AN ITERATIVE FREQUENCY-DOMAIN LAYERED SPACE-TIME RECEIVER FOR SDMA SYSTEMS WITH SINGLE-CARRIER TRANSMISSION

Reza Kalbasi[1], *Rui Dinis*[2], *David Falconer*[1] *and, Amir Banihashemi*[1]

[1]BCWS Centre, Carleton University, Ottawa, Canada, {kalbasi, ddf, ahashemi}@sce.carleton.ca
[2]CAPS-IST, Tech. Univ. of Lisbon, Portugal, rdinis@ist.utl.pt

ABSTRACT

The use of multiple antennas at the BS (Base Station) allows significant improvements on the spectral efficiency of wireless communications systems by increasing the number of simultaneous users on a given cell.

In this paper we introduce a new iterative multiuser detection scheme for systems requiring high-rate transmission in severe time-dispersive channels. We consider the use of single-carrier modulations combined with frequency-domain equalization techniques, which are known to be excellent candidates for severe time-dispersive channels. The BS employs multiple antennas and consists of an iterative LST (Layered Space-Time) receiver combined with frequency-domain equalization techniques.

Our performance results show that the proposed receiver structure has excellent performance, which can be very close to the matched filter bound, even for severe time-dispersive channels and in the presence of strong interfering channels.

1. INTRODUCTION

Future wireless systems are required to support high quality of service at high data rates. Moreover, due to power and bandwidth constraints, these systems are also supposed to operate with small transmit powers, especially at the MTs, (Mobile Terminals) and to have high spectral efficiencies.

By using SDMA (Space-Division Multiple Access) techniques employing multiple receive antennas at the BS (Base Station) we can increase the number of simultaneous users in a given cell [1]. These MIMO techniques (Multi-Input Multi-Output) allow significant increase in the system spectral efficiency, while reducing the transmit power requirements for the MTs.

For such high data rates, we can have severe time-dispersion effects associated with the multipath propagation. In this case, conventional time-domain equalization schemes are not practical, since the signal processing requirements can be very high. This is especially serious when time-domain equalization methods are employed in high data rate, MIMO systems [2].

The block transmission techniques, with appropriate cyclic prefix and frequency-domain equalization schemes, were shown to be a better alternative for severe time-dispersive channels, allowing superior performance with a lower implementation complexity. The OFDM (Orthogonal Frequency Division Multiplexing) modulations is the most popular block transmission technique. SC (Single Carrier) modulations using FDE (Frequency-Domain Equalization) are an attractive alternative approach based on this principle. As with OFDM modulations, the data blocks are preceded by a cyclic prefix, long enough to cope with the channel length. The received signal is transformed to the frequency domain, equalized in the frequency domain and then transformed back to the time domain. This SC approach with FDE has the same overall complexity as OFDM. However, the SC schemes have lower envelope fluctuations than the corresponding OFDM schemes, while offering similar, or even better, performance [3].

Recently, a new SC system with decision feedback equalization has been proposed for Single-Input Single-Output (SISO) channels [4, 5]. This frequency domain DFE was extended to MIMO systems in [6]. However, as with conventional, time-domain DFE, it can suffer from error propagation, especially for long feedback filters. The IB-DFE (Iterative Block DFE) schemes are a promising approach for SC transmission, with very good performance and alleviating the error propagation effects [7, 8].

This paper deals with multiuser scenarios in severe time dispersive channels, with a single-carrier modulation employed by each user in the uplink. We combine the IB-DFE ideas of [7, 8] with the LST principles of [9] to define a class of frequency domain MIMO receivers, with iterative LST multiuser detection. Our approach is to consider each user as a layer and then cancel the ISI and the multi-user interference, layer by layer. At each iteration, the a-priori knowledge of the estimated layers (users) from the previous iteration is employed.

