Uplink of Base Station Cooperation Systems with SC-FDE Modulations and IB-DFE Receivers

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Abstract - This paper considers the uplink transmission in BS (Base Station) cooperation schemes where users in adjacent cells share the same physical channel and the signals received by each BS are sent to a CPU (Central Processing Unit) that combines the different received signals associated to a given user and/or performs the user separation. The signals are modulated through SC (Single-Carrier) schemes combined with FDE (Frequency-Domain Equalization) techniques and with iterative frequency-domain receivers based on the IB-DFE concept (Iterative Block Decision Feedback Equalization). Our performance results show performance results close to the MFB (Matched Filter Bound), where the proposed receivers allow enhancement in macro-diversity gains as well as an efficient user separation, making these techniques an excellent choice for the uplink transmission in future broadband wireless systems employing BS cooperation schemes[1].

Index Terms: Uplink transmission, BS cooperation, SC-FDE, IB-DFE, MFB

I. Introduction

The requirements for wireless services are expected to continue to increase, demanding more capacity and an increasing efficiency use of radio resources. Future spectral efficiency improvements will be focused on interference-reducing techniques that require the cooperation of the network elements, since the point-to-point link capacities are already close to the fundamental Shannon limit [1]. Conventional cellular systems adopt different frequencies at different cells, with high frequency reuse factors. The overall systems spectral efficiency and capacity are conditioned by the frequency reuse factor, typically decreasing linearly with it. Since the spectrum is a scarce and expensive resource in wireless communication systems, it is mandatory to pursue the designing of systems that operate in universal frequency reuse (i.e., with frequency reuse factor 1). However, the design of such systems requires efficient interference management and/or interference cancelation methods, particularly for users at the cell edge. BS (Base Station) cooperation appears as the most promising approach to achieve interference mitigation between different cells, improving the fairness of the system and increasing the overall capacity [2]. For this reason, it is already under study in LTE [3], namely under the so-called ”coordinated multi-point concept” that although not included in the current releases, will probably be specified for the future ones.

In conventional cellular architectures different cells are regarded as separate entities and each MT (Mobile Terminal) is assigned to a given cell (and, consequently, a given BS). The MT transmits its signals to the corresponding BS and when this signal is received by another BS it is regarded as interference. In BS cooperation architectures the signals between different MTs and BSs are collected and processed by a CPU (Central Pressing Unit) so as to perform the user separation and/or interference mitigation. The signal separation in the downlink transmission (i.e., the link from the BSs to the MTs) of BS cooperation schemes is usually achieved by appropriate preprocessing schemes [4]. In the uplink transmission (i.e., the link from the MTs to the BSs) the overall signals received by different BSs (with contributions from all MTs) are sent to the CPU that performs the signal separation to extract the data blocks transmitted by each MT before sending them to the corresponding BS [2]. These BS cooperation schemes involve interference mitigation, allowing the use of the same physical channel by MTs in adjacent cell, which means that the overall system capacity can be significantly improved. Moreover, BS cooperation schemes also have an inherent macro-diversity nature due to the use of widely spaced antennas, allowing improved overall coverage with reduced transmit power requirements.

Block transmission techniques, combined with frequency-domain processing are choice candidates for broadband wireless systems, like OFDM (Orthogonal Frequency Division Multiplexing) and SC-FDE (Single-Carrier with Frequency domain Equalization), which have similar overall signal processing requirements and achievable performance. However, the receiver complexity is higher for SC-FDE and the transmitter complexity is higher for OFDM. If we take also into account that the envelope fluctuations of single-carrier signals are much lower than the envelope fluctuations of OFDM signals with the same constellations, SC-FDE is clearly preferable for the uplink transmission while OFDM is interesting mainly for the downlink transmission [5], [6].

In this paper we consider the uplink transmission in BS cooperation schemes. We consider the use of SC-FDE signals combined with iterative frequency-domain receivers based

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on the IB-DFE concept (Iterative Block Decision Feedback Equalization) [7], [8], [9]. Users in adjacent cells share the same physical channel and the signals received by each BS are sent to a CPU that performs the user separation while taking full advantage of all received signals.

This paper is organized as follows: in sec. II we describe the BS cooperation scenario considered in this paper and sec. III concerns the receiver design. A set of performance results is presented in sec. IV and sec. V concludes the paper.

