Chapter XIII
Joint Beamforming and Space-Time Coding for MIMO Channels

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ABSTRACT

This chapter introduces joint beamforming (or precoding) and space-time coding for multiple input multiple output (MIMO) channels. First, we explain key ideas of beamforming and space- time coding and then we discuss the joint design of beamformer and space-time codes and its benefits. Beamforming techniques play a key role in smart antenna systems as they can provide various features, including spatially selective transmissions to increase the capacity and coverage increase. STC techniques can offer both coding gain and diversity gain over MIMO channels. Thus, joint beamforming and STC is a more practical approach to exploit both spatial correlation and diversity gain of MIMO channels. We believe that joint design will be actively employed in future standards for wireless communications.

INTRODUCTION

The last decade has seen an increased interest in the study of smart antenna and multiple input multiple output (MIMO) channels. In particular, after Foschini (1998) and Telatar (1999) showed that multiple antenna systems are capable of providing large capacity increase in wireless transmissions, there have been an increased number of research studies for MIMO channels in various aspects, including propagations, space-time transmission schemes, and receiver design. Smart antenna systems are some of the particular examples to exploit the potential of MIMO channels. Beamforming techniques are crucial for smart antenna systems. Conventional beamforming techniques have been well developed for the signal reception to exploit diversity gain and/or suppress interfering signals (Winters, 1998). Provided that the channel state information (CSI) is known at the transmitter equipped with multiple antennas, beamforming is available for the signal transmission to provide spatial selectivity. In multiuser communications, this spatial selectivity leads to the spatial multiplexing gain and space division multiple access (SDMA).

Transmit beamforming can provide not only spatial selectivity, but also transmit diversity gain (Lo, 1999; Choi, 2002a). Transmit diversity can be achieved if multiple (independent) fading channels available by the transmitter. Generally, transmit diversity gain can be exploited by beamforming if instantaneous CSI is available at the transmitter. On the other hand, if statistical properties of CSI (e.g., the spatial correlation of MIMO channels) are only available, beamforming gain can be achieved, but not diversity gain. Thus, the CSI at the transmitter is often critical to exploit the transmit diversity gain. However, one general drawback of the methods relying on instantaneous CSI at the transmitter is feasibility and the need of feedback of CSI from the receiver to the transmitter.

Limited feedback issue becomes important for closed-loop transmit diversity including the beamforming methods relying on instantaneous CSI. In (Choi, 2002a; Love, 2003; Mukkavilli, 2003), beamforming methods are considered with limited feedback that provides partial CSI to the transmitter.

If CSI is not available at the transmitter, space-time coding (STC) can be applied. A number of STC methods have been investigated to improve the system performance (Alamouti, 1998; Tarokh, 1998; Tarokh, 1999a; Tarokh, 1999b). So called Orthogonal Space-Time Block Codes (OSTBCs) became quite popular in the context of space-time transmit diversity since they can provide a full diversity with low complexity, however mostly with the drawback of reduced data rates. It is known that the performance can be degraded if channels are spatially correlated (Bolcskei, 2000). The code designs criteria in (Alamouti, 1998) and (Tarokh, 1998) assume that transmit and receive antennas are uncorrelated and each element of the MIMO channel matrix fades independently. However, this is not necessary to be true in practice. For example, in outdoor wireless systems, the base-station (BS) antennas are placed high above the ground and close to each other. In such a scenario, the BS antennas are unobstructed and see no local scatterers leading to high correlation between the BS antennas (Salz, 1994).

In general, the availability of CSI at the transmitter is important to the MIMO channel capacity. Provided that the CSI is known at the transmitter, multiple parallel channels (or eigenmodes) can be built using singular value decomposition (SVD). Then, an optimal power allocation algorithm called as *water-filling principle* (Telatar, 1999) across multiple parallel channels can be applied. The water-filling transmission scheme pours power on the eigenmodes of the MIMO channel in such a way that more power is delivered to stronger eigenmodes and less or no power to the weaker eigenmodes. Another strategy with full CSI at the transmitter is *beamforming* (Mukkavilli, 2003; Zhou, 2004) where only the strongest eigenmode is used.

In general, a transmission using a STC performs worse than a system using a beamforming technique (Mukkavilli, 2001; Larsson, 2002). This stems from the fact, that STBC systems spreads the available power uniformly in all directions in space, while beamforming uses information about the channel to steer energy in the direction of the receiver. The gap in the performance between the two methods can be quite significant, especially in highly correlated channels.

Recently, it has been attempted to jointly design beamformer and space-time encoder to compensate each other when MIMO channels are correlated and the instantaneous CSI is not available (Bahrami, 2006; Choi, 2004). In this chapter, we explain key ideas of beamforming and STC. In addition, more importantly, we discuss the joint design of beamformer and space-time codes and its benefits as mentioned above.

BEAMFORMING DESIGN

In this section, we focus on beamformer design. Beamforming is possible with/without instantaneous CSI and the resulting performance varies (Choi, 2002a). Assuming that the receiver knows the perfect CSI, we show different beamforming methods depending on the availability of instantaneous CSI with diversity gain in this section.

Beamforming over MIMO Channels

Suppose that there are n_t transmit antennas and n_r receive antennas. Denote by $h_{p,q}$ the channel coefficient from the qth transmit antenna to the pth receive antenna. Then, the received signal from the pth antenna over flat fading channels is written as

$$r_p = \sum_{q=1}^{n_t} h_{p,q} s_q + v_p, \quad p = 1,2,\ldots,n_r \ ,$$