

# Space-Time Block Coding for Wireless Communications: Performance Results

Vahid Tarokh, *Member, IEEE*, Hamid Jafarkhani, *Member, IEEE*, and A. Robert Calderbank, *Fellow, IEEE*

**Abstract**—We document the performance of space-time block codes [13], [14], which provide a new paradigm for transmission over Rayleigh fading channels using multiple transmit antennas. Data is encoded using a space-time block code, and the encoded data is split into  $n$  streams which are simultaneously transmitted using  $n$  transmit antennas. The received signal at each receive antenna is a linear superposition of the  $n$  transmitted signals perturbed by noise. Maximum likelihood decoding is achieved in a simple way through despreading of the signals transmitted from different antennas rather than joint detection. This uses the orthogonal structure of the space-time block code and gives a maximum likelihood decoding algorithm which is based only on linear processing at the receiver. We review the encoding and decoding algorithms for various codes and provide simulation results demonstrating their performance. It is shown that using multiple transmit antennas and space-time block coding provides remarkable performance at the expense of almost no extra processing.

**Index Terms**—Diversity, multipath channels, multiple antennas, space-time codes, wireless communication.

## I. INTRODUCTION

**I**N MOST situations, the wireless channel suffers attenuation due to destructive addition of multipaths in the propagation media and to interference from other users. The channel statistic is significantly often Rayleigh which makes it difficult for the receiver to reliably determine the transmitted signal unless some less attenuated replica of the signal is provided to the receiver. This technique is called diversity, which can be provided using temporal, frequency, polarization, and spatial resources [3], [6], [7]–[9], [11], [16], [17]. In many situations, however, the wireless channel is neither significantly time-variant nor highly frequency selective. This forces the system engineers to consider the possibility of deploying multiple antennas at both the transmitter and receiver to achieve spatial diversity.

Only recently has transmit diversity been studied extensively as a method of combating detrimental effects in wireless fading channels because of its relative simplicity of implementation and feasibility of having multiple antennas at the base station. The first bandwidth efficient transmit diversity scheme was proposed by Wittneben [18], and it includes the delay diversity scheme of Seshadri and Winters [10] as a special

case. Later Foschini introduced a multilayered space-time architecture [4].

More recently, space-time trellis coding has been proposed [12] which combines signal processing at the receiver with coding techniques appropriate to multiple transmit antennas and provides significant gain over [10] and [18]. Specific space-time trellis codes designed for two–four transmit antennas perform extremely well in slow fading environments (typical of indoor transmission) and come within 2–3 dB of the outage capacity computed by Telatar [15] and independently by Foschini and Gans [5]. The bandwidth efficiency is about three–four times that of current systems. The space-time codes presented in [12] provide the best possible tradeoff between constellation size, data rate, diversity advantage, and trellis complexity. When the number of transmit antennas is fixed, the decoding complexity of space-time trellis coding (measured by the number of trellis states in the decoder) increases exponentially as a function of both the diversity level and the transmission rate.

In addressing the issue of decoding complexity, Alamouti discovered a remarkable scheme for transmission using two transmit antennas [1]. Space-time block coding, introduced in [13] and [14], generalizes the transmission scheme discovered by Alamouti to an arbitrary number of transmit antennas and is able to achieve the full diversity promised by the transmit and receive antennas. These codes retain the property of having a very simple maximum likelihood decoding algorithm based only on linear processing at the receiver [13], [14]. For real signal constellations (such as PAM), they provide the maximum possible transmission rate allowed by the theory of space-time coding [12]. For complex constellations, space-time block codes can be constructed for any number of transmit antennas, and again these codes have remarkably simple decoding algorithms based only on linear processing at the receiver. They provide full spatial diversity and half of the maximum possible transmission rate allowed by the theory of space-time coding. For complex constellations and for the specific cases of three and four transmit antennas, these diversity schemes were improved to provide 3/4 of the maximum possible transmission rate [13], [14].

The purpose of this paper is to evaluate the performance of the space-time block codes constructed in [13] and [14] and to provide the details of the encoding and decoding procedures. We begin by considering encoding and decoding algorithms for some of these codes. We then provide simulation results confirming that with space-time block coding and

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