Chapter XII
MIMO Beamforming

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ABSTRACT

Transmit beamforming improves the performance of multiple-input multiple-output antenna system (MIMO) by exploiting channel state information (CSI) at the transmitter. Numerous MIMO beamforming schemes are proposed in open literature and standard bodies such as 3GPP, IEEE 802.11n and 802.16d/e. This chapter describes the underlying principle, evolving techniques, and corresponding industrial applications of MIMO beamforming. The main limiting factor is the cumbersome overhead to acquire CSI at the transmitter. The solutions are categorized into FDD (Frequency Division Duplex) and TDD (Time Division Duplex) approaches. For all FDD channels and radio calibration absent TDD channels, channel reciprocity is not available and explicit feedback is required. Codebook-based feedback techniques with various quantization complexities and feedback overheads are depicted in this chapter. Furthermore, we discuss transmit/receive (Tx/Rx) radio chain calibration and channel sounding techniques for TDD channels, and show how to achieve channel reciprocity by overcoming the Tx/Rx asymmetry of the RF components.

INTRODUCTION

It is well known that antenna phase array can form one directional radiation pattern (i.e., beam) to enhance transmit (or receive) signal energy at a desired direction. The directivity is obtained by constructive interference among multiple antenna signals in the desired direction. This is called transmit (or receive) beamforming. Beamforming can be applied to MIMO system by exploiting the multiple antennas at the transmitter and receiver. For example, 3×2 a MIMO beamforming forms two beams and sends two data streams as shown in Figure 1. The received power can be increased by about 1.8 dB over that of 2×2 MIMO. We call beamforming techniques in MIMO system MIMO beamforming. The principle of MIMO beamforming and the ideal beamforming algorithm, i.e. SVD beamforming (Telatar, 1995) are illustrated in Figure 2 and Figure 1. The transformation of input and output signal spaces is illustrated in Figure 2 for a 3×2 example. In general, the singular value decomposition of an $M \times N$ channel matrix **H** is

$$\mathbf{H} = \underbrace{\left[\mathbf{u}_1 \ \cdots \ \mathbf{u}_M\right]}_{\mathbf{U}} \begin{bmatrix} \sigma_1 & & & & \\ & \ddots & & & \\ & & \sigma_M & 0 \ \cdots & 0 \end{bmatrix} \underbrace{\left[\mathbf{v}_1 \cdots \mathbf{v}_N\right]}_{\mathbf{V}}^{*} \tag{1}$$

where **U** and **V** are unitary matrix[b]; σ_i is the i-th singular value with $\sigma_1 \geq \cdots \geq \sigma_M$. The transformation of **H** rotates input vector $\mathbf{v}_i$ to output vector $\mathbf{u}_i$ and amplifies the length by σ_i for $i = 1, \cdots, M$. Since the transformation is linear, the input space $S\{\mathbf{v}_1, \cdots, \mathbf{v}_K\}$[c] is transformed to the output space $S\{\mathbf{u}_1, \cdots, \mathbf{u}_K\}$ for $K \leq M$, where K is the number of active data streams. As a result, the signal space $S\{\mathbf{v}_{M+1}, \cdots, \mathbf{v}_N\}$ is converted into zero vector, i.e. null space. This is illustrated in Figure 2.

The capacity-achieving SVD beamforming algorithm (Telatar, 1995) exploits these properties and converts the matrix channel into M parallel scalar channels. The data symbol x_i is sent by beamforming vector $\mathbf{v}_i$ as shown in Figure 1. The data symbol vector **x** is weighted by a beamforming matrix **Q** and beamformed signal $\mathbf{z} = \mathbf{Q}\mathbf{x}$ is sent by the antennas. There can be many choices of **Q**. In the SVD beamforming algorithm, **Q** – **V**. The signal model is

$$\mathbf{y} = \mathbf{H}\mathbf{Q}\mathbf{x} + \mathbf{n}, \tag{2}$$

where **n** is independent, identically distributed (i.i.d.) additive, white, Gaussian noise (AWGN) vector; the entry of **H** is modeled as i.i.d. complex, circularly symmetric, Gaussian random variables for non-light-of-sight (NLOS) channels. At the receiver end, the received signal **y** is spatially decoupled by $\mathbf{U}^*$ as

$$\hat{\mathbf{x}} = \mathbf{U}^*\mathbf{y} = \mathbf{U}^*\left(\mathbf{U}\Sigma\mathbf{V}^*\mathbf{V}\mathbf{x} + \mathbf{n}\right) = \begin{bmatrix} \sigma_1 x_1 \\ \vdots \\ \sigma_M x_M \end{bmatrix} + \tilde{\mathbf{n}}, \tag{3}$$

where $\tilde{\mathbf{n}}$ has the same distribution as that of **n** because $\mathbf{U}^*$ is unitary. Since M parallel scalar channels are established in (3), transmission power can be optimally loaded across the channels using the water filling technique (Cover, 2006) to maximize the link capacity. For example, it is desirable to send less than M streams and put all power in the one or two strongest scalar channels in low signal to noise ratio (SNR) region. Therefore, only the first K columns of **V**, denoted $\mathbf{V}_B$, is required to be sent back. Quantization of $\mathbf{V}_B$ is one of the major topics in this chapter.

One of the main challenges of applying MIMO beamforming techniques to practical systems is the acquisition of CSI or beamforming matrix at the transmitter. In FDD and radio calibration absent TDD, channel reciprocity is not valid and CSI feedback from receiver to transmitter is essential. Quantization of CSI is also required, except in some analog modulation (Thomas, 2005; Marzetta, 2006). The transmitter computes the beamforming matrix based on the feedback and conducts the beamforming.

The simplest solution is to quantize the channel matrix element by element (i.e. scalar quantization) and feed the quantization indexes back. This is employed in fixed and slow fading wireless systems such as 802.16d[d] and 802.11n[e]. However, the feedback of the quantization indexes consumes significant amount of system bandwidth and reduces (and even cancels) the throughput gain delivered by MIMO beamforming. In practical systems, the feedback data is robustly modulated and heavily coded to prevent feedback error and the consequent loss. Therefore, the feedback channel has a low efficiency. The problem becomes more severe for mobile wireless systems due to time variations in mobile channels and consequently the need for frequent CSI updates. It is essential to design efficient feedback schemes for mobile wireless systems. The second challenge is the complexity in computing the feedback. The complexity in performing quantization and quantization codebook storage can be an issue for mobile device when high resolution feedback is needed. The third challenge is feedback latency. The latency is between 1-20 ms for cellular system like 3GPP and 802.16e[f]. Channel coherency in the order of this scale makes feedback stale and limits the application of MIMO beamforming to high mobility channel.

LITERATURE SURVERY

Notable journal publications are overviewed in this section and the other literature related to industrial application will be introduced in the subsequent sections. MIMO transmit and receive beamforming was proposed in (Winters, 1987),

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