FREQUENCY DOMAIN MULTIUSER DETECTORS FOR ULTRA-WIDEBAND SHORT-RANGE COMMUNICATIONS

Simone Morosi, Tiziano Bianchi

Dipartimento di Elettronica e Telecomunicazioni, University of Florence
Via S. Marta 3, 50139, Firenze, Italy - Tel/Fax: +39 055 4796485
e-mail: {morosi, bianchi}@lenst.det.unifi.it)

ABSTRACT

In this paper, we propose an original multiuser detector for high rate short-range impulse radio ultra-wideband systems. The proposed receiver relies on both the introduction of the cyclic prefix at the transmitter and the use of a frequency domain multiuser detector at the receiver. Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) detection strategies have been investigated and compared with the classical RAKE, considering a scenario where several mobile terminals transmits to a base station in an indoor environment characterized by severe multipath propagation. The results show that the MMSE receiver achieves the best performance, irrespective of the number of active terminals.

1. INTRODUCTION

Recently, Impulse Radio communication systems [1] have been the subject of a massive research activity: these systems rely on the use of baseband pulses of very short duration and are considered as one of the candidates for the future Ultra-wideband (UWB) radio systems [2]. In particular, UWB-IR communications have been considered for their low power spectral density and for the moderate interference upon the narrow band systems operating in the licensed bands: these features are particularly interesting for future high rate short-range radio applications. Conversely, the short duration of the pulses increases considerably the multipath resolution [3]: hence, UWB-IR has to face an extremely frequency-selective channel.

IR multiuser communication systems rely on the use of Time Hopping (TH) spread-spectrum signals and impulsive modulation techniques such as Pulse Position Modulation (PPM) [1]. In these systems the same symbol is repeated many times, according to a specific random code, so providing a high processing gain. Hence, RAKE receivers has been taken into account as one of the most suitable solution for this kind of communications. Nevertheless, these receivers are vulnerable to Multiple Access Interference (MAI) with remarkable losses in terms of performance and system capacity also for a moderate number of active interfering users. This problem is particularly harmful in the case of asynchronous systems [4], e.g, the uplink between the Mobile Terminals (MTs) and the Access Point (AP).

This work was supported by Italian National Research Program VICOM

Many alternative strategies can be adopted for facing the channel impairments in radio systems: Frequency Domain Equalization (FDE) [5], proposed and studied for a single-carrier single-user environment, can be applied to multiuser short-range IR communications, affording a good complexity/performance trade off.

In this paper, an original Frequency Domain Multiuser Detector (FDMUD) for UWB-IR short-range multiuser communications will be proposed and simulated in an extremely frequency selective environment, aiming to highlight how the orthogonality loss and the rise of both Self Inteference and MAI can be effectively coped with. Particular attention will be dedicated to the maximum number of users that can be correctly detected by the FDMUD and by the conventional RAKE receiver.

2. SYSTEM MODEL

In the uplink of an UWB-IR communication system, the signal which is transmitted by the ℓth user is [6]

$$s_\ell(t) = \sum_{m=-\infty}^{+\infty} w_{tx}(t - mT_f - c_\ell(m)T_c - \tau(b_\ell(\lfloor m/N_f \rfloor)) - \tau_\ell) \tag{1}$$

where T_f and T_c are the frame and the chip periods, respectively, and $b_\ell(i) = \pm 1$ is the ith binary symbol transmitted by the ℓth user. In particular, since $\lfloor x \rfloor$ stands for the integer part of x, eq. (1) indicates that the same bit is transmitted over N_f consecutive frame periods. We assume that N_c chips exactly fit in one frame period, i.e., $T_f = N_c T_c$. Each active user is associated with a time-hopping pattern $c_\ell(m)$. In the most general case, $c_\ell(m)$ can be modeled as a periodic pseudo-random sequence with period N_f. Pulse position modulation is implemented by means of an additional pulse shift $\tau(b)$. In the binary case, we have $\tau(b) = \{0, T_w\}$

depending on $b = \{1, -1\}$, where $T_w = T_c/2$. Finally, we suppose that each user transmits with a different delay τ_ℓ.

