CHAPTER 6

Advances in MIMO-OFDM
Channel Estimation

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6.1. Introduction

The first generation (1G) of mobile phone systems became publicly available in the mid 1980s. Over the next decade, the market penetration for mobile telephony was to increase, and by the early 1990s, the second generation (2G) of mobile phone systems had been introduced. In 2G systems, new digital communications standards were implemented, leading to improved voice quality and the efficient use of the available radio frequency spectrum. In these standards, users were separated by time slots (TDMA) as well as frequency (FDMA), which meant that more users could be supported for a given cell radius and fixed number of radio frequency channels. Despite the success of 2G mobile communications systems such as GSM, the development of the next generations of mobile wireless communications systems is being driven by the demand for video streaming and wireless Internet at increased data rates. Indeed, the third generation (3G) systems, which support services at rates of up to 2Mbps, have been deployed leading to the multimedia convergence of audio, video, and data. Current 3G technologies are based on the separation of users by using unique codes (CDMA), and hence allow for greater spectral efficiency and higher data rates. Whilst 3G networks are already in their early stages of deployment, plans are being made for the introduction of the fourth generation (4G) of wireless networks. It is expected that standards such as 4G will integrate mobile communications specified by International Mobile Telecommunications (IMT) standards and Wireless Local Area Networks (WLAN) at data delivery rates of 50-100Mbps [1].

The main challenge in implementing these new generations of wireless networks is delivering high quality of service requirements whilst increasing the network capacity in terms of the total number of users and the data throughput.

One of the most promising methods for achieving the desired system performance levels is through the deployment of the MIMO-OFDM technology which exploits spatial and frequency diversity in order to increase the reliability and data throughput for high data rate (wideband) QAM symbol transmission. Systems operating at high data rates in the presence of radio wave scatterers experience multipath propagation which causes Inter-Symbol Interference (ISI). Inter-Symbol Interference here refers to the phenomenon where symbols that have been transmitted previously arrive via a longer, non-direct path at the same time as the symbols arriving via the direct path. Orthogonal Frequency Division Multiplexing (OFDM) is a digital modulation technique that solves the ISI problem [2]. If the communications system is also equipped with multiple-input multiple-output (MIMO) antennas, independent fading across communicating antenna elements can be assumed provided that the antenna separation at the transmitter and receiver is adequate. This channel independence can be exploited to overcome channel fading through the distribution of redundant copies of transmit data across the independent spatial channels using the so-called diversity schemes [3]. Alternatively, data rates can be boosted through the transmission of multiple data streams in parallel using spatial multiplexing schemes [4]. In addition, joint optimization schemes [5] focusing on transmitting and receiving multiple streams using linear or non-linear processing methods can achieve improved Bit Error Rates (BERs) via diversity, as well as increased data rates through spatial multiplexing. The diversity, spatial multiplexing and joint optimization schemes can be extended from single user systems to multi-user systems as described in the literature [6]. Indeed, Spatial Division Multiple Access (SDMA) schemes, where users are separated by their location dependent channel conditions, is a challenging topic that has received a great deal of research interest. Such systems are pertinent to the technological requirements of future networks as they combine MIMO-OFDM data throughput and reliable transmission capabilities with stringent spectral usage [6,7].

However, the superior performance promised by the MIMO-OFDM technology relies on the availability of accurate Channel State Information (CSI) at the receiver. For example, in single user systems, schemes such as Alamouti space-frequency coding require CSI at the receiver in their implementation. Alternatively, zero forcing receivers used in spatial multiplexing MIMO systems require CSI in order to de-multiplex the transmitted data. Another example is that for the joint optimization scheme, the solution of the Minimum Mean Square Error (MMSE) transmit-receive linear precoders and decoders requires CSI to be known at either end of the wireless link. So apparent are the implications of imperfect CSI on system performance, that various studies have been conducted into the repercussions of CSI error on capacity and BER performance in MIMO systems. In the literature [1], the effects of imperfect CSI on a space time coding MIMO system are evaluated through simulation.

