frame), and the monopulse is time-shifted in each frame according to the symbol value; e.g., it is shifted by τ_m if $I_u(\lfloor k/N_f\rfloor) = m$, for $m \in [0, 1, \ldots, M-1]$. The u-th user's transmitted waveform is then given by:

$$\nu_u(t) = \mathcal{P}_u \sum_{k=-\infty}^{+\infty} w\left(t - kT_f - \tilde{c}_u(k)T_c - \tau_{I_u(\lfloor k/N_f\rfloor)}\right), \quad (1)$$

The work in this paper was supported by the ARL/CTA Grant No. DAAD19-01-2-011, and by a DARPA sub-contract from General Dynamics.

where $\mathcal{P}_u$ is the u-th user's transmission power, $w(t)$ denotes the ultra-short monopulse, and $\tilde{c}_u(k) \in [0, N_c-1]$ is a periodic TH sequence with period $P_{\tilde{c}} = N_f$. The role of $\tilde{c}_u(k)$ is to enable multiple access, and security in e.g., military communications. One way to model this mapping is to have M parallel branches each realizing a shifted version of the pulse stream, and re-express (1) as $\nu_u(t) = \sum_{m=0}^{M-1} \nu_{u,m}(t)$, where

$$\nu_{u,m}(t) = \mathcal{P}_u \sum_{k=-\infty}^{+\infty} s_{u,m}(\lfloor k/N_f \rfloor) w_m \left(t - kT_f - \tilde{c}_u(k)T_c\right)$$

upon defining the time-shifted pulses $w_m(t) := w(t - \tau_m)$, and $s_{u,m}(\lfloor k/N_f \rfloor) := \delta(I_u(\lfloor k/N_f \rfloor) - m), \forall m \in [0, M-1]$. Recalling that $T_f = N_c T_c$ for $T_g = 0$, we infer that $w_m(t)$ is shifted by an integer multiple of T_c. Let us consider a chip-rate code sequence $c_u(n)$ defined via $\tilde{c}_u(k)$ as follows:

$$c_u(n) := \delta(\lfloor n/N_c \rfloor N_c + \tilde{c}_u(\lfloor n/N_c \rfloor) - n). \quad (2)$$

It can be readily verified that the period of $c_u(n)$ in (2) is $P_c = N_c P_{\tilde{c}}$. Clearly, $c_u(n)$ and $\tilde{c}_u(k)$ are related by a mapping between the chip index n, and the frame index k. Through this mapping, the u-th user's chip sequence on the m-th branch $\nu_{u,m}(n)$ can be conveniently expressed as:

$$\nu_{u,m}(n) = s_{u,m}(\lfloor n/(N_c N_f) \rfloor) c_u(n), \quad (3)$$

and consequently

$$\nu_{u,m}(t) = \mathcal{P}_u \sum_{n=-\infty}^{+\infty} \nu_{u,m}(n) w_m \left(t - nT_c\right).$$

Notice that the information carrying stream $I_u(\lfloor n/(N_c N_f) \rfloor)$, and thus $s_{u,m}(\lfloor n/(N_c N_f) \rfloor)$, does not change over the duration of $N_f T_f$ seconds ($N_f N_c$ chips). It is spread by the TH address $c_u(n)$ to generate the chip sequence $\nu_{u,m}(n)$ in (3).

We cast the TH address assigned to each user into vector form

$$\tilde{\mathbf{c}}_u := [\tilde{c}_u(0), \ldots, \tilde{c}_u(P_{\tilde{c}} - 1)]^T. \quad (4)$$

To facilitate separation of multiple users, we select $\tilde{c}_u(n) \neq \tilde{c}_\mu(n)$, $\forall n \in [0, P_{\tilde{c}} - 1]$ and any two users u, μ. Let us further define the chip-rate TH spreading code vectors

$$\mathbf{c}_u = [c_u(0), \ldots, c_u(P_c - 1)]^T, \qquad c_u(n) \in [0, 1] \quad (5)$$

with $c_u(n)$ defined in (2). It can be readily shown that no collision occurs since these code vectors are mutually orthogonal, i.e., $\mathbf{c}_u^{\mathcal{H}} \mathbf{c}_\mu = N_f \delta(u - \mu)$. Recalling the total number of chips in one frame is N_c, it follows that the number of such TH addresses can be at most N_c. If the number of active users satisfies $N_u \leq N_c$, then N_u out of the N_c such TH addresses can be uniquely assigned to the N_u users.

