Channel Estimation for MIMO-OFDM Systems: The Recent Trends

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Abstract: The essence of modern telecommunication systems in this era of emerging wireless technology is invariably Multiple Input Multiple Output (MIMO), in combination with Orthogonal Frequency Division Multiplexing (OFDM) forming the much promising MIMO-OFDM systems. These systems form an attractive air-interface for the next generation Wireless Local Area Network (WLAN) and Wireless Fidelity (Wi-Fi) Systems. The MIMO-OFDM systems are characterized by enviably High Data Transmission Rates, along with excellent Spectral Efficiency and robustness against Noise with extremely small Bit Error Rate (BER), while providing excellent SNR characteristics. One of the challenges faced by a Wireless Engineer in these systems is the precise determination of Channel Estimation (CE), which has attracted a lot of research in recent times. In this paper, we present various Channel Estimation techniques being explored over the years, to complement the excellent features offered by this technology.

Keywords: Blind CE, Channel Estimation (CE), MIMO, MIMO-OFDM, OFDM, Pilot based CE.

I. Introduction

'MIMO' as its nomenclature suggests is comprised of a large multitude of transmitting and receiving antennas to communicate equally (or nearly so!) in all 3-dimensional space providing superior communication performance [1], [2]. This technology has attracted a lot of attention in recent years, with many an enthusiast wireless engineer taking up the issues and challenges of these systems as research problems. MIMO in combination with OFDM systems offer considerable increase in Throughput and Coverage without additional utilization of Bandwidth or increased Transmit Power [3].

These systems conveniently utilize a wireless communication phenomenon called *multipath* propagation where the transmitted signal hits the walls, ceilings, floorings and other objects, undergoes reflections a multitude of times, before ultimately reaching the receiving antennas, taking different angles and at slightly different times.

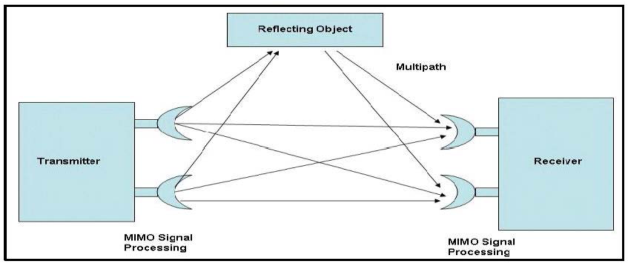

Fig. 1: MIMO Architecture

These systems are often used in combination with a spectrally efficient transmission technique called Orthogonal Frequency Division Multiplexing (OFDM) forming MIMO-OFDM systems to avoid Inter Symbol Interference (ISI) and also achieve increased Data Transmission Rate and Signal-to-Noise Ratio (SNR) performance [4] of design and equipment. Fig. 1 describes the architecture of MIMO systems employed in modern communication systems.

OFDM is a form of Frequency Division Multiplexing (FDM) which consists of a single channel in turn employing multiple Sub-Carriers on adjacent frequencies, along with advantage of inherent 'Orthogonality.' In a normal situation any overlapping adjacent channels tend to interfere with one another giving rise to Adjacent Channel Interference (ACI). But, this does not happen in OFDM systems, because the Sub-carriers are systematically made Orthogonal to each other. This technicality permits the Sub-Carriers to overlap without interference. As a result, OFDM systems are capable of maximizing Spectral Efficiency without causing ACI [5].

OFDM can be viewed as either a modulation technique or a multiplex technique or a combination of both. OFDM is commonly employed in many emerging and upcoming telecommunication protocols because of its many advantages over the traditional FDM techniques. The various advantages of OFDM systems include greater Spectral Efficiency, reduced Inter-Symbol Interference (ISI), resilience to multi-path distortion and capability to deal efficiently with large delay spreads.

Fig. 2 illustrates the Orthogonality principle offered by the OFDM systems.

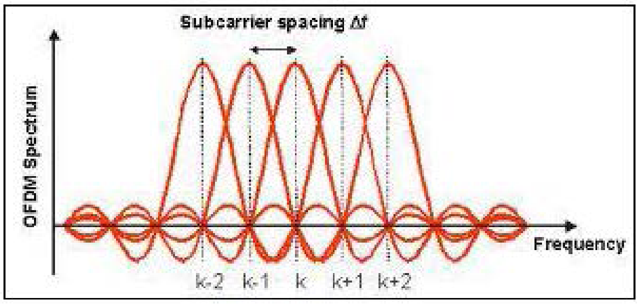

Fig. 2: Orthogonality Principle of OFDM

The heart of an OFDM operation is the Inverse Fast Fourier Transforms (IFFT) at the transmitter which complements the Fast Fourier Transforms (FFT) at the receiver. Linear mapping between *N*-complex data symbols and *N*-complex OFDM symbols is performed, which automatically transforms the high data rate stream into *'N'* low data rate bit streams, while simultaneously providing immunity against multipath fading.

