Efficient Detection and Quantization Requirements for the Uplink of Base Station Cooperation Systems

F.Casal Ribeiro$^{(1,2)}$, R.Dinis$^{(1,3)}$, F.Cercas$^{(1,2)}$, A.Silva$^{(1,4)}$

$^{(1)}$ IT - Instituto de Telecomunicações, Portugal $^{(2)}$ ISCTE - Instituto Universitário de Lisboa, Portugal

$^{(3)}$ FCT - Universidade Nova de Lisboa, Portugal $^{(4)}$ Universidade de Aveiro, Portugal

Abstract - This paper considers the uplink transmission in BS (Base Station) cooperation schemes employing SC-FDE schemes (Single-Carrier with Frequency-Domain Equalization), where MTs (Mobile Terminals) in adjacent cells share the same physical channel. We study the quantization requirements when sending the received signals at different BSs to a central unit that performs the separation of different MTs using iterative frequency-domain receivers. Our performance results show that a relatively coarse quantization, with only 4 or 5 bits in the in-phase and quadrature components of the complex envelope can be sufficient to allow close-to-optimum macro-diversity gains as well as an efficient separation of the transmitted signals associate to each MT.[1]

I. Introduction

Conventional cellular systems adopt different frequencies at different cells, with frequency reuse factors of 3, or even more. Clearly, 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 systems, it would be desirable to design systems operating in universal frequency reuse (i.e., with frequency reuse factor 1).

The most promising approach to achieve this goal is by employing BS (Base Station) cooperation techniques, which are already under study for LTE [1]. In fact, BS cooperation allows not only universal frequency reuse, but also substantial macro-diversity effects, improving significantly the overall performance of wireless systems, as well as the coverage and power requirements associated to each individual link. The basic idea behind BS cooperation architectures is that the signals transmitted between different MTs and BSs are collected and processed by a central unit (that can be placed outside the BSs) where the user separation and/or interference mitigation is performed. For the downlink case (i.e., the transmission from the BSs to the MTs), this is usually achieved by appropriate pre-processing schemes [2], [3], [4]. In the uplink case (i.e., the transmission from the MTs to the BSs), the overall signals received by different BSs (with contributions from all MTs) are sent to the central unit where the separation of the transmitted contributions associated to different MTs is performed [5]. However, BS cooperation schemes presents considerable challenges, namely at the user separation level and in the signalling requirements.

In this paper we consider the uplink of broadband wireless systems with BS cooperation architectures. The MTs employ SC-FDE schemes (Single-Carrier with Frequency domain Equalization), generally recognized as the best candidates for the uplink of broadband wireless systems due to relatively low envelope fluctuations of the transmitted signals and the fact that most signal processing is performed at the receiver (i.e., at the BS side) [6]. MTs in adjacent cells can share the same physical channel and the signals received by a given BS are digitalized, through appropriate sampling and quantization procedures, and the corresponding bits are sent to the central unit where the separation of the signals associated to different MTs is performed using iterative frequency-domain receivers based on the IB-DFE concept (Iterative Block Decision Feedback Equalization) [7], [8], [9]. The quantization requirements for the signals received at a given BS are studied in detail.

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

II. System Characterization

We consider a cellular system with overlapping cells, each one associated to a given BS. We assume that there are P MTs sharing the same physical channel and we have $R \geq P$ BSs receiving their signals that can cooperate to improve the overall system performance. This means that, contrarily to conventional systems where the BS performs the detection of the signals of its MTs, in our BS cooperation architecture the overall signals received at each BS, are sent to a central unit that performs the separation of the different transmitted signals and sends them to the corresponding BS. As an alternative, the central unit can be placed at one of the cooperating BSs, which reduces the signalling requirements and allows improved performances since the signals associated to one BS are not quantized.