2.2. Channel Model

The transmitted signal $\nu_{u,m}(t)$ propagates through a channel $g_u(t)$, and is filtered by a multi-branch receiver with the filter on the m'-th branch $\bar{w}_{m'}(t)$ matched to $w_{m'}(t)$, where $m' \in [0, M-1]$. With $\star$ denoting convolution, let $h_{u,m',m}(l) := (w_m \star g_u \star \bar{w}_{m'})(t)|_{t=lT_c}$ be the chip-sampled discrete time equivalent FIR channel. The FIR channel $h_{u,m',m}(l)$ of order L_u includes the u-th user's asynchronism in the form of delay factors as well as transmit-receive filters, and frequency-selective multipath effects. Let $\eta_{m'}(n) := (\eta \star \bar{w}_{m'})(t)|_{t=nT_c}$ denote sampled noise. The chip-sampled matched filter output of the m'-th branch at the receiver is

$$x_{m'}(n) = \sum_{u=0}^{N_u-1} \sum_{m=0}^{M-1} \sum_{l=0}^{L} \mathcal{P}_u h_{u,m',m}(l) \nu_{u,m}(n-l) + \eta_{m'}(n),$$

where N_u is the number of users, $L := \max_u L_u$, and M is the number of PPM pulse shapers.

We here focus on a cellular quasi-synchronous system in the *uplink*, where the mobile users attempt to synchronize with the base-station's pilot waveform, and have a coarse common timing reference. Asynchronism among users is thus limited to only a few chip intervals; the maximum asynchronism $\tau_{max,a}$ arises between the nearest and the farthest mobile users. With $\tau_{max,s}$ denoting maximum multipath spread, which is found using field measurements from the operational environment, the maximum channel order can be found as $L = \lceil (\tau_{max,s} + \tau_{max,a})/T_c \rceil$. In fact, the *downlink* model (from the base station to the user of interest μ) can be treated as a special case of the uplink model, where $h_{u,m',m}(l) = h_{\mu,m',m}(l), \forall u \in [0, N_u - 1]$ and $\tau_{max,a} = 0$.

3. DIGITAL MS-BS-IRMA

As aforementioned, when the number of active users satisfies $N_u \leq N_c$, then N_u out of the N_c mutually orthogonal TH addresses can be uniquely assigned to the N_u users and deterministic Multiuser separation becomes possible. But what if the number of active users $N_u > N_c$?

In such cases, it is inevitable that more than one users are assigned the same TH address. Recall from Section 2 that identical information symbols are sent over N_f frames. This can be viewed as encoding each symbol with a repetition code. In order to distinguish between different users who share the same TH address, we can replace the repetition code with a user-signature pattern that will henceforth be referred to as multiuser (MU) address. Let the u_B-th MU address be expressed as

$$\mathbf{d}_{u_B} := [d_{u_B}(0), \ldots, d_{u_B}(N_f - 1)]^T, \quad d_{u_B}(n) \in [1, -1] \quad (6)$$

and it is designed to satisfy $\mathbf{d}_{u_B}^{\mathcal{H}} \mathbf{d}_{\mu_B} = N_f \delta(u_B - \mu_B), \forall u_B, \mu_B \in [0, N_f - 1]$.

Specifically, if the number of users N_u satisfies $N_u \leq N_c N_f$, then a given TH address has to be assigned to $\lfloor N_u/N_c \rfloor$ or $\lceil N_u/N_c \rceil$ users, which form a user group. In order to be able to resolve users in the same group, we assign an additional set of MU addresses by employing a unique mapping to each of the $\lfloor N_u/N_c \rfloor$ or $\lceil N_u/N_c \rceil$ users in the same group, in order to distinguish them from each other. Note that the same MU address can be assigned to several users that belong to different groups, since the groups are differentiated via their unique TH addresses. Systematically, we assign the TH and MU addresses to each user, e.g., the u-th user ($u \in [0, N_c N_f - 1]$), as follows:

A) Assign to the u-th user the TH address with index $u_A = u \pmod{N_c}$;

B) Assign to the u-th user the MU address with index $u_B = \lfloor u/N_c \rfloor$.