This paper is organized as follows. The proposed iterative LST multiuser receiver is described in Section 2. Section 3 presents a set of performance results. Finally, section 4 is concerned with the conclusions of the paper.

2. ITERATIVE LST MULTIUSER DETECTION

2.1. System Model

We consider an uplink single-carrier MIMO system with P users, transmitting independent data blocks, and N receive antennas at the BS, as depicted in figure 1. The time-domain block transmitted by the pth user is $\{s_{m,p}; m = 0, 1, \ldots, M-1\}$, with $s_{m,p}$ denoting the mth data symbol of the pth user, which is selected from a given constellation (e.g., a QPSK constellation) under an appropriate mapping rule. A cyclic prefix (CP), preceding each block, is used to avoid interblock interference and to make the linear convolution associated with the channel equivalent to a cyclic convolution, with respect with the useful, M-length, part of the block. At the receiver, the CP is discarded.

The time-domain block at the nth receive antenna is $\{y_m^{(n)}; m = 0, 1, \ldots, M-1\}$. The corresponding frequency-domain block, obtained after an appropriate DFT (Discrete Fourier Transform)

0-7803-8484-9/04/$20.00 ©2004 IEEE

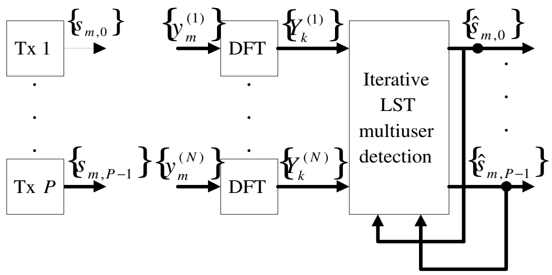

Fig. 1. System model

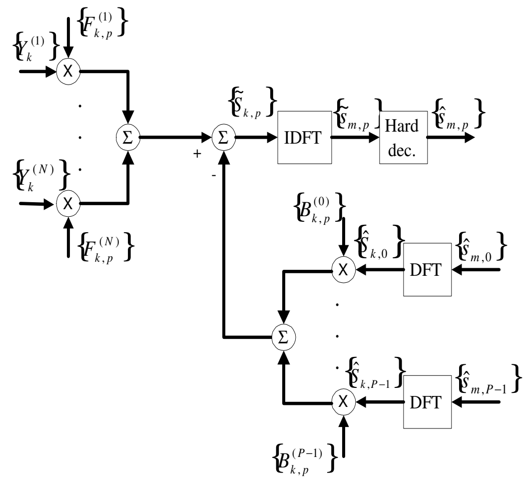

Fig. 2. Detection of the pth layer, for a given iteration

operation, is $\{Y_k^{(n)}; k = 0, 1, \ldots, M-1\}$, where

$$Y_k^{(n)} = \sum_{p=0}^{P-1} S_{k,p} H_{k,p}^{(n)} + N_k^{(n)}, \tag{1}$$

with block $\{S_{k,p}; k = 0, 1, \ldots, M-1\}$ denoting the DFT of the block $\{s_{m,p}; m = 0, 1, \ldots, M-1\}$. $\{H_{k,p}^{(n)}\}$ and $\{N_k^{(n)}\}$ ($k = 0, 1 \ldots, M-1$) denote the DFT of channel impulse response from user p to the nth antenna, and the DFT of the noise at the nth antenna, respectively.

2.2. Receiver Structure

We consider a frequency-domain iterative multiuser receiver that combines IB-DFE principles [7, 8] with LST interference cancelation [9], each iteration consisting of P detection stages, one for each user.

Following the common conventions for LST receivers, the data blocks for the different users are regarded as layers. To detect a particular layer, the other layers are considered as interferers. For the first iteration and the detection of a given layer, the interference from previously detected layer is canceled, as with conventional wide band LST receivers [10]. However, contrarily to conventional broadband LST receivers, this interference cancelation takes into account the reliability of each of the previously detected layers. For the remaining iterations, we cancel the interference from all users (using the most updated version of each layer), as well as the residual ISI from the layer that is being detected. This means that the proposed receiver structure can be regarded as a serial multiuser detection scheme, with interference and residual ISI cancelation.