In order to assimilate the advantages of OFDM Systems, a major challenge to be faced in MIMO-OFDM systems is the precise determination of Channel-Estimation. This becomes necessary in order to recognize the information symbols as the receiver. A thorough knowledge of Channel State Information (CSI) is essential in order to equalize the received symbols and receive it correctly in spite of signal attenuation and phase drifts suffered due to the very many challenges offered to the signal while it travels down the wireless communication channel [6].

In this paper, we present an overview of the Channel Estimation techniques employed over the years to improve the system performance of the MIMO-OFDM Systems. The rest of the paper is organized as follows: Section II presents an overview of Channel Models. An introduction to Channel Estimation is presented in Section III and the various techniques and recent trends of research in this direction, are presented in Section IV. Finally, Conclusions are presented in Section V.

II. Channel Models

The MIMO-OFDM channels are most often subjected to *Fading* which is rapid fluctuations of amplitudes, phases or multipath delay experienced by a radio signal over a period of time. Fading is caused due to *Multipath* propagation and *Shadowing* from obstacles, leading to two main forms of Fading in MIMO-OFDM systems [7].

A. Multipath Propagation

Multipath Propagation is caused by presence of scattering and reflecting objects in the communication channel, resulting in radio signals reaching the receiving antennas through two or more paths, thereby creating ambiguities of multiple versions of the transmitted signals. This results in random variation of phase and amplitudes of signals, at the same time causing unnecessary delays in signals reaching the receiving antennas. *Rayleigh Fading* occurs when the magnitudes of signals reaching the receiving antennas follow approximately a Rayleigh Distribution [8].

B. Shadowing from Obstacles

Obstacles in the communication paths produce Shadowing effect (a virtual shadow!) which obstructs the propagation path between transmitter and receiver, resulting in reduced signal strength and ambiguities in the received signal, and rarely in extreme cases, no signal at all [8].

C. Additive White Gaussian Noise (AWGN)

A combination of White Noise (the adjective 'white' indicates a combination of any type of Noise) which follows a Gaussian distribution is termed the Additive White Gaussian Noise (AWGN). This model does not possess any inherent capability that can account for Fading, Frequency Selectivity, Interference, Nonlinearity or Dispersion.

III. Channel Estimation

A. Channel Estimation

One of the many challenges faced by a wireless Engineer working on the MIMO-OFDM systems is the precise, accurate determination and estimation of the Channel characteristics. Channel Estimation involves the precise determination of the frequency response of the channel in order that all of the bits transmitted from the transmitter is received at the receiver with at least a probability of error as possible, with least BER and ISI and with a maximum SNR.

B. Goals

The main goal of Channel Estimation is to measure the effects of the Channel characteristics on known or partially known set of transmission parameters. OFDM systems are especially suited for Channel Estimation, because of the Sub-Carriers being as closely spaced as possible.

C. Channel Estimation Techniques

1. Pilot Based Channel Estimation

Based on previous experiences, Channel Estimation is performed by a set of bit sequences known to both transmitter and receiver, called the 'Training Sequence.' The transmitter sends these sequences as 'Pilots' to guide and steer the receiver (or somehow make the receiver to be aware) of the characteristics of the channel. The receiver then uses these known 'Training Bits' and the corresponding received samples for estimating the Channel [9]. Pilot based CE techniques can be of *Least Squares (LS)* or *Minimum Mean Square Error (MMSE)*.

i. Least Squares (LS)

The idea of LS is that the Channel can be precisely estimated if the *Squared Error* (to take care of both positive and negative values) between *Estimation* and *Detection* is minimized [10].

ii. Minimum Mean Square Error (MMSE)

The MMSE Channel Estimation method provides better (linear) Estimate of the Channel by taking the Minimum value of the average of the Squared Error [10].

***2.** Blind Channel Estimation*

In addition to Training methods, Channel Estimation can be performed using Blind or Semi-Blind techniques. Widely used techniques under this category use the concept of channel being represented as second order statistics of a long vector whose size is greater than or equal to the number of Subcarriers [11], [12], [13]. A variation of the Blind methods is based on Linear Prediction (LP) which also employs second order statistics of a short vector and with lesser complexity as compared to the former [12].

IV. The Recent Trends

A lot of research is on in the area of Channel Estimation in MIMO-OFDM systems. Some of the recent trends in this direction are presented here.