The signal transmitted by the ℓth user can be represented more conveniently as

$$s_\ell(t) = \sum_{k=-\infty}^{+\infty} w_{tx}(t - kT_w - \tau_\ell) \left[q_\ell(k) b_\ell(\lfloor k/N_w \rfloor) + p_\ell(k)\right] \tag{2}$$

where $N_w = 2N_c N_f$ and we define

$$q_\ell(k) = \begin{cases} \frac{1}{2} & \text{if } k = 2[mN_c + c_\ell(m)] \\ -\frac{1}{2} & \text{if } k = 2[mN_c + c_\ell(m)] + 1 \\ 0 & \text{elsewhere} \end{cases} \tag{3}$$

and $p_\ell(k) = |q_\ell(k)|$. In particular, both $q_\ell(k)$ and $p_\ell(k)$ are periodic with period equal to N_w. If we consider a set of N_u active users $I_u = \{\ell_1, \ell_2, \ldots, \ell_{N_u}\}$, the signal which is received by the base station after matched filtering is

$$r(t) = \sum_{\ell \in I_u} \sum_{k=-\infty}^{+\infty} \phi_\ell(t - kT_w - \tau_\ell) x_\ell(k) + n(t), \tag{4}$$

where $\phi_\ell(t) = w_{rx}(t) * g_\ell(t) * w_{tx}(t)$, $w_{rx}(t)$ is the impulse response of the filter matched to the received pulse waveform, $g_\ell(t)$ models the effects of both the antennas and the multipath channel relative to the ℓth user, $n(t)$ models the thermal noise and $x_\ell(k) \triangleq [q_\ell(k) b_\ell(\lfloor k/N_w \rfloor) + p_\ell(k)]$. We express the delay of the ℓth user as $\tau_\ell = d_\ell T_w + \delta_\ell$. If we sample $r(t)$ with period T_w, then a full digital transmission model can be obtained as

$$y(n) \triangleq r(nT_w) = \sum_{\ell \in I_u} \sum_{k=-\infty}^{+\infty} h_\ell(n - k - d_\ell) x_\ell(k) + e(n), \tag{5}$$

where $h_\ell(n) \triangleq \phi_\ell(nT_w - \delta_\ell)$ represents the equivalent discrete time channel impulse response of the UWB-IR system relative to the ℓth user and $e(n) \triangleq n(nT_w)$. The above equation can be expressed in a more convenient form as

$$y(n) \triangleq r(nT_w) = \sum_{\ell \in I_u} \sum_{k=-\infty}^{+\infty} h'_\ell(n - k) x_\ell(k) + e(n), \tag{6}$$

where for each user ℓ we consider the equivalent channel $h'(n) \triangleq h(n - d_\ell)$. In (6), the effect of the different delays τ_ℓ is modeled by the increased maximum delay spread of each equivalent channel response.

2.1. Block Representation

Let us subdivide the discrete signal $x_\ell(n)$ in blocks of M samples. In the following, we will assume $M = N_b N_w$, so that a group of N_b bits is exactly spread over a block of M samples. We define the vector $\mathbf{x}_\ell(i) = [x_\ell(iM), x_\ell(iM + 1), \ldots, x_\ell(iM + M - 1)]^T$, consisting of the samples of the signals transmitted by the ℓth user: the samples are relative to the bits in the ith block. We can express $\mathbf{x}_\ell(i)$ as

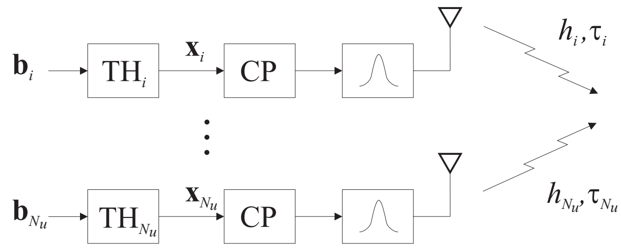

Fig. 1. Block representation of the N_u UWB-IR MPs transmitting asynchronously.