For a given iteration, the receiver structure for the detection of the pth layer is illustrated in figure 2. We have N frequency-domain feedforward filters and P frequency-domain feedback filters. The feedforward filters are designed to minimize both the ISI and the interference that cannot be canceled by the feedback filters, due to decision errors in the previous detection steps. This structure can be regarded as an equalizer capable of combating the ISI and with interference suppression properties.

After an IDFT operation, the corresponding time-domain outputs are passed through a decision device so as to estimate the transmitted layer. At the next iteration, these steps are repeated with a-priori knowledge of the estimated layers from the previous detection steps. The detection procedure can be summarized as follows:

- First iteration:
  (1) Detect layer 0.
  (2) Detect layer 1 by (partially) removing the interference from user 0.
  (3) Detect layer 2 by (partially) removing the interference from layers 0 and 1.
  (4) Proceed until the detection of layer $P-1$.
- Remaining iterations
  (1) Repeat the detection of layer 0, now removing the interference from all layers ($p \neq 0$) and the residual ISI ($p = 0$).
  (2) Repeat the detection of layer 1, now removing the interference from all layers ($p \neq 1$) and the residual ISI ($p = 1$).
  (3) Proceed until the detection of layer $P-1$.

2.3. Derivation of the Coefficients

The frequency-domain samples associated with the pth user at the output of the equalizer are given by

$$\begin{aligned}\tilde{S}_{k,p} &= \sum_{n=1}^{N} F_{k,p}^{(n)} Y_k^{(n)} - \sum_{p'=0}^{P-1} B_{k,p}^{(p')} \hat{S}_{k,p'} = \\ &= \sum_{n=1}^{N} F_{k,p}^{(n)} Y_k^{(n)} - B_{k,p}^{(p)} \hat{S}_{k,p} - \sum_{p' \neq p} B_{k,p}^{(p')} \hat{S}_{k,p'} \end{aligned} \tag{2}$$

where $F_{k,p}^{(n)}$ ($k = 0, 1, \ldots, M-1$, $n = 1, 2, \ldots, N$) denotes the kth feedforward coefficients at antenna n and $B_{k,p}^{(p')}$ ($k = 0, 1, \ldots, M-1$, $p' = 0, 1, \ldots, P-1$) denotes the kth feedback coefficient, associated with the pth user. The frequency-domain block $\{\hat{S}_{k,p'}; k = 0, \ldots, M-1\}$ is the DFT of the block $\{\hat{s}_{m,p'}; m = 0, \ldots, M-1\}$, with $\hat{s}_{m,p'}$ denoting the hard decision estimates for the p'th user transmitted symbols, associated with the ith iteration for $p' < p$ and to $i-1$ iteration for $p' \geq p$ (for the first iteration, $\hat{s}_{m,p'} = 0$ for $p' \geq p$).

The symbol estimates $\hat{s}_{m,p}$ at the output of equalizer can be written as

$$\hat{s}_{m,p} = \rho_p s_{m,p} + \delta_{m,p}, \quad (3)$$

where the "symbol error terms" $\delta_{m,p}$ are uncorrelated with the transmitted symbols $s_{m,p}$ and the correlation coefficient ρ_p is given by

$$\rho_p = \frac{E[\hat{s}_{m,p} s^*_{m,p}]}{E_{S,p}} = \frac{E[\hat{S}_{k,p} S^*_{k,p}]}{M E_{S,p}}. \quad (4)$$

with $E_{S,p} = E[|s_{m,p}|^2]$ denoting the average symbol energy for the pth user. These correlation coefficient can be estimated from the time-domain samples associated with the equalizer output, $\tilde{s}_{m,p}$, as described in [8]. The corresponding frequency-domain samples, $\hat{S}_{k,p}$, can also be written as

