CHANNEL-INDEPENDENT SUPPRESSION OF MULTI-USER AND INTER-TONE INTERFERENCE IN A DMT-CDMA SYSTEM BASED ON BLOCK SPREADING

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ABSTRACT

In this paper we present a new receiver for a DMT-CDMA system based on block spreading that completely suppresses the multi-user interference (MUI) and inter-tone interference (ITI), without using any channel information. This total suppression of MUI and ITI is obtained by the use of a shift-orthogonal set of code sequences, on which the proposed receiver is based. Simulation results show that the performance of the proposed receiver for a DMT-CDMA system based on block spreading, considering a scenario where the power of each tone is adjusted to the power of the channel at the corresponding frequency (good scenario for this type of receiver), is comparable to the performance of a linear multi-user equalizer for a classical DMT-CDMA system, considering a scenario where the power of each tone is the same (good scenario for this type of receiver).

1. INTRODUCTION

Lately, many schemes have been proposed to combine code-division multiple-access (CDMA) with discrete multi-tone (DMT) modulation [1, 2, 3, 4]. In this paper we discuss a new combination of CDMA with DMT modulation, which we will call DMT-CDMA based on block spreading. In a DMT-CDMA system based on block spreading each user first DMT-modulates his bit stream and then spreads the resulting symbol sequence using the block spreading scheme presented in [5, 6]. For such a DMT-CDMA system based on block spreading we present a new receiver that completely suppresses the multi-user interference (MUI) and inter-tone interference (ITI), without using any channel information. This total suppression of MUI and ITI is obtained by the use of a shift-orthogonal set of code sequences, on which the proposed receiver is based. Note that the proposed receiver is a generalization of the receiver presented in [7], where we assumed that the DMT symbol size of the DMT modulation is equal to the block size of the block spreading scheme. Further note that the proposed receiver is related to the recently developed MUI-free receiver for a direct-sequence CDMA (DS-CDMA) system based on block spreading (see [5, 6]).

In section 2, the data model for a DMT-CDMA system based on block spreading is presented. Section 3 then introduces the proposed receiver. Simulation results comparing the proposed receiver for a DMT-CDMA system based on block spreading with a linear multi-user equalizer for a classical DMT-CDMA system are presented in section 4. Finally, conclusions are given in section 5.

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2. DATA MODEL

In a J-user DMT-CDMA system based on block spreading, the jth user ($j = 1, 2, \ldots, J$) first transforms his bit stream into a DMT symbol sequence $\tilde{\mathbf{s}}_j^{dmt}[\kappa]$, which can be written as

$$\tilde{\mathbf{s}}_j^{dmt}[\kappa] = \begin{bmatrix} \tilde{s}_{j,1}[\kappa] & \cdots & \tilde{s}_{j,P}[\kappa] \end{bmatrix}^T,$$

where P is the DMT symbol size and $\tilde{s}_{j,p}[\kappa]$ is the DMT subsymbol sequence for the pth tone ($p = 1, 2, \ldots, P$).

Then, we perform an inverse discrete Fourier transformation (IDFT) on $\tilde{\mathbf{s}}_j^{dmt}[\kappa]$:

$$\mathbf{s}_j^{dmt}[\kappa] = \sqrt{P}\mathcal{I}_P\tilde{\mathbf{s}}_j^{dmt}[\kappa],$$

where $\mathcal{I}_P$ represents the $P \times P$ IDFT matrix. Next, the corresponding symbol sequence $s_j[k]$, satisfying

$$\mathbf{s}_j^{dmt}[\kappa] = \begin{bmatrix} s_j[\kappa P] & \cdots & s_j[(\kappa+1)P-1] \end{bmatrix}^T,$$

is blocked with block size L, leading to the symbol block sequence $\mathbf{s}_j[k]$:

$$\mathbf{s}_j[k] = \begin{bmatrix} s_j[kL] & \cdots & s_j[(k+1)L-1] \end{bmatrix}^T.$$

This symbol block sequence $\mathbf{s}_j[k]$ is then spread by a factor N with the length-N code sequence $c_j[n]$ ($c_j[n] \neq 0$, for $n = 0, 1, \ldots, N-1$, and $c_j[n] = 0$, for $n < 0$ and $n \geq N$), resulting into the chip block sequence $\mathbf{x}_j[n]$:

$$\mathbf{x}_j[n] = \mathbf{s}_j[k]c_j[n \bmod N], \quad \text{with } k = \left\lfloor \frac{n}{N} \right\rfloor.$$

