Multiuser Coded FDM-CPM Systems with MIMO Transmission

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Abstract—**Performance of coded Frequency-Division Multiplexed Continuous Phase Modulation (FDM-CPM) systems with Multiple Input Multiple Output (MIMO) transmission is investigated. The system is designed to achieve high spectral efficiency by exploiting the multiplexing gain of MIMO techniques. Moreover, a FDM MultiUser (MU) scheme with tight inter-carrier frequency spacing is used to increase spectral efficiency. It is shown that, using this scheme, significant improvement both in terms of bit error rate and spectral efficiency are obtained when compared to the single-antenna MU scenario. To take advantage of the multiplexing gain of MIMO systems, a Minimum Mean Square Error (MMSE) MIMO detector and a low-complexity iterative algorithm for Inter-Carrier Interference (ICI) cancellation are considered. Numerical simulations have been performed to assess the performance improvement achieved with the proposed frequency-division multiplexed CPM multiuser MIMO system.**

Keywords-Continuous Phase Modulation; Frequency-Division Multiplexed system; inter-carrier interference cancellation; multiuser MIMO receiver

I. INTRODUCTION

In the past few years, several methods have been proposed for MultiUser (MU) detection of CPM signals [1], [2], [3], [4]. In [1] and [2], the use of CPM for MU communication over Additive White Gaussian Noise (AWGN) channels and serially concatenated CPM over Rayleigh fading channels were studied. Multiple Input Multiple Output (MIMO) systems [5] can improve bandwidth efficiency by exploiting the channel spatial diversity thus allowing for a transmission of more data streams simultaneously. MIMO systems are often implemented using Space-Time Codes (STC) to increase the reliability of transmission. STC for MIMO CPM systems were previously proposed with appropriate design criteria in [6], and a soft-decision iterative receiver was described [7]. Hesse et al. [8] introduced a new family of orthogonal STC for CPM. These codes offer good performance and low decoding complexity. A non-binary space-time coded scheme with m-ary CPM was developed in [9].

Nevertheless, optimal MU receivers [1] and the MIMO CPM receivers with STC [6], [7], [9] exhibit significantly higher complexity. MIMO CPM receivers for STC studied in [6-9] do not concern MU scenario. In literature [3], [4] the multiuser Frequency-Division Multiplexed (FDM) systems using CPM over AWGN channel were investigated. In [10], a method of estimating Channel State Information (CSI) has been shown to considerably improve performance of MU FDM-CPM systems. However, MIMO techniques are not considered in [3], [4], [10].

This paper investigates the performance of multiuser coded FDM-CPM systems with MIMO transmission. To ensure system simplicity, the employed MIMO scheme does not use Space-Time Codes. The system achieves a high Spectral Efficiency (SE) and low Bit Error Rate (BER), provided that an appropriate low-complexity iterative algorithm for Inter-Carrier Interference (ICI) cancellation is implemented in the MU receiver.

The paper is organized as follows. In Section II, we discuss the system model. In Section III, the simulation results are presented and, finally, conclusions are drawn in Section IV.

II. SYSTEM MODEL

In FDM uplink wireless transmission, the spectral efficiency can be improved by reducing the inter-carrier frequency spacing. Thereby, inter-channel interference increases. The ICI greatly depends on the normalized inter-carrier frequency spacing $\Delta_f T$, where T is the symbol interval and Δ_f is the frequency spacing in Hz between carriers. The carrier spacing $\Delta_f T$ is fixed to the value needed to achieve a desired Asymptotic Spectral Efficiency (ASE).

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The ASE_{MIMO} of a frequency-division multiplexed uplink MIMO transmission with inter-carrier frequency spacing $\Delta_f T$ is defined as

$$ASE_{MIMO} \triangleq \lim_{E_b/N_0 \to \infty} SE_{MIMO} = M_T \cdot \frac{R_C \log_2 M}{\Delta_f T} \quad (1)$$

