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Soft MIMO detection through sphere decoding and box optimization

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ABSTRACT

Achieving optimal detection performance with low complexity is one of the major challenges, mainly in multiple-input multiple-output (MIMO) detection. This paper presents three low-complexity Soft-Output MIMO detection algorithms that are based mainly on Box Optimization (BO) techniques. The proposed methods provide good performance with low computational cost using continuous constrained optimization techniques. The first proposed algorithm is a non-optimal Soft-Output detector of reduced complexity. This algorithm has been compared with the *Soft-Output Fixed Complexity* (SFSD) algorithm, obtaining lower complexity and similar performance. The two remaining algorithms are employed in a turbo receiver, achieving the max-log Maximum a Posteriori (MAP) performance. The two Soft-Input Soft-Output (SISO) algorithms were proposed in a previous work for soft-output MIMO detection. This work presents its extension for iterative decoding. The SISO algorithms presented are developed and compared with the SISO *Single Tree Search* algorithm (STS), in terms of efficiency and computational cost. The results show that the proposed algorithms are more efficient for high order constellation than the STS algorithm.

1. Introduction

Soft-Output (SO) detection implies significant challenges for practical receiver implementations, particularly in the context of multiple-input multiple-output (MIMO) wireless communication systems. SO detection achieves significantly better performance than Hard-Output (HO) detection and is needed to reach optimum performance of the modern coding systems [1]. On the other hand, an iterative receiver that employs Soft-Input Soft-Ouptut (SISO) detection improves the performance of a Non-Iterative Soft-Output (NISO) detection [1], since the near-optimal performance of turbo receivers is achieved by exchanging soft extrinsic information between a SISO detector and a SISO decoder in an iterative loop.

Throughout the paper we are going to use the following notation: SISO will denote a detector in an iterative receiver (the detector takes the received signal and the soft information provided by the channel decoder as inputs); NISO will denote a non iterative detection (the detector takes the received signal as input but does not process any information provided by the channel decoder, so no iteration is performed between the detector and the decoder); and SO is used to denote both cases. The problems that arise from these technologies (NISO and SISO) for MIMO detection are computationally very complex, furthermore the complexity exponentially increases when antenna number increases. Thus, it is necessary to develop efficient algorithms in both cases if these techniques are to be used in practical applications. Furthermore several strategies such us the max-log approximation [2] ($\log \Sigma_i \exp(\phi_i) \approx \max \phi_i$) can be employed to reduce the complexity of the exact computation.

There are several SO algorithms for MIMO systems [3–8], and they offer different tradeoffs between performance and complexity. The *Repeated Tree Search* (RTS) and the *Single Tree Search* (STS) algorithms provide the max-log SO solution. Both algorithms use an HO Sphere Decoder (SD) to compute the extrinsic information and have been thoroughly discussed for the NISO case in [8] and for the SISO case in [9], including the application of a clipping boundary to both algorithms. The STS algorithm reduces the computational cost of the solution with respect to the RTS algorithm. Moreover, there are several non-optimal max-log NISO detection algorithms such us *Soft-Output Fixed-complexity SD* (SFSD) [10], the *Smart Ordering and Candidate Adding* (SOCA) [11] or *Soft-Output K-Best* [12]. Among these methods, SFSD reaches almost max-log Maximum Likelihood (ML) performance with low complexity.

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Table 1
The main features of the algorithms.

Algorithm	SO	SISO	No clipping	Clipping	Performance	Ref
BOHD	No	No	Yes	No	max-log ML	[14]
SFSD	Yes	No	Yes	No	almost max-log ML	[10]
BOHD-SO	Yes	No	Yes	No	almost max-log ML	this work
RTS	Yes	Yes	Yes	Yes	max-log MAP	[15]
STS	Yes	Yes	Yes	Yes	max-log MAP	[8,9]
BORTS	Yes	No	Yes	Yes	max-log ML	[13]
DTS	Yes	No	No	Yes	max-log ML	[13]
SISO-BORTS	Yes	Yes	Yes	Yes	max-log MAP	this work
SISO-DTS	Yes	Yes	No	Yes	max-log MAP	this work

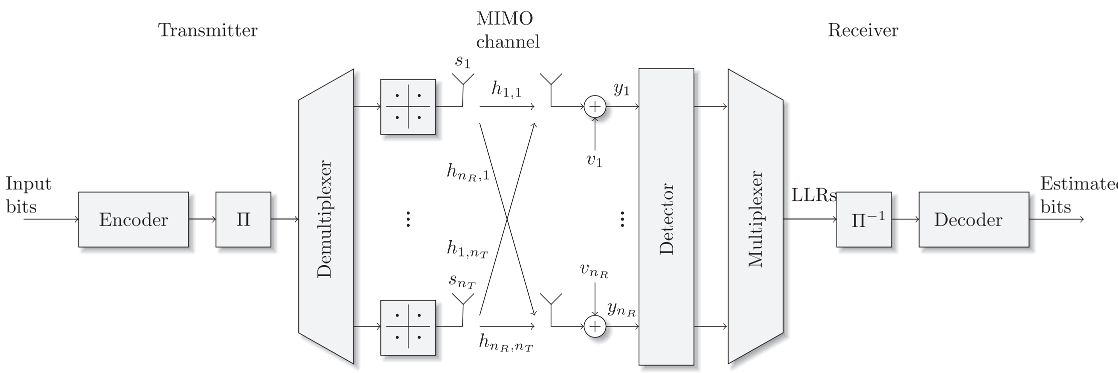

Fig. 1. Block diagram of a MIMO-BICM system with n_T transmitting antennas and n_R receiving antennas.