$$\mathbf{x}_\ell(i) = \left[b_\ell(iN_b)\mathbf{q}_\ell^T + \mathbf{p}_\ell^T, \ldots, b_\ell(iN_b + N_b - 1)\mathbf{q}_\ell^T + \mathbf{p}_\ell^T\right]^T \tag{7}$$

where $\mathbf{q}_\ell = [q_\ell(0),\ q_\ell(1),\ \ldots,\ q_\ell(N_w - 1)]^T$ and $\mathbf{p}_\ell = [p_\ell(0),\ p_\ell(1),\ \ldots,\ p_\ell(N_w - 1)]^T$. If we define the vector of the bits transmitted to the ℓth user in the ith block as $\mathbf{b}_\ell(i) = [b_\ell(iN_b), b_\ell(iN_b + 1), \ldots, b_\ell(iN_b + N_b - 1)]^T$, eq. (7) can be rewritten in a more compact form as

$$\mathbf{x}_\ell(i) = \boldsymbol{\mathcal{Q}}_{\ell,M} \mathbf{b}_\ell(i) + \boldsymbol{p}_{\ell,M}, \tag{8}$$

where $\boldsymbol{\mathcal{Q}}_{\ell,M} = \mathbf{I}_{N_b} \otimes \mathbf{q}_\ell$, $\boldsymbol{p}_{\ell,M} = \mathbf{1}_{N_b} \otimes \mathbf{p}_\ell$, $\otimes$ indicates Kronecker product and $\mathbf{1}_{N_b}$ is an all-ones vector of size N_b.

In order to perform FDE [5], each block is extended by means of a cyclic prefix of length K.If $K \geq L'_\ell$ for each ℓ, where L'_ℓ indicates the lenght of the equivalent digital channel $h'_\ell(n)$, then the channel does not cause any interference between adjacent blocks and for each active user the effect of UWB-IR channel can be modeled as a circular convolution between the channel impulse response and the block of M samples. Hence, if we define the received vector after cyclic prefix removal as $\mathbf{y}(i) = [y(iM), y(iM + 1), \ldots, y(iM + M - 1)]^T$, then the input-output relation of the UWB-IR system with cyclic prefix can be expressed as

$$\mathbf{y}(i) = \sum_{\ell \in I_u} \boldsymbol{\mathcal{H}}_\ell \mathbf{x}_\ell(i) + \mathbf{e}(i), \tag{9}$$

where $\boldsymbol{\mathcal{H}}_\ell$ are circulant matrices which model the channel effects on the ℓth user and $\mathbf{e}(i) = [e(iM), e(iM + 1), \ldots, e(iM + M - 1)]^T$.

3. RECEIVER SCHEMES

3.1. RAKE

The decision variable for a RAKE receiver using maximum ratio combining (MRC) can be expressed as

$$v_\ell^{RAKE}(i) = \sum_{k \in I_{rp}} h_\ell^*(k - d_\ell) z_\ell(i, k) \tag{10}$$

where with I_{rp} we indicate the set of the resolvable channel paths and we let $z_\ell(i,k) = \sum_{r=0}^{N_f-1}[y(2(N_c(iN_f + r) + c_\ell(r)) + k) - y(2(N_c(iN_f + r) + c_\ell(r)) + k + 1)]$. Finally, the value of the ith bit received by the ℓth user is decided according to the sign of $v_\ell(i)$.