It is evident that given a user u, its $\{u_A, u_B\}$ pair is uniquely determined and vice versa. Therefore, if the number of users $N_u \leq N_c N_f$, the probability of collisions is zero. Hereafter, we consider the fully loaded system with $N_u = N_f N_c$ users.

Based on our multi-stage user signature spreading code assignment, we are going to introduce user-specific block-spreading codes, and design the corresponding multi-stage block-spreading scheme, which will be shown capable of separating multiple users,

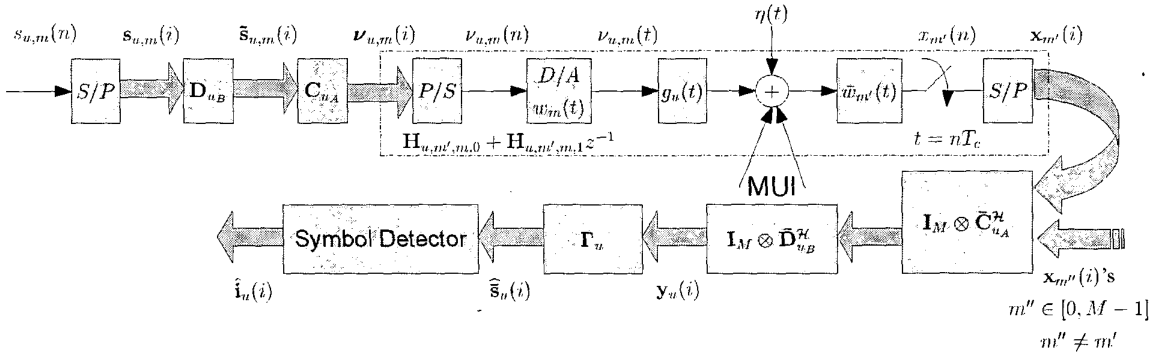

Fig. 1. Continuous and discrete-time equivalent system model of the u-th user (only the m-th branch at the transmitter and the m'-th branch at the receiver are shown).

and eliminating the MUI deterministically at the receiver, regardless of the underlying frequency-selective channels of maximum order L.

3.1. Digital Transmitter Design

During the k-th frame, the u-th user signals $\tilde{s}_{u,m}(k) := s_{u,m}(\lfloor k/N_f \rfloor) d_{u_B}(k)$ on the m-th branch by invoking his/her MU address. This can be viewed as a process in which each symbol is spread by the user's MU address. Notwithstanding, instead of spreading over a *single symbol*, we here use block spreading that operates on a *block of symbols*. Specifically, the information stream on the m-th branch of the u-th user $s_{u,m}$ is first parsed into $K \times 1$ vectors $\mathbf{s}_{u,m}(i) := [s_{u,m}(iK), \ldots, s_{u,m}(iK+K-1)]^T$, and then block-spread by a user-specific $Q \times K$ spreading matrix $\mathbf{D}_{u_B} := \mathbf{d}_{u_B} \otimes \mathbf{I}_K$ to obtain the output vector $\tilde{\mathbf{s}}_{u,m}(i) = \mathbf{D}_{u_B}\mathbf{s}_{u,m}(i)$, where $\tilde{\mathbf{s}}_{u,m}(i) := [\tilde{s}_{u,m}(iQ), \ldots, \tilde{s}_{u,m}(iQ+Q-1)]^T$ and $Q = N_f K$.

Similar to the MU address block-spreading, we introduce the TH spreading matrix $\mathbf{C}_{u_A}$ for the u-th user; and use it to recast (3) in a matrix-vector form $\boldsymbol{\nu}_{u,m}(i) = \mathbf{C}_{u_A}\tilde{\mathbf{s}}_{u,m}(i)$, where the $P \times 1$ vector on the m-th branch is $\boldsymbol{\nu}_{u,m}(i) := [\nu_{u,m}(iP), \ldots, \nu_{u,m}(iP+P-1)]^T$. To specify the $P \times Q$ TH address matrix $\mathbf{C}_{u_A}$ which guarantees the MUI elimination, we start from the TH address vector $\mathbf{c}_{u_A}^{(q)} := [c_{u_A}(qN_c), \ldots, c_{u_A}(qN_c + N_c - 1)]^T$, $q \in [0, N_f - 1]$, where $c_{u_A}(n)$ is defined in (2), and let $\mathbf{C}_{u_A}^{(q)} := \mathbf{c}_{u_A}^{(q)} \otimes \mathbf{T}_{zp}$. $\mathbf{T}_{zp} := [\mathbf{I}_K, \mathbf{0}_{K \times L}]^T$ is termed zero-padding (ZP) matrix because upon pre-multiplication with a $K \times 1$ vector, it appends L zeros. Based on $\mathbf{C}_{u_A}^{(q)}$'s, we select the TH spreading matrices as $\mathbf{C}_{u_A} := \mathrm{diag}\{\mathbf{C}_{u_A}^{(0)}, \mathbf{C}_{u_A}^{(1)}, \ldots, \mathbf{C}_{u_A}^{(N_f-1)}\}$. It can be verified using definition of Kronecker product that $P = (K+L)P_c$.

