CHAPTER

1

MIMO Systems: Multiple Antenna Techniques

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1.1. Abstract

This chapter reviews most known multiple antenna techniques for single-user point-to-point systems, from how multiple antennas help provide diversity and multiplexing to the detection techniques for these systems. Finally, this chapter also discusses the possibility of using multiple antennas for multiuser systems for spatial multiplexing.

1.2. Literature Review

The concept of multiple antennas can be traced back long time ago. In 1960's, antenna array was applied in military radar systems for signal copying, direction finding and signal separation [1,2]. These signal parameter estimations need high resolution. Many algorithms have been proposed in this field, such as the maximum likelihood (ML) based approach [3] and maximum entropy (ME) based approach [4]. The main limitations of these approaches are the bias and high sensitivity. These problems were solved by Schimidt [5,6] and Bienvenu [7] independently. Particularly, Schimidt's method is known as MUSIC (Multiple Signal Classification), which can provide substantial performance improvement at the cost of high computational complexity and storage consumption. Then, another scheme, ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques), is proposed to achieve performance close to that of MUSIC but with a significantly reduced complexity [8].

In wireless communication systems, due to the limited physical size of mobile devices, the application of multiple antennas is initially proposed for base stations (BS) only. Investigations on these multiple antenna systems focus on beamforming, estimation of direction of arrival (DOA), and spatial diversity. The aforementioned algorithms like MUSIC and ESPRIT can be employed to realize the beamforming and the estimation of DOA, where the received/transmitted signals from/for different antennas are coherently combined to point at a specific direction. In this way, the co-channel interference from other mobile stations (MS) can be reduced in the uplink and the transmission power can be focused to the desired MS in the downlink. For example, in [9,10,11] and some references therein, multiple antennas are deployed at BS to obtain receive diversity and/or co-channel interference rejection in the uplink based on the DOA. It is demonstrated that significant capacity improvement can be achieved. Then, in [10,12], the antennas at the BS are used as a transmit beamformer in downlink. By focusing the transmit energy in the direction of the desired MS, transmit beamforming increases the signal-to-noise ratio (SNR) at the MS. Similar to the single-input single-output (SISO) system with only one antenna at both sides, the aforementioned receive diversity and transmit diversity achieving systems are called single-input multiple-output (SIMO) and multiple-input single-output (MISO) systems, respectively.

Nowadays, multiple-input multiple-output (MIMO) systems have become one of the hottest research topics due to the magnificent enhancement brought by multiple antenna techniques. The possibility to deploy multiple antennas at both sides of the communication link lays on the following facts: 1) the developments in hardware miniaturization and advances in antenna design make the deployment of multiple antennas at the small MS more feasible; 2) wireless applications like wireless local area network (WLAN) and fixed wireless access (FWA) allow large physical sized devices that can afford multiple antennas, such as laptop computers. The research on MIMO systems starts from early 1990's. Telatar [13] found that using MIMO system, there could be a dramatic improvement in the system throughput while no extra spectrum is needed. In 1996, Foschini published the famous paper [14], where he proposed a Bell Labs Layered Space-Time (BLAST) architecture for MIMO systems and it was shown that high spectral efficiencies such as 10 to 20 bits/s/Hz can be achieved. Then, an elegant space time block coding (STBC) architecture was proposed by Alamouti [15], which is simple yet effective in obtaining spatial diversity. Alamouti code has led to a research fervor on STBC. In summary, MIMO can be employed to achieve both transmit and receive diversity, or make the system throughput increase linearly with the minimum number of the transmit and receive antennas.

1.3. Space-Time Coding

Transmitter diversity was firstly proposed in [16,17] for BS simulcasting, where copies of the same symbol are transmitted through multiple antennas at different time, creating an artificial multipath distortion at the receiver.

A ML sequence detection or a minimum mean square error (MMSE) equalizer can be employed to resolve the multipath interference and obtain diversity gain. This delay coding scheme can be taken as a repetition channel coding in spatial domain. The idea of channel coding in space and time domains was generalized by Tarokh *et al.* in [18] and the so-called space-time coding (STC) was introduced. There are several kinds of STC with different structures.

1.3.1. Space-Time Block Coding

Alamouti discovered an elegant STBC scheme for MIMO systems with two transmit antennas. As shown in Figure 1.1, the input symbols to the STBC encoders are divided into groups of two symbols. In the first symbol duration, two symbols, s_1 and s_2, are transmitted simultaneously from antenna #1 and #2, respectively. Then, in the next symbol duration, the signals $-s_2^*$ and s_1^* are transmitted from antenna #1 and #2, respectively. Assuming that $h_{1,1}$ and $h_{1,2}$ are the fading coefficients corresponding to the first and second transmit antenna to the receive antenna, respectively, and are constant over two consecutive symbol time, the signals received over two consecutive symbol periods are

$$y_1 = \left(h_{1,1}, h_{1,2}\right)\begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + n_1 = h_{1,1}s_1 + h_{1,2}s_2 + n_1 \tag{1.1}$$

and

$$y_2 = \left(h_{1,1}, h_{1,2}\right)\begin{pmatrix} -s_2^* \\ s_1^* \end{pmatrix} = -h_{1,1}s_2^* + h_{1,2}s_1^* + n_2 \quad . \tag{1.2}$$