An SC-FDE scheme is employed by each MT and the data block associated to the p MT ($p = 1, 2, ..., P$) is $\{s_{n,p}; n = 0, 1, ..., N-1\}$, where constellation symbol $s_{n,p}$ is selected from a given constellation. The corresponding frequency-domain block is $\{S_{k,p}; k = 0, 1, ..., N-1\}$ = DFT $\{s_{n,p}; n = 0, 1, ..., N-1\}$. As with other block transmission techniques,

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an appropriate cyclic prefix is appended to each data block. 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 $\{y_n^{(r)}; n=0,1,...,N-1\}$. 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. This means that if the cyclic prefix is long enough it can be shown that

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

where $N_k^{(r)}$ denotes the channel noise at the rth BS 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., $E[|H_{k,p}^{(r)}|^2]=1$).

The received signals at the rth BS, $\{y_n^{(r)}; n=0,1,...,N-1\}$, are quantized[2], leading to

$$y_n^{Q(r)} = f_Q(\mathrm{Re}\{y_n^{(r)}\}) + j f_Q(\mathrm{Im}\{y_n^{(r)}\}), \tag{2}$$

where $f_Q(\cdot)$ denotes the quantization characteristic. Naturally, the quantized signals will have a quantization noise term, i.e.,

$$y_n^{Q(r)} \approx y_n^{(r)} + \nu_n^{Q(r)}, \tag{3}$$

with $\nu_n^{Q(r)}$ denoting the quantization noise term. We can define a SQNR (Signal-to-Quantization Noise Ratio) as

$$\mathrm{SQNR} = \frac{E[|y_n^{Q(r)}|^2]}{E[|\nu_n^{Q(r)}|^2]}. \tag{4}$$

The SQNR is a function of the number of quantization levels 2^m, with m denoting the number of bits required for the real and imaginary parts of each quantized sample, and the type of quantizer (i.e., if we have an uniform quantizer or not). Although non-uniform quantizers are interesting for signals with large dynamic range, an uniform quantizer is enough when $2\sigma^2 = E[|y_n^{(r)}|^2]$ is known, with σ denoting the standard deviation of $\mathrm{Re}\{y_k^{(r)}\}$ and $\mathrm{Im}\{y_k^{(r)}\}$, namely when we have ideal average power control. Therefore, in this paper we will only consider uniform quantizers, i.e., $f_Q(\cdot)$ has 2^m levels equally spaced between the saturation levels $-A_M$ and A_M.

[2]For the sake of simplicity, we will describe only the case where the signals associated to each BS are quantized. The extension for other cases is straightforward.

Fig. 1 shows the impact of the normalized saturation level A_M/σ and the number of quantization bits[3] m on SQNR. Clearly, there is an optimum normalized saturation level for each value of m, since the quantizer's saturation becomes too frequent if A_M/σ is small and the quantization interval becomes too high when A_M/σ is high. In this paper we assume always the optimum saturation level for each value of m.

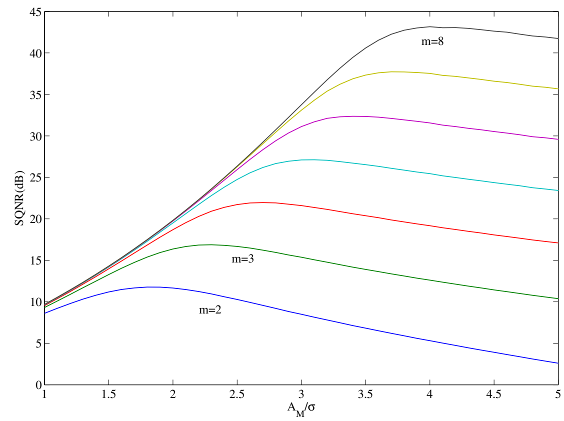

Fig. 1. SQNR as a function of the normalized saturation level A_M/σ and the number of quantization bits m.

The frequency-domain block associated to the quantized signal at the rth BS is $\{Y_k^{Q(r)}; k=0,1,...,N-1\}$ = DFT $\{y_n^{Q(r)}; n=0,1,...,N-1\}$, where

$$Y_k^{Q(r)} \approx Y_k^{(r)} + N_k^{Q(r)} \approx \sum_{p=1}^{P} S_{k,p} H_{k,p}^{eq(r)} + N_k^{eq(r)}, \tag{5}$$

where $\{N_k^{Q(r)}; k=0,1,...,N-1\}$ = DFT $\{\nu_n^{Q(r)}; n=0,1,...,N-1\}$ and $N_k^{eq(r)}$ is the equivalent overall noise, including channel noise and quantization noise.