Notice that the MU block-spreading is performed at the frame-level, i.e., a block of K symbols are spread into Q frame-rate signals (each of duration T_f); whereas the TH block-spreading is performed at the chip-level, i.e., the block of Q frame-rate signals are further spread into P chip-rate signals (each of duration T_c) by the TH spreading matrices $\mathbf{C}_{u_A}$.

As the output of the two-stage block-spreading module, the signal block to be transmitted on the m-th branch of the u-th user is given by $\boldsymbol{\nu}_{u,m}(i) = \mathbf{C}_{u_A}\mathbf{D}_{u_B}\mathbf{s}_{u,m}(i)$, where u_A and u_B are indices of the TH and MU addresses assigned to the u-th user, respectively.

3.2. Input-Output Matrix-Vector Model

The block diagram in Fig. 1 describes our MS-BS-IRMA model in either *uplink* or *downlink* operation, where only one branch of the u-th user is shown. The input-output block relationship of our system can be described in matrix-vector form as:

$$\mathbf{x}_{m'}(i) = \sum_{u_A=0}^{N_c-1} \sum_{u_B=0}^{N_f-1} \sum_{m=0}^{M-1} \mathcal{P}_u [\mathbf{H}_{u,m',m,0}\mathbf{C}_{u_A}\mathbf{D}_{u_B}\mathbf{s}_{u,m}(i) + \mathbf{H}_{u,m',m,1}\mathbf{C}_{u_A}\mathbf{D}_{u_B}\mathbf{s}_{u,m}(i-1)] + \boldsymbol{\eta}_{m'}(i), \tag{7}$$

where the address assigning rules are used; $\mathbf{x}_{m'}(i)$ and $\boldsymbol{\eta}_{m'}(i)$ are $P \times 1$ blocks; $\mathbf{H}_{u,m',m,0}$ and $\mathbf{H}_{u,m',m,1}$ are $P \times P$ lower and upper triangular Toeplitz matrix with first column $[h_{u,m',m}(0), \ldots, h_{u,m',m}(L), 0, \ldots, 0]^T$, and first row $[0, \ldots, 0, h_{u,m',m}(L), \ldots, h_{u,m',m}(1)]$, respectively. Notice that the $\mathbf{s}_{u,m}(i-1)$ dependent term in (7) accounts for the so-called Inter-Block Interference (IBI).

3.3. Digital Receiver Design

Since PPM is a non-linear modulation, the receivers will operate in three steps: 1) linear filtering to separate multiple users, and thus render the multiple-access channel equivalent to a set of single-user ISI channels; 2) single-user channel equalizing to eliminate channel effects; and 3) symbol detecting.

The first step of the receiver employs a multiuser separating front-end, which is described by the despreading matrices $\bar{\mathbf{C}}_{\mu_A}$ and $\bar{\mathbf{D}}_{\mu_M}$ for the μ-th user. The goal of this step is to extract the μ-th user's signal from $\mathbf{x}_{m'}(i)$, and yield the MUI-free block:

$$\mathbf{y}_{\mu,m'}(i) = \bar{\mathbf{D}}_{\mu_B}^{\mathcal{H}} \bar{\mathbf{C}}_{\mu_A}^{\mathcal{H}} \mathbf{x}_{m'}(i), \qquad \forall m' \in [0, M-1]. \tag{8}$$

At the second step, the MUI-free output $\mathbf{y}_\mu(i) := [\mathbf{y}_{\mu,0}^T(i), \ldots, \mathbf{y}_{\mu,M-1}^T(i)]^T$ can be equalized by *any* single user equalizer; e.g., a linear equalizer $\boldsymbol{\Gamma}_\mu$ will yield symbol block estimates $\hat{\mathbf{s}}_\mu(i) = \boldsymbol{\Gamma}_\mu \mathbf{y}_\mu(i)$, where $\hat{\mathbf{s}}_\mu(i) := [\hat{\mathbf{s}}_{\mu,0}^T(i), \ldots, \hat{\mathbf{s}}_{\mu,M-1}^T(i)]^T$.

