CHANNEL ESTIMATION AND INTERCARRIER INTERFERENCE REDUCTION FOR ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING IN FAST TIME-VARYING CHANNELS

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I declare that this thesis entitled "*Channel Estimation and Intercarrier Interference Reduction for Orthogonal Frequency Division Multiplexing in Fast Time-Varying Channels*" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....
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Date : February 2013

To my beloved family, especially my wife and my children.

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ABSTRACT

Orthogonal frequency division multiplexing (OFDM) is an attractive technique for wireless communications. However, in high-mobility scenarios, the time-variation of mobile radio channels over an OFDM symbol leads to a loss of subcarrier orthogonality, and resulting in intercarrier interference (ICI) which severely degrade the OFDM performance and introduce an irreducible error floor. In this thesis, a novel scheme is proposed to estimate the channel in OFDM systems. The key idea is to distort the data of OFDM symbol in frequency domain, such that an impulse signal is used to estimate the channel, in time domain at pilot samples. Then, a piecewise linear model is used to estimate the channel variation over an OFDM symbol. Simulation results show the proposed scheme can achieve a substantial improvement in the bit error rate (BER) performance of OFDM compared with Zhao, Chang, and Mostofi schemes. Moreover, the error floor significantly is reduced, particularly, at low signal to noise ratio (SNR) regions compared with the previously mentioned schemes. Recently, Mostofi proposed a channel estimation scheme to mitigate ICI in OFDM system by approximating the channel variation over OFDM symbol by piecewise linear model. But, for high Doppler spread the channel over OFDM symbol exhibit high order variation. Thus, a generalisation of Mostofi scheme is proposed, where a general polynomial model is used to estimate the channel. Simulation results show that at a high Doppler spread, the generalised scheme show remarkable improvement in the BER performance of OFDM over the Mostofi scheme. Additionally, in this thesis, a modified of "better than" raised cosine pulse-shape is proposed to improve the performance of OFDM in the presence of frequency offset. Simulation results demonstrate that the proposed pulse outperforms raised-cosine pulse and "better than" raised cosine pulse in terms of BER performance, ICI reduction and SIR enhancement.

ABSTRAK

Pemultipleksan pembahagian frekuensi ortogon (OFDM) adalah satu teknik yang menarik untuk komunikasi wayarles. Walau bagaimanapun, dalam senario-senario mobiliti tinggi, perubahan masa saluran radio mudah alih lebih simbol OFDM membawa kepada kerugian keortogonan subpembawa, serta menghasilkan gangguan antara pembawa (ICI) yang boleh mengakibatkan kemerosotan prestasi OFDM secara serius dan mewujudkan lantai ralat yang tidak boleh direndahkan lagi. Dalam tesis ini, satu skim baru telah diperkenalkan untuk menganggar perubahan saluran dalam sistem OFDM. Idea utamanya adalah untuk mengganggu data simbol OFDM pada frekuensi domain melalui penggunaan isyarat denyut bagi menganggar saluran dalam domain masa pada isyarat perintis. Kemudian, model linear sesecebis digunakan untuk menganggar variasi saluran atas simbol OFDM. Keputusan simulasi menunjukkan bahawa skim yang dicadangkan boleh mencapai peningkatan besar dalam prestasi kadar bit kesalahan (BER) berkaitan OFDM dibanding dengan skim-skim yang diperkenalkan oleh Zhao, Chang, dan Mostofi. Tambahan pula, ia adalah signifikan bagi merendahkan lantai ralat terutamanya pada bahagian isyarat kepada nisbah bunyi (SNR) rendah dibandingkan dengan skim terdahulu. Baru-baru ini, Mostofi telah memperkenalkan skim penganggaran saluran untuk mengurangkan ICI dalam sistem OFDM dengan mengganggarkan variasi saluran atas simbol OFDM mengunakan model linear. Walau bagaimanapun, bagi saluran dengan sebaran Doppler yang tinggi atas satu simbol OFDM, hasil keputusan menunjukkan variasi tertib yang agak tinggi. Maka, satu skim Mostofi umum dicadangkan, di mana model polinomial am digunakan untuk menganggar saluran. Hasil simulasi menunjukkan bahawa pada sebaran Doppler yang tinggi, skim umum yang dicadangkan menunjukkan peningkatan memberansangkan dari segi prestasi BER OFDM berbanding skim asal yang dicadangkan Mostofi. Disamping itu, dalam tesis ini, dedenyut berbentuk “lebih baik” kosinus berbangkit yang diubahsuai telah dicadangkan untuk meningkatkan prestasi OFDM dalam keadaan ofset frekuensi. Keputusan simulasi menunjukkan bahawa denyut yang dicadangkan mengatasi prestasi BER, menunjukkan peningkatan SIR dan pengurangan kuasa ICI denyut kosinus berbangkit dan denyut “lebih baik” kosinus berbangkit.