3.2. Frequency Domain Detection

Frequency domain detection (FDD) [5] is a possible solution to the inter-path interference which is caused by the autocorrelation functions of the time-hopping sequences. Consider the block model in (9). Since matrix $\boldsymbol{\mathcal{H}}_\ell$ is circulant, it can be diagonalized by using a Discrete Fourier Transform (DFT) as $\boldsymbol{\mathcal{H}}_\ell = \mathbf{W}_M^H \mathbf{\Lambda}_\ell \mathbf{W}_M$, where $\mathbf{W}_M$ is an $M \times M$ Fourier transform matrix and $\mathbf{\Lambda}_\mathcal{H}$ is a $M \times M$ diagonal matrix whose entries represent the channel frequency response. Therefore, (9) can be expressed as a function of $\mathbf{\Lambda}_\ell$ as

$$\mathbf{y}(i) = \mathbf{W}_M^H \sum_{\ell \in I_u} \mathbf{\Lambda}_\ell \mathbf{W}_M \left[\boldsymbol{\mathcal{Q}}_{\ell,M} \mathbf{b}_\ell(i) + \boldsymbol{p}_{\ell,M}\right] + \mathbf{e}(i). \tag{11}$$

In the single user case, FDD alone is able to eliminate inter-path interference. However, when several active users are considered, the different channel responses cause a loss of orthogonality among users and a more sophisticated multiuser detection (MUD) approach is needed in order to face inter-user interference. Let us rewrite (11) as

$$\mathbf{y}(i) = \mathbf{W}_M^H \left[\mathbf{\Phi} \boldsymbol{b}(i) + \boldsymbol{\omega}\right] + \mathbf{e}(i) \tag{12}$$

where $\mathbf{\Phi} \triangleq [\mathbf{\Lambda}_1 \mathbf{W}_M \boldsymbol{\mathcal{Q}}_{1,M}, \ldots, \mathbf{\Lambda}_{N_u} \mathbf{W}_M \boldsymbol{\mathcal{Q}}_{N_u,M}]$, $\boldsymbol{\omega} \triangleq \sum_{\ell \in I_u} \mathbf{\Lambda}_\ell \mathbf{W}_M \boldsymbol{p}_{\ell,M}$ and $\boldsymbol{b}(i) \triangleq \left[\mathbf{b}_1^T(i), \ldots, \mathbf{b}_{N_u}^T(i)\right]^T$. Relying on the model in (11), a frequency domain MUD (FD-MUD) approach can be derived. The vector of the decision variables for all active users, indicated as $\boldsymbol{v}(i) = [\mathbf{v}_1^T(i), \ldots, \mathbf{v}_{N_u}^T(i)]^T$, can be expressed in a general form as

$$\boldsymbol{v}(i) = \boldsymbol{\mathcal{A}} \mathbf{\Phi}^H \left[\mathbf{W}_M \mathbf{y}(i) - \boldsymbol{\omega}\right] \tag{13}$$

where $\boldsymbol{\mathcal{A}}$ represents a decorrelating block that is designed according to the selected criterion (see Fig. 2). In this paper, we will focus on two linear decorrelating criteria, Zero Forcing (ZF) and Minimum Mean Squared Error (MMSE), due their good tradeoff between performance and complexity. The ZF detector is implemented by letting $\boldsymbol{\mathcal{A}}$ equal to the inverse of the users' autocorrelation matrix, i.e.,

$$\boldsymbol{\mathcal{A}}^{ZF} = \left(\mathbf{\Phi}^H \mathbf{\Phi}\right)^{-1}. \tag{14}$$

In this case, the effect of the different channels is exactly compensated and if we use orthogonal time hopping sequences, also MAI can be completely eliminated. Nevertheless, it is well known that this solution amplifies the noise at the receiver, and hence a performance degradation for low SNR values is expected.

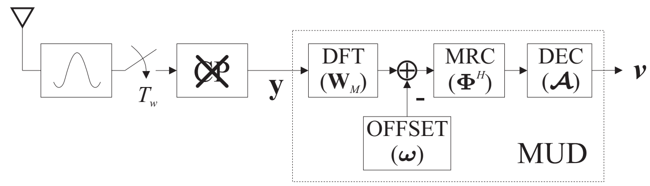

Fig. 2. Block representation of the AP receiver using multi-user detection.

