



Ain Shams University
Faculty of Engineering
Electronics and Communications Engineering Department

Performance Evaluation of OFDM System Subjected to Frequency Offsets in General Fading Channels

A Thesis
Submitted in partial fulfillment for the requirements
Of the degree of Master of Science in Electrical Engineering
(Electronics and Communications Engineering)

Submitted by

Muhammad Ismail Muhammad

B.Sc. in Electrical Engineering
Electronics and Communications Engineering Dept.
Ain Shams University, 2007

Supervised by

Prof. Dr. Salwa Hussein El Ramly

Dr. Abdel Aziz M. Al Bassiouni

Electronics and Communications Engineering Dept.
Ain Shams University
Faculty of Engineering

Cairo 2009



Ain Shams University
Faculty of Engineering
Electronics and Communications Engineering Department

Judgment Committee

Name : Muhammad Ismail Muhammad
Thesis : Performance Evaluation of OFDM System Subjected
to Frequency Offset in General Fading Channels
Degree : Master of Science in Electrical Engineering

Name, Title and Affiliation

Signature

Prof. Dr. Emad Al-Deen Khalaf Al-Hussaini
Electronics and Communications Engineering Dept.
Faculty of Engineering, Cairo University

Prof. Dr. Mohamed Marzok Ibrahim
Electronics and Communications Engineering Dept.
Faculty of Engineering, Ain Shams University

Prof. Dr. Salwa Hussein El Ramly
Electronics and Communications Engineering Dept.
Faculty of Engineering, Ain Shams University

Dr. Abdel Aziz Mahmoud Al Bassiouni
Business Development Director
Teletech, Egypt.

Date: / /



**Ain Shams University
Faculty of Engineering
Electronics and Communications Engineering Department**

Statement

This dissertation is submitted to Ain Shams University in partial fulfillment of the degree of Master of Science in Electrical Engineering (Electronics and Communications Engineering).

The work included in this thesis was carried out by the author at the department of Electronics and Communications Engineering, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

No part of this thesis was submitted for a degree or qualifications at any other university or institution.

Name : Muhammad Ismail Muhammad
Signature :
Date :



Ain Shams University
Faculty of Engineering
Electronics and Communications Engineering Department

Curriculum Vitae

Name of the researcher : Muhammad Ismail
Muhammad

Date of Birth : 20 – 11 – 1985

Place of Birth : Cairo

Nationality : Egyptian

First University Degree : B.Sc. in Electrical
Engineering
(Electronics and
Communications)
Faculty of Engineering,
Ain Shams University.

Certification Date : July 2007

Name : Muhammad Ismail Muhammad

Signature :

Date :

Thesis Abstract

Muhammad Ismail Muhammad, "Performance Evaluation of OFDM System Subjected to Frequency Offset in General Fading Channels", Master of Science dissertation, Ain Shams University, 2009

Orthogonal frequency division multiplexing (OFDM) is a multi-carrier transmission technique that has been recently recognized as an excellent method for high speed bi-directional wireless communications. It provides a good performance against the most severe multi-path propagation conditions.

OFDM is sensitive to frequency synchronization errors, which results in inter-carrier interference (ICI) and degrades system's performance.

This research work aims to investigate the combined effects of carrier frequency offset (CFO) and fading conditions on system's performance. Nakagami-m fading channel is used as a multi-path propagation model for its ability to emulate fading channels whose conditions are either less severe than, the same as, or more severe than the Rayleigh fading model.

Closed form expressions of BER/SER for OFDM system subjected to CFO over Nakagami-m fading channel are developed. The impact of CFO and severe fading conditions on performance is revealed.

CFO mitigation techniques are introduced to improve system's performance when subjected to CFO. Closed form BER/SER expressions are developed for polynomial cancelation coding (PCC)-OFDM and the ameliorated ICI cancelation OFDM when subjected to CFO in Nakagami-m fading channel, and system improvement is emphasized.

To combat the severe fading conditions, diversity reception is applied. Space diversity reception is employed at the receiver and maximum ratio combining (MRC) is used. The effect of correlation among diversity branches is considered. Expressions of BER/SER for PCC-OFDM subjected to CFO with diversity reception over Nakagami-m fading channel are developed, and in some cases expressions result in a closed form.