The work described in this paper focuses on low-cost SO MIMO detection algorithms. We propose three methods: one for NISO case called *Box Optimizacion Hard Detector with soft-output* (BOHD-SO), which exhibits a non-optimal max-log ML performance; and two SISO methods, *SISO Box Optimization Repeated Tree Search* (SISO-BORTS) and SISO *Double Tree Search* (SISO-DTS), with max-log Maximum a Posteriori (MAP) performance based on a previous work reported in [13]. These algorithms reduce the complexity based on the use of continuous constrained optimization methods where the bounds are fixed, hence the name of *Box Optimization* (BO). As the target of this work, this auxiliary technique is used to implement different low-complexity SO detection algorithms.

The work described in [13] has as its main goal the improvement in efficiency of NISO max-log detection algorithms, where the iteration at the receiver was not considered. In the present paper we meaningfully extend the work presented in [13] to the Soft-Input case. Thereby in the present work the *a priori* information is incorporated by extending BORTS and DTS presented in [13] to the SISO detection.

Furthermore, a new method called BOHD-SO has been proposed. This algorithm is based on the BO algorithm and the HO ML detector described in [14]. Therefore, the BOHD-SO algorithm has been proposed and evaluated for NISO detection. Since it is a sub-optimal algorithm, it will be compared with the SFSD algorithm in terms of efficiency and accuracy. It has been proved that the use of the BOHD-SO algorithm in a turbo receiver does not improve the performance detection, for this reason it is only presented for the NISO case.

Table 1 summarizes the main features of the proposed and referenced algorithms.

2. Model description

Let us consider a MIMO Bit-Interleaved Coded-Modulation (BICM)[16] system with n_T transmit antennas and n_R receive antennas ($n_R \geq n_T$), as shown Fig. 1. In this system, the sequence of information bits is encoded using an error-correcting code and is passed through a bitwise interleaver before being demultiplexed into n_T streams. The bits are mapped into a complex symbol s_i, which is taken from a constellation Ω of size $|\Omega| = M$ and hence carrying $k = \log_2 M$ code bits each, $s_i \leftrightarrow (x_{i,1}, \cdots, x_{i,k})$ with $x_{i,b} \in \{0, 1\}$. Thus, the mapper translates $n_T k$ bits to one transmit symbol vector $\mathbf{s}$. In the following, the index $i \in \{1, \cdots n_T\}$ refers to the antenna index and the index $b \in \{1, \cdots, k\}$ refers to the bit index within symbol s_i. The transmit symbol vector is given by $\mathbf{s} = (s_1, \cdots, s_{n_T})^T$ and the complex baseband model can be written as

$$\mathbf{y} = \mathbf{Hs} + \mathbf{v}. \quad (1)$$

Here, $\mathbf{H} \in \mathbb{C}^{n_R \times n_T}$ is the MIMO channel matrix, which is composed of independent elements $h_{ij} \sim \mathcal{N}(0, 1)$, and $\mathbf{v}$ denotes an additive white Gaussian noise (AWGN) complex vector with elements $v_j \sim \mathcal{N}(0, \sigma_n^2)$ where σ_n^2 represents the noise variance per complex dimension.

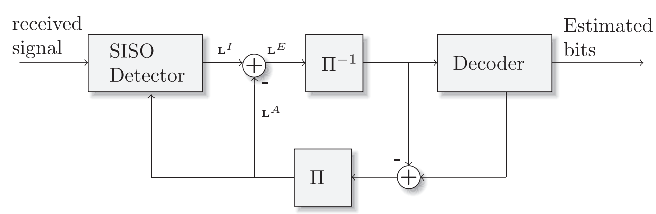

Fig. 2. Block diagram of an ID-BICM receiver.

A BICM with Iterative Decoding (ID-BICM) can be used on the receiver side. Fig. 2 shows the block diagram of an ID-BICM receiver. In this case, a SISO detector is needed. On the other hand, when iterations are not performed, the detector used is a NISO detector, see Fig. 1.

First of all, let us to review the formulation of a SISO detection in an ID-BICM receiver since it is the general case. Afterwards, the NISO detection will be presented as a specific case of SISO detection. *Extrinsic* soft information in the form of log-likelihood ratios (LLRs) and denoted by $\mathbf{L}^E$ is exchanged between the detector and