Channel Estimation In MIMO -OFDM Wireless Communication Systems

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ABSTRACT

The global explosion in the use of wireless (handheld) devices - that rely heavily on wireless infrastructures/systems for their functioning - necessitates the need for robust and efficient wireless communication systems. MIMO-OFDM wireless systems have been shown to improve spectral efficiency and reliability among other advantages. However, their deployment in mobile time-varying environments requires very accurate estimation of the channel characteristics. This paper reviews channel estimation in MIMO-OFDM wireless communication systems and their suitability for mobile time-varying channel environments.

Keywords: Wireless communication, MIMO-OFDM, Channel state information, Channel estimation.

1 INTRODUCTION

WIRELESS communication are expected to achieve high data rates, low bit-error rates and low delay; their performance are however, primarily determined by the environment and wireless channel characteristics. Wireless channels are highly prone to multipath propagation and are time-variant in nature. Thus, signals propagating them are subject to frequency-selective fading and intersymbol interference [1]; these results in an undesirable and/or catastrophic degradation of transmitted signals.

While OFDM segments wide band high-rate signals into multiple independent flat-fading narrowband subchannels that are resistant to frequency-selective fading, MIMO antenna systems drastically improves diversity and reliability in a wireless link [1], [4]. OFDM modulation and MIMO antenna technology when deployed together in a wireless system mitigate against the effects of frequency-selective fading and intersymbol interference to appreciable levels [2]. High data rates, low delays and low bit-error rates are achievable in MIMO-OFDM wireless communication systems.

For a fixed transmitter-receiver pair, channel characteristics have minimal effects on the transmitted signal. However, a relative motion between the transmitter and receiver (especially when the mobility is high), causes the effects of channel characteristics to become more pronounced and requires serious investigation [10].

An overview of MIMO-OFDM wireless systems is presented, and the peculiar case of relative mobility between transmitter-receiver pair is investigated, with emphasis on estimation of the channel state information in such systems.

2 OVERVIEW OF THE WIRELESS COMMUNICATION SYSTEM

2.1 The Wireless Communication Channel

Wireless communication has rapidly become the preferred communication technique over the old traditional wired communication. The explosion in the use of mobile phones and other portable communication devices for voice and data communication all over the world has further contributed to the pressure on broadband wireless communication systems [7]. This has necessitated more intensive research on these systems (wireless communication systems) both in the academia and industries.

In light of the heavy traffic on wireless systems for voice and data (i.e. broadband) communication, they are expected to achieve high data rates, low delay and low bit-error rate (BER) [2]. Primarily, wireless systems are governed by the wireless channel characteristics and the environment. Contrary to the wire channel, which is typically static and predictable, the wireless channel is rather dynamic and unpredictable, which makes its analysis pretty daunting [1]. Thus, researches in wireless systems have been focused on these two important components.

2.2 Effects of Environment on Wireless Signal Propagation

The frequency spectrum allotted to communication over wireless links (channels) is in the gigahertz (GHz) range;

and given the inverse relationship between frequency and wavelength i.e. from:

$$v = f\,\lambda \quad (1)$$

$$f = v / \lambda \quad (2)$$

where v is the velocity which is constant at 3 million m/s. The wavelength of transmitted signals propagating at this very high frequencies are in the millimetre range. This extremely short wavelength makes the signals propagating the wireless channel susceptible to diverse environmental conditions. Principal among these are reflection, refraction, diffraction, scattering from various physical objects – trees, buildings, water bodies, vehicles e.t.c. – that are always present in any wireless communication environment [5]. These bodies cause minor to significant attenuation, phase-shift and delay in the signals propagating from the transmitter to the receiver. At the receiver, these signals arrive at different times with varying strengths and may combine either constructively or destructively, resulting in amplification, attenuation (or even cancellation) of the transmitted signal. This is multipath propagation. Multipath propagation causes certain frequency components of the transmitted signal to be affected more that others i.e. frequency-selective fading - which prevents total recovery of the transmitted signal at the receiver [1], [5]. Frequency-selective fading is a fading mechanism peculiar to broadband signals.