In matrix format (5) is equivalent to

$$\mathbf{Y}_k^Q = \mathbf{H}_k^T \mathbf{S}_k + \mathbf{N}_k, \tag{6}$$

with $\mathbf{Y}_k^Q = [Y_k^{Q(1)} \; Y_k^{Q(2)} \; ... \; Y_k^{Q(R)}]^T$, $\mathbf{S}_k = [S_{k,1} \; S_{k,2} \; ... \; S_{k,P}]^T$, $\mathbf{N}_k = [N_k^{eq(1)} \; N_k^{eq(2)} \; ... \; N_k^{eq(R)}]^T$ and

$$\mathbf{H}_k^T = \begin{bmatrix} H_{k,1}^{eq^{(1)}} & \cdots & H_{k,P}^{eq^{(1)}} \\ \vdots & \ddots & \vdots \\ H_{k,1}^{eq^{(R)}} & \cdots & H_{k,P}^{eq^{(R)}} \end{bmatrix} \tag{7}$$

III. Iterative Frequency-Domain User Separation

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 the signals associated to different MTs using the same physical channel and it is able

[3]Actually, the number of quantization bits is $2m$, since we need m bits for the real part and m bits for the imaginary part, according to (2).

to take full advantage of macro-diversity effects. Ideally we should sort the MTs according to their overall power, given by

$$\sum_{k=1}^{N-1}\sum_{r=1}^{R}|\xi_{p,r}H_{k,p}^{(r)}|^2, \tag{8}$$

and detect the MTs from the one with larger overall power to the one with smaller overall power[4]. 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 (see Fig. 2). 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 MTs for each detection (and interference cancelation) procedure.

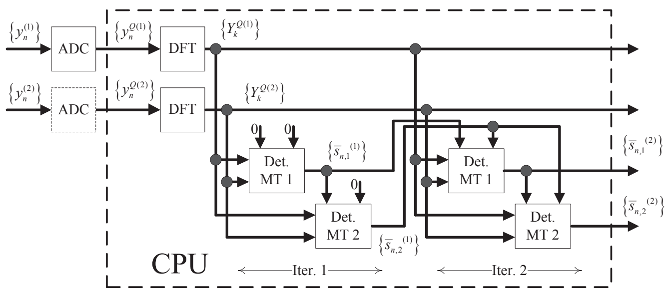

Fig. 2. Iterative receiver structure for $P = 2$ MTs and $R = 2$ cooperating BSs with quantization.

At the ith iteration, the estimated symbols associated to the pth MT $\{\hat{s}_{n,p}^{(i)}; n = 0, 1, ..., N-1\}$ 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

$$\tilde{S}_{k,p}^{(i)} = \mathbf{F}_{k,p}^{(i)^T}\mathbf{Y}_k^Q - \mathbf{B}_{k,p}^{(i)^T}\bar{\mathbf{S}}_k^{(p,i-1)}, \tag{9}$$

with $\mathbf{F}_{k,p}^{(i)} = [F_{k,p}^{(i,1)}\ F_{k,p}^{(i,2)}\ ...\ F_{k,p}^{(i,R)}]^T$ denoting the feedforward coefficients, $\mathbf{B}_{k,p}^{(i)} = [B_{k,p}^{(i,1)}\ B_{k,p}^{(i,2)}\ ...\ B_{k,p}^{(i,P)}]^T$ denotes the feedback coefficients and vector $\bar{\mathbf{S}}_k^{(p,i-1)} = [\bar{S}_{k,1}^{(i)}\ ...\ \bar{S}_{k,p-1}^{(i)}\ \bar{S}_{k,p}^{(i-1)}\ ...\ \bar{S}_{k,P}^{(i-1)}]^T$, 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. The elements of $\bar{\mathbf{S}}_k^{(p,i-1)}$ are associated to the current 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).