where R_C is the rate of the puncturedchannel code,M is the size of the CPM input alphabet and M_T is the number of transmit antennas, which is assumed to be $\leq M_R$, the number of receiver antennas. In [4], it was shown that it is possible to obtain a major improvement in SE thanks to a simple iterative ICI cancellation technique applied at the multiuser CPM receiver. The overall receiver complexity grows only linearly with the number of users. In this paper, MU FDM-CPM systems with $M_T x M_R$ antennas (MIMO($M_T x M_R$) *systems*) are investigated, their performance is assessed and compared to Single-Input Single-Output (SISO) scheme. The MIMO schemes are used in their full spatial multiplexing configuration. Figure 1 shows a block diagram of the proposed system. At the input, each kth user binary information sequence $a_0, \ldots, a_{k-1}$, is converted into several (M_T) parallel streams. Each data stream is conveyed to one of M_T encoding modulators, each consisting of an outer Convolutional Encoder (CE) connected to the inner CPM modulator through an interleaver. A rate 1/3 systematic recursive CE with four states and good distance properties [11] has been chosen. Its connection polynomials (in octal notation) are $(7; 5; 3)_8$, where 7_8 represents the coefficients of the feedback polynomial [9]. In order to achieve higher rates, the CE output is punctured as in [9]: a rate-matching algorithm is used to obtain coding rate R_C=3/8. The interleaver that connects the outer encoder to the CPM modulator is a symbol, spread (S-random) interleaver [12] whose parameters are set according to the code word size. The convolutional encoding, puncturing, interleaving, and modulation are realized by the CE-CPM blocks shown in Figure 1. Each user signal is characterized by a distinct phase φ_k and delay τ_k, as typically occurs in uplink systems. Ideal power control is considered here. As a result, the received signal power is equal for all users. The signal at the receiver input can be written as

$$\mathbf{r} = \sum_{k=0}^{K-1} \mathbf{H}_k \mathbf{x}_k + \mathbf{u} = \mathbf{H}\mathbf{x} + \mathbf{u}. \quad (2)$$

where $\mathbf{r} \in \mathbb{C}^{M_R}$ is the received signal vector, $\mathbf{H_k} \in \mathbb{C}^{M_R x M_T}$is the channel matrix of user k with elements representing the fading coefficients between the transmit and receive antennas, $\mathbf{x_k} \in \mathbb{C}^{M_T}$ is the transmitted symbol vector of user k, $\mathbf{u} \in \mathbb{C}^{M_R}$is the additive noise, modeled as a zero-mean complex Gaussian random vector. $\mathbf{H}$ is the joint channel matrix $M_R x k M_T$ and $\mathbf{x}$ is the joint transmitted symbol vector of length kM_T.

Each receive antenna receives a faded superposition of the M_T simultaneously transmitted signals corrupted by additive white Gaussian noise. The fading is assumed to be flat anddistributed according to a Rayleigh *pdf*. The random path gains between transmit antenna i and receive antenna j, $g_{i,j}(t)$, are independent complex Gaussian random variables with zero mean and variance per dimension 1/2. The fading is slow, such that the $M_T x M_R$fading coefficients are constant during a frame, but vary from frame to frame. The AWGN noise components $n_j(t)$, are independent zero-mean complex Gaussian random processes with power spectral density N_0. The received signal on antenna j is then:

$$r_j(t) = \sum_{k=0}^{K-1} \sum_{i=0}^{M_T-1} g_{k,i,j} x_{k,i}\left(t - \tau_k, \boldsymbol{a}_{k,i}\right) \quad (3)$$

$$\cdot\, e^{j(2\pi k \Delta_f t + \varphi_k)} + n_j(t), \quad j = 0, \ldots, M_R - 1$$

The MIMO receiver in the proposed FDM-CPM system (see Figure 1) uses a Minimum Mean Square Error (MMSE) multiuser detection technique [6] and low-complexity iterative algorithm to ICI cancellation. The MMSE block computes the cost function, i.e., minimizes:

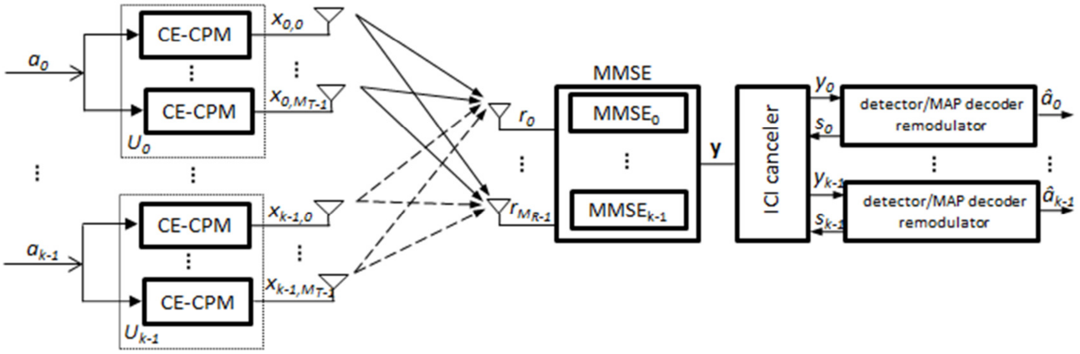

Figure 1. Block diagram of the MU coded FDM-CPM MIMO system.