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LIST OF ABBREVIATIONS

3G - Third Generation
3GPP - 3rd Generation Partnership Project
4G - Fourth Generation
AWGN - Additive White Gaussian Noise
BER - Bit Error Rate
BEM - Basis Expansion Modeling
BPSK - Binary Phase Shift Keying
BTRC - “better than” Raised-Cosine Pulse
CFO - Carrier Frequency Offset
CIR - Carrier Interference Ratio
CIR - Channel Impulse Response
CM - Cyclic Mean
CSI - Channel State Information
dB - Decibel
D/A - Digital-to-Analog (Converter)
DAB - Digital Audio Broadcasting
DFT - Discrete Fourier Transform
DVB - Digital Video Broadcasting
FDM - Frequency Division Multiplexing
FEQ - Frequency-Domain Equalizer
FFT - Fast Fourier Transform
ICI - Intercarrier Interference
IDFT - Inverse Discrete Fourier Transform
IFFT - Inverse Fast Fourier Transform
IMT - International Mobile Telecommunication
ISI - Inter Symbol Interference

ISP	-	Improved Sinc Power
ITU-R	-	International Telecommunications Union – Radio
LM	-	Linear model
LMMSE	-	Linear Minimum Mean Square Estimation
LPF	-	Low-Pass Filter
LS	-	Least Squares
LTE	-	Long-Term Evolution
MMSE	-	Minimum Mean Square Error
MSE	-	Mean-Square Error
OFDM	-	Orthogonal Frequency Division Multiplexing
OFDMA	-	Orthogonal Frequency Division Multiple Access
PAPR	-	Peak-to-Average Power Ratio
P-BEM	-	Polynomial BEM
PDP	-	Power Delay Profile
PLM	-	Piecewise Linear Model
PSD	-	Power Spectral Density
PSK	-	Phase-Shift Keying
QAM	-	Quadrature Amplitude Modulation
QPSK	-	Quadrature Phase Shift Keying
RC	-	Raised-Cosine Pulse
Rect	-	Rectangular Pulse
RF	-	Radio Frequency
Rx	-	Receiver Side
SER	-	Symbol Error Rate
SCM	-	Single-Carrier Modulation
SC	-	Self-Cancellation
SIR	-	Signal to Interference Ratio
SNR	-	Signal to Noise Ratio
SOCW	-	Second Order Continuity Window
SP	-	Sinc Power Pulse
TFT-OFDM	-	Time-Frequency Training OFDM
Tx	-	Transmitter Side
WiMAX	-	Worldwide Interoperability for Microwave Access
WSSUS	-	Wide-Sense Stationary Uncorrelated Scattering Process

