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Turbo Receivers for Single User MIMO LTE-A Uplink

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***Abstract*—The paper deals with turbo detection techniques for Single User Multiple-Input-Multiple-Output (SU MIMO) antenna schemes. The context is on the uplink of the upcoming Long Term Evolution - Advanced (LTE-A) systems. Iterative approaches based on Parallel Interference Cancellation (PIC) and Successive Interference Cancellation (SIC) are investigated, and a low-complexity solution allowing to combine interstream interference cancellation and noise enhancement reduction is proposed. Performance is evaluated for Orthogonal Frequency Division Multiplexing (OFDM) and Single Carrier Frequency Division Multiplexing (SC-FDM) as candidate uplink modulation schemes for LTE-A. Simulation results show that, in a 2x2 antenna configuration, the turbo processing allows a consistent improvement of the link performance, being SC-FDM the one having higher relative gain with respect to linear detection. The turbo receiver's impact is however much reduced for both modulation schemes in a 2x4 configuration, due to the higher diversity gain provided by the additional receive antennas.**

***Index Terms*—LTE-A, MIMO, OFDM, SC-FDM, turbo receiver, PIC, SIC**

I. Introduction

The 3rd Generation Partnership Project (3GPP) is currently specifying the system requirements for the upcoming Long Term Evolution - Advanced (LTE-A) systems, aiming at target peak data rates of 1 Gbits/s in local areas and 100 Mbit/s in wide areas. While in the previous Release 8 [1] only single transmit antenna schemes have been standardized for the uplink, multiple-input-multiple-output (MIMO) techniques are expected to be deployed to meet these ambitious requirements. Orthogonal Frequency Division Multiplexing (OFDM) has been selected in the Release 8 for the downlink due to its high robustness to multipath as well as its flexibility, allowing to easily share resources among users while keeping full intra-cell orthogonality [2]. In this scheme, the modulated symbols are split over narrowband subcarriers and transmitted in parallel over the wireless channel; a cyclic prefix (CP) is inserted to mitigate the intersymbol interference (ISI) and the intercarrier interference (ICI), allowing simple equalization in the receiver. Despite its advantages, OFDM suffers from high Peak to Average Power Ratio (PAPR) of the transmitted signals, which requires higher power backoff in the transmitter to avoid distortions, and hence leading to lower power efficiency. This is particularly critical in uplink because of the power consumption constraint in the User Equipment (UE). Therefore, Single Carrier Frequency Division Multiplexing (SC-FDM) has been selected for the uplink in LTE [1]. This modulation scheme exploits the same benefits in terms of multipath mitigation and flexibility as OFDM. However, data symbols are transmitted serially in the time domain, leading to a consistent reduction of the PAPR [3]. Nevertheless, the choice of the uplink modulation scheme for LTE-A has not yet been finalized. It has been shown that OFDM generally outperforms SC-FDM in terms of spectral efficiency when linear receivers are used [4]; this is because SC-FDM systems suffer from an effect called “noise enhancement”, which degrades the estimation of the data symbols. In a previous study [5], we implemented an iterative receiver for a single-input-multiple-output (SIMO) SC-FDM system, showing that the noise enhancement can be overcome by the non-linear detection. That makes the performance of SC-FDM similar to OFDM.

In this paper, we extend the previous work to a double stream Single User MIMO scheme for the upcoming LTE-A systems. Iterative approaches based on parallel and successive interference cancellation are investigated, and a new turbo processing solution allowing to reduce the computational complexity is proposed. Both parallel and successive interference cancellation have been widely treated in literature, for CDMA as well as OFDM systems (e.g.,[6],[7] and [8]). Their aim is basically a progressive reduction of the interstream interference by including in the detection process a previous estimate of the transmitted data sequences. Here, since our main scope is leveraging SC-FDM performance, we combine in the iterative processing (even called *turbo* processing) both the traditional interstream interference removal provided by the aforementioned techniques and the noise enhancement reduction.

