SPATIAL MULTIPLEXED CODED MC-CDMA WITH ITERATIVE RECEIVER

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Abstract - In this paper, the combination of spatial multiplexing with coded Multi-Carrier Code Division Multiplex Access (MC-CDMA) for a Multiple Input Multiple Output (MIMO) Rayleigh fading multipath channel is considered. A practical receiver structure performing iteratively MIMO detection, multi-user despreading and channel decoding is presented. The MIMO detector, employing a linear Minimum Mean Square Error (MMSE) Parallel Soft Interference Canceller (PSIC) equalizer, allows to cope with Co-Antenna Interference (CAI). Simulation results show the efficiency of the iterative receiver for spatial multiplexed coded MC-CDMA that brings spatial diversity, increasing data rate and multi-user flexibility.

Keywords - MIMO, spatial multiplexing, MC-CDMA, iterative receiver.

I. Introduction

MC-CDMA appears to be suitable for future mobile radio communication systems. MC-CDMA has the properties desirable for high data wireless services owing to its robustness to frequency selective channel, efficient utilization of bandwidth and multi-user flexibility [1]. Moreover, by applying channel coding and bit interleaving, robustness against channel fading is improved [2]. On the other hand, multiple antenna systems were also demonstrated to be a very promising field of research in order to significantly increase the capacity of future wireless communication systems [3][4]. In [5], a first system based on Layered Space-Time architecture (LST) including Successive Interference Cancellation (SIC) at the receiver, was designed in order to exploit such capacity. In parallel, spatial diversity has also received significant interest in recent years in order to combat fadings of wireless networks [6], and Space-Time Block Coding (STBC) has been proposed as an effective technique that exploits space-time diversity at a low complexity cost [7]. However space-time coding schemes provide full diversity but generally do not increase data rate. Better spectral efficiencies are achieved by combining channel coding with spatial multiplexing [8][9] or by concatenating random code and LST architecture [10]. Nevertheless, these last systems require an iterative receiver in order to remove the CAI brought by spatial multiplexing.

In [11], the authors investigate space-time diversity for MC-CDMA system with turbo coding by using orthogonal STBC. In this paper, MC-CDMA is combined with convolutional code as channel coding and spatial multiplexing in order to exploit both capacity and spatial diversity provided by the MIMO system. An iterative receiver is proposed to take benefit from the decoded data of each user to improve MIMO equalization.

II. System Model

A. Transmitter

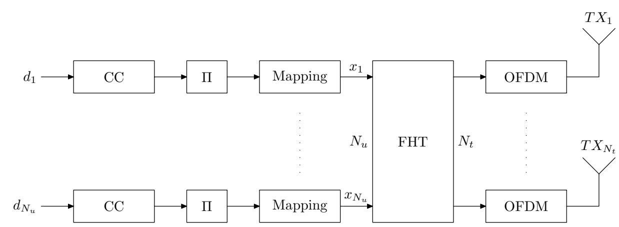

Fig. 1
MC-CDMA MIMO Transmitter

The transmitter scheme is shown in Figure 1. First, each user's data d_j is individually convolutionally encoded (CC), bit interleaved (Π) and mapped into complex symbols. The multi-user coded symbol vector is denoted $\underline{\mathbf{x}}$:

$$\underline{\mathbf{x}} = \begin{bmatrix} x_1 & \dots & x_j & \dots & x_{N_u} \end{bmatrix}^T \quad (1)$$

where N_u is the number of active users and $[.]^T$ denotes the transpose operation. The multiuser coded sequence is spread using a Fast Hadamard Transform (FHT) well known to provide very good performance in a downlink MC-CDMA scenario [12]. We consider that the length of the spreading sequence is equal to L_c. The spread vector $\underline{\mathbf{s}} \in \mathbb{C}^{L_c \times 1}$ is given by:

$$\underline{\mathbf{s}} = \mathbf{C} \cdot \underline{\mathbf{x}} \quad (2)$$

where $\mathbf{C}$ is the $L_c \times N_u$ matrix of user's spreading codes:

$$\mathbf{C} = \begin{bmatrix} \mathbf{c}_1 & \dots & \mathbf{c}_j & \dots & \mathbf{c}_{N_u} \end{bmatrix} \quad (3)$$

and

$$\mathbf{c_j} = \begin{bmatrix} c_{1j} & \dots & c_{kj} & \dots & c_{L_cj} \end{bmatrix}^T \quad (4)$$