LIST OF SYMBOLS

$\mathbf{0}$	-	All-Zero Matrix
$\mathbf{1}$	-	All-One Matrix
E_b	-	Energy per Transmitted Bit
E_S	-	Energy per Transmitted Symbol
$exp(\cdot)$	-	The Exponential Operation
$erfc(.)$	-	The complementary error function
f_d	-	Maximum Doppler frequency
f_{Doppler}	-	Doppler Shift
B_D	-	Doppler Spread of the Channel
B_S	-	Bandwidth of the Baseband Signal
$E\{.\}$	-	Expectation of a Random Variable
f_c	-	Carrier frequency
f_k	-	Subcarrier Frequency Associated with the *k*-th Subcarrier
$\boldsymbol{F}^H$	-	*N*-point IFFT matrix
J_0	-	Modified Bessel Function with Zero Order
$h_{l,n}$	-	The *l*-th Time-Domain Channel Path at *n*-th Sample
$H_{k,m}$	-	The Frequency-Domain Channel Coefficient
$\boldsymbol{h}_{var}$	-	Time-Domain Channel Matrix
$\boldsymbol{H}_{var}$	-	Frequency-Domain Channel Matrix
I	-	Identity Matrix
L	-	Length of Channel Impulse Response
N	-	FFT Size
N_f	-	Periods of Pilot Symbols in Frequency Domain
N_g	-	Length of Added Cyclic-Prefix
N_t	-	Periods of Pilot Symbols in Time Domain
T_c	-	Coherence Time

T_g - Guard Interval
T_s - Duration of the Transmitted Baseband Signal
T_{sa} - Sampling Interval
T_u - OFDM Symbol Duration without Cyclic Prefix
T_{win} - Windowing Interval
$\tau_{\max}$ - Multipath Maximum Delay Spread
v - Maximum Channel Delay in samples
var{.} - Variance of a Random Variable
w_n - The n-th Sample of Additive Gaussian Noise
$\mathbf{W}$ - Frequency Domain Gaussian Noise Vector
$\mathbf{X}$ - Frequency Domain Transmitted Signal Vector
$\mathbf{Y}$ - Frequency Domain Recieved Signal Vector
X_k - Data Symbol Transmitted on the k-th Subcarrier
Y_k - Data Symbol Received on the k-th Subcarrier
ε - Normalized Doppler Frequency
α - Roll-off Factor
σ_w^2 - Gaussian Noise Variance
Δf - Subcarrier Spacing
δf - Frequency Offset
$(\cdot)^H$ - Hermitian (Conjugate) Transpose of a matrix
$(\cdot)^T$ - The Transposition Operation
$(\cdot)^\#$ - Pseudo-Invers of a Matrix, defined by $[(.)^H(.)]^{-1}(.)$
$(\cdot)^*$ - Complex Conjugate
$(\cdot)^{-1}$ - Matrix Inverse
$\lfloor . \rfloor$ - The largest Integer That Is Not Greater than Its Argument
$\otimes$ - The Kronecher Product Operator of Two Matrices

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Future mobile communication systems should be able to support high data rate, high mobility, and high quality of services and applications such as multimedia streaming, wireless Internet access and high rate Internet surfing, and real-time video.

In general, it is hard to realize a communication system that supports both high data rate transmission and high mobility of transmitters and/or receivers. Since, high data rate and high mobility result in frequency- and time-selective, i.e., doubly selective fading channels.

Orthogonal Frequency Division Multiplexing (OFDM) is one of the most attractive multicarrier transmission techniques for future wireless systems because of its spectral efficiency, robustness against frequency-selective channels, and high tolerance to multipath channels, such as combating intersymbol interference (ISI). However, a major drawback of OFDM is its vulnerability to the time-variation of the channel, which is a direct effect of high mobility. A typical scenario of time-varying channel is a receiver mounted on high-speed trains, cars, or airplanes, where the channel becomes a rapid time-varying one. In high mobility environments, large Doppler spread results in rapid channel variation in time that gives rise to a loss of subcarrier orthogonality, resulting in intercarrier interference (ICI) and performance degradation. ICI is a crosstalk between subcarriers, which describes the interference from other subcarriers into the subcarrier of interest.

1.2 Background

A multicarrier system in general and OFDM system, in particular, is much more sensitive to frequency offset than a single-carrier system. OFDM is highly susceptible to frequency synchronization errors, due to the narrow spacing between subcarriers. Such errors are generated by phase noise, sampling frequency, residual carrier frequency offset (CFO), and Doppler spread (B_D).

