

称号及び氏名 博士（工学） Dongguo Li

学位授与の日付 2007年3月31日

論文名 「Studies on Channel Estimation and Equalization for OFDM Systems in Mobile Environment (OFDM 移動通信システムを対象としたチャネル推定および等化技術に関する研究)」

論文審査委員 主査 山下 勝己  
副査 勝山 豊  
副査 大橋 正治

#### 論文要旨

Since Guglielmo Marconi sent and received his first electromagnetic signal across the sea in 1896, the world has entered into a wireless communication age. Today, wireless communication has become an indispensable element in our daily lives, and been essentially fully digitalized by the end of last century. In contrast to the poor information-carrying ability of the initial telecommunication system, the state-of-the-art digital communication technology makes huge amount of information. For instance, multimedia information can be transferred instantaneously. In the past decade, requirements for speed and reliability of information transmission have increased very quickly and certainly they will keep growing in the coming future. This ever increasing demand is the major driving force for the development of the communication technology, which pushes researchers unceasingly to discover new methods to overcome various technical obstacles in the communication systems.

Orthogonal frequency division multiplexing (OFDM) is such a technology that allows a large amount of data to be transmitted quickly and reliably, with a minimum of loss or interference. Comparing with the traditional communication method of limited capability and weakness in noise, OFDM is considered today to be a reliable choice for high bit-rate transmissions and is now widely adopted and tested in many communication systems. Specifically, OFDM has been chosen for digital audio and video broadcasting, for high-speed modems over twisted pairs as

xDSL, and, more recently, for broadband wireless local area networks (HIPERLAN/2, IEEE802.11a/g and UWB standards).

OFDM enables very simple equalization of frequency-selective finite impulse response (FIR) channels through the implementation of the inverse fast Fourier transform (IFFT) and the insertion of a guard interval (GI) of length which should be larger than the channel memory at the transmitter. Presented in each block of transmitted symbols, the GI consists of redundant symbols circularly replicated from the samples after IFFT implementing. At the receiver end, GI is discarded to avoid inter symbol interference (ISI), and the fast Fourier transform (FFT) of each truncated block is then implemented. A combination of IFFT and GI at the transmitter with the FFT at the receiver converts the frequency-selective channel into parallel flat-faded subchannels, each corresponding to a different subcarrier. Unless they are zero, the flat fading can be simply compensated by dividing each subchannel output with the channel attenuation at the corresponding subcarrier. Since the channel is usually unknown, the succeeding research is carried out with the assistance of pilot sequence, or called training sequence, which is known at the receiver and is transmitted before the information-bearing signal sequence being sent. It has to be noted that an equivalent problem to channel equalization is channel identification, since pilot sequence can be used to identify the channel first, then the equalizer is designed in accordance with the obtained channel information. Obviously, channel estimator based equalization approaches have the disadvantage of excessive elaboration and costly hardware requirement.

The conventional pilot-aided channel estimation and equalization method can solve many problems in static communication, however, in a ubiquitous society, people request contact with others through communication network at any time and anywhere. That means, under any conditions, the communication system should ensure the fluency of data transmission. In this thesis, we focus our interesting on channel estimation and equalization in mobile wireless OFDM systems. Different from the stationary communication system, the Doppler shift, especially in high speed mobile communication systems, becomes the main barrier in improving the system transmission performance. As the channel is fading in time domain, each subcarrier of the multicarrier signal is convoluted by the channel. Thus the bandwidth of each subcarrier is expanded and its power leaks on others. That is the so called inter carrier interference (ICI) which deteriorates the system performance significantly. Hence the information of the time-varying channel is necessary.

With the aim to eliminate the ICI, time domain-pilot is thought as a simple and realizable method as it can compensate the time fading straightly. On the other hand, the pilot-free method can equalize the channel without bandwidth loss, which presents its advantage especially in high speed bit rate systems. MIMO has recently emerged as one of the most significant technical breakthroughs in modern communications as it is expected to solve the bottleneck of traffic capacity and enhance anti-interference feature of the system. Along these lines, the main components of this thesis and the major results of the presented work can be summarized as follows:

Chapter 1 introduces the history of the channel estimation and equalization research, and provides an overview of the thesis.

Chapter 2 introduces the frame form of OFDM signal and establishes a mathematical model for a baseband OFDM system, which is the foundation of this thesis.

Chapter 3 analyzes the multipath channel feature in mobile communication circumstance. It can be cognized that the frequency spectrum of the channel fading envelope (CFE) is limited in the maximum Doppler shift and each of the paths is independent. That means each path of the CFE is continuous curve in time domain and the fading degree is in direct proportion to the velocity of the receiver. Thus the CFE can be expanded in Taylor series. Utilizing the mathematical model obtained in chapter 2, the channel parameters, i.e. the coefficients of the Taylor series, in time domain, is used to establish a system transfer relation with the transmitted and received data which expressed in frequency domain. Therefore adjusting the value of received data after hard decision, the channel estimates can be changed. This conclusion will help us to obtain the optimal channel estimates in later.

Chapter 4 proposes serious fashions in channel estimation and introduces a method to decrease the computation complexity. Since the CFE is continuous curve, if any samples on the CFE are known, the whole CFE can be reconstructed so long as those samples meet the Nyquist theory.

