

Space-Time Coding: an Overview

Giuseppe Caire, Petros Elia and K. Raj Kumar

Abstract—This work provides an overview of the fundamental aspects and of some recent advances in space-time coding (STC). Basic information theoretic results on Multiple-Input Multiple-Output (MIMO) fading channels, pertaining to capacity, diversity, and to the optimal Diversity-Multiplexing Tradeoff (DMT), are reviewed. The code design for the quasi-static, outage limited, fading channel is recognized as the most challenging and innovative with respect to traditional “Gaussian” coding. Then, a survey of STC constructions is presented. This culminates with the description of families of codes that are optimal with respect to the DMT criterion and have error performance that is very close to the information theoretic limits. The paper concludes with some important recent topics, including open problems in STC design.

Keywords: Space-Time Coding, MIMO systems, fading channels, Diversity-Multiplexing Tradeoff.

I. INTRODUCTION

Since the seminal work of Telatar [1], Foschini and Gans [2], Tarokh *et al.* [3], and Guey *et al.* [4], multiple antenna transmission/reception has emerged as a key tool to achieving high spectral and power efficiency in wireless communications. Loosely speaking, signaling schemes that exploit both the classical Shannon degrees of freedom (time-frequency) and the additional spatial degrees of freedom (antennas) are referred to as *Space-Time Codes* (STC), a term popularized by [3]. The literature on STC is extremely vast (an incomplete sample is provided, for example, by [5], [6], [7], [8] and references therein).

Several settings have been developed on the basis of different physical channel models and, for each setting, information theoretic results and associated coding schemes have been addressed.

The general complex baseband channel for space-time signaling with M transmit and N receiving antennas is given by the Multi-Input Multi-Output (MIMO) Gaussian linear channel model¹

$$\mathbf{y}_t = \sqrt{\rho} \mathbf{H}_t \mathbf{x}_t + \mathbf{w}_t, \quad t = 1, \dots, T \quad (1)$$

where T denotes the code block length (expressed in “channel uses”), $\{\mathbf{x}_t \in \mathbb{C}^{M \times 1} : t = 1, \dots, T\}$ are the transmitted vectors, $\{\mathbf{y}_t \in \mathbb{C}^{N \times 1} : t = 1, \dots, T\}$ are the received vectors, $\{\mathbf{w}_t \in \mathbb{C}^{N \times 1} : t = 1, \dots, T\}$ are the channel Gaussian noise vectors, assumed temporally and spatially white with i.i.d. entries $\sim \mathcal{CN}(0, 1)$, and $\{\mathbf{H}_t : t = 1, \dots, T\}$ is the $N \times M$ channel

matrix process with the elements $h_{i,j,t}$ representing the fading coefficients between the j -th transmit and the i -th receive antenna at time t . Without loss of generality, we assume a normalized channel such that $\frac{1}{MT} \sum_{t=1}^T \mathbb{E}[\text{tr}(\mathbf{H}_t^H \mathbf{H}_t)] = 1$. We hasten to say that the above model encompasses also the case of a general frequency and time-selective fading channel, where the index t denotes an “abstract” index corresponding to some predetermined sequence of time-frequency bins, obtained for example by using OFDM. In this case, $\mathbf{H}_t$ denotes the MIMO channel response at time-frequency bin t . The following average transmit power constraint is enforced:

$$\frac{1}{T} \sum_{t=1}^T \mathbb{E}[\|\mathbf{x}_t\|^2] \leq 1. \quad (2)$$

With the above normalizations, ρ represents the average transmit SNR (total transmit power divided by the noise power spectral density), that corresponds to the average received SNR per receiving antenna.

With respect to code construction, it turns out that the optimal code design varies quite significantly depending on the basic model assumptions. Section II provides an overview of the main settings and the related information theory and coding results. Section III focuses on the case of quasi-static fading, originally considered in [3], for which the asymptotic performance in high-SNR is characterized by the *diversity-multiplexing tradeoff* (DMT) studied in [10]. This case offers perhaps the richest and most original coding design problem, that has been the subject of very active research in the recent past. Section IV reviews a number of space-time coding constructions some of which achieve the optimal DMT of [10]. Finally, Section V presents some recent research thrusts. Since most of this work is still on-going, this section is intended more as a motivation for future work than as a comprehensive overview of a well settled set of results. Conclusions are pointed out in Section VI. Due to space limitation and to the tutorial nature of this paper, we omit the proofs of the results and we provide pointers to the corresponding literature.

II. RELIABLE COMMUNICATIONS WITH MULTIPLE ANTENNAS

The early information theoretic analysis of the MIMO channel (1) focused on the *ergodic capacity*. The assumption underlying the ergodic setting is that the random matrix process $\{\mathbf{H}_t\}$ is stationary and ergodic, and that the block length T is arbitrarily large. As a matter of fact, as of today the capacity of such channels is generally still unknown and only the low-SNR (see for example [11]) and high-SNR (see for example [12], [13], [14]) have been characterized through asymptotically tight bounds.

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²**Notations:** T denotes transpose and H denotes Hermitian transpose. The notation $\mathbf{v} \sim \mathcal{CN}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ indicates that $\mathbf{v}$ is a proper [9] complex Gaussian random vector with mean $\boldsymbol{\mu}$ and covariance matrix $\boldsymbol{\Sigma}$. For real Gaussian random vector we use the notation $\mathbf{v} \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$.

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Introduction to MIMO Communications Jerry R.

Hampton, 2014 This accessible guide contains everything you need to get up to speed on the theory and implementation of MIMO techniques

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$y - y_1 = m(x - x_1)$ where m is the slope of the line and (x_1, y_1) is a point on the line any point works to write an equation in point slope form given a graph of that equation first determine the slope by picking two points then pick any point on the line and write

it as an ordered pair h, k

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point slope is a specific form of linear equations in two variables $y - b = m(x - a)$ when an equation is written in this form m gives the slope of the line and a, b is a point the line passes through this form is derived from the slope formula want to learn more about point slope form check out this video