II. System Characterization

The system is characterized by partially overlapping cells, each one associated to a given BS, where P MTs share the same physical channel (i.e., they transmit simultaneously at the same frequency band) with R receiving BSs, that can cooperate to improve the overall system performance. Each MT employs a SC-FDE scheme, which corresponds to a block transmission technique, where an appropriate cyclic prefix is appended to each data block. If the cyclic prefix is long enough[2] it can be shown that the received signal at a certain BS r is given by

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

where $S_{k,p}$ corresponds to the DFT of the time-domain data block, $\{s_{n,p}; n = 0,1,...,N-1\}$, associated to the pth MT ($p = 1,2,...,P$), and where constellation symbol $s_{n,p}$ is selected from the data according to a given mapping rule (e.g., a QPSK constellation with Gray mapping). The useful time-domain received block (i.e., after removing the samples associated to the cyclic prefix) at the rth BS is $\{y_n^{(r)}; n = 0,1,...,N-1\}$ ($r = 1,2,...,R$), and the corresponding frequency-domain block is $\{Y_k^{(r)}; k = 0,1,...,N-1\}$ = DFT $\{y_n^{(r)}; n = 0,1,...,N-1\}$. Also, in (1), $N_k^{(r)}$ denotes the channel noise at the rth antenna and the kth frequency and $H_{k,p}^{eq(r)} = \xi_{p,r} H_{k,p}^{(r)}$, where $H_{k,p}^{(r)}$ denotes the channel frequency response between the pth MT and the rth BS, for the kth frequency. The coefficient $\xi_{p,r}$ is a weighting factor that accounts for the combined effects of power control and propagation losses, i.e., the average received power associated to the pth MT at the rth BS is $|\xi_{p,r}|^2$ (without loss of generality, we assume a normalized channel frequency response, i.e., $\mathbb{E}\left[\left|H_{k,p}^{(r)}\right|^2\right]$).

Considering the systems global contributions, (1) can be extended to a matrix format, as

$$\mathbf{Y}_k = \mathbf{H}_k^{eq} \mathbf{S}_k + \mathbf{N}_k, \tag{2}$$

with $\mathbf{Y}_k = \left[Y_k^{(1)}, \ldots, Y_k^{(R)}\right]^T$, $\mathbf{S}_k = [S_{k,1}, \ldots, S_{k,P}]^T$, $\mathbf{N}_k = \left[N_k^{(1)}, \ldots, N_k^{(R)}\right]^T$ and

$$\mathbf{H}_k^{eq} = \begin{bmatrix} H_{k,1}^{eq^{(1)}} & \ldots & H_{k,P}^{eq^{(1)}} \\ \vdots & \ddots & \vdots \\ H_{k,1}^{eq^{(R)}} & \ldots & H_{k,P}^{eq^{(R)}} \end{bmatrix}. \tag{3}$$

III. Iterative Receiver Design

In this section we consider the receiver design for BS cooperation schemes. For this purpose, we employ an iterative frequency-domain receiver based on the IB-DFE concept [9] that allows an efficient separation of the signals associated to different MTs using the same physical channel and is able take full advantage of macro-diversity effects. Ideally we should sort the MT according to their overall power, given by

$$\sum_{k=1}^{N-1} \sum_{r=1}^{R} |\xi_{p,r} H_{k,p}^{(r)}|^2, \tag{4}$$

and detect the MTs from the one with larger overall power to the one with smaller overall power[3]. However, it can be shown that our iterative receiver is highly robust to the detection order, provided that the number of iterations is high enough (in fact, the main advantage of a proper detection order is that we typically can reduce slightly the number of required iterations for best performance). For each iteration we detect all MTs in a successive way, using the most updated estimates of the transmitted data symbols associated to each MT to cancel the corresponding residual interference. Therefore, our receiver can be regarded as an iterative SIC (Successive Interference Cancelation) scheme. However, as with conventional IB-DFE receivers, we take into account the reliability of the data estimates associated to a certain MT for each detection (and interference cancelation) procedure.