Finally, the corresponding chip sequence $x_j[n]$, satisfying

$$\mathbf{x}_j[n] = \begin{bmatrix} x_j[nL] & \cdots & x_j[(n+1)L-1] \end{bmatrix}^T,$$

is transmitted at a rate NP/T^{dmt} (the chip rate), where T^{dmt} is the DMT symbol period. The transformation from DMT symbol sequence $\tilde{\mathbf{s}}_j^{dmt}[\kappa]$ to chip sequence $x_j[n]$ is depicted in figure 1.

If we sample the receive antenna at the chip rate, the received sequence can be written as

$$y[n] = \sum_{j=1}^{J} \sum_{n'=-\infty}^{+\infty} g_j[n']x_j[n-n'] + e[n],$$

where $e[n]$ is additive noise and $g_j[n]$ is the discrete-time channel from the jth user to the receive antenna. If we further block the received sequence $y[n]$ with block size L, leading to the received block sequence $\mathbf{y}[n]$:

$$\mathbf{y}[n] = \begin{bmatrix} y[nL] & \cdots & y[(n+1)L-1] \end{bmatrix}^T,$$

we can write

$$\mathbf{y}[n] = \sum_{j=1}^{J} \sum_{n'=-\infty}^{+\infty} \mathbf{G}_j[n']\mathbf{x}_j[n-n'] + \mathbf{e}[n],$$

where $\mathbf{e}[n]$ is similarly defined as $\mathbf{y}[n]$ and $\mathbf{G}_j[n]$ is the discrete-time $L \times L$ matrix channel from the jth user to the receive antenna, given by

$$\mathbf{G}_j[n] = \begin{bmatrix} g_j[Ln] & \cdots & g_j[L(n-1)+1] \\ \vdots & \ddots & \vdots \\ g_j[L(n+1)-1] & \cdots & g_j[Ln] \end{bmatrix}.$$

We make the following assumptions:

Assumption 1. *The block size L is a divisor of the DMT symbol size P.*

Assumption 2. *The channels $\{g_j[n]\}_{j=1}^J$ are zero outside $[0, L-1]$.*

Because of this last assumption, the $L \times L$ matrix channels $\{\mathbf{G}_j[n]\}_{j=1}^J$ are zero outside $[0, 1]$, with

$$\mathbf{G}_j[0] = \begin{bmatrix} g_j[0] & \cdots & 0 \\ \vdots & \ddots & \vdots \\ g_j[L-1] & \cdots & g_j[0] \end{bmatrix},$$

$$\mathbf{G}_j[1] = \begin{bmatrix} 0 & g_j[L-1] & \cdots & g_j[1] \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & g_j[L-1] \\ 0 & 0 & \cdots & 0 \end{bmatrix}.$$

3. PROPOSED RECEIVER

We first apply a bank of 2 modified block correlators (see [5, 6]). The first modified block correlator for the jth user despreads the received block sequence $\mathbf{y}[n]$ matched to $\mathbf{G}_j[0]$, using the code sequence $\underline{c}_j[n]$, where

$$\underline{c}_j[n] = \begin{cases} 0, & \text{for } n = 0 \\ c_j[n], & \text{for } n \neq 0 \end{cases},$$

while the second modified block correlator for the jth user despreads the received block sequence $\mathbf{y}[n]$ matched to $\mathbf{G}_j[1]$, using the code sequence $\overline{c}_j[n]$, where

$$\overline{c}_j[n] = \begin{cases} c_j[n], & \text{for } n \neq N-1 \\ 0, & \text{for } n = N-1 \end{cases}.$$

