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Contribution of state modelling in efficient MAP symbol-by-symbol demodulation schemes for CPM-MIMO systems

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ABSTRACT

In [1], a state space model was derived for the demodulation of Continuous Phase Modulation (CPM) signals, based on which the demodulation problem was solved through the symbol-by-symbol Bayesian estimation built around the MAP Symbol-by-symbol Detector (MAPSD). In this paper, a new state space model considered in the augmented state composed of the symbol and the phase state is proposed and the corresponding modified MAPSD demodulation scheme is presented. The main contribution of the paper however consists in deriving optimal and suboptimal symbol-by-symbol MAP detection schemes for MIMO systems operating with CPM signals. For this, a state model description of the corresponding demodulation problem is introduced based on which two CPM-MIMO Bayesian demodulators are proposed. The first one uses a Zero Forcing (ZF) pre-processing block to separate the different CPM signals followed by a bank of MAPSD based CPM demodulators. The second demodulator consists in a joint decision feedback (DF) CPM-MIMO MAPSD detector. Simulations confirm the good performance in term of BER of both proposed structures. Particularly, high BER's performance of the partially joint CPM-MIMO-MAPSD/DF is recorded and an emphasis is made on the implementation simplicity of this new detector with no constraint on the modulation index or the alphabet size.

1. Introduction

The CPM modulation technique offers significant advantages in terms of spectral efficiency and robustness to nonlinearities compared to linear digital modulation techniques. Thereby, CPM is used in GSM, bluetooth and other commercial and military wireless systems [2]. The constant envelope property of CPM signals makes them adequate for more recent applications such as future aeronautical telemetry as suggested in [3], where a SC-FDMA multiple access technique is used for vehicle based-band CPM samples to reduce the Peak-to-Average Power Ratio (PAPR). Referring to the performance of CPM systems, the latter depends strongly on the parameters controlling the modulated signals as well as on the decoding algorithms used to recover the transmitted symbols [4]. Indeed, highly efficient CPM schemes are obtained by introducing memory in the modulation operation which makes the CPM demodulation task more complex. Thus, CPM modulation can be considered as a channel coding technique which can be concatenated with convolutional codes [5] or with irregular repeat accumulate codes [6] to achieve even lower BER (Bit Error Rate) performance.

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To take advantage of the sptral efficiency induced by the CPM modulation memory, several optimal CPM demodulation/equalization techniques can be employed [4]. Optimal CPM demodulation, which is the problem addressed in this work, is based generally on Maximum Likelihood Sequence Detection (MLSD) schemes implemented with the computationally efficient Viterbi algorithm [7–12]. Among such MLSD based solutions, many demodulation algorithms are derived using the Laurent decomposition of binary CPM signals and the resulting demodulator is then structured into a bank of matched filters followed by a Viterbi module search. This structure is also used to deal with cochannel [10] or multi-user [11] CPM signal detection. Commonly, the complexity of MLSD-based CPM decoders grows for long partial response lengths or for high modulation alphabet size. Consequently, several suboptimal ML CPM demodulation algorithms were derived, in order to reduce the complexity of the required algorithms, by approximating or truncating the Laurent expansion [11,12]. Dimensionality reduction of CPM signal representations was also treated in [13] using the principle component analysis.

On the other hand, many other optimal Bayesian CPM demodulators designed to minimize the achieved symbol error probability provide the maximum *a posteriori* (MAP) symbol estimates instead of the ML ones. In [14], MLSD detection is replaced by a MAP sequence detector implemented using the forward/backward recursions. In some similar works, MAP symbol-by-symbol demodulation is preferred when soft output metrics are to be used to enhance the receiver performance [15–18]. In this paper, the problem of CPM demodulation is also considered within a MAP symbol-by-symbol detection framework by proposing a state space representation of the demodulation problem as introduced in our earlier work [1]. As the state to estimate, which is actually a finite-length symbol sequence, in the derived CPM state space model is finite-value, the well-known optimal Bayes filtering equations can be implemented, without approximation, to deal with the MAP CPM symbol detection as done in [27]. In fact, in the available literature on MAP symbol-by-symbol Bayesian CPM demodulation, and here we cite precisely the works of Balasubramanian et al. [17], of Gertsman et al. [15] and of Abend and Fritchmann [4], the corresponding CPM Bayesian demodulation algorithms are based on the recursive determination of the infinite horizon conditional *a posteriori* symbol pdf (probability density function) through marginalization and using the Bayes rule; but in different ways, at different stages and hence with different layouts. The particularity of the proposed solutions in this paper is that the symbol pdf derivation used here follows directly from the Bayes filtering equations running in two stages, namely the prediction and the filtering or updating steps (see [21,22]).