They can be rearranged into a matrix form as follows

$$\mathbf{y} = \begin{pmatrix} y_1 \\ y_2^* \end{pmatrix} = \underbrace{\begin{pmatrix} h_{1,1} & h_{1,2} \\ h_{1,2}^* & -h_{1,1}^* \end{pmatrix}}_{\mathbf{H}_{\mathbf{eff}}}\begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2^* \end{pmatrix} \tag{1.3}$$

where $\mathbf{H}_{\mathbf{eff}}$ is the effective channel matrix. Since $\mathbf{H}_{\mathbf{eff}}$ is orthogonal, by a simple linear operation $\mathbf{H}_{\mathbf{eff}}^H\mathbf{y}$, the 2 by 1 MISO system can be split into two separate parallel SISO systems as follows

$$\mathbf{z} = \mathbf{H}_{\mathbf{eff}}^H\mathbf{y} = \left(\left|h_{1,1}\right|^2 + \left|h_{1,2}\right|^2\right)\begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} h_{1,1}^* n_1 + h_{1,2} n_2^* \\ h_{1,2}^* n_1 - h_{1,1} n_2^* \end{pmatrix} \tag{1.4}$$

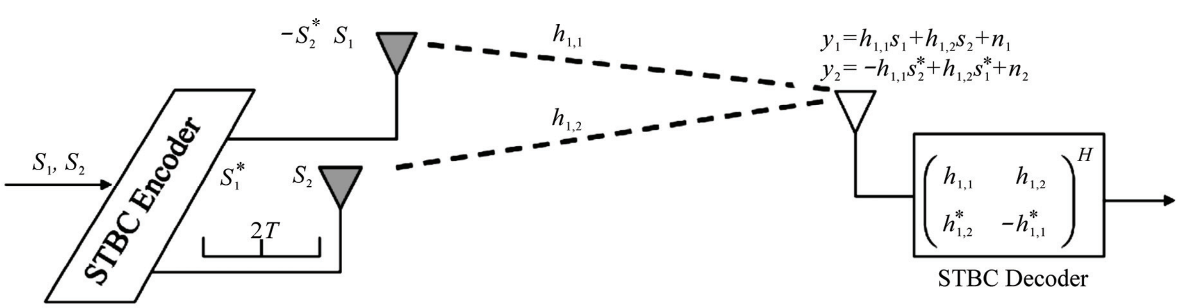

Figure 1.1. Alamouti code

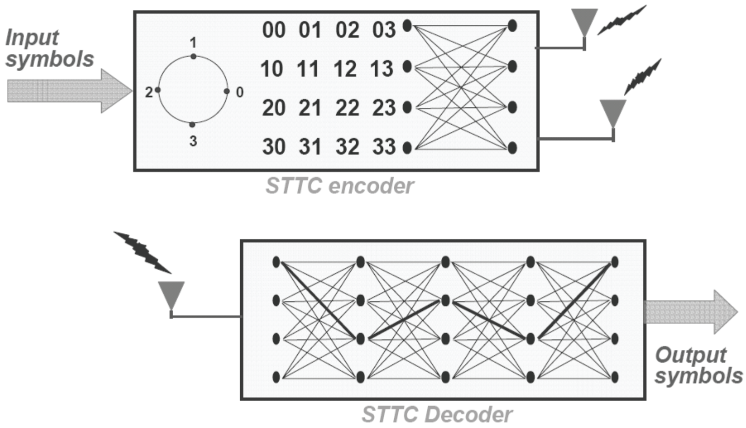

Figure 1.2. A 4-state space time trellis code

This orthogonal property can be extended to the case where the receiver has multiple antennas. It can be seen that the Alamouti scheme decouples the vector ML decoding problems into scalar problems. Therefore, the scheme can realize full diversity while reduce the receiver complexity dramatically. It will be shown later that the Alamouti code provides a performance gain similar to that obtained by using one transmit antenna and two receive antennas with maximum ratio combiner (MRC) except for a power reduction of 2 (3 dB).

The Alamouti scheme can be generalized to an arbitrary number of antennas [19] and is able to achieve the full diversity promised by the number of transmit and receive antennas. Note that in the previous example with two transmit antennas, two different data symbols are transmitted in two symbol durations. Thus the coding rate is $2 \text{ symbols}/2 \text{ durations} = 1$, or the full rate. However, for arbitrary number of antennas, full rate is not always achievable. Letting the i^{th} row contain the data symbols transmitted at the i^{th} antenna in different symbol durations, two STBC with coding rate 3/4 and 1/2 are given by

$$\begin{bmatrix} s_1 & -s_2^* & s_3^*/\sqrt{2} & s_3^*/\sqrt{2} \\ s_2 & s_1^* & s_3^*/\sqrt{2} & -s_3^*/\sqrt{2} \\ s_3/\sqrt{2} & s_3/\sqrt{2} & \dfrac{-s_1 - s_1^* + s_2 - s_2^*}{2} & \dfrac{s_2 + s_2^* + s_1 - s_1^*}{2} \end{bmatrix} \quad \textbf{(1.5)}$$

and

$$\begin{bmatrix} s_1 & -s_2 & -s_3 & -s_4 & s_1^* & -s_2^* & -s_3^* & -s_4^* \\ s_2 & s_1 & s_4 & -s_3 & s_2^* & s_1^* & s_4^* & -s_3^* \\ s_3 & -s_4 & s_1 & s_2 & s_3^* & -s_4^* & s_1^* & s_2^* \\ s_4 & s_3 & -s_2 & s_1 & s_4^* & s_3^* & -s_2^* & s_1^* \end{bmatrix} \quad \textbf{(1.6)}$$

respectively.

1.3.2. Space-Time Trellis Codes (STTC)