$$\hat{S}_{k,p} = \rho_p S_{k,p} + \Delta_{k,p}, \quad (5)$$

where $\{\Delta_{k,p}; k = 0, 1, \ldots, M-1\}$ = DFT $\{\delta_{m,p}; m = 0, 1, \ldots, M-1\}$. Since the "symbol error terms" are uncorrelated with the transmitted symbols, we have $E[|\Delta_{m,p}|^2] = ME[|\delta_{m,p}|^2] = (1-\rho_p^2) M E_{S,p}$. It can be shown that time-domain samples associated with the equalizer output, $\tilde{s}_{m,p}$, can be written as [8]:

$$\tilde{s}_{m,p} = \gamma_p s_{m,p} + \varepsilon^{eq}_m, \quad (6)$$

where ε^{eq}_m denotes the overall noise plus interference and γ_p is the average overall channel frequency response for the pth user [8]. The signal to interference plus noise ratio (SNIR) for the pth user in the frequency domain, is defined as:

$$SNIR^F_{k,p} = \frac{|\gamma_p|^2 M E_{S,p}}{[|\varepsilon^{Eq}_{k,p}|^2]}, \quad (7)$$

where $\varepsilon^{Eq}_{k,p}$ is the overall noise plus interference in frequency domain. By combining (2) and (7) and some algebraic computation, the optimum feedback coefficients for the pth user that maximize (7) at a particular iteration are

$$B^{(p)}_{k,p'} = \rho_{p'} \Big(\sum_{n'=1}^{N} F^{(n')}_{k,p'} H^{(n')}_{k,p'} - \gamma_p \delta(p'-p) \Big), \; p' = 0, 1, \ldots P-1. \quad (8)$$

The feedforward coefficients satisfy the set of N equations:

$$(1-\rho_p^2) H^{(n)*}_{k,p} \sum_{n'=1}^{N} F^{(n')}_{k,p} H^{(n')}_{k,p}$$
$$+ \sum_{p' \neq p} (1-\rho_{p'}^2) H^{(n)*}_{k,p'} \sum_{n'=1}^{N} F^{(n')}_{k,p} H^{(n')}_{k,p'} + \frac{F^{(n)}_{k,p}}{SNR_p} =$$
$$= \gamma_p (1-\rho_p^2) H^{(n)*}_{k,p}, \;\; n = 1, 2, \ldots, N, \quad (9)$$

where $SNR_p = \frac{E_{S,p}}{2\sigma_N^2}$ and σ_N^2 denotes the variance of both the in-phase and quadrature components of the channel noise.

3. SIMULATION RESULTS

In this section, we consider the use of the proposed receiver in an SDMA system where each user has 1 transmit antenna and the base station has a number of antennas N, equal or greater than the number of users P. The data block consists of $M = 64$ QPSK data symbols, plus CP (similar results were obtained for other values of M). The channel has uncorrelated Rayleigh fading on different frequencies, corresponding to a channel with severe time-dispersion effects and a rich multipath propagation. We consider uncoded BER (Bit Error Rate) performance, under perfect synchronization and channel estimation conditions.

Let us first consider the case where all the users have the same average power. Figure 3 shows the BER for different users and iterations, for $P = 4$ users and a base station with $N = 4$ antennas. From this figure, we can observe that the users' performances after the first iteration are very different: almost 7dB at BER=10^{-4} from the first user ($p = 0$) to the fourth ($p = 3$). This difference decreases as we increase the number of iterations, with all users having almost the same performance after the third iteration. Moreover, the resulting performance can be very close to the MFB (Matched Filter Bound) after just four iterations. This shows that, for moderate SNRs, the proposed receiver is able to eliminate a significant part of the ISI and the interference.