Finally, symbol detection is performed based on the soft estimates $\hat{\mathbf{s}}_\mu(i)$.

Starting from the MS-BS transmitter design in Section 3.1, we will propose de-spreading matrices $\{\bar{\mathbf{C}}_{u_A}\}_{u_A=0}^{N_c-1}$ and $\{\bar{\mathbf{D}}_{u_B}\}_{u_B=0}^{N_f-1}$, which enable separation of superimposed multiuser signals deterministically, regardless of multipath propagation through frequency-selective ISI channels.

Based on the MU address vectors $\mathbf{d}_{u_B}$, we select the MU separating (despreading) matrices as $\bar{\mathbf{D}}_{u_B} := \mathbf{d}_{u_B} \otimes \mathbf{I}_{K+L}$, which has dimension $N_f(K+L) \times (K+L)$. Recall that at this stage the spreading is performed at the frame level. The MU separating by $\bar{\mathbf{D}}_{u_B}$ can be viewed as frame-interleaving followed by block-despreading.

As to the selection of the $P \times N_f(K+L)$ TH separating matrices $\bar{\mathbf{C}}_{u_A}$, let $\bar{\mathbf{C}}_{u_A} := \mathrm{diag}\{\bar{\mathbf{C}}_{u_A}^{(0)}, \bar{\mathbf{C}}_{u_A}^{(1)}, \ldots, \bar{\mathbf{C}}_{u_A}^{(N_f-1)}\}$, with $\bar{\mathbf{C}}_{u_A}^{(q)} := \mathbf{c}_{u_A}^{(q)} \otimes \mathbf{I}_{K+L}$.

The properties of Kronecker products can be used to verify the following mutual orthogonality relationships between any two users u and μ:

$$\begin{aligned} \bar{\mathbf{D}}_{\mu_B}^{\mathcal{H}} \bar{\mathbf{D}}_{u_B} &= N_f \delta(\mu_B - u_B)\mathbf{I}_{K+L}, \\ \bar{\mathbf{C}}_{\mu_A}^{\mathcal{H}} \bar{\mathbf{C}}_{u_A} &= \delta(\mu_A - u_A)\mathbf{I}_{N_f(K+L)}. \end{aligned} \quad (9)$$

which will be shown later to facilitate deterministic MUI elimination.

Based on the (de-)spreading matrix pairs, we have the following observations:

Proposition 1 : *The $\mathbf{s}_{u,m}(i-1)$ dependent term in (7), which accounts for IBI, vanishes.*

Proposition 2 : *The channel matrix $\mathbf{H}_{u,m',m,0}$ commutes with the block-spreading matrices $\mathbf{C}_{u_A}$ and $\mathbf{D}_{u_B}$ in (7). Specifically, it holds that $\mathbf{H}_{u,m',m,0}\bar{\mathbf{C}}_{u_A}\mathbf{D}_{u_B}\mathbf{s}_{u,m}(i) = \bar{\mathbf{C}}_{u_A}\bar{\mathbf{D}}_{u_B}\check{\mathbf{H}}_{u,m',m}\mathbf{s}_{u,m}(i)$, where $\check{\mathbf{H}}_{u,m',m}$ is a $(K+L) \times K$ Toeplitz matrix with first column $[h_{u,m',m}(0), \ldots, h_{u,m',m}(L), 0, \ldots, 0]^T$.*

For proofs, please refer to [9].