When detecting the pth MT, at the ith iteration, the estimated symbols $\{\hat{s}_{n,p}^{(i)}; n = 0,1,...,N-1\}$ are the hard decisions of the time-domain detector output $\{\tilde{s}_{n,p}^{(i)}; n = 0,1,...,N-1\}$ = IDFT $\{\tilde{S}_{k,p}^{(i)}; k = 0,1,...,N-1\}$, where $\tilde{S}_{k,p}^{(i)}$ is given by

$$\tilde{S}_{k,p}^{(i)} = \mathbf{F}_{k,p}^{(i)^T} \mathbf{Y}_k - \mathbf{B}_{k,p}^{(i)^T} \bar{\mathbf{S}}_k^{(p,i-1)}, \tag{5}$$

with $\mathbf{F}_{k,p}^{(i)^T} = [F_{k,p}^{(i,1)}, \ldots, F_{k,p}^{(i,R)}]^T$ denoting the feedforward coefficients and $\mathbf{B}_{k,p}^{(i)^T} = [B_{k,p}^{(i,1)}, \ldots, B_{k,p}^{(i,P)}]^T$ denote the feedback coefficients. The vector $\bar{\mathbf{S}}_k^{(p,i-1)} = [\bar{S}_{k,1}^{(i)}, \ldots, \bar{S}_{k,p-1}^{(i)}, \bar{S}_{k,p}^{(i-1)}, \ldots, \bar{S}_{k,P}^{(i-1)}]^T$, where the block $\{\bar{S}_{k,p}^{(i)}; k = 0,1,...,N-1\}$ is the DFT of the block of time-domain average values conditioned to the detector output $\{\bar{s}_{n,p}^{(i)}; n = 0,1,...,N-1\}$ for user p and iteration i. Clearly, the elements of $\bar{\mathbf{S}}_k^{(p,i-1)}$ are associated to the current

[2]In conventional block transmission schemes the cyclic prefix is required to be longer than the overall impulse response (including channel effects and transmit and receive filters). However, in BS cooperation schemes it might be necessary to have a slightly longer cyclic prefix to account for different propagation times between MTs and BSs, since the useful part of each bock should overlap.

[3]Actually, the users should be ordered according to the signal-to-noise plus overall interference (including residual ISI (Inter-Symbol Interference) and residual inter-user interference) at the FDE output, but usually there is strong correlation between it and the overall power associated to that MT.

iteration for MTs already estimated in this iteration and the previous iteration for the MT currently being detected, as well as the MTs that were not yet detected in the current iteration (this is a natural consequence of the SIC nature of our iterative receiver).

It can be shown that the average values $\bar{s}_{n,p}^{(i)}$ for normalized QPSK constellations (i.e., $s_{n,p} = \pm 1 \pm j$) are given by (see [10])

$$\bar{s}_{n,p}^{(i)} = \tanh\left(\frac{\left|L_{n,p}^{I\ (i)}\right|}{2}\right) + j\tanh\left(\frac{\left|L_{n,p}^{Q\ (i)}\right|}{2}\right), \quad (6)$$

where

$$L_{n,p}^{I\ (i)} = \frac{2}{\sigma_{n,p}^{2\ (i)}} \mathrm{Re}\{\tilde{s}_{n,p}^{(i)}\}, \quad (7a)$$

$$L_{n,p}^{Q\ (i)} = \frac{2}{\sigma_{n,p}^{2\ (i)}} \mathrm{Im}\{\tilde{s}_{n,p}^{(i)}\}, \quad (7b)$$

and

$$\sigma_{n,p}^{2\ (i-1)} = \frac{1}{2N}\sum_{n'=0}^{N-1}\left|\hat{s}_{n',p}^{(i-1)} - s_{n',p}\right|^2. \quad (8)$$

Naturally, the hard decisions are $\hat{s}_{n,p}^{(i)} = \mathrm{Re}\{\tilde{s}_{n,p}^{(i)}\} + j\mathrm{Im}\{\tilde{s}_{n,p}^{(i)}\} = \mathrm{Re}\{\bar{s}_{n,p}^{(i)}\} + j\mathrm{Im}\{s_{n,p}^{(i)}\}$.

It can be shown that $\bar{\mathbf{S}}_k^{(i)} \simeq \mathbf{P}^{(i)}\hat{\mathbf{S}}_k^{(i)}$, where $\mathbf{P}^{(i)} = diag(\rho_1^{(i)}, \ldots, \rho_P^{(i)})$, with the correlation coefficients

$$\rho_p^{(i)} = \frac{E[\hat{s}_{n,p}s_{n,p}^*]}{E[|s_{n,p}|^2]} \quad (9)$$

being a measure of the reliability of the estimates associated to the ith iteration, which are approximately given by

$$\rho_p^{(i)} \approx \frac{1}{2N}\sum_{n=0}^{N-1}\left(\left|\rho_{n,p}^{I\ (i)}\right| + \left|\rho_{n,p}^{Q\ (i)}\right|\right), \quad (10)$$

with

$$\rho_{n,p}^{I\ (i)} = \tanh\left(\frac{\left|L_{n,p}^{I\ (i)}\right|}{2}\right), \quad (11a)$$

$$\rho_{n,p}^{Q\ (i)} = \tanh\left(\frac{\left|L_{n,p}^{Q\ (i)}\right|}{2}\right), \quad (11b)$$