The remainder of the paper is structured as follows. In

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Section I, the MIMO LTE-A system is presented. Section II describes the principles of the iterative detection, focusing on Parallel and Successive Interference Cancellation. Section III shows our proposed turbo processing strategy with limited complexity. In Section IV, simulation results are presented and discussed. Finally, Section V summarizes the conclusions.

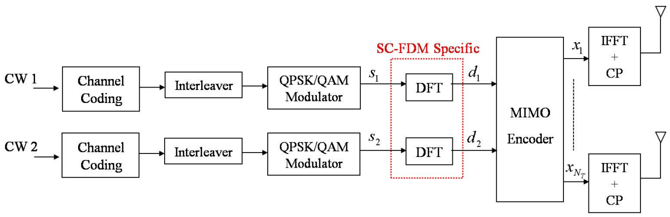

Fig. 1. MIMO transmitter with 2 codewords.

II. System Model

A simplified baseband model of a MIMO OFDM/SC-FDM transmitter with 2 codewords (CWs) and N_T transmit antennas is depicted in Fig.1. For each CW, the information bits are independently encoded, interleaved, and finally mapped to QPSK/M-QAM symbols, yielding the vectors $\mathbf{s_i}$, i=1,2. Then, a Discrete Fourier Transform (DFT) is performed in the case of SC-FDM, spreading each data symbol over all the subcarriers, obtaining the vectors $\mathbf{d_i}$. For OFDM instead, each data symbol is mapped over one subcarrier, i.e. $\mathbf{d_i} = \mathbf{s_i}$. Symbols $\mathbf{d_i}$ are then mapped over the transmit antennas by the MIMO encoder block. Finally, an Inverse Fast Fourier Transform (IFFT) is applied and a CP is appended. Assuming that the channel response is static over the duration of an OFDM symbol, and the CP is long enough to cope with the delay spread of the channel, the received signal after CP removal and fast Fourier transform (FFT) can be written as follows:

$$\mathbf{y}[k] = \mathbf{H}[k]\mathbf{x}[k] + \mathbf{w}[k] \tag{1}$$

where $\mathbf{x}[k] = [x_1(k), x_2(k), \dots, x_{N_T}(k)]^T$ is a vector containing the encoded complex transmitted MIMO symbols at subcarrier k from the N_T transmit antennas, $\mathbf{w}[k] = [w_1(k), w_2(k), \dots, w_{N_R}(k)]^T$ is the additive white Gaussian noise vector with $E[w_i(k)w_i(k)^*] = \sigma_w^2$ and

$$\mathbf{H}[k] = \begin{bmatrix} h_{11}(k) & \dots & h_{1N_T}(k) \\ \vdots & \ddots & \vdots \\ h_{N_R1}(k) & \dots & h_{N_RN_T}(k) \end{bmatrix} \tag{2}$$

is the channel transfer function matrix at subcarrier k. $h_{ij}(k)$ denotes the complex channel gain from the transmit antenna j to the receive antenna i. In this study, it is assumed that $E[s_i(k)s_i(k)^*] = 1$ and that the transmitted power is equally distributed among the transmit antennas.

III. Iterative detection

The structure of the considered turbo receiver is shown in Fig.2. The equalizer and the turbo decoder are joint in a loop, benefiting from the mutual information exchange. The aim is improving the performance with respect to the linear receiver by iteratively enhancing the reliability of the data estimates for each CW. The turbo decoder provides an estimate of all the coded bits in the form of likelihood ratios, that are subsequentely interleaved and modulated as done in [5] to get a *soft* estimate of the transmitted symbols. These soft estimates are then fed back to an interference canceller, allowing to progressively remove the mutual interference contribution. In SC-FDM systems, the inverse discrete Fourier transform (IDFT) performed at the receiver spreads the noise contribution from faded subcarriers over all the data symbols. Iterative processing aims even at reducing this noise enhancement. In the following, we present the principles of two widely adopted iterative detection techniques: Parallel Interference Cancellation and Successive Interference Cancellation.