Firstly, random phase noise is occurred due to the imperfection of the transmitter and receiver local oscillators (Zou *et al.*, 2007). Secondly, sampling frequency offset is occurred due to the mismatch in sampling clock of the transmitter and receiver local oscillators. Thirdly, residual frequency offset is defined as the residual value of CFO after compensation due to an imperfect carrier synchronization algorithm at the receiver. While, Doppler spread is generated as a result of a user's mobility and a relative motion of objects in the multipath channel. Hence, a transmitted signal follows different paths before arriving at the receiver, where each path has different frequency offset.

Since Doppler spread comprises a set of frequency offsets, it becomes difficult to get rid these frequency offsets by using frequency synchronization algorithms, where they developed to track a single-carrier frequency at a time. Therefore, the effect of Doppler spread on the performance of OFDM system became a serious problem.

In OFDM, a high rate serial data is converted (mapped) into a low rate parallel data (that are transmitted simultaneously), which are used to modulate the orthogonal subcarriers, at which the OFDM symbol duration is increased. However, thereby increasing the symbol duration the OFDM system became more vulnerable to time selectivity of the channel. That significantly destroys the orthogonality between subcarriers, leading to power leakage between subcarriers, known as ICI.

The ICI is proportional to the received signal power and cannot be overcome by increasing the signal power. It is also proportional to Doppler spread plus the square of the residual carrier offset and inversely to the subcarrier spacing (Chang, 2004; Das *et al.*, 2007). In additional, ICI results in an irreducible error floor, which means the bit error rate (BER) curve flattens out in the high signal-to-noise ratio (SNR) region. ICI is proportional to the symbol duration and Doppler frequency (Robertson and Kaiser, 1999; Zhang, 2004). Therefore, channel estimation and ICI mitigation of the frequency offset is most critical in OFDM receivers (Edfors *et al.*, 1996a).

1.3 Problem Statement

One of the most attractive features of OFDM is its high spectral efficiency due to precisely overlapping orthogonal subcarriers. However, one of the major drawbacks of such a modulation technique is its very high sensitivity to Doppler spread, which is the major factor of its performance degradation in a wireless multipath channel. The Doppler spread is induced due to a mobile environment, where the multipath channel is time variant.

In high-mobility scenarios, large Doppler spread results in rapid channel variation in time within one OFDM symbol period. Such a variation gives rise to a loss of subcarrier orthogonality, resulting in ICI and causing an irreducible error floor, which cannot overcome by increasing the signal power. As the mobility increases, the ICI increases and the performance of the OFDM system degrades severely.

Even many researchers proposed different techniques to mitigate ICI in OFDM due to Doppler spread, the achievements which have been done, do not significantly eliminate the ICI or significantly lower the error floor level, particularly at high Doppler spread. The ICI still make a limitation on the data rate and on the mobile speed, where the error floor still at high level (Hijazi and Ros, 2009; Jun-Han and Jong-Tae, 2010; Jun *et al.*, 2012).

1.4 Research Objectives

The main objective of this study is to support reliable communication (transmission) over rapidly time-varying multipath channels by developing a mitigation technique that is capable to combat or reduce the ICI effects imposed on the OFDM system due to Doppler spread.

More specifically:

i) To investigate the effects of ICI problem due to frequency offset in OFDM system.
ii) To investigate the performance of OFDM system over different propagation channels, including additive white Gaussian channel (AWGN) in the present of frequency offset, slow time-varying channel, and fast time-varying channel.
iii) To develop a robust ICI mitigation technique for OFDM system in fast varying channel.
iv) To investigate the performance of OFDM system with existing ICI mitigation techniques, such as channel estimation techniques, self-cancelation techniques, and pulse-shaping over time-varying channel under high mobility condition.

1.5 Scope of Work

Future wireless communication systems demand to support high data rate with high mobility (100 Mbps for mobile application at speed 350 km/h). Therefore, OFDM as a strong candidate for future wireless communication systems must be able to satisfy these requirements. However, in high mobility scenarios, the time-variation of the channel sets a limit to the transmission rate of OFDM and degrades its performance severely. Usually the rate of channel variation in time identifies by Doppler frequency, which is proportional to carrier frequency and vehicle velocity. Therefore, the ICI caused by the time-variation of channel is usually depends on the OFDM symbol duration T_u, and Doppler frequency f_d.