Introducing the notations

$$\underline{\mathbf{c}}_j = \begin{bmatrix} c_j[1] & \cdots & c_j[N-1] \end{bmatrix}^T,$$
$$\overline{\mathbf{c}}_j = \begin{bmatrix} c_j[0] & \cdots & c_j[N-2] \end{bmatrix}^T,$$

the output of the first modified block correlator can be written as

$$\begin{aligned} \mathbf{z}_{j,0}[k] &= \sum_{n=0}^{N-1} \underline{c}_j^*[n]\mathbf{y}[kN+n] \\ &= \underline{\mathbf{c}}_j^H \underline{\mathbf{c}}_j \mathbf{G}_j[0]\mathbf{s}_j[k] + \mathbf{q}_{j,0}[k] + \mathbf{p}_{j,0}[k] + \mathbf{n}_{j,0}[k], \end{aligned}$$

while the output of the second modified block correlator can be written as

$$\begin{aligned} \mathbf{z}_{j,1}[k] &= \sum_{n=0}^{N-1} \overline{c}_j^*[n]\mathbf{y}[kN+n+1] \\ &= \overline{\mathbf{c}}_j^H \overline{\mathbf{c}}_j \mathbf{G}_j[1]\mathbf{s}_j[k] + \mathbf{q}_{j,1}[k] + \mathbf{p}_{j,1}[k] + \mathbf{n}_{j,1}[k]. \end{aligned}$$

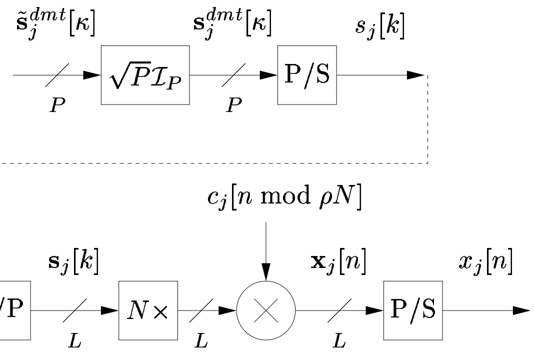


Figure 1: Transformation from DMT symbol sequence to chip sequence.

In these formulas $\mathbf{q}_{j,0}[k]$ and $\mathbf{q}_{j,1}[k]$ represent the residual inter-chip-block interference (ICBI):

$$\begin{aligned}\mathbf{q}_{j,0}[k] &= \underline{\mathbf{c}}_j^H \overline{\mathbf{c}}_j \mathbf{G}_j[1]\mathbf{s}_j[k],\\ \mathbf{q}_{j,1}[k] &= \overline{\mathbf{c}}_j^H \underline{\mathbf{c}}_j \mathbf{G}_j[0]\mathbf{s}_j[k],\end{aligned}$$

$\mathbf{p}_{j,0}[k]$ and $\mathbf{p}_{j,1}[k]$ represent the residual multi-user interference (MUI):

$$\mathbf{p}_{j,0}[k] = \sum_{\substack{j'=1\\ j'\neq j}}^{J} \underline{\mathbf{c}}_j^H \underline{\mathbf{c}}_{j'} \mathbf{G}_{j'}[0]\mathbf{s}_{j'}[k] + \underline{\mathbf{c}}_j^H \overline{\mathbf{c}}_{j'} \mathbf{G}_{j'}[1]\mathbf{s}_{j'}[k],$$

$$\mathbf{p}_{j,1}[k] = \sum_{\substack{j'=1\\ j'\neq j}}^{J} \overline{\mathbf{c}}_j^H \underline{\mathbf{c}}_{j'} \mathbf{G}_{j'}[0]\mathbf{s}_{j'}[k] + \overline{\mathbf{c}}_j^H \overline{\mathbf{c}}_{j'} \mathbf{G}_{j'}[1]\mathbf{s}_{j'}[k]$$

and $\mathbf{n}_{j,0}[k]$ and $\mathbf{n}_{j,1}[k]$ represent the residual additive noise:

$$\begin{aligned}\mathbf{n}_{j,0}[k] &= \sum_{n=0}^{N-1} \underline{c}_j^*[n]\mathbf{e}[kN+n],\\ \mathbf{n}_{j,1}[k] &= \sum_{n=0}^{N-1} \overline{c}_j^*[n]\mathbf{e}[kN+n+1].\end{aligned}$$

Assume now that a shift-orthogonal set of code sequences is used (see [5, 6]):

Definition 1. *A set of J length-N code sequences $\{c_j[n]\}_{j=1}^J$ is shift-orthogonal, if and only if*

$$\left\{\begin{array}{l} \underline{\mathbf{c}}_j^H \underline{\mathbf{c}}_{j'} = \overline{\mathbf{c}}_j^H \overline{\mathbf{c}}_{j'} = \eta\delta[j-j'] \\ \underline{\mathbf{c}}_j^H \overline{\mathbf{c}}_{j'} = \overline{\mathbf{c}}_j^H \underline{\mathbf{c}}_{j'} = 0 \end{array}\right. , \quad \textit{for } j, j' = 1, 2, \ldots, J,$$

where $\eta = (N-1)/N$ and $\delta[\cdot]$ is the discrete-time impulse function.