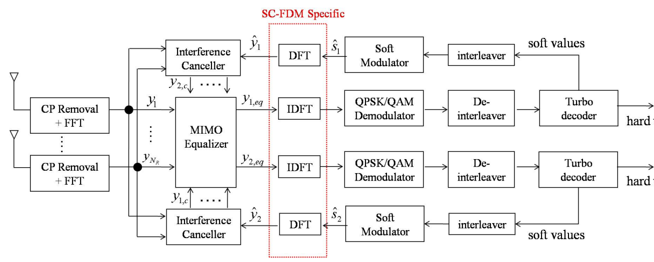

Fig. 2. MIMO Turbo Receiver.

A. Parallel Interference Cancellation (PIC)

In the PIC technique, all the CWs are detected in parallel, interleaved, re-modulated and sent back to the interference canceller, whose output for the m-th CW in the subcarrier k at n-th iteration can be written as follows:

$$\mathbf{y}^n_{m,c}[k] = \mathbf{y}[k] - \mathbf{H}_{Z-\{m\}}[k]\widehat{\mathbf{d}}^{n-1}_{Z-\{m\}}[k] \tag{3}$$

where $Z = \{1, 2\}$ is the set of the CWs'indexes, $\mathbf{H}_{Z-\{m\}}$ denotes the column of $\mathbf{H}$ corresponding to the antennas on which the $(Z - \{m\})$-th CW has been mapped, and $\widehat{\mathbf{d}}^{\mathbf{n-1}}_{\mathbf{Z-\{m\}}}$ is the frequency domain soft estimate of the $(Z - \{m\})$-th CW, obtained in the previous iteration. Note that for SC-FDM, $\widehat{\mathbf{d}}^{\mathbf{n-1}}_{\mathbf{Z-\{m\}}}$ is obtained through a DFT operation over the soft modulated symbols $\widehat{\mathbf{s}}^{\mathbf{n-1}}_{\mathbf{Z-\{m\}}}$ (for OFDM, $\widehat{\mathbf{d}}^{\mathbf{n-1}}_{\mathbf{Z-\{m\}}} = \widehat{\mathbf{s}}^{\mathbf{n-1}}_{\mathbf{Z-\{m\}}}$). The residual error after the interference cancellation should be taken into account in the equalization. The frequency domain equalization for the m-th CW in subcarrier k can be carried out as follows [8]:

$$\mathbf{y}^n_{m,eq}[k] = \mathbf{H}^H_m[k]\left[\mathbf{H}[k]\mathbf{Q}_n\mathbf{H}^H[k] + N_T\sigma_w^2\mathbf{I}_{N_R}\right]^{-1}\mathbf{y}^n_{m,c}[k] \tag{4}$$

where $(\cdot)^H$ denotes the hermitian operator, $\mathbf{I_{N_R}}$ is the $N_R \times N_R$ identity matrix, and $\mathbf{Q_n} = \mathbf{diag}\left[\mathbf{q_1}, \cdots, \mathbf{q_{N_T}}\right]$ is the $N_T \times N_T$ diagonal matrix of the residual interference powers, whose j-th element can be expressed as:

$$q_j = \begin{cases} 1, & \text{if } \ j = m \\ 1 - \widehat{\sigma}^2_{Z-\{m\},n-1} & \text{if } \ j \neq m \end{cases} \tag{5}$$

where $\widehat{\sigma}^2_{Z-\{m\},n-1}$ is the variance of the soft modulated symbols of the $(Z-\{m\})$-th CW at *(n-1)*-th iteration. It can be computed as follows:

$$\widehat{\sigma}^2_{Z-\{m\},n-1} = \frac{1}{N_{sub}} \sum_{k=1}^{N_{sub}} \left| \widehat{s}^{n-1}_{Z-\{m\}}[k] \right|^2 \quad (6)$$

where N_{sub} is the number of subcarriers. Note that at the beginning, when no apriori information is available, $\widehat{\sigma}^2 = 0$ and Eq.(4) acts as a traditional Minimum Mean Square Error (MMSE) equalizer. The receiver performs the tasks described above for a number of iterations; after that, the turbo decoder takes hard decisions about the transmitted bits.