The average values $\bar{s}_{n,p}^{(i)}$ for normalized QPSK constellations (i.e., $s_{n,p} = \pm 1 \pm j$) can be computed as described in [10], [11]. The optimum feedforward and feedback coefficients that maximize the signal to overall noise plus interference at the detector output are given by

$$\mathbf{F}_{k,p}^{(i)} = \mathbf{\Lambda}_{k,p}^{(i)}\mathbf{H}_k^H\mathbf{\Theta}_{k,p}^{(i)} \tag{10}$$

and

$$\mathbf{B}_{k,p}^{(i)} = \mathbf{H}_k\mathbf{F}_{k,p}^{(i)} - \mathbf{\Gamma}_p, \tag{11}$$

respectively

$$\mathbf{\Lambda}_{k,p}^{(i)} = \left(\mathbf{H}_k^H\left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2}\right)\mathbf{H}_k + \frac{\sigma_N^2}{\sigma_S^2}\mathbf{I}_R\right)^{-1}, \tag{12}$$

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

$$\mathbf{\Theta}_{k,p}^{(i)} = \kappa\left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2}\right)\mathbf{\Gamma}_p - \frac{\lambda_p^{(i)}}{2\sigma_S^2 N}\mathbf{\Gamma}_p, \tag{13}$$

with κ selected to ensure that

$$\frac{1}{N}\sum_{k=0}^{N-1}\sum_{r=1}^{R}F_{k,p}^{(r,i)}H_{k,p}^{eq(r)} = 1. \tag{14}$$

$\mathbf{I}_K$ denotes a $K \times K$ identity matrix and $\mathbf{\Gamma}_p$ is a column vector with 0 in all positions except the pth position that is 1. The $\mathbf{P}^{(i)}$ matrix in (12) is given by $\mathbf{P}^{(i)} = diag(\rho_1^{(i)}, \ldots, \rho_P^{(i)})$, where

$$\rho_p^{(i)} = \frac{E[\hat{s}_{n,p}s_{n,p}^*]}{E[|s_{n,p}|^2]} \tag{15}$$

is a measure of the reliability of the estimates associated to the ith iteration that can be obtained as described in [10].

If we have only the pth MT transmitting then

$$F_{k,p}^{(r,i)} = \frac{\kappa H_{k,p}^{eq(r)*}}{\frac{\sigma_N^2}{\sigma_S^2} + \sum_{r'=1}^{R}\left|H_{k,p}^{eq(r')}\right|^2} \tag{16}$$

and

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

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

IV. Performance Results

This section presents a set of performance results considering the proposed iterative frequency-domain receivers for the uplink of BS cooperation schemes employing SC-FDE modulations with the corresponding quantization impact. 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. Channels between different MTs and different BSs are uncorrelated and severely time-dispersive,

[4]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.

each one with rich multipath propagation and uncorrelated Rayleigh fading for different multipath components. We assume perfect synchronization and channel estimation, with the useful part of the blocks transmitted by different MTs arriving[5] at each BS simultaneously. The MFB (Matched Filter Bound) is also obtained for each scenario.

Let us start by considering the case where we have only 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 $[\xi_{1,1}\ \xi_{1,2}] = [0\ 0]$ (dB), i.e., the links between the MT and each BS have the same average power. Fig. 3 shows the BER performance for a linear FDE (i.e., only one iteration of our iterative receiver) and different quantization scenarios. Fig. 4 illustrates the 4th iteration of our receiver, under the same conditions of Fig. 3. As expected, the performance improves with the number of quantization levels 2^m, with almost ideal results for $m = 4$ or 5. The performance with BS cooperation is always better than when we use only the received signal associated to one BS (i.e., without macro-diversity), although the difference is higher for the linear FDE. Finally, it should also be pointed out that the performance of the iterative receiver with 4 iterations is very close to the MFB.