The stream $\underline{\mathbf{s}}$ is divided into N_t substreams that are individually Orthogonal Frequency Division Multiplex (OFDM) modulated and simultaneously transmitted from a different antenna. In practice, OFDM modulation and demodulation are easily carried out in the digital domain by performing respectively Inverse Fast Fourier Transform (IFFT) and FFT operations. Furthermore the insertion of a guard interval, chosen greater than the delay spread of the channel, between adjacent OFDM symbols guarantees the absence of Inter Symbol Interference (ISI). In this paper, frequency non-selective Rayleigh fading per carrier is considered. Under these assumptions and considering ideal time and frequency interleavings, the independent complex channel fading coefficients are assumed uncorrelated for each subcarrier k. A MIMO channel with N_t transmit antennas and N_r receive antennas is considered. Therefore the theoretical channel response for the kth subcarrier from transmit antenna t to receive antenna r can be estimated by $h_{rt,k} = \rho_{rt,k} e^{i\theta_{rt,k}}$. At each receive antenna, the signal is corrupted by Additive White Gaussian Noise (AWGN) of variance σ_n. We assume that the channel coefficients and the noise variance are unknown at the transmitter side but perfectly known at the receiver. If $\mathbf{s}_k \in \mathbb{C}^{N_t \times 1}$ is the vector containing the N_t symbols of subcarrier k, then the corresponding receive vector $\mathbf{r}_k \in \mathbb{C}^{N_r \times 1}$ obtained after OFDM demodulation for the kth subcarrier can be expressed with the following formula:

$$\mathbf{r}_k = \mathbf{H}_k \cdot \mathbf{s}_k + \mathbf{n}_k \tag{5}$$

where $\mathbf{H}_k \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix:

$$\mathbf{H}_k = \begin{bmatrix} h_{11,k} & h_{21,k} & \dots & h_{N_t 1,k} \\ h_{12,k} & h_{22,k} & \dots & h_{N_t 2,k} \\ \vdots & \vdots & \ddots & \vdots \\ h_{1N_r,k} & h_{2N_r,k} & \dots & h_{N_t N_r,k} \end{bmatrix} \tag{6}$$

and $\mathbf{n}_k \in \mathbb{C}^{N_r \times 1}$ is the noise vector.

B. *Non iterative receiver scheme*

At the receiver side, the orthogonality between users has to be restored by applying a multi-antenna equalization process before despreading. A MMSE space-time equalization per subcarrier can be performed by applying a matrix $\mathbf{G}_k \in \mathbb{C}^{N_t \times N_r}$ to the receiver vector $\mathbf{r}_k$.

$$\mathbf{G}_k = \left(\mathbf{H}_k^H \mathbf{H}_k + \sigma_n^2 \mathbf{I}\right)^{-1} \mathbf{H}_k^H \tag{7}$$

where $\mathbf{I}$ is the $N_t \times N_t$ identity matrix and $[.]^H$ denotes the transpose conjugate operation.
After equalization, the resulting signal $\tilde{\mathbf{s}}_k \in \mathbb{C}^{N_t \times 1}$ is:

$$\tilde{\mathbf{s}}_k = \mathbf{G}_k \mathbf{H}_k \mathbf{s}_k + \mathbf{G}_k \cdot \mathbf{n}_k \tag{8}$$

The final step consists in despreading the global equalized vector $\underline{\tilde{\mathbf{s}}} \in \mathbb{C}^{L_c \times 1}$ in order to determine each user data.

$$\tilde{x}_j = \mathbf{c}_j^H \cdot \underline{\tilde{\mathbf{s}}} \tag{9}$$

Finally soft demapping and channel decoding are processed. This classical receiver both exploits spectral efficiency achieved by spatial multiplexing and multi-access flexibility provided by MC-CDMA.