Then, it is clear that the 2 modified block correlators completely remove the ICBI and MUI, and $\mathbf{z}_{j,0}[k]$ and $\mathbf{z}_{j,1}[k]$ can be written as

$$\mathbf{z}_{j,0}[k] = \eta\mathbf{G}_j[0]\mathbf{s}_j[k] + \mathbf{n}_{j,0}[k], \tag{1}$$
$$\mathbf{z}_{j,1}[k] = \eta\mathbf{G}_j[1]\mathbf{s}_j[k] + \mathbf{n}_{j,1}[k]. \tag{2}$$

Next, we construct

$$\begin{aligned}\mathbf{z}_{j,0}^{dmt}[\kappa] &= \left[\mathbf{z}_{j,0}^T[\kappa P/L] \quad \cdots \quad \mathbf{z}_{j,0}^T[(\kappa+1)P/L-1]\right]^T,\\ \mathbf{z}_{j,1}^{dmt}[\kappa] &= \left[\mathbf{z}_{j,1}^T[\kappa P/L] \quad \cdots \quad \mathbf{z}_{j,1}^T[(\kappa+1)P/L-1]\right]^T.\end{aligned}$$

In this context, note that we can write

$$\mathbf{s}_j^{dmt}[\kappa] = \left[\mathbf{s}_j^T[\kappa P/L] \quad \cdots \quad \mathbf{s}_j^T[(\kappa+1)P/L-1]\right]^T.$$

Further, applying a simple transformation on $\mathbf{z}_{j,1}^{dmt}[\kappa]$:

$$\bar{\mathbf{z}}_{j,1}^{dmt}[\kappa] = \mathbf{J}_P^L \mathbf{z}_{j,1}^{dmt}[\kappa],$$

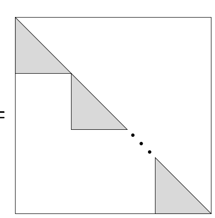
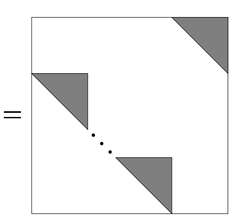
where $\mathbf{J}_n$ is defined as the $n \times n$ cyclic shift matrix

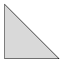
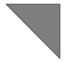
$$\mathbf{J}_n = \begin{bmatrix} 0 & \cdots & 0 & 1\\ 1 & \cdots & 0 & 0\\ \vdots & \ddots & \vdots & \vdots\\ 0 & \cdots & 1 & 0 \end{bmatrix},$$

it is clear from (1) and (2) that

$$\begin{aligned}\mathbf{z}_{j,0}^{dmt}[\kappa] &= \eta\mathbf{G}_{j,0}^{dmt}\mathbf{s}_j^{dmt}[\kappa] + \mathbf{n}_{j,0}^{dmt}[\kappa],\\ \bar{\mathbf{z}}_{j,1}^{dmt}[\kappa] &= \eta\bar{\mathbf{G}}_{j,1}^{dmt}\mathbf{s}_j^{dmt}[\kappa] + \bar{\mathbf{n}}_{j,1}^{dmt}[\kappa],\end{aligned}$$

where $\mathbf{n}_{j,0}^{dmt}[\kappa]$ is similarly defined as $\mathbf{z}_{j,0}^{dmt}[\kappa]$, $\bar{\mathbf{n}}_{j,1}^{dmt}[\kappa]$ is similarly defined as $\bar{\mathbf{z}}_{j,1}^{dmt}[\kappa]$ and $\mathbf{G}_{j,0}^{dmt}$ and $\bar{\mathbf{G}}_{j,1}^{dmt}$ are the $P \times P$ channel matrices for the jth user, given by

$\mathbf{G}_{j,0}^{dmt} =$  , $\bar{\mathbf{G}}_{j,1}^{dmt} =$  , with

 $= \mathbf{G}_j[0]$,  $= \mathbf{G}_j[1]$.