Therefore, we designed a new pilot symbol which inserts between the data symbols in time domain (TDP) with suitability density. The pilot symbol is set in the place which keeps the distance with the data symbol to ensure that it not be polluted. Through this form, the channel impulse response (CIR) can be obtained corresponding pilot time slot. Here, we introduce the linear fashion, spline function and low pass filter (LPF) method to approximate the truth channel with different velocities to tradeoff the complexity and the estimation accurately. Comparing with

the traditional block-type pilot or comb-type pilot technique, our proposed method has eliminated the ICI completely, which obtain an accepted performance whatever in the long path delay channel or high velocity receive, while the traditional method almost cannot work at all. However, even the proposed TDP method is more flexible and accurate in time varying channel estimates than the conventional pilot-aided technique, the system transmission efficiency is restricted with the length of the channel time delay.

Chapter 5 proposes 2 sorts of novel channel estimation and equalization methods to acquire more efficacy of the bandwidth. One of the methods is founded on the relation expression of the channel parameters in time domain and the transmitted&received data in frequency domain. Assuming the channel during the pre-symbol period was estimated perfectly, the linear extrapolation was applied to estimate the transmitted data roughly first. The error was amended through the hard decision. The recovered data from the decision was reused in new estimates of the channel parameter. Thus the new recovered data was obtained once more. Applying the algorithm iteratively as this flow, the optimal result could be obtained through comparing covariance of the input and output in the decision. The other pilot-free method utilized the GI, which would be cut and thrown before FFT in traditional receiver, to obtain the CIR during both ends of the symbol. This time, we just inserted a GI length zero sequence between every two symbols in time domain. Thus the conjunctive symbol would not overlap each other. We also assumed the channel during the pre-symbol period was estimated perfectly. Applying the linear extrapolation of the pre-symbol to recover the samples of the GI in time domain, the estimated samples could be used in estimating the channel which corresponding with the end GI samples. Thereby, the whole channel could be reconstructed by linear interpolation simply. Comparing with the pilot-aided technique and the blind equalizer, our proposed method obtained more effective bandwidth and fewer computational amount with simpler system structure and practicable. Although the proposed GI based method is not as good as the iterative algorithm method because the former one needed zero padded which accounts for the bandwidth loss, it was more practical due to its lighter computational burden. It can be found that the proposed methods are applicable even when the CFE is varying during one OFDM symbol without the bandwidth-consuming pilot. Moreover, the statistics of the transmitted data and channel is not necessary, which simplifies the system construct.

Chapter 6 applies the TDP method in MIMO-OFDM system to acquire higher bandwidth efficiency introduced. For the MIMO-OFDM system in doubly-selective channels, we propose a stagger time domain pilot structure, which eliminates the cross interference in the pilot section and makes the CFE estimation methods in OFDM system be applied into MIMO-OFDM system straightforwardly. Then, the obtained channel estimates are transferred into frequency domain to help the cascade equalizer to suppress the ICI and cross interference, thus the transmitted data can be recovered. In contrast to the conventional MMSE equalizer, which deals with the huge system transfer matrix directly, we propose a downsizing MMSE equalizer, which first separates the MIMO-OFDM system into several subsystems by small transfer matrix with optimal size, then set up a MMSE estimator for each subsystem and finally combines their results as the equalizer output. Since the proposed equalizer takes the advantage of underlying structure of original system transfer matrix sufficiently, it can achieve the satisfied approximation to the conventional MMSE equalizer with significantly reduced computational complexity. Our simulation results demonstrate the validity of the proposed stagger pilot structure and the downsizing MMSE equalizer.

Chapter 7 makes a conclusion for the research and gives some topics for future research.

#### 審査結果の要旨

本論文は、OFDM (Orthogonal Frequency Division Multiplexing) 移動通信システムにおいて、高速移動時に生じる搬送波間干渉を軽減するための新たなチャネル推定および等化技術を提案したものである。得られた主な結果は、以下の項目に要約できる。

- (1) OFDM シンボル内で変化するチャネル特性を推定するため、時間領域で挿入する新たなパイロット構造を提案すると共に、同パイロット信号を用いてチャネル特性を推定し得る LPF 法およびスプライン関数法を提案している。提案手法では、実際のチャネル特性に近いチャネル推定値が得られ、また、良好なビット誤り率特性が得られている。
- (2) 伝送効率を高めるため、パイロット信号を利用しないブラインド等化技術が報告されている。しかし、同手法は、大きな処理遅延が生じるため実用化には不向きである。提案手法では、初期シンボルでのチャネル特性のみを利用したセミブラインド手法を提案し、若干の処理遅延により良好な伝送特性が得られることを、計算機シミュレーションにより検証している。

- (3) 送受信側に複数のアンテナ素子を設けた MIMO-OFDM ( Multi-Input Multi-Output OFDM ) 通信システムを対象モデルに、シンボル内で変化するチャネル特性を推定するための新たなパイロット構造を提案すると共に、チャネル特性を導出する際に必要とする、計算量の軽減化を図ることができる新たに近似手法を提案している。

以上の諸成果は、次世代移動通信システムに求められる高速移動領域での実用化に向けた基礎的な知見や基盤を与えるものであり、この分野の技術の発展に貢献するところ大である。また、申請者が自立して研究活動を行うに十分な能力と学識を有することを証したものである。学位論文審査委員会は、本論文の審査ならびに最終試験の結果から、博士(工学)の学位を授与することを適当と認める。