Moreover, $\hat{\mathbf{S}}_k^{(i)} \approx \mathbf{P}^{(i)}\mathbf{S}_k + \mathbf{\Delta}_k$, where $\mathbf{\Delta}_k = [\Delta_{k,1}, \ldots, \Delta_{k,P}]^T$, with zero mean and uncorrelated with $\mathbf{P}^{(i)}$. For the first iteration, i.e. $i = 1$, $\bar{\mathbf{S}}_k^{(0)}$ is a null vector and $\mathbf{P}^{(0)}$ is a null matrix.

The optimum feedforward and feedback coefficients that maximize the signal to overall noise plus interference at the detector output are given by

$$\begin{cases}\mathbf{F}_{k,p}^{(i)} = \mathbf{\Lambda}_{k,p}^{(i)}\mathbf{H}_k^H\mathbf{\Theta}_{k,p}^{(i)} \\ \mathbf{B}_{k,p}^{(i)} = \mathbf{H}_k\mathbf{F}_{k,p}^{(i)} - \mathbf{\Gamma}_p,\end{cases} \quad (12)$$

where

$$\mathbf{\Lambda}_{k,p}^{(i)} = \left(\mathbf{H}_k^H\left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2}\right)\mathbf{H}_k + \frac{\sigma_N^2}{\sigma_S^2}\mathbf{I}_L\right)^{-1}, \quad (13)$$

with σ_S^2 and σ_N^2 denoting the variance of the signal and noise samples, respectively, and

$$\mathbf{\Theta}_{k,p}^{(i)} = \left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2}\right)\mathbf{\Gamma}_p - \frac{\lambda_p^{(i)}}{2\sigma_S^2 N}\mathbf{\Gamma}_p. \quad (14)$$

$\mathbf{I}_P$ denotes a $P \times P$ identity matrix and $\mathbf{\Gamma}_p$ is a column vector with 0 in all positions except the pth position that is 1.

If we have only the pth MT transmitting we have

$$F_{k,p}^{(r,i)} = \frac{\kappa H_{k,p}^{eq(r)*}}{\frac{\sigma_N^2}{\sigma_S^2} + \sum_{r'=1}^{R}\left|H_{k,p}^{eq(r')}\right|^2}, \quad (15)$$

with κ selected to ensure that

$$\frac{1}{N}\sum_{k=0}^{N-1}\sum_{r=1}^{R}F_{k,p}^{(r,i)}H_{k,p}^{eq(r)} = 1, \quad (16)$$

and

$$B_{k,p}^{(i)} = \sum_{r'=1}^{R}F_{k,p}^{(r',i)}H_{k,p}^{eq(r')} - 1, \quad (17)$$

respectively, which corresponds to an ideal macro-diversity scenario [11].

IV. Performance Results

In this section we present a set of performance results considering the proposed iterative frequency-domain receivers for the uplink of BS cooperation schemes employing SC-FDE modulations. The blocks associated to each MT have N=256 data symbols, selected from a QPSK constellation under a Gray mapping rule, plus an appropriate cyclic prefix. The channel between different MTs and different BSs are uncorrelated and severely time-dispersive, each one with rich multipath propagation and uncorrelated Rayleigh fading for different multipath components. We assume perfect synchronization and channel estimation. It is assumed that the useful part of the blocks transmitted by different MTs arrive at each BS simultaneously. In practice, this could be accomplished by employing extended cyclic prefixes, with duration longer than the maximum overall channel impulse response plus the difference between the maximum and minimum propagation delay between MTs and BSs, provided that we have accurate channel estimates.