Using Propositions 1 and 2, we have[c.f. (7)]

$$\mathbf{x}_{m'}(i) = \sum_{u_A=0}^{N_c-1} \bar{\mathbf{C}}_{u_A} \sum_{u_B=0}^{N_f-1} \bar{\mathbf{D}}_{u_B} \sum_{m=0}^{M-1} \mathcal{P}_u \check{\mathbf{H}}_{u,m',m}\mathbf{s}_{u,m}(i) + \boldsymbol{\eta}_{m'}(i). \quad (10)$$

Based on (9) and (10), we can re-express (8) as:

$$\mathbf{y}_{\mu,m'}(i) = N_f \mathcal{P}_\mu \sum_{m=0}^{M-1} \check{\mathbf{H}}_{\mu,m',m}\mathbf{s}_{\mu,m}(i) + \tilde{\boldsymbol{\eta}}_{m'}(i), \quad (11)$$

with the substitution $\tilde{\boldsymbol{\eta}}_{m'}(i) := \bar{\mathbf{D}}_{\mu_M}^{\mathcal{H}} \bar{\mathbf{C}}_{\mu_A}^{\mathcal{H}} \boldsymbol{\eta}_{m'}(i)$. Notice that the block de-spreading operation $\bar{\mathbf{D}}_{\mu_B}^{\mathcal{H}} \bar{\mathbf{C}}_{\mu_A}^{\mathcal{H}}$ has indeed separated the desired user μ perfectly from the MUI. Considering the $MK \times 1$ blocks $\mathbf{s}_\mu(i) := [\mathbf{s}_{\mu,0}^T(i), \ldots, \mathbf{s}_{\mu,M-1}^T(i)]^T$, we have from (11):

$$\mathbf{y}_\mu(i) = N_f \mathcal{P}_\mu \check{\mathbf{H}}_\mu \mathbf{s}_\mu(i) + \tilde{\boldsymbol{\eta}}(i), \quad (12)$$

where $\mathbf{y}_\mu(i)$ and $\tilde{\boldsymbol{\eta}}(i)$ are $M(K+L) \times 1$ vectors generated by concatenating the output blocks from the receiver filters matched to the M waveforms, and $\check{\mathbf{H}}_\mu$ is the $M(K+L) \times MK$ matrix:

$$\check{\mathbf{H}}_\mu := \begin{bmatrix} \check{\mathbf{H}}_{\mu,0,0} & \check{\mathbf{H}}_{\mu,0,1} & \cdots & \check{\mathbf{H}}_{\mu,0,M-1} \\ \check{\mathbf{H}}_{\mu,1,0} & \check{\mathbf{H}}_{\mu,1,1} & \cdots & \check{\mathbf{H}}_{\mu,1,M-1} \\ \vdots & \vdots & \ddots & \vdots \\ \check{\mathbf{H}}_{\mu,M-1,0} & \check{\mathbf{H}}_{\mu,M-1,1} & \cdots & \check{\mathbf{H}}_{\mu,M-1,M-1} \end{bmatrix}.$$

Eqs. (11) and (12) disclose that the superimposed received signals from multiple users can be separated deterministically, regardless of the FIR multipath channels. This is due to the fact that the transceiver design preserves the code orthogonality among users even after *unknown* multipath propagation. Similar to [10], multipath channels with CIBS transmissions cause ISI within each symbol block, but they do not give rise to inter-chip interference (ICI) within the code vector; i.e., ICI is replaced by ISI. Recall that in our MS-BS-IRMA design, the one-step zero-padding in the second spreading stage eliminates the inter-chip interference and maintains the orthogonality among the spreading codes of both stages, namely TH and MU addresses, which in turn guarantees the deterministic multiuser separation at the receiver, as well as preserves the Maximum Likelihood (ML) optimality [9].

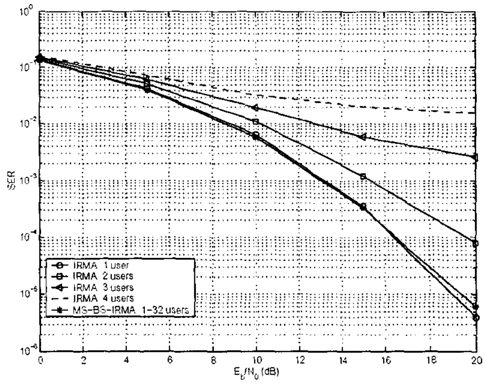

Fig. 2. Comparing SER performance of a conventional IRMA system with a MS-BS-IRMA system as the number of active users increases (channel model 1).

Therefore, our chosen (de-)spreading codes have successfully converted a multiuser detection problem, that has to deal with MUI in the presence of time dispersive channels, into a set of equivalent single user equalization problems without loss of optimality.