B. Successive Interference Cancellation (SIC)

In the SIC technique the CWs are first ordered depending on some criterion, and the detection and the decoding processes are performed sequentially. The CWs are usually ordered according to their equivalent channel gain, so that the CW with highest equivalent channel gain is detected first. The equivalent channel gain of the *m*-th CW at the *n*-th iteration can be expressed as follows:

$$\tilde{H}^n_m = \frac{1}{N_{sub}} \sum_{k=1}^{N_{sub}} \mathbf{H}^H_m[k] \left[\mathbf{H}[k]\mathbf{Q_n}\mathbf{H}^H[k] + N_T\sigma^2_w \mathbf{I}_{N_R} \right]^{-1} \mathbf{H}_m[k] \quad (7)$$

The selected CW is detected, soft modulated and fed back to the interference canceller, whose output can be written as follows:

$$\begin{aligned} \mathbf{y}^n_{m,c}[k] &= \mathbf{y}[k] - \mathbf{H}_{Z-\{m\}}[k]\widehat{\mathbf{d}}^p_{Z-\{m\}}[k],\ where \\ & p = n \text{ if } Z-\{m\} = argmax_{i=1,2}\tilde{H}^n_i \\ & p = n-1 \text{ if } Z-\{m\} \neq argmax_{i=1,2}\tilde{H}^n_i \end{aligned} \quad (8)$$

The equalizer's output for the *m*-th CW in subcarrier *k* is given by:

$$\mathbf{y}^n_{m,eq}[k] = \mathbf{H}^H_m[k] \left[\mathbf{H}[k]\tilde{\mathbf{Q}}_n\mathbf{H}^H[k] + N_T\sigma^2_w\mathbf{I}_{N_R} \right]^{-1} \mathbf{y}^n_{m,c}[k] \quad (9)$$

where $\tilde{\mathbf{Q}}_n = diag\left[\tilde{q}_1, \cdots, \tilde{q}_{N_T}\right]$, whose generic *j*-th element can be written as:

$$\tilde{q}_j = \begin{cases} 1, & \text{if } \ j = m \\ 1-\widehat{\sigma}^2_{Z-\{m\},n} & \text{if } \ j \neq m, j = argmax_{i=1,2}\tilde{H}^n_i \\ 1-\widehat{\sigma}^2_{Z-\{m\},n-1} & \text{if } \ j \neq m, j \neq argmax_{i=1,2}\tilde{H}^n_i \end{cases} \quad (10)$$

IV. Turbo processing with limited complexity

An obvious drawback of the iterative detection techniques is their computational complexity, increasing with the number of iterations. However, since an estimate of the transmitted CWs is available at each iteration, the turbo processing presented above is redundant once at least one of them has been correctly detected. In LTE, a cyclic redundancy code (CRC) is appended to the information bits of the CW to check if the detection process has been successful. Here, we propose to use this error-detection capability to reduce the turbo processing complexity. In fact, checking the CRC allows to stop the iterative process once CWs are correctly decoded. Furthermore, we combine in the same process both the interstream interference removal and the noise enhancement reduction for SC-FDM. For simplicity, in the following we will refer to a double transmit antenna system.

Let us suppose to perform the generic *n*-th iteration of the PIC or SIC algorithm. After both CWs have been detected, their CRC is checked by taking hard decisions on the soft bits. The possible options and the subsequent behaviour to be adopted are the followings:

- Both CWs are not successfully detected. Continue performing PIC or SIC in the *(n+1)*-th iteration.
- Only one CW is successfully detected. In this case, the interstream interference can be fully removed from the wrong CW. Therefore, the MIMO system is virtually reduced to a single-input-multiple-output one, and the noise enhancement reduction strategy for SC-FDM presented in [5] can be adopted. To sum up, the following steps have to be performed:
  - *(n+1)*-th iteration: feed back only the correct CW for interstream interference removal and equalization;
  - from *(n+2)*-th iteration: re-modulate the wrong CW obtaining $\widehat{\mathbf{d}}^{\mathbf{n+1}}_{\mathbf{wr}}$ and use the equalizer coefficients defined in [5], that have been shown to reduce the noise enhancement of SC-FDM in a SIMO system. We distinguish between forward coefficients, which aim at increasing the Signal-to-Noise Ratio (SNR), and feedback coefficients, designed at the purpose of reducing the noise contribution in the estimated sequence. The forward coefficient at the *q*-th receive antenna in subcarrier *k* can be defined as follows:

