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Space–time spreading–multiplexing for MIMO wireless communication systems using the PARATUCK-2 tensor model ☆

André L.F. de Almeida [a,b], Gérard Favier [a,*], João C.M. Mota [b]

[a] I3S Laboratory, University of Nice-Sophia Antipolis, CNRS, France
[b] GTEL-Wireless Telecom Research Group, Federal University of Ceará, Fortaleza, Brazil

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ABSTRACT

In this paper, we present a new space–time spreading–multiplexing model for multiple-input multiple-output (MIMO) wireless communication systems relying on a tensor modeling of the transmitted and received signals. At the transmitter, we exploit the core of a PARATUCK-2 tensor model composed of a precoding matrix and two allocation matrices that allow to control the spreading and multiplexing of the data streams across the space dimension (transmit antennas) and time-dimension (time-slots). Different MIMO schemes combining space–time multiplexing and diversity can be derived from the proposed model. The identifiability and uniqueness of the PARATUCK-2 tensor model for the received signal are discussed and subsequently exploited for a joint blind channel estimation and symbol detection. The bit-error-rate performance of different transmit schemes derived from the proposed tensor model is evaluated by means of computer simulations.

1. Introduction

It is well known for some time that multiple-input multiple-output (MIMO) wireless communication systems employing multiple antennas at both the transmitter and the receiver provide multiplexing gains [1] and/or diversity gains [2] to increase the data rate (i.e. higher spectral efficiency) and/or the reliability of the transmission (i.e. lower error rate) without additional bandwidth. In order to provide multiple-accessing capabilities to MIMO systems, several approaches make use of code-division multiple-access (CDMA) technology by associating multiple transmit antennas and multiple user signals to orthogonal spreading transforms in different manners [3,4]. Optionally, when current channel state is known in advance at the transmitter, some form of precoding can also be used to improve system performance [5].

The use of tensor decompositions for modeling MIMO transceivers with blind signal processing has been addressed in several recent works [6,8–12]. The approach of Sidiropoulos and Budampati [6], therein called *Khatri–Rao space–time (KRST) codes*, relies on a PARAllel FACtor (PARAFAC) model [7]. By precoding each data stream over multiple symbol periods, a joint blind channel estimation and symbol detection is afforded by means of a PARAFAC modeling of the received signal tensor. The work [8] presents a generalized block-tensor model for multiple-access MIMO transceivers. The common feature of the solutions [6] and [8] is the use of pure spatial multiplexing, where each data stream is transmitted by a single transmit antenna and coded across the time-dimension only. Consequently, no transmit spatial diversity is allowed and the number of data streams is restricted to be equal to the number of transmit antennas. To overcome

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* Corresponding author. Tel.: +33 492 942 736; fax: +33 492 942 896.
E-mail addresses: andre@gtel.ufc.br (A.L.F. de Almeida), favier@i3s.unice.fr (G. Favier), mota@gtel.ufc.br (J.C.M. Mota).

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this limitation, the work in [9] uses a constrained tensor model which can be viewed as a "structured" PARAFAC model with an *a priori* known model structure. This allows to model, in addition to spatial multiplexing, a wider class of MIMO transmissions characterized by a joint space and time spreading. In order to cope with multiuser downlink transmissions, de Almeida et al. [10] formulated a block-constrained version of the tensor model of [9], which allows a multiuser space–time transmission with different spatial spreading factors (diversity gains) as well as different multiplexing factors (code rates) for the users.

More general space–time spreading structures were recently proposed relying on a third-order CONstrained FACtor (CONFAC) tensor model [11,12]. The approach of de Almeida et al. [11] introduces two constraint matrices with *variable* 1's and 0's structure into the tensor model. These constraint matrices are referred therein as stream and code *allocation matrices*. As opposed to the approach of [9,10] where the two constraint matrices have a fixed structure, in [11] the structure of the constraint matrices can be controlled to design transmit schemes with different spatial multiplexing, code multiplexing and transmit antenna assignments for the data streams. The work [12] further generalizes [11] by including a third allocation matrix that defines the mapping of the precoded signals to the transmit antennas. In this case, the constrained structure of the CONFAC model is fully exploited at the transmitter (for designing finite-sets of MIMO transmission schemes) as well as at the receiver (for blind signal processing).