2.3 Effects of Channel Characteristics on Wireless Signal Propagation

In addition to the effects of multipath propagation-induced frequency-selective fading, frequency-selective fading is also induced by the effects of channel characteristics on the propagating signals [1]. In wireless communication, the delay spread of a channel is the maximum time delay that takes place during transmission of a signal through the channel; and it varies directly with changes in environmental conditions [4], [9]. For low-rate narrowband signals, the symbol periods or pulse duration are large compared to the channel delay spread, thus they undergo flat fading but not frequency-selective fading. Flat fading affects all the frequency components within the transmitted signal band equally [1]. In contrast, broadband signals have pulse durations that are small relative to the channel delay spread; this causes multiple delayed paths that act like a filter on the transmitted signal sequence leading to fading at selected frequencies i.e. frequency-selective fading. Frequency-selective fading in broadband high frequency transmission creates intersymbol interference (ISI) in the received signal [1], [3].

While multipath propagation and frequency-selective fading are the major mechanisms that deter accurate signal detection and recovery in a static scenario, a relative mobility between the transmitter and receiver also further affects the channel characteristics, and hence signal recovery. This is the Doppler spread or shift that causes the channel characteristics to change rapidly at every instance of time, and may lead to minor to severe attenuation of transmitted signal [1]. Its effects actually becomes more significant as the relative speed of motion between the transmitter and receiver increases. Thus, in a high mobility environment, the wireless communication system, and of course, the wireless channel becomes frequency-selective and highly time-variant i.e. the channel characteristics changes very ‘’rapidly’’ with time. This will have catastrophic consequences on signal recovery at the receiver terminal [6].

In light of the foregoing, the performance of wireless communication systems hinges primarily on the channel, hence wireless channels have been a major research dimension in recent years in the field of communication.

Technically, the receiver in a wireless link needs to accurately estimate the channel characteristics in order to fully recover the transmitted signals. In a high mobility environment however, this estimation has to be carried out as frequently as possible because the channel varies rapidly with time. The channel matrix coefficients have to be computed at every instance of time for accurate signal detection at the receiver, in order to feed back accurate channel state information (CSI) to the transmitter [6].

3 THE ROLE OF MIMO AND OFDM

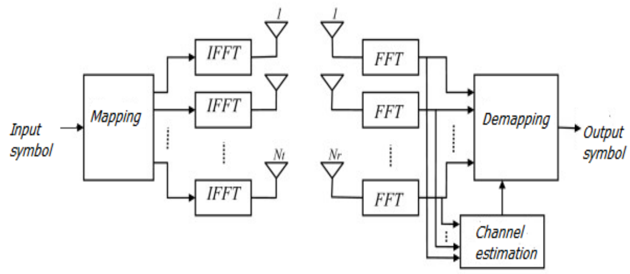

Fig. 1. A simple MIMO-OFDM Block

Multiple-input multiple-output communication involves using multiple antennas at the transmitter and receiver ends of a wireless communication link to transmit multiple data streams concurrently within the same frequency band [5]. The MIMO transmission creates parallel channels over the same time and frequency i.e. spatial multiplexing to achieve high capacity and link reliability without the need for additional power of spectrum. Thus MIMO transmission exploits the multipath fading mechanism to increase data rate and system capacity [2], [5].

However, in order for MIMO systems to function, there has to be a means of “slicing” the carrier signal into multiple subcarriers that modulate the low-frequency information data. These parallel low-rate subcarriers can then be transmitted and received via the multiple antenna

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configuration. Orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation technique that creates these parallel subchannels that are low-rate or narrowband in nature [2]. By inserting cyclic prefix between the subchannels, orthogonality is maintained and intersymbol interference is totally eliminated [7].

Hence, a combination of MIMO and OFDM i.e. MIMO-OFDM not only drastically improves channel capacity and data rates, it also combats frequency-selective fading thereby improving link reliability [2].

Although, channels capacity of a MIMO-OFDM system has been shown to increase linearly with the number of antennas at both ends, this holds only when perfect knowledge of the wireless channel is available at the receiver. Unfortunately however, knowledge of the channel i.e. channel state information (CSI) is never known at the receiver prior to transmission. Hence, accurate estimation of the channel is very crucial and plays a significant role in MIMO-OFDM system deployment [6].

4 CHANNEL ESTIMATION TECHNIQUES FOR MIMO-OFDM SYSTEMS

Estimation of channel state information (CSI) constitutes a bottleneck in MIMO-OFDM systems. CSI entails identifying information about the channel to enhance accurate recovery of the transmitted signals at the receiver under the prevailing channel conditions [10]. It is estimated at the receiver and fed back to the transmitter to provide known channel properties for a wireless link. The rate of acquisition of CSI is determined by the rate of change of the channel conditions with time [4].