Striking a compromise between performance and complexity, here we consider only linear equalizers. Depending on how $\boldsymbol{\Gamma}_\mu$ is selected, we obtain the following linear receivers:

- *MF receiver:* $\boldsymbol{\Gamma}_\mu^{MF} := \check{\mathbf{H}}_\mu^{\mathcal{H}}/N_f$,
- *ZF receiver:* $\boldsymbol{\Gamma}_\mu^{ZF} := \left(\check{\mathbf{H}}_\mu^{\mathcal{H}}\check{\mathbf{H}}_\mu\right)^{-1}\check{\mathbf{H}}_\mu^{\mathcal{H}}/N_f$,
- *MMSE receiver:*

$$\boldsymbol{\Gamma}_\mu^{MMSE} = N_f \mathbf{R}_\mu \check{\mathbf{H}}_\mu^{\mathcal{H}} \left[\mathbf{R}_{\tilde{\eta}} + N_f^2 \check{\mathbf{H}}_\mu \mathbf{R}_\mu \check{\mathbf{H}}_\mu^{\mathcal{H}}\right]^{-1},$$

where $\mathbf{R}_\mu := \mathbf{E}\{\mathbf{s}_\mu(i)\mathbf{s}_\mu^{\mathcal{H}}(i)\}$, and $\mathbf{R}_{\tilde{\eta}} := \mathbf{E}\{\tilde{\boldsymbol{\eta}}(i)\tilde{\boldsymbol{\eta}}^{\mathcal{H}}(i)\}$.

Symbol detection is then performed based on the soft estimates $\hat{\mathbf{s}}_\mu(i)$ according to $\hat{I}_\mu(iK+k) = \arg\max_m\{\hat{s}_{\mu,m}(iK+k)\}$, $m \in [0, M-1]$ and $k \in [0, K-1]$. We have seen so far how MS-BS-IRMA replaces ICI by ISI, and thereby converts a multiuser detection problem into a set of equivalent single user equalization problems. Now we look at the simulated performance.

4. SIMULATION RESULTS

In our simulations, the monopulse is chosen to be the second derivative of the Gaussian function, which has a pulse width of $0.7ns$ and is normalized to have unit energy. The system parameters are as follows: constellation size $M = 2$, which corresponds to a binary modulation, with every symbol transmitted repeatedly over $N_f = 8$ frames, and each frame composed of $N_c = 4$ chips.

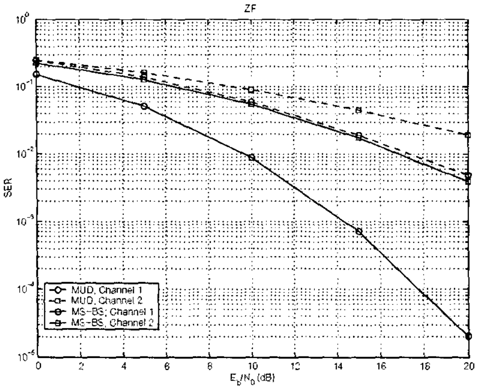

Fig. 3. SER vs. E_b/N_0 for ZF receiver with binary symbols and $N_f = 8$, $N_c = 4$. Block size $K = 2$. Number of active users in MUD-IRMA system: 4. Number of active users in MS-BS-IRMA system: 32.

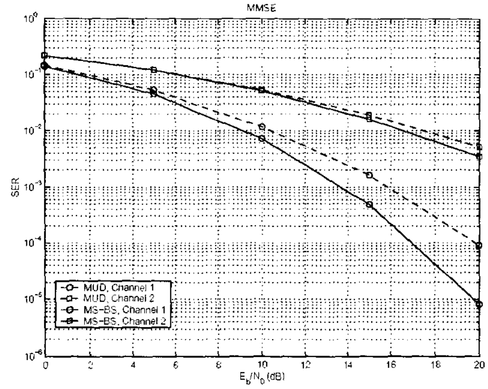

Fig. 4. SER vs. E_b/N_0 for MMSE receiver with binary symbols and $N_f = 8$, $N_c = 4$. Block size $K = 2$. Number of active users in MUD-IRMA system: 4. Number of active users in MS-BS-IRMA system: 32.

As in [7], we have chosen the frame duration $T_f = 100ns$, which is also the maximum delay spread.