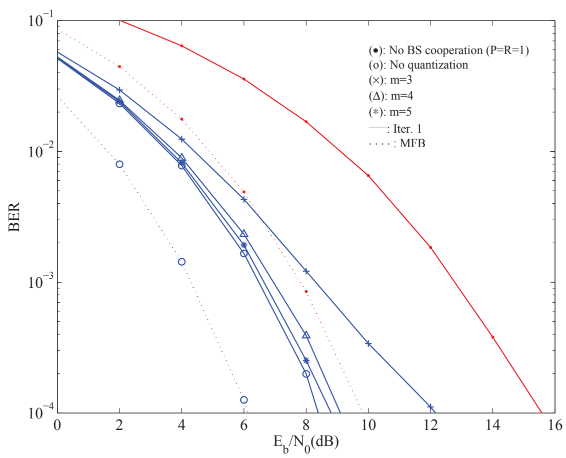

Fig. 3. BER performance for a macro-diversity scenario with $R = 2$ cooperating BSs and a linear FDE (1st iteration).

Fig. 5 compares the cases having quantization at both BSs with the case where there is quantization at a single BS and the central unit is placed at the second BS, for the case where $m = 4$. From this figure we can observe that there is a slight improvement when the quantization is performed only at one BSs, although the difference is significative only for the linear FDE.

Let us now consider the case where we have more than one MT per physical channel ($P = 2$) and $R = 2$ cooperating

[5] 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.

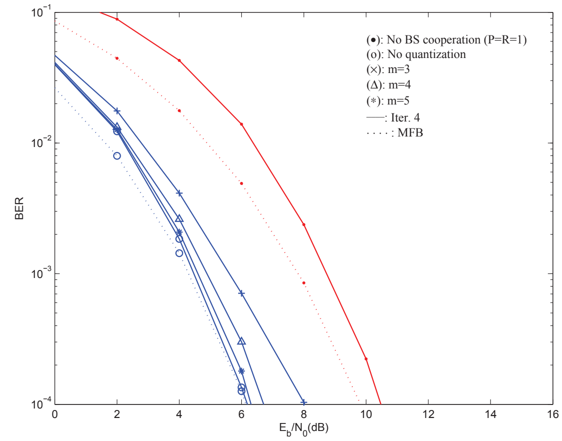

Fig. 4. BER performance for a macro-diversity scenario with $R = 2$ cooperating BSs and our IB-DFE (4th iteration).

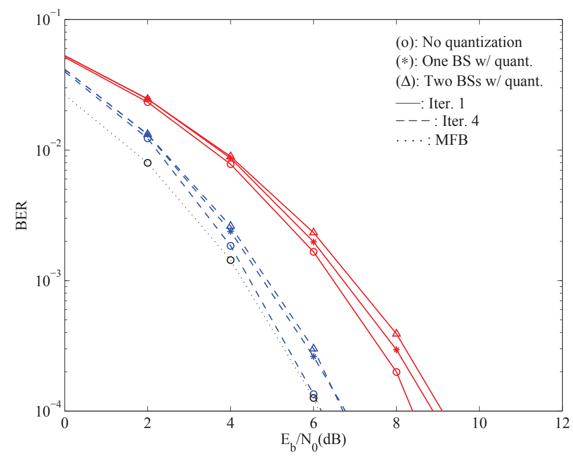

Fig. 5. BER performance for a macro-diversity scenario with $R = 2$ cooperating BSs with quantization in only one BS and in both BSs (both cases with $m = 4$).

BSs and $\xi_{p,r} = -3$dB for all p and r. This can be regarded as a scenario where both MTs are at the cell's edge and the MTs are transmitting with half the power they would transmit in a conventional scenario (i.e., when $P = R = 1$). Fig. 6 shows the impact of the number of iterations on the BER performance for each MT. From this figure it is clear that the BER performance improves significantly with iterations, with results close to the MFB after just 4 iterations. The MT that is first detected has worse performance because it faces stronger interference levels. This difference is higher for the first iteration and it reduces as we increase the number of iterations, becoming almost negligible with 4 iterations. This means that our iterative receiver is able to perform MTs separation while taking advantage of signal contributions associated to MTs that are received at each BS.