$$E[(\mathbf{Mr}-\mathbf{x})(\mathbf{Mr}-\mathbf{x})^H]. \tag{4}$$

It amounts to finding the elements of matrix $\mathbf{M}$:

$$\mathbf{M}=(\mathbf{H}^H\mathbf{H}+N_0\mathbf{I})^{-1}\mathbf{H}^H \tag{5}$$

where $\mathbf{H}^H$ denotes the conjugate transpose of matrix $\mathbf{H}$ and $\mathbf{I}$ is the identity matrix. Finally we obtain the signal vector $\mathbf{y}$ as

$$\mathbf{y}=\sum_{k=0}^{K-1}\mathbf{M}_k\mathbf{r}_k. \tag{6}$$

The function of the MMSE block is to compensate for the effect of the channel by inverting the channel matrix according to the MMSE criterion (4, 5). The signal $\mathbf{y}$ from MMSE reaches the ICI cancellation block. The receiver carries out ICI cancellation through a set of single-user MAP detector/remodulator blocks, as described by Perotti et al. [4]. The remodulators make use of the output of the MAP detector to compute the remodulated signal $s_k^{(i)}(t)$ relative to the *k*th user and *i*th iteration. The channel decoder performs two iterations loops. The *inner* loop is formed by the ICI canceller, the MAP detector, the CPE SISO decoder and the remodulator, while the *outer* loop involves the CPE SISO decoder, the CE SISO decoder, the interleaver and the deinterleaver between the inner CPE decoder and the outer CE decoder. ICI cancellation can be performed while executing the decoding iterations to enhance the receiver performance. In such case, after the inner CPE decoder is executed, remodulation is performed. Then, interference cancellation is performed and the CPM receiver, including the inner CPE decoder, is again executed. The decoder starts decoding a received code word executing N_{IC} *inner* iterations. Then, it executes N_D times an *outer* iteration followed by an inner iteration. This way, ICI cancellation is performed as part of the decoding iterations and it results in an improved ICI cancellation [4]. On the final *outer* iteration, a decision is made on the transmitted data symbols $\hat{a}_0, \dots, \hat{a}_{k-1}$.

III. NUMERICAL SIMULATIONS AND DISCUSSION

Computer simulations have been made to evaluate the performance of the proposed MU serially concatenated CE FDM-CPM MIMO system. Different combinations of parameter setups for the MU FDM-CPM MIMO systems have been simulated. The most representative results have been selected for the presentation (hence the choice of parameters $\Delta_f T$, M, L, h). For comparison, performance of the MU FDM-CPM SISO system and the SISO and MIMO(2x2) systems with single user (no ICI) are also evaluated. We assume perfect knowledge of CSI at the receiver. In the considered system, we use full response (L=1) CPM modulation with the following parameters: M=4, h=1/5, L=1, RECtangular pulse shape (REC), $\Delta_f T=0.5$, R_C=3/8, which implies an *ASE*=1.5 bits/s/Hz for the SISO system, and 3 or 4.5 bits/s/Hz for the MIMO system with two or three transmit antennas (M_T=2, 3), respectively. Simulations have been executed using information data words consisting of 1000 bits. The number of iterations in the receiver was experimentally fixed as a good trade-off between receiver performance and complexity. One ICI cancellation iteration (N_{IC}=4) is performed before decoding, then four decoding iterations (N_D=4) are performed.

The main results of this investigation are shown in Figure 2 and Figure 3. The spectral efficiency and bit error rate of the considered system are provided. Figure 2 shows the SE of the proposed FDM-CPM MIMO system. We observe that the MIMO transmission with ICI cancellation exhibits a significant SE improvement in comparison to SISO systems. Results show that spatial diversity can be exploited without the need of complex space-time coding techniques by using the proposed receiver, thus leading to considerably improved utilization of the available channel degrees of freedom comparing to the SISO case. Finally, we show the error rates obtained for proposed MU FDM-CPM MIMO receiver, Figure 3.

Different combinations of parameter setups for the MU FDM-CPM MIMO systems have been simulated.

Performance of the proposed receiver has been assessed and it has been shown that when the intercarrier frequency spacing, modulation scheme, and code rate are carefully chosen, performance close to the single-carrier (no ICI) may be obtained. The results for SISO and MIMO(2x2) systems show that for the BER=10^{-4} performance of the multiuser systems with ICI cancellation is close to that of the single-carrier systems. The curves (SISO) and MIMO(2x2) are as close as 0.5 dB and 0.7 dB to the BER curves (no ICI) for no ICI SISO and MIMO(2x2) systems, respectively.