Let us start by considering the case where we have just one MT (i.e., $P = 1$) and $R = 2$ cooperating BSs, corresponding to an ideal macro-diversity scenario. The power associated to the different links is characterized by $[\xi_{1,1}\ \xi_{1,2}] = [0\ \beta]$ (dB), i.e, we have a main link between the MT and its BS and a secondary link to another BS whose average power is β dB below the average power associated to the main link. Fig. 1 shows the BER performance of our iterative receiver for different values of β ($\beta = -\infty$ corresponds to the case where we do not have BS cooperation). Clearly, there is a significant performance improvement when we combine the received signals associated to different BSs, even when the average received power at one BS is substantially lower than the average received power at the other BS. The performance

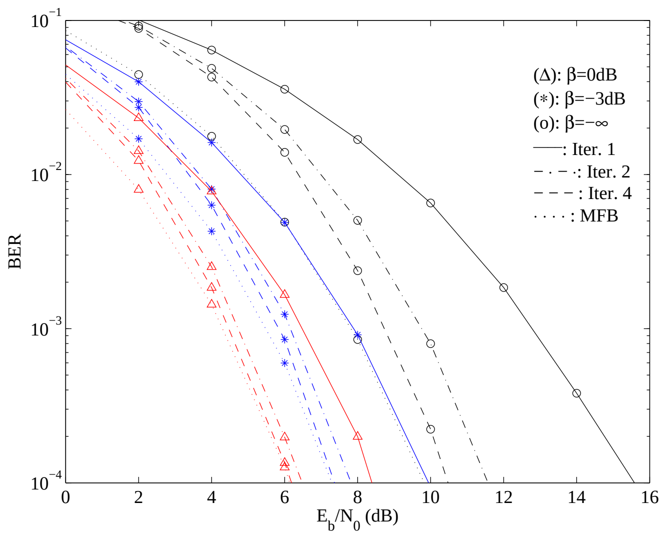

Fig. 1. BER performance for a macro-diversity scenario with $R = 2$ cooperating BSs.

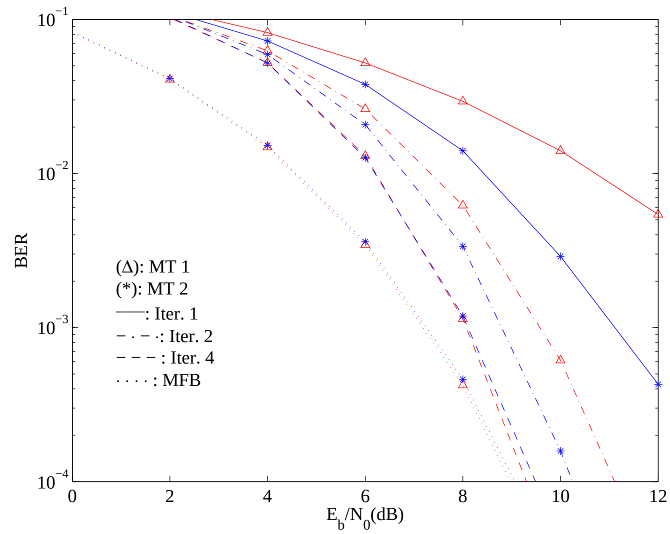

Fig. 2. BER performance for a BS cooperation scenario with $P = R = 2$.

improvement is higher for the linear FDE (one iteration), which is due to the higher residual ISI at the FDE output, and the performance of the iterative receiver is already close to the MFB after just 4 iterations. Moreover, the macro-diversity also reduces the shadowing effects and improves overall coverage, which means that BS cooperation is important even when we have only a single MT.

Let us consider now a BS cooperation scenario with $P = 2$ MTs and $R = 2$ BSs. The power associated to the different links is characterized by the matrix

$$\mathbf{\Xi} = \begin{bmatrix} \xi_{1,1} & \xi_{1,2} \\ \xi_{2,1} & \xi_{2,2} \end{bmatrix} \text{(dB)}, \qquad (18)$$

with $\xi_{1,1} = \xi_{1,2} = \xi_{2,1} = \xi_{2,2} = -3$ dB, where both MTs are at the cell's edge with perfect average power control, which corresponds to a scenario with strong interference between MTs at both BSs. Fig. 2 illustrated the described scenario. The second MT presents a better performance since when the first MT is being detected there's no information regarding the MTs separations process, hence the information provided from the detection of the first MT provides an accurate detection for the second MT. As expected, the BER values are close to the MFB after 4 iterations, which means that our receiver is able to efficiently separate the MTs while taking advantage of the signal contributions associated to a given MT at each BS.

V. Conclusions

In this paper we considered the receiver design for the uplink transmission in BS cooperation schemes employing SC-FDE signals. The user detection and/or separation was made using iterative frequency-domain receivers. Our performance results showed that the proposed receivers allow significant macro-diversity gains as well as an efficient user separation, with performance close to the MFB, making these techniques an excellent choice for future broadband wireless systems employing BS cooperation schemes.

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