We focus especially on extending the idea of state modelling to coherent demodulation of CPM signals included within a MIMO system. This is motivated by the fact that state modelling of several digital communication problems, allowing the use of consequent optimal filters, has been shown to offer near optimal performance in many applications [23–26]; as well as by the fact that MAP symbol-by-symbol demodulation of CPM-MIMO signals has not been treated before, which is the main novelty of the paper. Globally, we consider that formulating the CPM demodulation problem, whether in the SISO or MIMO case, as a state space representation, accommodates the demodulation problem and the problem of estimation of all the related parameters characterizing the receiver input to a variety of nonlinear Bayesian estimation tools, that have been extensively studied in the literature and have been shown to perform optimally.

Indeed, CPM modulation is shown to provide high data rates performance when used in layered space–time systems [19] such as MIMO systems. Several CPM-MIMO receivers based whether on MLSD joint symbol sequence detection and the Laurent decomposition [12] or on the blind signal separation at the front-end of a frequency discriminator based CPM demodulator [20] are detailed in the corresponding references. In this work, a state space model, considered in the transmitted data streams and describing the joint demodulation problem within a CPM-MIMO system, is derived by up-sampling the mixture of the different CPM modulated signals. We develop then a first solution which consists in cancelling the MIMO channel effect using a ZF block followed by a bank of one of the proposed single-antenna MAPSD-based CPM demodulation schemes. Moreover, as the observation vector at the demodulator input is related to the phase states corresponding to the different entries, another solution integrating a decision feedback (DF) mechanism is suggested around the MAPSD-based detection when dealing with the joint demodulation of these entries mixed via the MIMO channel. The attractive benefits of the so-proposed MAPSD CPM demodulation schemes using DF, whether in the SISO or MIMO case, consist in complexity reduction compared to MLSD or MAP solutions considering the cumulative phase in the search process, besides the fact that they do not need a fractional value of the modulation index and are applicable for any modulation alphabet (no need of Laurent expansions of binary CPM signals).

The paper is organized as follows. Section 2 recalls the different state space models derived to deal with the single-antenna CPM demodulation problem in the additive white Gaussian noise context; it also details the new state space model considered in the phase and the symbol state as well as the resulting MAP symbol-by-symbol detection schemes based on the MAPSD. In Section 3, the state space model for the CPM-MIMO demodulation is derived then the proposed alternatives for the CPM-MIMO MAP symbol-by-symbol demodulation and their principles are presented. Section 4 presents the simulation results and Section 5 gives the conclusion.

Notations: $(\cdot)^*$ denotes the complex conjugate operator, $\propto$ the proportionality operator. Vectors are typed in bold characters. If $\mathbf{x}=[x_1,x_2,\ldots,x_n]^T$ is a column vector of length n, then we denote by $\mathbf{x}[i:j]=[x_i,x_{i+1},\ldots,x_j]^T$ and $\mathbf{x}[i]=x_i$ the ith component of $\mathbf{x}$. If $\mathbf{x}_1,\ldots,\mathbf{x}_n$ is a collection of n column vectors, then $vec(\mathbf{x}_i|_{i=1}^n)=[\mathbf{x}_1^T\ldots\mathbf{x}_n^T]^T$. When $\mathbf{x}$ is a vector $n\times 1$ then $e^{\mathbf{x}}=[e^{x_1},e^{x_2},\ldots,e^{x_n}]^T$. A Gaussian random variable (r.v.) x is designed by $\mathcal{N}(m_x,\sigma_x^2)$ with mean $m_x=E\{x\}$ and variance $\sigma_x^2=E\{|x|^2\}-|m_x|^2$. I_M is the identity matrix of dimension $M\times M$. We denote by F_L the one step