The expression of $\boldsymbol{\mathcal{A}}$ for the MMSE detector is given by

$$\boldsymbol{\mathcal{A}}^{MMSE} = \left(\mathbf{\Phi}^H \mathbf{\Phi} + \frac{\sigma_e^2}{\sigma_b^2} \mathbf{I}_{N_b N_u}\right)^{-1}. \tag{15}$$

where σ_e^2 is the noise variance and σ_b^2 indicates the power of transmitted symbols. This solution avoids noise amplification at the detector when the SNR is low.

4. SIMULATION RESULTS

The proposed receivers have been tested by simulating a short-range UWB-IR link between a variable number of MTs and an AP. All users are assumed to be not farther than 7 meters from the AP. Hence, the maximum round trip delay is equal to 50 ns: since the pulse duration T_w is equal to 2 ns, this delay corresponds to 25 samples of the received signal.

The information bits are modulated by means of a 2-PPM and repeated over $N_f = 4$ frames each consisting of $N_c = 4$ chips, resulting in an uncoded rate of 15.6 Mbit/s.

The channel has been simulated according to the model in [3], yielding a digital channel model with 100 sample-spaced resolvable replicas. When using FDMUD, each block of $M = 1024$ samples is extended by means of a cyclic prefix of 128 samples, so that the channel and the lack of synchronism do not cause any interference between adjacent blocks. The bit error rate (BER) for the system using RAKE receiver and the systems using FDD with ZF equalization (FDD-ZF) and MMSE equalization (FDD-MMSE) has been evaluated by averaging over 10000 independent channel realizations. Perfect knowledge of the channel parameters has been assumed.

In Fig. 3 we show the comparison of BER performance vs E_b/N_0 ratio for a single user communication: though no multiple access interference has been introduced, the long delay spread of the multipath components cause a remarkable level of self-interference which limits the RAKE receiver performance. On the other hand, both FDMUD receivers are effective in facing channel impairments.

In Fig. 4 we consider a multiuser environment where a fully loaded UWB-IR system with 4 users is simulated. While the RAKE receiver performance is greatly impaired and the error floor is evident also for medium to low E_b/N_0

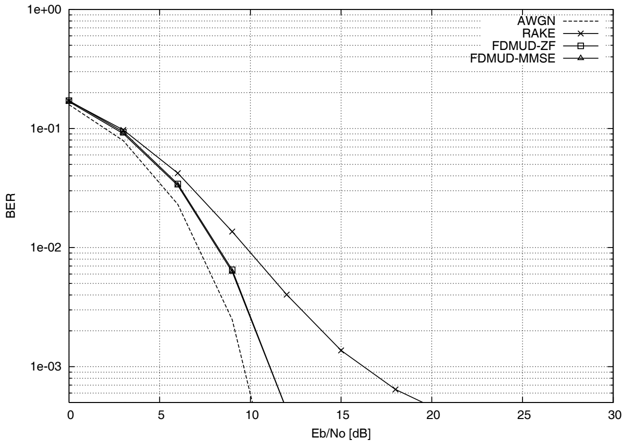

Fig. 3. Performance comparison for $N_u = 1$.

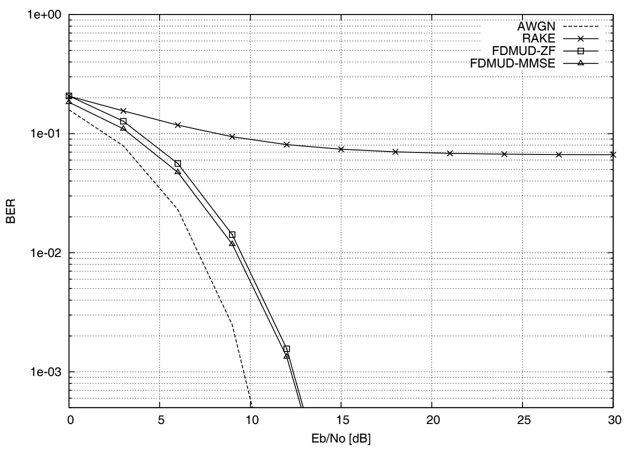

Fig. 4. Performance comparison for $N_u = 4$.