CSI can either be instantaneous or statistical [1]. In the former, the impulse response of the transmitted sequence is used to obtain the current channel condition while in the latter, statistical characteristics of the channel – fading distribution, channel gain, spatial correlation e.t.c. are obtained and used for estimating CSI. Instantaneous CSI is well estimated for slow-fading systems where the channel conditions vary with a period higher than the symbol duration while statistical CSI can be reasonably estimated in fast-fading systems where the channel conditions vary with a period less than the symbol duration. In a high-mobility wireless environment, the CSI changes rapidly with time, and statistical CSI are most useful to estimate such channel [1].

Realistically, full knowledge of the CSI is never at the receiver prior to transmission, and the estimation of the channel is not perfect due to noise and other factors or conditions during transmission. Based on these availability and quality of CSI at the receiver, it (CSI) can be further categorised into three [11]:

1. *Perfect CSI:* Here, the receiver has a complete knowledge of the instantaneous channel realisation and the detection of symbols in this case is termed coherent detection. This is the most commonly assumed scenario when analysing wireless channels, but it is not achievable in reality.
2. *Imperfect CSI:* In this case, the receiver has an inaccurate or incomplete knowledge about the parameters that describe the channel; hence the estimator relies on the partial information obtained about the channel for its estimation.
3. *No CSI:* Where there is no information about the state of the channel or its statistics, the estimator relies on other means of information about the entire system to reasonable estimate the channel. This is referred to as non-coherent detection.

The algorithms and/or techniques for channel estimation can be broadly categorise into three [1]:

1. Training (or Pilot Symbol)-based Channel Estimation
2. Blind Channel Estimation
3. Semi-blind Channel Estimation

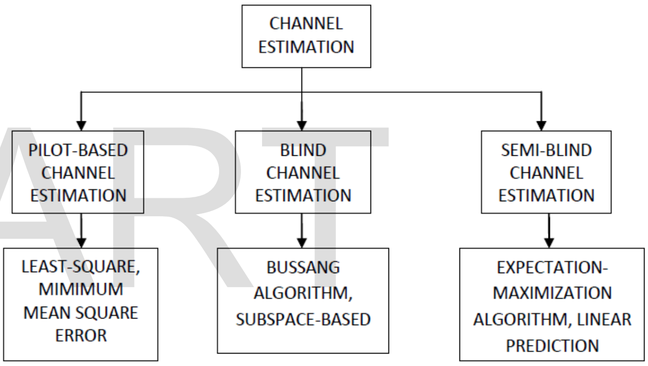

Fig. 2. Classification of Channel Estimation Algorithms

4.1 Training-based Channel Estimation

Training-based channel estimation involves the insertion of pilot symbols (at the transmitter) into all subcarriers of an OFDM symbol block within a specific period [1]. These pilot symbols are also referred to as training symbols, and are the reference signals used by both transmitter and receiver for estimating the channel. Initially, the CSI corresponding to the pilot symbols are estimated, the information obtained is then extended to the adjoining data symbols for estimating the channel [1], [2].

The training-based channel estimation techniques assumes that all subcarriers in the OFDM block are orthogonal, and free of inter-channel interference (ICI). Thus, for an OFDM block of N subcarriers, the pilot symbols are given by the diagonal matrix, X given by [1]:

$$\mathbf{X} = \begin{bmatrix} X[0] & 0 & \cdots & 0 \\ 0 & X[1] & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & X[N-1] \end{bmatrix}$$

X(k) represents a pilot tone at the kth subcarrier; E{X(k)} = 0; k = 0, 1, 2,...N-1.
Taking the channel gain of each of the subcarriers as H[k], and given the channel vector, H = H[0], H[1], ... H[N-1]^T and noise vector, Z = Z[0], Z[1], ... Z[N-1]^T, with E{Z(k)} = 0; k = 0, 1, 2,...N-1. Then the received training signal can be represented by the vector, Y[k].

$$\mathbf{Y} \triangleq \begin{bmatrix} Y[0] \\ Y[1] \\ \vdots \\ Y[N-1] \end{bmatrix} = \begin{bmatrix} X[0] & 0 & \cdots & 0 \\ 0 & X[1] & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & X[N-1] \end{bmatrix} \begin{bmatrix} H[0] \\ H[1] \\ \vdots \\ H[N-1] \end{bmatrix} + \begin{bmatrix} Z[0] \\ Z[1] \\ \vdots \\ Z[N-1] \end{bmatrix}$$

$$\mathrm{Y = XH + Z} \qquad (3)$$

This technique however, is not very efficient in terms of bandwidth due to the overhead incurred by the pilot symbols [1].