Figure 4 shows the average BER performance after four iterations, for different N and P. Once again, the BER performance after four iterations are close to the corresponding MFBs, regardless of N and P.

Let us consider now a scenario where the received powers are not the same for all users, due to a wrong power control and/or different uncoded BER requirements for different users. We will consider $N = 4$ receive antennas and $P = 4$ users, with the received powers for users 0 and 1 being 6dB larger than the received powers for users 2 and 3. For a given iteration, the receiver detects first the high-power users and then the low-power ones. Figure 5 shows the BER performance for the different users. Once again, the iterative detection procedure allows significant performance gains and after four iterations, the BER performances are similar for users with the same average power. We can also note that the performances of the low power users are asymptotically close to the MFB. However, for the high power users, the performances are about 1.5dB away from the MFB, at BER=10^{-4}. This results from the fact that the BER is much lower for the high-power users, allowing an almost perfect cancellation of their effects on the low power users, which can have performance close to the MFB. However, the higher BERs for the low-power users preclude an appropriate interference cancellation on the high-power users, at least for moderate BERs (see also figure 6, where all BER are expressed as a function of the E_b/N_0 of the low power users, and MFB was shifted 6dB to the left for the high power users).

4. CONCLUSIONS

In this paper we propose a low complexity iterative receiver structure for multiple users with multiple antennas for severe frequency selective channels. The proposed multiuser detection combines IB-DFE principles with LST techniques. We evaluated the performance of the proposed receiver for different scenarios and different number of antennas at BS and users. Our results show that we can have almost optimum performances with just a few iterations. This makes proposed receiver suitable for broadband wireless communications.

5. REFERENCES

[1] R.D. Gitlin, J. Salz, and J.H. Winters, "The impact of antenna diversity on the capacity of wireless communication

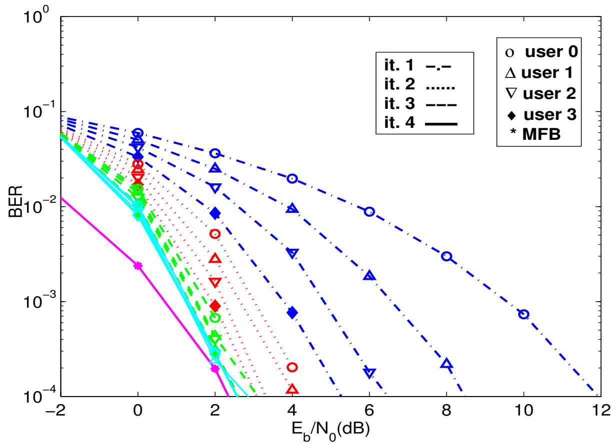

Fig. 3. BER for different users with the same average power, differnt iterations (it.),and matched filter bound (MFB)

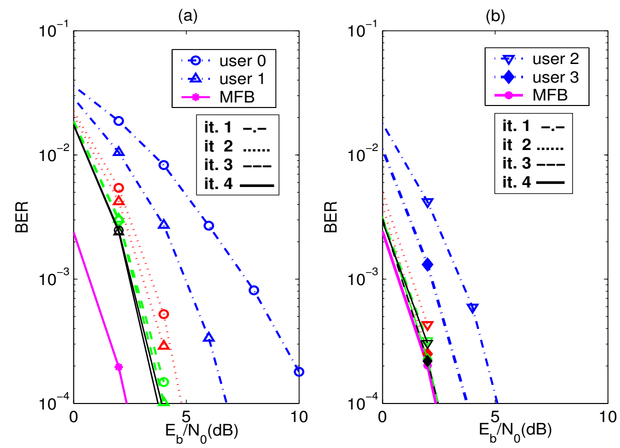

Fig. 5. BER for the high power users (a) and the low power users (b) for different iterations (it.), as well as the corresponding MFBs