III. Proposed iterative receiver

The optimal signal decoding would consist of an Maximum Likelihood (ML) detection based on a super trellis including the effect of channel coding, spreading, interleaving and space-time channel. However this receiver is extremely complex and does not lead itself to a feasible decoding algorithm. In this paper, a sub-optimum detection scheme based on iterative ”turbo” equalization principle [13] is carried out performing iterative joint MIMO equalization, multi-user detection and decoding. Relative low complexity is achieved by using mainly linear elements. Two main decoding stages, a MIMO multi-user equalizer and a Soft Output Viterbi Algorithm (SOVA) channel decoder, exchange the information learned from one stage to another iteratively. Each stages are separated by interleaver and deinterleaver in order to decorrelate the outputs before feeding them to the next decoding stage.

A. *Description of the iterative decoding scheme*

The proposed receiver is depicted in Figure 2. The MIMO multi-user equalizing stage first consists of a PSIC decoder per subcarrier, optimized under the MMSE criterion, that generates soft estimates $\tilde{\mathbf{s}}_k$ of spread signal $\mathbf{s}_k$. After rebuilding vector $\underline{\tilde{\mathbf{s}}}$, equalized symbols are despread to produce M-ary data symbol estimates x_j for each user. The demapper produces Logarithm Likelihood Ratio (LLR) of coded bits $\Lambda_1(\tilde{c}_j)$. These LLRs are fed via a desinterleaving module (Π^{-1}) to the channel decoding stage. The channel decoder produces on the one hand a posteriori LLRs on bits $\Lambda_2^{post}(\hat{d}_j)$ that are used to estimate user's j transmitted binary data $\hat{d}_j$. On the other hand, the channel decoder computes extrinsic LLRs using the Berrou-Adde algorithm [14]:

$$\Lambda_2^{extr}(\hat{c}_j) = ln \frac{Pr\{c_j = 1/\Lambda_1(\tilde{c}_j)\}}{Pr\{c_j = 0/\Lambda_1(\tilde{c}_j)\}} \tag{10}$$

These extrinsic values are again interleaved (Π) and then soft converted to M-ary estimated symbols $\hat{x}_j$. All the estimated symbols $\hat{x}_j$ of each user are spread into vector $\underline{\hat{\mathbf{s}}} \in \mathbb{C}^{L_c \times 1}$ in order to estimate the spread vector transmitted on the kth subcarrier, $\hat{\mathbf{s}}_k \in \mathbb{C}^{N_t \times 1}$. Finally the latest vector feeds the MMSE MIMO PSIC equalizer. Because data of all users must be decoded, we talk about multi-user detection.

B. *MMSE MIMO PSIC equalizer*

For the subcarrier k, received signal $\mathbf{r}_k$ is corrupted by CAI represented by off-diagonal terms of $\mathbf{H}$. In order to remove CAI, a PSIC optimized under the MMSE criterion is used. At the first iteration because no prior information on transmitted spread symbols is available, the MMSE MIMO equalizer introduced in section II-B is used, leading to the first equalized vector $\tilde{\mathbf{s}}_k^{(1)} \in \mathbb{C}^{N_t \times 1}$

$$\tilde{\mathbf{s}}_k^{(1)} = \left(\mathbf{H}_k^H \mathbf{H}_k + \sigma_n^2 \mathbf{I}\right)^{-1} \mathbf{H}_k^H \mathbf{r}_k \tag{11}$$