$$C_{ff,q}\left(k\right) = \frac{1}{1+\beta\widehat{\sigma}^2_{wr,n+1}} \frac{h^*_{q,wr}\left(k\right)}{\left(1-\widehat{\sigma}^2_{wr,n+1}\right)\sum_{q=1}^{N_R}\left|h_{q,wr}\left(k\right)\right|^2 + \sigma^2_w} \quad (11)$$

where

$$\beta = \frac{1}{N_{sub}} \sum_{k=1}^{N_{sub}} \frac{\sum_{q=1}^{N_R}\left|h_{q,wr}\left(k\right)\right|^2}{\left(1-\widehat{\sigma}^2_{wr,n+1}\right)\sum_{q=1}^{N_R}\left|h_{q,wr}\left(k\right)\right|^2 + \sigma^2_w} \quad (12)$$

The feedback coefficient in subcarrier *k* can be expressed as:

$$C_{fb}\left(k\right) = \sum_{q=1}^{N_R} h_{q,wr}\left(k\right) C_{ff,q}\left(k\right) - 1 \quad (13)$$

Therefore the resultant output of the equalizer is given by:

$$y^{n+2}_{wr,eq}[k] = \underline{\mathbf{C_{ff}}}[k]\mathbf{y}^{n+1}_{wr,c}[k] - C_{fb}(k)\widehat{\mathbf{d}}^{n+1}_{wr}[k] \quad (14)$$

where $\underline{\mathbf{C_{ff}}}[\mathbf{k}] = [\mathbf{C_{ff,1}}(\mathbf{k}), \cdots, \mathbf{C_{ff,N_R}}(\mathbf{k})]$. For further details, we refer to [5].

- Both CWs are successfully detected: jump to the detection of the next data frame.

TABLE I
SIMULATION PARAMETERS

Carrier frequency	2 GHz
Sampling frequency	15.36 MHz
Subcarrier spacing	15 KHz
FFT size	1024
Used subcarriers	600
CP length	$5.2^a/4.68^b$ μs
Slot duration	0.5 ms
Symbols per slot	7
MIMO schemes	(2x2, 2x4) SM
User speed	3 kmph
MCS settings	QPSK: 1/6, 1/3, 1/2, 2/3 16QAM: 1/2, 2/3, 3/4 64QAM: 2/3, 4/5
Channel code	3GPP Rel.8 compliant Turbo code with basic rate 1/3
Turbo decoder iterations	8
Receiver scheme	MMSE, PIC, SIC

[a] First OFDM/SC-FDM symbol in a slot.
[b] $2^{th} - 7^{th}$ OFDM/SC-FDM symbol in a slot.

V. PERFORMANCE EVALUATION

The performance of the turbo receiver is evaluated by Monte Carlo simulations. We use as a reference 10 MHz LTE configuration parameters [1]. The main simulation parameters are gathered in Table I. An urban micro channel model (SCM-D) [9] is used in the simulations, and perfect channel knowledge is assumed. In the following, we will assume that an iteration of both PIC and SIC is completed once an estimate of both CWs is available by exploiting the feedback information. The linear MMSE equalization can instead be considered as the 0-*th* iteration of the PIC scheme.

Fig.3 shows the performance of PIC and SIC for a 2x2 SC-FDM system in terms of Block Error Rate (BLER), assuming 16QAM 2/3. Linear MMSE performance is also included. Both iterative techniques lead to a consistent gain over linear detection, up to 5 dB with 6 iterations. Most of the gain is already obtained after the first iteration. Note that at the first iteration PIC performs better than SIC because in the latter the soft interference is removed only from one CW. However, for higher number of iterations both techniques tend to perform similarly. It can be seen (Fig.4) that SIC converges slightly faster than PIC. This is because in SIC one of the soft estimates used in the interference cancellation is obtained in the current iteration, while in PIC both are obtained in the previous iteration.