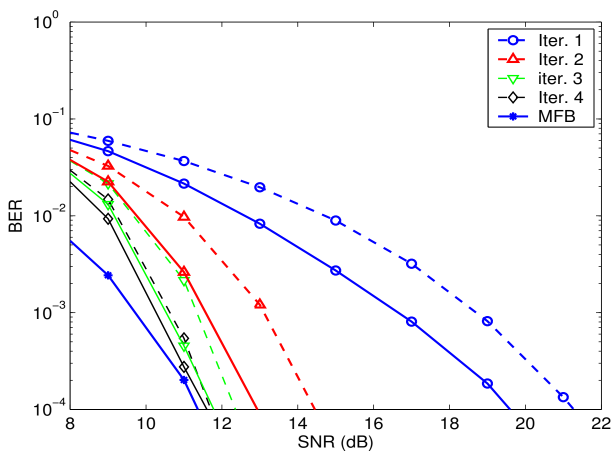

Fig. 4. Average BER for different antennas and users configuration,4th iteration and matched filter bound performance (MFB)

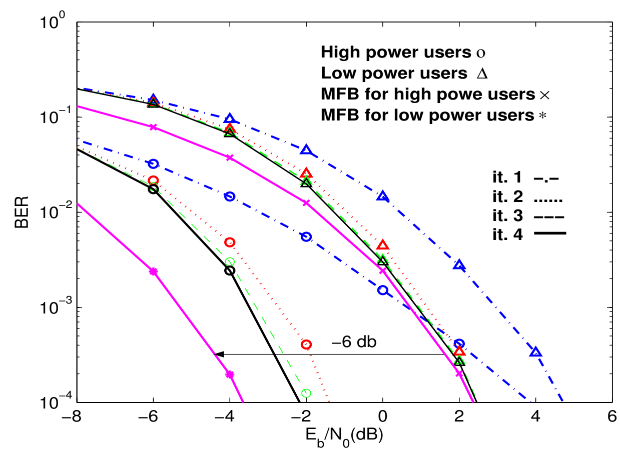

Fig. 6. Average BER for the high power and the low power users for different iterations (it.)

systems," *IEEE Trans. Commun.*, vol. 42, 1994.

[2] N. Al-Dhahir and A H. Sayed, "The finite-length multi-input milti-output MMSE-DFE," *IEEE Trans. Signal Processing*, vol. 48, pp. 2921–2936, Oct. 2000.

[3] Donald Arseneau, "The url.sty package," Mar. 1999.

[4] D. Falconer, S. Ariyavisitakul, A. Benyamin-seeyar, and B. Edison, "Frequency domain equalization for single-carrier broadband wireless systems," *IEEE Commun. Mag.*, vol. 4, pp. 58–66, Apr. 2002.

[5] N. Benvenuto and S. Tomasin, "On the comparison between OFDM and single carrier with DFE using a frequency domain feedforward filter," *IEEE Trans. Commun.*, vol. 50, pp. 947–955, June 2002.

[6] J. Tubbax, L. Vanderperre, S. Donnay, and M. Engels, "Single-carrier communications using decision-feedback equalization for multiple antennas," in *Proc. ICC'03*, Anchorage,Ak , USA, May 2003.

[7] N. Benvenuto and S. Tomasin, "Block iterative DFE for single carrier modulation," *IEEE Electronic Letters*, vol. 38, pp. 1144–1145, sept. 2002.

[8] R. Dinis, A. Gusmo, and N. Esteves, "On broadband block transmission over strongly frequency-selective fading channels," in *Proc. Wireless 2003*, Calgary, Canada, July 2003.

[9] G. J. Foschini, "Layered-space-time architecture for wireless communication in a fading enviroment when using multi-element antennas," *Bell Labs Tech J.*, pp. 41–59, Autumn 1996.

[10] A. Lozano and C. Papadias, "Layered space-time receiver for frequency-selective wireless channels," *IEEE Trans. Commun.*, vol. 50, pp. 65–73, Jan. 2002.