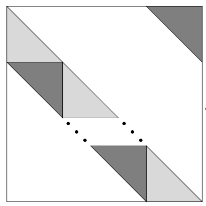
If we then simply sum $\mathbf{z}_{j,0}^{dmt}[\kappa]$ and $\bar{\mathbf{z}}_{j,1}^{dmt}[\kappa]$

$$\mathbf{z}_j^{dmt}[\kappa] = \mathbf{z}_{j,0}^{dmt}[\kappa] + \bar{\mathbf{z}}_{j,1}^{dmt}[\kappa],$$

we obtain

$$\mathbf{z}_j^{dmt}[\kappa] = \eta \mathbf{G}_j^{dmt} \mathbf{s}_j^{dmt}[\kappa] + \mathbf{n}_j^{dmt}[\kappa],$$

where $\mathbf{n}_j^{dmt}[\kappa]$ is similarly defined as $\mathbf{z}_j^{dmt}[\kappa]$ and $\mathbf{G}_j^{dmt}$ is the $P \times P$ channel matrix for the jth user, given by

$$\mathbf{G}_j^{dmt} = \mathbf{G}_{j,0}^{dmt} + \bar{\mathbf{G}}_{j,1}^{dmt} =$$  . (3)

Note that if the additive noise $e[n]$ is zero-mean white with variance σ_e^2, we obtain

$$\mathbf{R}_{\mathbf{n}_j^{dmt}} = \mathrm{E}\{\mathbf{n}_j^{dmt}[\kappa]\mathbf{n}_j^{dmtH}[\kappa]\} = 2\eta\sigma_e^2 \mathbf{I}_P.$$

We then perform a discrete Fourier transform (DFT) on $\mathbf{z}_j^{dmt}[\kappa]$:

$$\begin{aligned}\tilde{\mathbf{z}}_j^{dmt}[\kappa] &= 1/\sqrt{P}\mathcal{F}_P \mathbf{z}_j^{dmt}[\kappa] \\ &= \eta \mathcal{F}_P \mathbf{G}_j^{dmt} \mathcal{I}_P \tilde{\mathbf{r}}_j^{dmt}[\kappa] + 1/\sqrt{P}\mathcal{F}_P \mathbf{n}_j^{dmt}[\kappa].\end{aligned}$$

Because $\mathbf{G}_j^{dmt}$ is a circular matrix (see (3)), it is then clear that the inter-tone interference (ITI) is completely removed:

$$\tilde{\mathbf{z}}_j^{dmt}[\kappa] = \eta \mathrm{diag}\{\mathcal{F}_P \mathbf{g}_j^{dmt}\} \tilde{\mathbf{r}}_j^{dmt}[\kappa] + 1/\sqrt{P}\mathcal{F}_P \mathbf{n}_j^{dmt}[\kappa],$$

where $\mathrm{diag}\{\mathbf{x}\}$ represents a square diagonal matrix with $\mathbf{x}$ as diagonal and $\mathbf{g}_j^{dmt}$ is the $P \times 1$ channel vector for the jth user, given by

$$\mathbf{g}_j^{dmt} = \begin{bmatrix} g_j[0] & g_j[1] & \cdots g_j[P-1] \end{bmatrix}^T.$$

Finally, every tone is rotated and scaled in the appropriate way by means of a linear 1-tap frequency domain equalizer (FEQ). As an estimate for $\tilde{\mathbf{s}}_j^{dmt}[\kappa]$, we then obtain

$$\begin{aligned}\hat{\tilde{\mathbf{s}}}_j^{dmt}[\kappa] &= \mathbf{\Lambda}_j \tilde{\mathbf{z}}_j^{dmt}[\kappa] \\ &= \eta \mathbf{\Lambda}_j \mathrm{diag}\{\mathcal{F}_P \mathbf{g}_j^{dmt}\} \tilde{\mathbf{s}}_j^{dmt}[\kappa] \\ &\quad + 1/\sqrt{P}\mathbf{\Lambda}_j \mathcal{F}_P \mathbf{n}_j^{dmt}[\kappa],\end{aligned}$$

where $\mathbf{\Lambda}_j$ is a $P \times P$ diagonal matrix whose diagonal elements are the linear 1-tap FEQ's for the jth user. We can use zero-forcing (ZF) or minimum mean-square error (MMSE) linear 1-tap FEQ's. However, if the DMT subsymbol sequences $\{\tilde{s}_{j,p}[\kappa]\}_{p=1}^P$ are PSK-modulated and the additive noise $e[n]$ is zero-mean white with variance σ_e^2 ($\mathbf{R}_{\mathbf{n}_j^{dmt}} = 2\eta\sigma_e^2\mathbf{I}_P$), the ZF and MMSE linear 1-tap FEQ's for the jth user have the same performance and can, without any loss in performance, be replaced by

$$\mathbf{\Lambda}_j = \mathrm{diag}\{\mathcal{F}_P \mathbf{g}_j^{dmt}\}^H.$$

The proposed receiver is depicted in figure 2.