A. Adjustable Phase Shift Pilots (APSPs)

Starting from the concept of Pilot based CE techniques; Li You *et al.* [14] propose a variation of *Adjustable Phase Shift Pilots (APSPs)* for channel acquisition to determine CE in MIMO-OFDM systems. It is found that by employing APSPs, the Pilot Overhead is considerably reduced.

The algorithm:

i. A Pilot Carrier and shifted versions of this in the frequency domain are considered which form the APSPs.

ii. As the name implies, the phase shifts for the different Pilots are Adjustable, making it more convenient to have more numbers of APS Pilots. This ensures that the Pilot Overhead is considerably reduced.

iii. The APSPs exploit two properties of the wireless channel;

- The channel matrix is found to be Sparse in most communication scenarios. The channel power is most of time concentrated in finite regions of delay and/or angles due to scattering limited to these regions. In such scenarios, channel sparsity can be resolved in the angular domain due to large number of antennas present in the MIMO-OFDM systems.
- It is observed that the channel sparsity patterns which indicate the distributions of channel powers in delay-angle domains for different users, are usually different.

iv. The channel sparsity can be determined by establishing a relationship between channel Space-Frequency Correlations and the channel Power Angle-Delay Spectrum in the massive antenna system, which in turn reveals the channel *Sparsity* in the MIMO-OFDM system.

v. With knowledge of channel sparsity, the channel acquisition is computed leading to an investigation of Channel Estimation and Channel Prediction in terms of Mean Square Error (MSE) distributions in the angle-delay domain.

B. Iterative Channel Estimation Using Virtual Pilot Signals

MIMO-OFDM systems are widely used in most modern telecommunications systems of today. In order to keep pace with the ever increasing demand for the MIMO-OFDM systems, the number of transmit and receive antennas are increased to improve *Throughput*, which is one of performance metrics of any wireless communication system. Throughput indicates the number of bits transmitted over the channel to reach the receiver in comparison to the ones generated by the transmitter. To meet the ever increasing demand of throughput requirements, the number of Pilots should also be proportionately increased.

Instead, Park *et al.* [15] employ 'Virtual Pilots' which use the decided (sliced) data symbols for re-estimation of the channel.

i. These virtual pilots should satisfy two conditions;

- Firstly, the quality of the virtual pilots should be good enough for channel estimation.
- Secondly, the quality of virtual pilots channels should be highly correlated with that of the pilot signals, otherwise the estimates may not meet the standards for which they are intended for.

ii. The Virtual Pilots are used iteratively which take care to see that there is never a shortage of Pilots used in estimation process.

iii. The technique employed is the Decision Directed Channel Estimation (DD-CE) technique which in turn uses the Soft Symbol decisions obtained by Iterative Detection and Decoding (IDD) scheme to enhance the quality of channel estimate.

iv. The soft information obtained iteratively selects reliable data tones, subtracts inter-stream interferences, and performs re-estimation of the channels.

C. I/Q Imbalance (IQI) for Uplink Multi-cell Massive MIMO Systems

Zarei *et al.* [16] have addressed the issue of In-phase/ Quadrature-phase Imbalance (IQI) at both the BS (Base Station) and the UTs (User Terminals) in MIMO systems. IQI is considered to be one of the important hardware impairments. This arises in the analogue parts of direct conversion transceivers and causes performance losses. To tackle this, the authors have proposed IQI aware Widely-Linear (WL) CE and data detection schemes for uplink multi-cell massive MIMO systems.

The work is summarized as follows:

i. The uplink of a multi-cell narrow band single-carrier massive MIMO system having universal frequency resuse was considered.
ii. A block flat fading channel is assumed.
iii. The detection schemes employed were IQU (IQ Unaware)-MMSE and IQA (IQ Aware)-WLMMSE and the system model was described by a complex-valued and a real-valued representation.
iv. Both schemes were subjected to exhaustive Channel Estimation, Data Detection, Asymptotic Sum Rate Analysis and Asymptotic Sum Rate Analysis for the Single Cell case.
v. The experimental results indicate that if left unattended, IQI causes severe performance losses even if the number of BS antennas is much larger than the UTs.
vi. The proposed IQA-WLMMSE receiver yields a substantially higher sum rate than the IQU-MMSE receiver and approaches the performance of the MMSE receiver in an ideal system without IQI.
vii. Further, it is observed that for both conventional receivers, IQI at the UTs is more harmful than IQI at the BS.

V. Conclusions

MIMO-OFDM is a promising technology which can be used to implement various IEEE standards and is the one which is easily adaptable to the present day communications. In this paper, a comprehensive study of various CE techniques and the recent trends and advances, which has contributed annals to existing research is put forward. The CE techniques which are basically of two categories, Pilot based or Blind techniques have undergone enhancements and refinements over the years to improve CE performance of the much promising MIMO-OFDM systems.

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