\[\text{The minimum separation distance for channel independence is considered to be of the order of a single wavelength.}\]
In obtaining the system performance results, it is assumed that CSI is estimated through use of Orthogonal Training Sequences and that errors in the CSI estimation are as a result of Additive White Gaussian Noise (AWGN) in the received symbols. CSI errors are known to degrade the BER performance and hence the diversity order of the MIMO system. Diversity order is defined as the slope of the Bit Error Rate (BER) curve as a function of the average receive Signal to Noise Ratio (SNR) on a log-log plot. In the literature [8], a time-domain analysis of imperfect channel estimation in spatial multiplexing OFDM based multiple-antenna transmission systems is provided. An analysis of the effects of imperfect CSI on the capacity of spatial multiplexing systems is presented in the literature [9] which shows that the lower and upper bounds of mutual information are tight for Gaussian inputs.

This chapter describes the challenge of MIMO-OFDM channel estimation when the number of antennas is very large, for example, in multi-user systems. For downlink communications in multi-user systems, the number of transmit base station antennas may be large when compared to the number receiving antennas for a particular user due to size constraints on the mobile device. For uplink communications, the total number of transmitting antennas may be very large when compared to the receiving antennas at the base station. Both these scenarios can be investigated by considering a single user \((nt, nr)\) MIMO-OFDM system where \((nt, nr)\) represents base station and a single user’s antenna for the downlink or the grouping of the user antennas and the base station antennas for the uplink. It can be shown that when the baud rate increases, the number of channel parameters to be estimated through the conventional approach increases. The main reason for this is that conventional time-multiplexed MIMO-OFDM channel estimators formulate a least squares problem where the received symbols are used to solve for the Channel Impulse Response (CIR) based on the convolution model of the frequency selective channel and a known training sequence. In such scenarios, channel estimators encountered with imperfect windowing results in an additional estimation error. In order to facilitate multi-user channel estimation, a generic MIMO-OFDM channel estimator will be developed for which the number of channel estimation parameters is less dependent on the maximum delay spread of the multipath channel. The development of the proposed MIMO-OFDM channel estimator is motivated by describing various SISO-OFDM estimators, namely the Least Squares (LS) estimators, Maximum Likelihood Estimators (MLE), and the optimal 2D-channel estimators based on Wiener filtering. Vectorization of the convolution channel model is then used to develop the conventional MIMO-OFDM channel estimator. Following this introduction to the state-of-the-art estimators, we show that the vectorization of the flat fading channel model presents a preferable solution, where the CSI in the MIMO-OFDM system can be represented in a reduced parameter sense using an arbitrary basis. The parsimonious representation of CSI variation in time or frequency results in improved channel estimation performance in the low SNR regimes as well as the accurate CSI estimation when the numbers of transmit antennas is large. We conclude by describing how the proposed method may be adapted to a superimposed pilot channel estimation scheme capable of accurate channel parameter estimation in time varying channels.

6.2. Channel and System Model

Figure 6.1 depicts a generic MIMO-OFDM system where a sequence of bits is coded for space-frequency communication and subsequently decoded at the receiver. It can be noted that the MIMO-OFDM system derives data from a single application (e.g. a video frame) on the mobile device, and after serial to parallel conversion followed by a Fast Fourier Transform (FFT) and the addition of a cyclic prefix, a serial binary stream is collated into \(nt\) parallel streams and communicated simultaneously via the transmitter antenna array. The output data streams consisting of \(N\) Quadrature Amplitude Modulation (QAM) symbols are usually referred to as OFDM symbols. In this implementation, QAM provides high data rates, efficient multiple access strategies and resistance to channel imperfections, amongst other advantages [10,11]. At the receiver, length \(N\) vectors of QAM symbols are formed at each antenna after IQ processing, cyclic prefix removal and FFT processing. QAM symbols from each antenna are then collated to form length \(nr\) vectors that are used to detect the transmitted data. For the transmission of OFDM symbol in multipath channels, a cyclic prefix (CP) must be added to the transmitted OFDM symbol in order to maintain orthogonality of the sub-carriers [12]. This is done by adding a repetition of some of the transmit QAM symbol to the beginning of each burst resulting in a length \((N + L - 1)\) OFDM symbol. \(L\) is the maximum number of non-zero elements in the CIR vector which is found by dividing