Fig.5 depicts a comparison between OFDM and SC-FDM for SIC receivers. As it can be observed, OFDM clearly outperforms SC-FDM when linear receivers are used. This is due to the noise enhancement in SC-FDM systems. OFDM performance can be further improved by the iterative detection. However, for OFDM the gain of SIC with respect to MMSE is limited to 3.5 dB. This allows reducing the performance

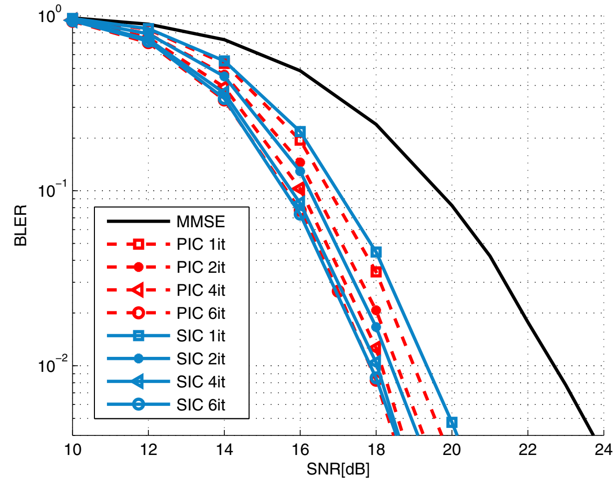

Fig. 3. BLER performance of SC-FDM in a 2x2 antenna system, with 16QAM 2/3.

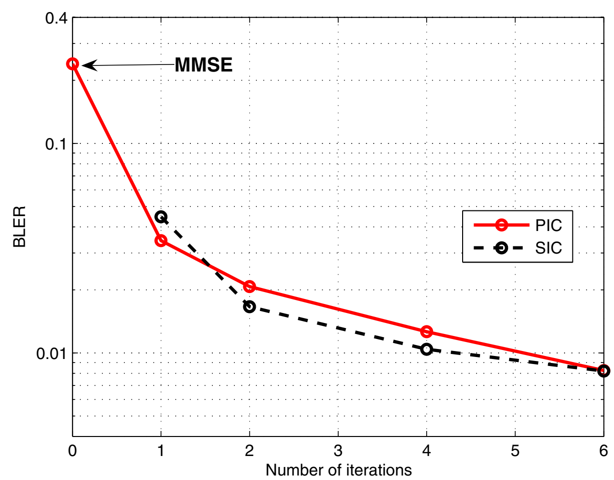

Fig. 4. SC-FDM PIC vs. SIC, SNR=18dB.

gap between OFDM and SC-FDM, to within 1 dB. The higher relative gain of SC-FDM compared to MMSE is due to the reduction of the noise enhancement provided by the turbo processing. Furthermore, comparing Fig.3 and Fig.5, it can also be noticed that the relative gain between different iterations is slightly higher for SC-FDM.

The gap between the modulation schemes with MMSE is quite reduced with a 2x4 antenna configuration, as presented in Fig.6. This is due to the increase of diversity, which averages the channel seen at the receiver. In this way, the deep fades of the channel are smoothed, and therefore the noise enhancement of SC-FDM is reduced. Here, the iterative processing only leads to a gain up to 2 dB for SC-FDM and 1.5 dB for OFDM, thus further reducing their performance gap.