Fig. 7 and 8 show the impact of quantization on the BER performance for different quantizers when quantization is performed at both BSs and when it is performed in only one

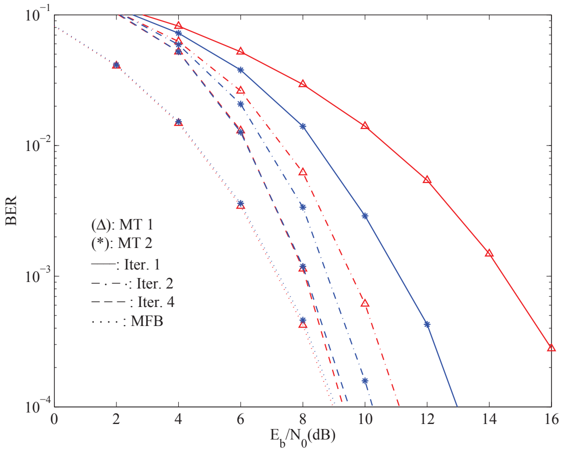

Fig. 6. BER performance for BS cooperation scenario without quantization (iterations 1, 2 and 4).

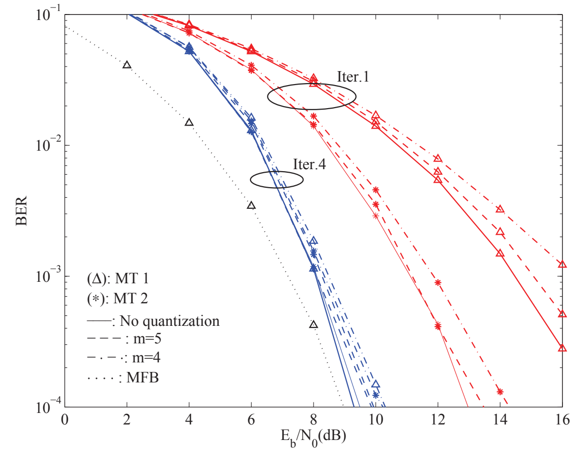

Fig. 8. BER performance with quantization on a single BS.

BS, respectively. Clearly, quantization degrades the system's performance, with slightly worse results when the quantization is performed at both BSs. As in the macro-diversity case ($P = 1$ and $R = 2$), $m = 5$ leads to almost optimum results and $m = 4$ leads to a slight degradation.

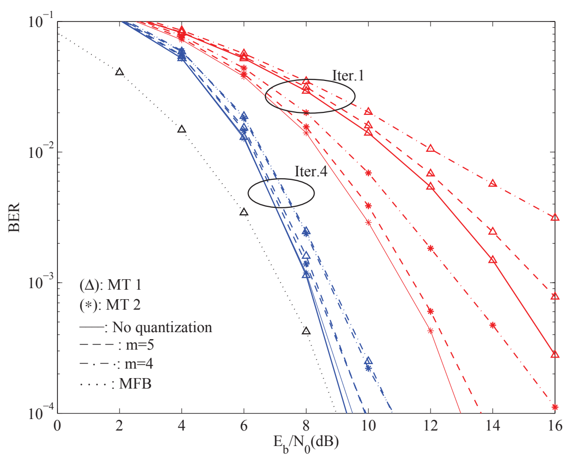

Fig. 7. BER performance with quantizers at both BSs.

From these results, it is clear that the number of bits per block for the link between each BS and the central unit $2mN$ can be around $8N$ or $10N$, for $m = 4$ or $m = 5$, respectively, with minimal performance degradation. Naturally, we might need a few more bits if we also need to transmit the value of $\xi_{p,r}$.

V. Conclusions

In this paper we considered the uplink of BS cooperation schemes based on SC-FDE modulations. The signals received at a given BS are sampled and quantized and the corresponding bits are sent to a central unit that performs the separation of the transmitted signals associated to each MT using an iterative frequency-domain receiver receiver based on the IB-DFE concept. The performance of our receiver with different quantization characteristics is studied in detail. It is shown that we can have excellent performances using only 4 or 5 bits to quantize the real and the imaginary parts of the complex envelope of the received signal at the BS.

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