In this work, we present a novel tensor-based space–time spreading–multiplexing model. At the transmitter, we exploit the structure of a PARATUCK-2 tensor model to design different precoder structures combining space–time multiplexing and diversity. The heart of the proposed tensor model is composed of two constraint matrices. These constraint matrices play the role of stream-to-slot and antenna-to-slot allocation matrices. Differently to the CONFAC model of de Almeida et al. [11,12], the two allocation matrices of the PARATUCK-2 core tensor jointly control the spatial and temporal allocations, i.e. the allocations of data streams to transmit antennas and time-slots. Moreover, the number of channel uses associated with the transmission of each data stream may be different from one data stream to another. Such a feature is not possible with the existing tensor-based space–time transmission models and is intrinsic to the PARATUCK-2 modeling. At the receiver, we capitalize on the structure of the PARATUCK-2 model for the received signal to perform a joint blind detection and channel estimation. The identifiability issue of the proposed tensor model is discussed and a simple blind receiver based on the alternating least squares (ALS) algorithm is presented.

The PARATUCK-2 model can be viewed as a generalization of the PARAFAC one. It mixes the properties of both PARAFAC [7] and TUCKER-2 [13] models. Consequently, it allows the flexibility of TUCKER-2 model while retaining PARAFAC's uniqueness properties. This model has been studied in the psychometrics literature [14] and subsequently exploited by Bro [15] to solve special data analysis problems in chemometrics. The first application of PARATUCK-2 in signal processing was proposed by Kibangou and Favier [16] for the blind joint identification and equalization of Wiener–Hammerstein communication channels. The present paper shows that this model is also useful to model the transmitted and received signals in MIMO wireless communication systems while affording a blind signal processing.

Despite the differences among PARAFAC, CONFAC and PARATUCK-2 modeling approaches, it is worth mentioning that they share common characteristics. First, they simultaneously exploit three diversity dimensions (*space*, *time* and *code*) that characterize the received signal tensor. Each diversity dimension is associated with a different matrix factor of the received signal tensor model as follows:

- The *space dimension* is created by the multiple-antenna channel and is associated with the *channel matrix*.
- The *time dimension* arises by collecting the received signal during several symbol periods and is associated with the *symbol matrix*.
- The *code dimension* is generated by precoding each transmitted symbol across multiple time-slots, and is associated with the *precoder matrix*.

The relationship involving channel, symbol and precoder matrices depends on the structure adopted to model the received signal tensor. In this work, such a relationship is defined by the PARATUCK-2 structure. The use of this tensor modeling allows to perform a blind joint symbol and channel estimation under identifiability conditions more relaxed than those of conventional matrix modeling based approaches, and without requiring statistical independence between transmitted signals. Instead, the receiver signal processing is *deterministic* and directly exploits the known structure of the received signal tensor. Moreover, tensor-based receivers are generally based on a joint detection of the transmitted signals (either from different users or from multiple transmit antennas).

We emphasize that the contribution of this work concerns both transmitter and receiver processing. At the transmitter, the PARATUCK-2 model structure is used to model space–time multiplexing–spreading. At the receiver, this structure is exploited to blindly estimate the transmitted symbols and the MIMO channel. Fig. 1 provides an illustration of the use of tensor models in a MIMO communication chain. The three signal dimensions that generally appear at the transmitter and receiver are highlighted.

The organization of the rest of this paper is as follows. Section 2 presents a brief overview of the main third-order tensor models. In Section 3, the proposed space–time multiplexing–spreading system is presented and the associated tensor signal model is formulated. In Section 4, some examples of space–time multiplexing–spreading designs are presented by focusing on the structure of the PARATUCK-2 constraint matrices. Section 5 discusses the identifiability and uniqueness issues of the proposed PARATUCK-2 tensor model. In Section 6, we present a blind PARATUCK-2 based receiver for joint channel estimation and symbol detection. Some simulation results