4.1.1 The Least-Square Channel Estimation

The least square (LS) estimator estimates the channel without any knowledge of the channel statistics; it relies on pilot signals and received signals for channel estimation [6]. Although, the least square estimates have very low computational complexity, their computation have a high mean square error [20]. The LS estimation of the channel vector, H is given by [1]:

$$H_{LS} = \underline{X}^{-1}\,\bar{Y} = \left[\frac{X_k}{Y_k}\right]^T \qquad (4)$$

(k = 0,..., N-1)

4.1.2 The Minimum Mean-Square Error Channel Estimation

The minimum mean-square error (MMSE) channel estimator performs better than the LS estimator, especially in a low signal-to-noise ratio environment; they minimise the mean-square error by using the second-order statistics of the channel conditions. However, the major drawback to this techniques is the high computational complexity [6]. For a Gaussian channel with channel vector, H that is uncorrelated with the channel noise, w, the MMSE estimate of H is given by [21]:

$$\tilde{H}_{MMSE} = FR_{hy}R^{-1}{}_{yy}\,y \qquad (5)$$

Where,

$$R_{hy} = E\{hy^H\} = R_{HY}\,F^H X^H \qquad (6)$$

$$R_{yy} = \mathrm{E}\{YY^H\} = XFR_{hh}\,F^H X^H + \sigma_n^2\,I_N \qquad (7)$$

Thus,

$$\widetilde{\tilde{H}}_{MMSE} = XFR_{hh}\,F^H X^H\,(XFR_{hh}\,F^H X^H + \sigma_n^2\,I_N)^{-1}\,\mathrm{Y} \qquad (8)$$

R_{hh} is the channel auto-correlation matrix, given by:

$$R_{hh} = \mathrm{E}\,[hh^H] \qquad (9)$$

σ_n^2 represents the noise variance,
and F = $[W_K^{nk}]$ is the discrete Fourier transform (DFT) matrix.

$$[W_K^{nk}] = \frac{1}{\sqrt{K}}^{-j2\pi\frac{nk}{K}} \qquad (10)$$

4.2 Blind Channel Estimation

Blind channel estimation technique involves using the statistical properties of the received signal to estimate the channel without any reference to the pilot symbols. This obviously has the advantage of incurring no overhead by virtue of the training symbols. It however, often requires a large number of received symbols to extract statistical properties of the channel for proper functioning [1]. Thus, the estimation process is rather complex and the performance is not as good as training-based channel estimation [6].

4.2.1 The Bussang Algorithm

The Bussang algorithm is a blind channel estimation technique that comprises a filter, zero-memory nonlinear estimator and a adaptive algorithm. The algorithm is applicable for single-carrier transmission but not OFDM systems because a nonlinear estimation of the received signal in an OFDM system is almost impractical [1], [13], [15].

4.2.2 The Subspace-based Channel Estimation

This channel estimation technique is well-suited for OFDM systems [17], [18] [19]. It uses the second-order statistical properties and orthogonal properties of the received signal. As the received signal space consists of the signal subspace and the noise subspace, the properties of the noise subspace that are orthogonal to the signal subspace are used to estimate the channel [1]. The task of accurately separating the signal subspace from the noise subspace involves a highly complex computation and a large number of received signals are needed to accurately estimate the statistical properties of the received signals[1].

4.3 Semi-blind Channel Estimation

The semi-blind channel estimation technique combines the blind channel estimation and training-based channel estimation techniques, and can be implemented where information on the input signals i.e. transmit and training symbols are not available; the estimation proceeds using 'unknown' factors that affect the channel characteristics [1]. When compared to the training-based method, based on bit error-rate (BER) and mean square error (MSE), and using the same set of training symbols, semi-blind channel estimation provides less BER and MSE than the training-based approach [12]. Semi-blind channel estimation technique is however, very inefficient in a time-varying channel like a high-mobility situation [1].