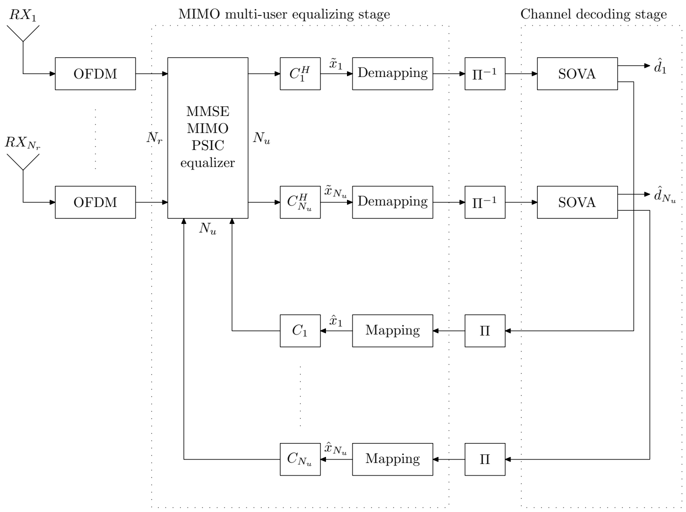

Fig. 2
Proposed iterative receiver

For next iterations, a soft MMSE interference canceller is performed using estimates of spread symbols provided by previous iterations. The expression of the equalized symbols vector obtained at the p-th iteration is the following:

$$\tilde{\mathbf{s}}_k^{(p)} = \left(\mathbf{D}_k + \sigma_n^2\mathbf{I}\right)^{-1}\left(\mathbf{H}_k^H\mathbf{r}_k - \mathbf{J}_k\hat{\mathbf{s}}_k^{(p-1)}\right) \qquad (12)$$

$\hat{\mathbf{s}}_k^{(p-1)} \in \mathbb{C}^{N_t \times 1}$ is the improved estimate vector $\mathbf{s}_k$ from iteration $p-1$ whereas $\mathbf{D}_k$ and $\mathbf{J}_k$ are $N_t \times N_t$ complex matrix containing respectively the diagonal and the off-diagonal elements of $\mathbf{H}_k^H\mathbf{H}_k$:

$$\mathbf{D}_k = Diag(\mathbf{H}_k^H\mathbf{H}_k) \quad \text{and} \quad \mathbf{J}_k = \mathbf{H}_k^H\mathbf{H}_k - \mathbf{D}_k \qquad (13)$$

The process is reiterated until all the CAI is completely removed.

IV. Simulation Results

Simulations have been carried out for independent Rayleigh flat fading channel environment for a 4 transmit antennas and 4 receive antennas scheme and perfect channel estimation. An half rate convolutional encoder with polynomial generators $(133, 177)_o$ is used and the bit interleaving size is fixed to 10000 bits. A Quadrature Phase Shift Keying (QPSK) with Gray mapping is used leading to a spectral efficiency per user $\eta = 4$ bps/Hz. The length of the spreading Walsh-Hadamard code is set to $L_c = 16$ and is equal to the number of subcarriers.

Figure 3 shows the Bit Error Rate (BER) performance of the iterative receiver for a full load system ($N_u = L_c$). From the 2^{nd} iteration, the iterative receiver notably outperforms the non-iterative scheme which corresponds to the first iteration. After 5 iterations, the process tends to the lower bound curve represented by a genie aided MIMO PSIC equalizer which would perfectly know all the transmitted data and would perfectly remove the CAI. Compared to the non-iterative receiver, the proposed receiver performs a significant gain, leading to a signal to noise ratio of 1.3 dB from the Gaussian curve at a BER equal to 10^{-4} for a full load 4×4 MIMO system. This gain is obtained owing to the MIMO PSIC equalizer that progressively cancels the CAI and consequently allows a better despreading process, restoring the orthogonality between the spreading codes and also decreasing the Multiple Access Interference (MAI) term. Moreover, even if such an iterative receiver may be a little complex to be implemented in a downlink MIMO MC-CDMA system, its performance results are very good and can be easily adapted for the uplink case.