The results in Figure 3 also show that the E_b/N_0 at BER=10^{-4} obtained by enhancing the number of receiver antennas from 2 to 4, while keeping constant the number of transmit antennas, in the proposed system, equals 8 dB. For BER=10^{-4} the MIMO(2x4) system yields performance improvement of about 3 dB with respect to the MIMO(3x4) system but the MIMO(2x4) system achieves lower *ASE* (3 bits/s/Hz) than the MIMO(3x4) system (4.5 bits/s/Hz). The same may be observed comparing the BER for the SISO system and the MIMO(2x2). In this case, the degradation is about 1 dB but the *ASE* for the MIMO(2x2) system is twice as large as in the SISO system. The degradation of the SISO system with respect to the MIMO(2x4) and MIMO(3x4) systems is about 7dB and 3.5 dB, respectively, with BER of about 10^{-4}. Additionally, the MIMO(2*x*4) and MIMO(3x4) systems prove higher *ASE* than the SISO system.

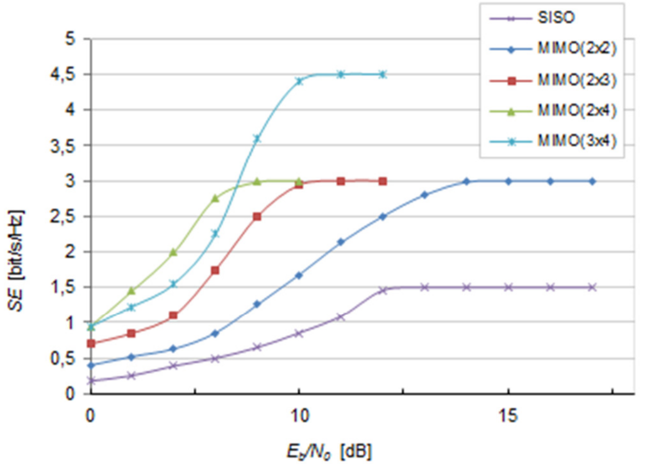

Figure 2. Spectral efficiency of MU coded FDM-CPM MIMO system with $\Delta_f T$=0.5, h=1/5, M=4, L=1, REC.

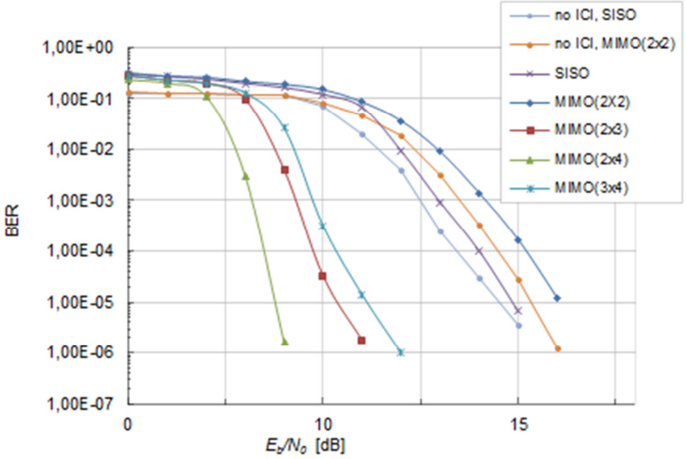

Figure 3. Bit error rate for the MU coded FDM-CPM MIMO system with various antenna configurations.

We compare the obtained results with those presented in [13], where MIMO CPM systems are designed. In [13], incoherent demodulator was adopted for full response MIMO CPM systems using blind signal separation in the receiver to separate the signals without any knowledge of the MIMO channel. The CPM scheme used therein is, e.g., quaternary with raised cosine (RC) transmit filter, h=1/4 and antenna configuration 2x4. Moreover, in [13] only a single user system (no ICI) is considered. The best results reported in [13] show that BER = 10^{-4} is achieved at E_b/N_0 close to 20 dB. Our MIMO(2x4) scheme with convolutional encoding reaches BER = 10^{-4} at E_b/N_0 =7 dB. The receiver in our system operates in presence of strong ICI and has perfect knowledge of the MIMO channel.

IV. CONCLUSION

In this paper, a multiuser coded FDM-CPM MIMO system has been proposed. Through simple MMSE-based multiuser detection and low-complexity iterative ICI cancellation, considerable improvements in both BER and SE are achieved with respect to single antenna systems, while the multiuser receiver complexity is kept low. The performance evaluation has been presented to demonstrate the superiority of the proposed multiuser FDM-CPM MIMO systems.

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