4.3.1 The Expectation-maximization (EM) Algorithm-based Channel Estimation

The EM Algorithm is a semi-blind channel estimation technique that obtains the maximum-likelihood estimate of a channel using iteration process. It is implemented where the only available information that determine the output are incomplete or unknown e.g. in signal processing, ergonomics and genetics [1]. For some D OFDM symbols with constellation size, C, the probability density function for "complete" or "known" data is given by the log-likelihood function [1]:

$$\log f(\mathbf{Y},\mathbf{X}|H) = \sum_{d=1}^{D} \log\left\{\frac{1}{C} f(Y^d|H,X^d)\right\} \quad (11)$$

Estimation of the channel, H is achieved in the EM algorithm by iteratively increasing the likelihood function in the above equation. The iteration process proceeds in two steps: the expectation and the maximization steps. The former entails taking the expectation over X, subject to Y, and using the latest H estimate i.e. $H^{(P)}$ to compute the expected value of the log-likelihood function of H as [1]:

$$Q(H|H^{(p)}) \triangleq E_X\left\{f(\mathbf{Y},\mathbf{X}|H)|Y,H^{(p)}\right\}$$

$$= \sum_{i=1}^{C}\sum_{d=1}^{D} \log\left\{\frac{1}{C} f(Y^d|H,X_i)\right\} \frac{f(Y^d|H^{(p)},X_i)}{C f(Y^d|H^{(p)})} \quad (12)$$

The latter involves determining the next latest estimate of H i.e. $H^{(P+1)}$ by maximizing the equation above over all possible values of H [1].

$$H^{(p+1)} = \arg\max_{H} Q(H|H^{(p)})$$

$$= \left[\sum_{i=1}^{C}\sum_{d=1}^{D} |X_i|^2 \frac{f(Y^d|H^{(p)},X_i)}{C f(Y^d|H^{(p)})}\right]^{-1} \times \left[\sum_{i=1}^{C}\sum_{d=1}^{D} |Y^d X_i^*| \frac{f(Y^d|H^{(p)},X_i)}{C f(Y^d|H^{(p)})}\right] \quad (13)$$

where:

$$f(Y|H,X) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{1}{2\sigma^2}|Y-H\cdot X|^2\right) \quad (14),$$

$$f(Y|H) = \sum_{i=1}^{C} \frac{1}{C}\cdot\frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{1}{2\sigma^2}|Y-H\cdot X_i|^2\right) \quad (15)$$

When deployed in MIMO-OFDM systems, the EM algorithm estimates each transmit-receive antenna pair separately to obtain their respective CSI for coherent signal detection [1]. In a practical situation, where a mobile user is situated at a cell boundary, the user will receive signals from adjacent base stations, and experiences inter-cell interference; EM algorithm can exploit the additional received data to improve the performance of channel estimation so long as the channel is time invariant over the symbol period [1]. To reduce their computational complexity, Lee K.I et al proposed a Decision-Directed EM estimation technique that combines the EM algorithm with the decision-directed channel estimation. This was achievable in slow time-varying channels [20].

The EM algorithm however, is computationally complex, and when used to estimate channels in MIMO-OFDM systems, becomes increasingly complex with the multiple (increased) transmitted signals. They are also not well-suited for estimating time-varying channels [1].

Other channel estimation techniques are the decision-directed channel estimation; adaptive channel estimation and few others.

In the decision-directed channel estimation, once the channel has been estimated by the pilot symbols, then it uses the previous channel estimates in the say, (n-1)th OFDM symbol period to estimate the nth channel. This technique achieves very high data rates but at the cost of additional processing delays [7].

The adaptive channel estimator is very suitable for estimating a rapidly time-varying channel. It uses adaptive algorithms to adapt or change its parameters as it gains more and current information about the dynamic environment [8].

4.4 Comparison of Channel Estimation Techniques

TABLE 1

Comparison of Channel Estimation Techniques

Channel Estimation Technique	Pilot Overhead Incurred	Bandwidth Efficiency	Computat-Ional Complexity	Mean Square Error & Bit Error Rate	Suitability For Mobile Time-Varying Channels
Training-based	High	Poor	Low	High	Very good
Blind	None	Very Good	High	Low	Good
Semi-blind	Low	Good	Medium	Average	Poor

5 CONCLUSION

Channel estimation plays a very crucial role in the performance of MIMO-OFDM wireless communication systems - especially, in a high-mobility environment where the channel characteristics vary highly with time and becomes unstable. Hence, the deployment of an efficient channel estimation algorithm that will reduce the effects of channel variations, and allow appreciable signal detection and recovery at the receiver is important. Such algorithm may involve the use of instantaneous or statistical information of the channel or a combination of both, or even some novel channel estimation algorithm/techniques to obtain perfect or near-perfect channel state information (for coherent signal detection). The semi-blind channel estimation effectively combine the advantages of the pilot-based and blind estimation techniques to achieve optimum performance in MIMO-OFDM wireless systems.

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