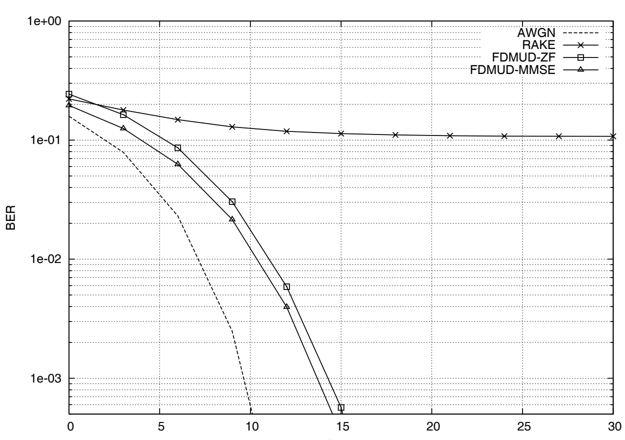

Fig. 5. Performance comparison for $N_u = 8$.

values,both FDMUD strategies are able to restore the orthogonality between users, since they perfectly compensates the effects of the channel and suppress the MAI.

Finally, in Fig. 5 the BER performance of the considered systems is shown in the case of system with 8 active users. In this case, the performance of both FDMUD detectors is only slightly impaired by the MAI. In particular, FDMUD-ZF performance is limited by noise enhancement, while FDMUD-MMSE performance is nearly the same of the single user case with great performance gain. Note that the performance of a correlation receiver for a single-user UWB-IR system in an AWGN channel with no multipath is reported for comparison in all the Figures.

5. CONCLUSIONS

In this paper, we proposed an original frequency domain multiuser detection strategy for high rate short-range impulse radio ultra-wideband systems. Detection strategies based on either the ZF or the MMSE criteria have been investigated. The proposed detectors have been compared with the classical RAKE, in a scenario where several mobile terminals transmit to an access point through a severe multipath channel. Simulation results have shown that both the FDMUD strategies are able to suppress the MAI. We found that the FDMUD-MMSE receiver achieves the best performance for any configuration of active terminals.

6. REFERENCES

[1] Moe Z. Win and Robert A. Scholtz, “Impulse radio: How it works,” *IEEE Commun. Lett.*, vol. 2, no. 2, pp. 36–38, Feb. 1998.

[2] D. Porcino and W. Hirt, “Ultra-wideband radio technology: potential and challenges ahead,” *IEEE Commun. Mag.*, vol. 41, no. 7, pp. 66–74, Jul. 2003.

[3] Dajana Cassioli, Moe Z. Win, and Andreas F. Molisch, “The ultra-wide bandwidth indoor channel: From statistical model to simulations,” *IEEE J. Select. Areas Commun.*, vol. 20, no. 6, pp. 1247–1257, Aug. 2002.

[4] S. Verdu, *Multiuser Detection*, Cambridge, UK: Cambridge Univ. Press, 1998.

[5] D. Falconer, S. L. Ariyavisitakul, A. Benyamin-Seeyar, and B. Eidson, “Frequency domain equalization for single-carrier broadband wireless systems,” *IEEE Commun. Mag.*, vol. 40, no. 4, pp. 58–66, Apr. 2002.

[6] Christophe J. Le Martret and Georgios B. Giannakis, “All-digital impulse radio with multiuser detection for wireless cellular systems,” *IEEE Trans. Commun.*, vol. 50, no. 9, pp. 1440–1450, Sept. 2002.