4. SIMULATION RESULTS

In this section we perform some simulations on a DMT-CDMA system based on block spreading and a classical DMT-CDMA system. For the DMT-CDMA system based on block spreading as well as for the classical DMT-CDMA system, we consider $J = 8$ users, DMT symbol size $P = 8$ and spreading factor $N = 17$. We design a shift-orthogonal set of J length-N BPSK code sequences $\{c_j[n]\}_{j=1}^J$, as explained in [5]. We assume that the channels $\{g_j[n]\}_{j=1}^J$ are causal of order 3. For the DMT-CDMA system based on block spreading we take block size $L = 4$ (hence, assumptions 1 and 2 are satisfied). We assume that the additive noise $e[n]$ is zero-mean white Gaussian with variance σ_e^2. Introducing the $P \times P$ diagonal matrix

$$\mathbf{P}_j = \mathrm{diag}\{\mathcal{F}_P \mathbf{g}_j^{dmt}\}^H \mathrm{diag}\{\mathcal{F}_P \mathbf{g}_j^{dmt}\},$$

we define the received energy per DMT symbol period (T^{dmt}) for the jth user as

$$E_j^{dmt} = \mathrm{E}\{\tilde{\mathbf{s}}_j^{dmtH}[\kappa]\mathbf{P}_j \tilde{\mathbf{s}}_j^{dmt}[\kappa]\}.$$

We then define the signal-to-noise ratio (SNR) for the jth user at the input of the receiver as

$$SNR_j = \frac{E_j^{dmt}}{P\sigma_e^2}.$$

We consider two scenarios:

1. Every DMT subsymbol sequence $\tilde{s}_{j,p}[\kappa]$ is QPSK-modulated with variance 1. Note that E_j^{dmt} then becomes
$$E_j^{dmt} = P\|\mathbf{g}_j^{dmt}\|^2.$$
2. Every DMT subsymbol sequence $\tilde{s}_{j,p}[\kappa]$ is QPSK-modulated with variance $\|\mathbf{g}_j^{dmt}\|^2\mathbf{P}_j^{-1}(p,p)$. Note that E_j^{dmt} then again becomes
$$E_j^{dmt} = P\|\mathbf{g}_j^{dmt}\|^2.$$