However, in Fast fading channel conditions, the channel variation during one OFDM symbol period exhibit high order variations, which can be approximated by a general polynomial of time (Chen and Kobayashi, 2002; Yeh and Chen, 2004).

On the other hand, OFDM is not a strong candidate for uplink data transmission, where it has a very high peak-to-average power ratio (PAPR), that requires an expensive power amplifier with high linearity, which drains the battery faster (Wang *et al.*, 2009).

Other impairments like phase noise, sampling frequency offset, residual frequency offset, and frequency offset due to synchronization errors between transmitter and receiver are beyond the scope of this thesis.

1.6 Significance of Research Work

OFDM system is highly attractive candidate modulation system for future wireless communications, which demand to support high data rate transmission at high mobility and high carrier frequency (Huang and Wu, 2006). One of the main impairments of OFDM is its sensitivity to time-variation of mobile radio channels due to Doppler spread, that is, introduces ICI which severely degrades the performance of OFDM (Robertson and Kaiser, 2000; Xuerong and Lijun, 2003). Therefore, it is very important to develop a mitigation technique to overcome or to reduce the effects of Doppler spread in OFDM systems.

1.7 Thesis Contributions

i) A novel scheme to estimate the variation of the channel in OFDM systems is proposed in this thesis. The main idea is to distort the data of OFDM symbol in the frequency domain, such that zeros are generated in the time domain. Then, these zeros are gathered to use it as a guard interval for an impulse signal. After that, an impulse signal is inserted as a pilot sample, which is used to estimate the channel at the pilot signal in OFDM symbol. Finally, a piecewise linear model (PLM) is used to estimate the channel variation over an OFDM symbol.

ii) Recently, Mostofi has been proposed a channel estimation scheme to mitigate ICI by approximating the channel variation over an OFDM symbol by a PLM. However, for high Doppler spread the channel over an OFDM symbol exhibit high order variation. In this thesis, a generalized scheme is proposed, where the channel variation over an OFDM symbol is approximated by a general polynomial model with more time domain samples instead of PLM with few time domain samples.

iii) A modified of “better than” raised cosine pulse-shape is proposed in this thesis to improve the performance of OFDM in the presence of frequency offset. The performance of the modified pulse is investigated and compared with a number of Nyquist pulses.

1.8 Thesis Organization

This thesis consists of six chapters. Chapter 1 serves as an introduction to the thesis. It covers topics such as problem statement, research objectives, scope of the work and its significance.

Chapter 2 gives a literature review of OFDM principles, and its advantages and disadvantages. Moreover, the ICI analysis and performance of OFDM in

AWGN channel with frequency offset impairment and in fast time-varying channel are given in this chapter. Then, the mobile radio propagation, modeling, characteristics of the mobile radio channel is described. Lastly, approaches for reducing ICI and recently related work are given.

Chapter 3 describes how the research carried on. The flow chart diagram of this research is presented. Then, the three proposed ICI mitigation techniques are described, the data-distortion based channel estimation scheme, the generalized of Mostofi channel estimation scheme and the modified pulse-shaping function. Additionally, the OFDM parameters, the simulation tools used in this research are given in this chapter.

Chapter 4 describes the mathematical and system models of the three proposed ICI mitigation techniques, the data-distortion based channel estimation scheme, the generalized of Mostofi scheme and the modified pulse-shaping function.

Chapter 5 discusses the simulation and the mathematical results of the three proposed ICI mitigation techniques. Where the performance of the data-distortion based channel estimation scheme, the generalized of Mostofi scheme and the modified pulse-shaping function are compared with other ICI mitigation techniques.

Finally, Chapter 6 gives a summary of the work that has been done. Also, contributions, and conclusions of the thesis, along with suggestions for future work are given in this chapter.

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