Two channel models are employed. In the first one, the channel has 400 paths equally spaced in time within the maximum delay spread. The path amplitudes are modeled as Gaussian variables, and they are linearly weighted with weights decreasing to zero at the maximum delay spread. The second channel model is generated according to [4, 2]. Rays resulted from multipath effect are modeled as clusters with Poisson distributed arriving times and Rayleigh distributed amplitudes. Parameters of this channel model are chosen as: $\Gamma = 33ns$, $\gamma = 5ns$, $1/\Lambda = 2ns$, and $1/\lambda = 0.5ns$.

Test case A: First we test the performance of MF (RAKE) receiver of a conventional IRMA system against our MS-BS-IRMA system in the presence of frequency-selective channels. Uplink scenario with perfect power control is considered. For both systems, we assume that adjacent symbols of a specific user are placed far apart to avoid ISI, and symbol-by-symbol reception is performed at the receiver. The number of users in the conventional IRMA system is increased from 1 up to 4. Because MUI is eliminated deterministically, our proposed system exhibits performance that remains invariant as the number of active users changes in the range of $1 \leq N_u \leq 32$. While in the conventional IRMA system, as the number of active users increases, the Symbol Error Rate (SER) performance degrades accordingly. Fig. 2 shows the ensemble performance over 1,000 channel realizations.

Test case B: To further illustrate the performance of the proposed IRMA scheme, we simulate both the novel MUI-free MS-BS-IRMA, and the MUD-IRMA in [3]. Recall that our proposed model applies to both uplink and downlink scenario, while the latter applies only to downlink. The aforementioned system parameters allow for maximum $N_u = N_c N_f = 32$ users in the MS-BS-IRMA system, and $N_u = N_c = 4$ in the MUD-IRMA system. The block size is chosen to be $K = 2$.

Figures 3 and 4 depict the ensemble SER performance over 1,000 channel realizations for the ZF and MMSE linear receivers based on the two digital IRMA schemes, namely MUD-IRMA and MS-BS-IRMA. In all cases, the MMSE receivers provide better performance. For all receivers and both channel models, the MS-BS receivers consistently outperform their MUD counterparts, while accommodating much more users.

5. REFERENCES

[1] J. R. Foerster, "The Effects of Multipath Interference on the Performance of UWB Systems in and Indoor Wireless Channel," in *Proc. of Vehicular Technology Conference*, Vol. 2, pp. 1176 -1180, Rhodes Island, Greece, Spring, 2001.

[2] H. Lee, B. Han, Y. Shin, and S. Im, "Multipath Characteristics of Impulse Radio Channels," in *Proc. of Vehicular Technology Conference Proceedings*, Tokyo, Spring 2000, pp. 2487 -2491.

[3] C. J. Le Martret and G. B. Giannakis, "All-digital PPM Impulse Radio for Multiple-Access through Frequency-Selective Multipath," in *Proc. of Sensor Array and Multichannel Signal Processing Workshop*, Boston, March 2000, pp. 22-26.

[4] A. A. M. Saleh and R. A. Valenzuela, "A Statistical Model for Indoor Multipath Propagation," *IEEE Journal on Selected Areas in Communications*, Vol. JSAC-5, no. 2, pp. 128-137, Feb. 1987.

[5] R. A. Scholtz, "Multiple Access with Time-hopping Impulse Radio," in *Proc. of the Milcom Conf.*, Boston, MA, USA, Oct. 1993, pp. 447-450.

[6] M. Z. Win, R. A. Scholtz, "Impulse Radio: How It Works," *IEEE Communications Letters*, Vol. 2, No. 2, pp. 36-38, Feb. 1998.

[7] M. Z. Win, R. A. Scholtz, "Ultra-Wide Bandwidth Time-Hopping Spread-Spectrum Impulse Radio for Wireless Multiple-Access Communications," *IEEE Transactions on Communications*, Vol. 48, No. 4, pp. 679-691, April 2000.

[8] P. H. Withington and L. W. Fullerton, "An Impulse Radio Communications System," *Proc. of the Intl. Conf. on Ultra-Wide Band, Short-Pulse Electromagnetics*, Brooklyn, NY, USA, Oct. 1992, pp.113-120.

[9] L. Yang and G. B. Giannakis, "Multi-Stage Block-Spreading for Impulse Radio Multiple Access through ISI Channels," *IEEE Journal on Selected Areas in Communications*, submitted January 2002.

[10] S. Zhou and G. B. Giannakis, and C. Le Martret, "Chip-Interleaved Block-Spread Code Division Multiple Access," *IEEE Trans. on Communications*, Feb. 2002 (to appear).