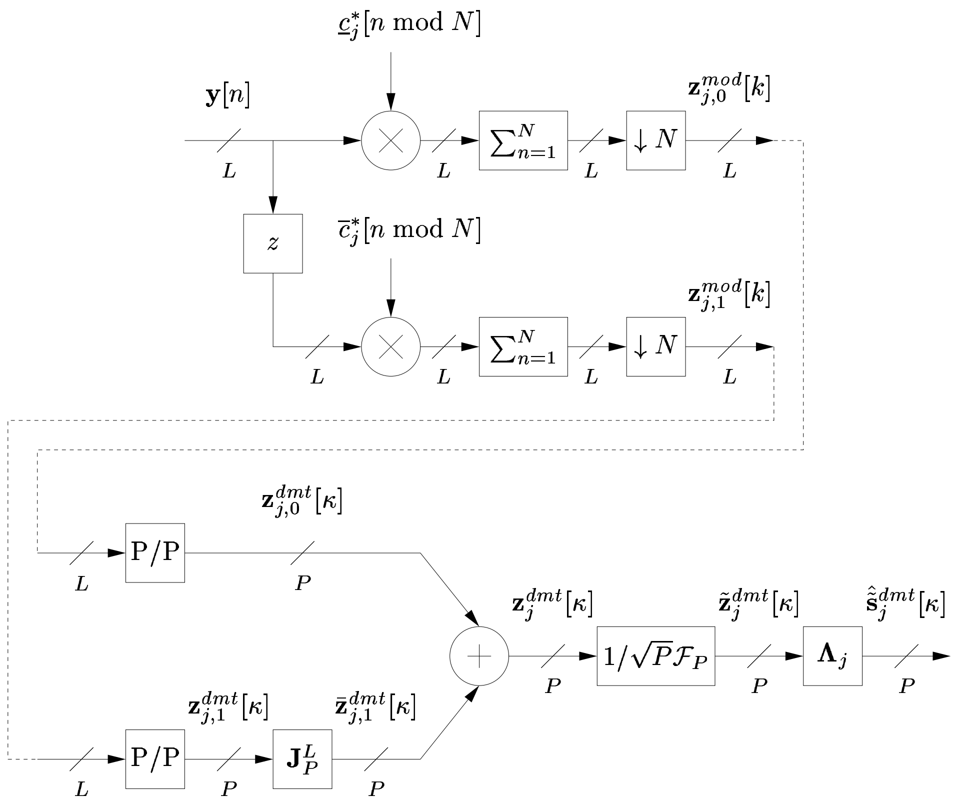


Figure 2: Proposed receiver.

Note that the second scenario does not require a feedback path from the receiver to the transmitter, if we consider a time division duplexing (TDD) approach (uplink and downlink channels are the same), while it does require a feedback path from the receiver to the transmitter, if we consider a frequency division duplexing (FDD) approach (uplink and downlink channels are different). Obviously, the first scenario does not require a feedback path, irrespective of the type of duplexing. We will always assume that

$$E_j^{dmt} = E_{j'}^{dmt}, \quad \text{for } j, j' = 1, 2, \ldots, J.$$

We now compare the proposed receiver for the DMT-CDMA system based on block spreading with a linear multi-user equalizer for the classical DMT-CDMA system. The linear multi-user equalizer we consider here is the zero-forcing (ZF) linear multi-user equalizer of length $N - 3$ (we choose this length because the channels $\{g_j[n]\}_{j=1}^J$ are causal of order 3). For all simulations we conduct 5000 trials using bursts of $K = 200$ data symbols. Figure 3 shows the average BER per user as a function of the SNR. For scenario 1, the proposed receiver performs worse than the linear multi-user equalizer. However, if we switch from scenario 1 to scenario 2, the performance of the proposed receiver improves, while the performance of the linear multi-user equalizer deteriorates. As a result, the performance of the proposed receiver for scenario 2 (good scenario for this type of receiver) is comparable with the performance of the linear multi-user equalizer for scenario 1 (good scenario for this type of receiver).

5. CONCLUSIONS

In this paper we have presented a new receiver for a DMT-CDMA system based on block spreading that completely suppresses the MUI and ITI, without using any channel information. This total suppression of MUI and ITI is obtained by the use of a shift-orthogonal set of code sequences, on which the proposed receiver is based. We have illustrated that the performance of the proposed receiver for a DMT-CDMA system based on block spreading, considering a scenario where the power of each tone is adjusted to the power of the channel at the corresponding frequency (good scenario for this type of receiver), is comparable to the performance of a linear multi-user equalizer for a classical DMT-CDMA system, considering a scenario where the power of each tone is the same (good scenario for this type of receiver).

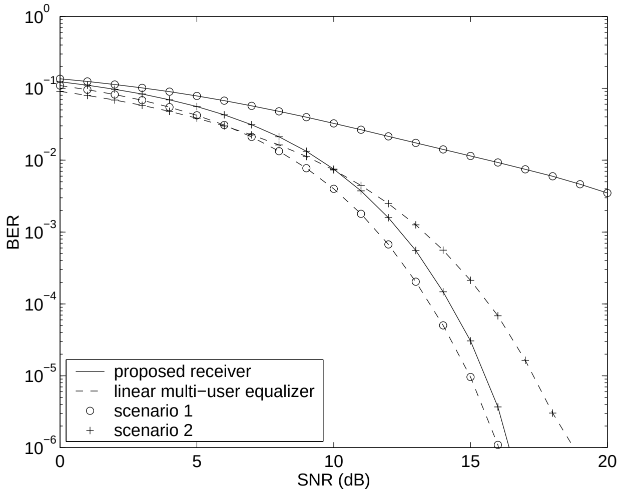


Figure 3: Average BER per user versus SNR.

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