Figure 4 presents the performance after 5^{th} iteration of

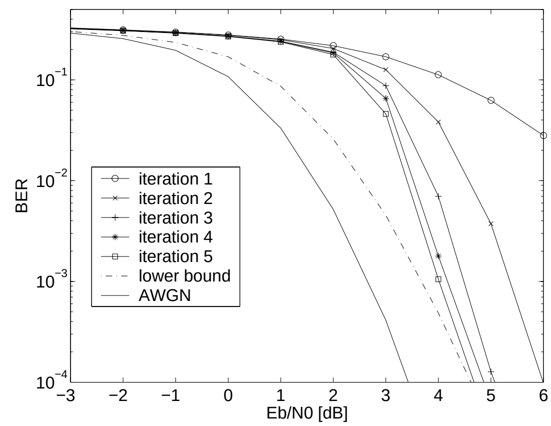

Fig. 3
BER performance of the iterative receiver for a MIMO 4×4 system at full load

the iterative receiver for different loads. As for Single Input Single Output (SISO) systems, performance obviously gets better when the load is reduced and Gaussian performance are obtained for a single user system. Nevertheless, for lower loads, since less MAI has to be removed, thus the iterative receiver reaches its optimal value with only few iterations. This phenomenon is highlighted in Figure 5 where BER evolution is plotted according to the number of iterations. The lower the load the faster the convergence speed, in fact for a 4/16 load, only 2 iterations are necessary while 5 iterations are needed at full load. Even if the system gives promising results, Figure 4 shows that the MAI term is not fully cancelled. So the performance could have been improved by performing MAI cancelling in the iterative process. However, such a detector will lead to a higher cost of complexity.

V. Conclusion

In this paper, coded MC-CDMA has been combined with spatial multiplexing. The studied association makes possible the exploitation of MIMO capacity and transmit diversity

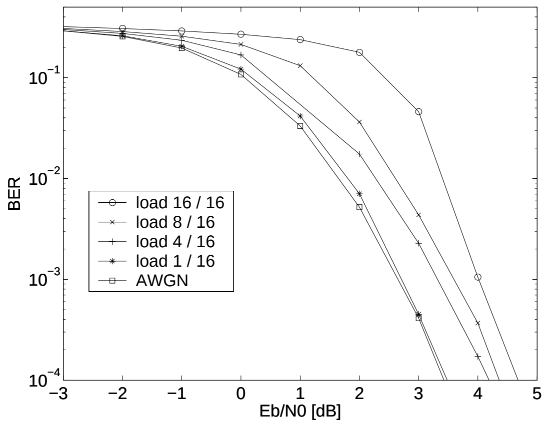

Fig. 4
BER performance of the iterative receiver for a MIMO 4×4 system at different loads, 5^{th} iteration

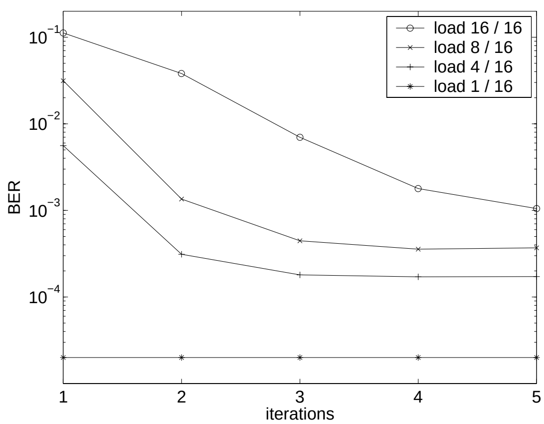

Fig. 5
Convergence behavior of the iterative receiver for a MIMO 4×4 system at different loads, SNR = 4 dB

while keeping MC-CDMA advantages. We have proposed an efficient iterative receiver performing jointly MMSE equalization, multi-user detection and channel decoding. By using a MIMO PSIC equalizer, the CAI is iteratively removed thus multi-antenna diversity is exploited and the MAI is decreased. The residual MAI between users could be treated in the iterative loop by using PIC or SIC multi user detector but these structures will lead to an additional complexity. For theoretical independent Rayleigh channel we demonstrate the efficiency of the proposed iterative receiver. In further studies, we will implement this detector over realistic MIMO channels and we will estimate the loss in performance due to the channel estimation.

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