The performance result on the whole SNR range, when link adaptation is used, is shown in Fig.7. The link adaptation is done based on average SNR and the corresponding curve

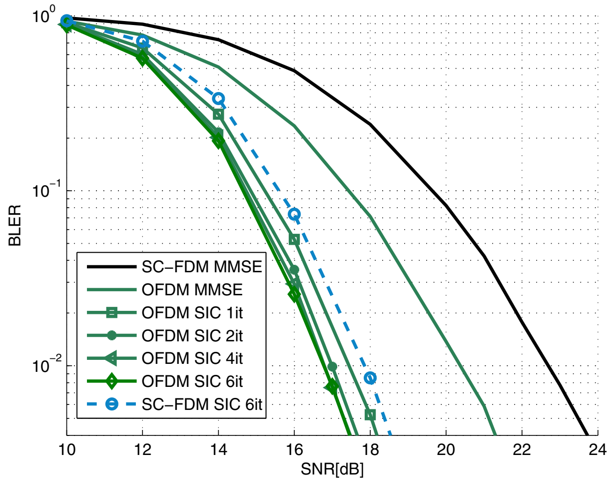

Fig. 5. Performance comparison between OFDM and SC-FDM in a 2x2 antenna system, with 16QAM 2/3.

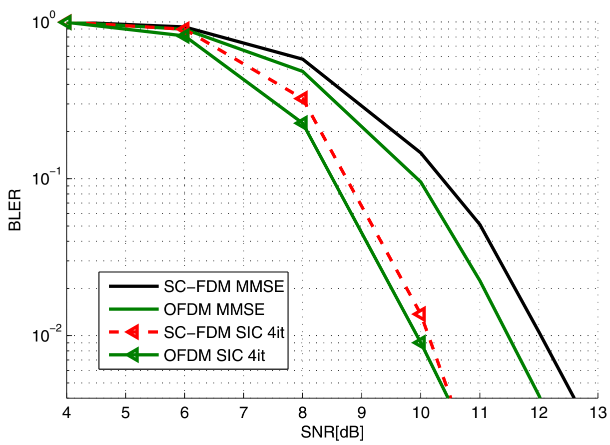

Fig. 6. Performance comparison between OFDM and SC-FDM in a 2x4 antenna system, with 16QAM 2/3.

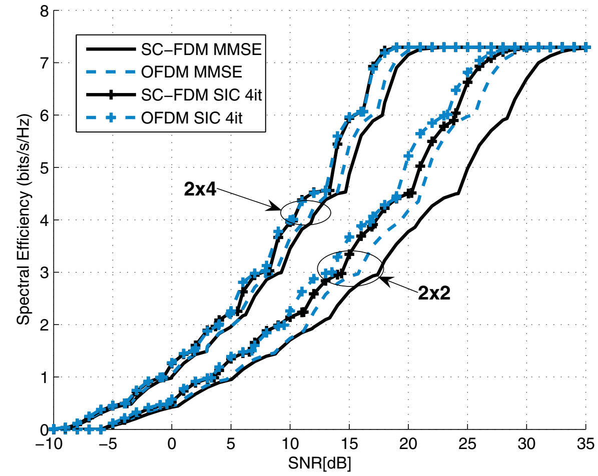

Fig. 7. Link adaptation curves for 2x2 and 2x4 antenna configurations.

results from the envelope of the spectral efficiency curves for several Modulation and Coding Schemes (MCSs). For low SNRs, OFDM performs as good as SC-FDM for both linear and iterative detection. The performance gap is relevant for high order MCSs, where the higher relative gain of the turbo receiver for SC-FDM is evident. OFDM and SC-FDM tend perform similarly in a 2x4 antenna system, as suggested by the previous results.

VI. Conclusions

In this paper, iterative detection techniques are presented and investigated in a Single User MIMO context for the uplink of the upcoming LTE-A standard, and a limited complexity solution combining interstream interference removal and noise enhancement reduction is proposed. Performance is evaluated for both OFDM and SC-FDM as candidate modulation schemes for the uplink of LTE-A. Simulation results show that the proposed solution leads to a gain in terms of BLER up to 5 dB over linear detection for a SC-FDM 2x2 antenna configuration, thus outperforming OFDM with linear MMSE receiver. For OFDM, the gain of the turbo processing over linear detection is limited to 3.5 dB. The diversity gain obtained by adding antennas at the receiver reduces the impact of the turbo processing: in fact, link adaptation based on average SNR shows no relevant difference in performance when the antenna configuration is increased to a 2x4 system.

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