Acknowledgement

All praise and glory go to Almighty Allah who gave me the strength and patience to carry out this work.

First and foremost gratitude is to the esteemed university, Ain Shams University, and its faculty of engineering members for their high quality education they supplied me with through my undergraduate and postgraduate studies.

My deep appreciation and gratitude go to my thesis advisors professor Salwa El Ramly, and Dr. Abdel Aziz Al Bassiouni for their constant guidance, support and valuable time they supplied me with through my work in this thesis.

Many thanks and appreciations go to my dear parents, sister and friends for their prayers and encouragement they supplied me with through my two years of postgraduate studies. Special thanks to my dear friend Moustafa Kohail for helping me with the presentation.

CONTENTS

LIST OF FIGURES.....	xi
LIST OF SYMBOLS.....	xiv
LIST OF ABBREVIATIONS.....	xv
CHAPTER 1 - INTRODUCTION.....	1
1.1. The Need for OFDM.....	1
1.2. Evolution towards OFDM.....	2
1.2.1. Single Carrier Modulation System.....	2
1.2.2. Multi Carrier Transmission 'FDM'.....	2
1.2.3. Orthogonal Frequency Division Multiplexing.....	3
1.3. Problem Statement and Thesis Contributions.....	4
1.4. Thesis IEEE Publications.....	5
1.5. Thesis Overview.....	5
CHAPTER 2 – OFDM AND COMMUNICATION CHANNEL FUNDAMENTALS.....	6
2.1. Introduction.....	6
2.2. OFDM Fundamentals.....	6
2.2.1. SCs Orthogonality.....	6
2.2.1.1. How to Achieve SCs Orthogonality.....	6
2.2.1.2. Orthogonality in Time Domain.....	7
2.2.1.3. Orthogonality in Frequency Domain.....	7
2.2.2. OFDM Signal.....	8
2.2.3. OFDM System Implementation.....	9
2.2.3.1. Historical View.....	9
2.2.3.2. System Modification – The Introduction of IFFT/FFT.....	10
2.3. Communication Channel Fundamentals.....	11
2.3.1. Fading Phenomena.....	12
2.3.2. Types of Communication Channels Based on Fading.....	12
2.3.3. Narrow Band Channels (Flat Fading).....	13
2.3.4. Wide Band Channels.....	20
2.4. OFDM in Communication Channels.....	20
2.4.1. OFDM Attractive Features.....	20
2.4.2. OFDM System Structure.....	23

2.4.3. OFDM Drawbacks.....	25
2.5. Conclusion.....	27

CHAPTER 3 - CFO PROBLEM IN OFDM SYSTEMS.....28

3.1. Introduction.....	28
3.2. CFO Problem Formulation.....	28
3.3. CFO Mitigation Techniques.....	31
3.3.1. CFO Estimation Techniques.....	32
3.3.1.1. Data Aided Techniques.....	33
3.3.1.2. Non Data Aided Techniques.....	34
3.3.1.3. Blind Techniques.....	35
3.3.2. CFO Reduction Techniques.....	37
3.3.2.1. Windowing Techniques.....	37
3.3.2.2. ICI Cancellation Techniques.....	38
3.3.3. CFO Mitigation Techniques Conclusion.....	43
3.4. Performance Evaluation in Absence of Fading.....	44
3.5. Performance Evaluation in General Fading Channel – The MGF Approach.....	46
3.6. Conclusion.....	49

CHAPTER 4 – PERFORMANCE EVALUATION IN GENERAL FADING CHANNEL.....50

4.1. Introduction.....	50
4.2. Exact Analysis of Conventional OFDM System Subjected to CFO over Nakagami-m Fading Channel.....	50
4.2.1. BPSK Modulation.....	50
4.2.1.1. Conditional Probability of Error.....	51
4.2.1.2. The Average Probability of Error over Nakagami-m Fading Channel	57
4.2.2. QPSK Modulation.....	66
4.2.2.1. Conditional Probability of Error.....	67
4.2.2.2. The Average Probability of Error over Nakagami-m Fading Channel	71
4.3. Exact Analysis of PCC- OFDM System Subjected to CFO over Nakagami-m Fading Channel.....	81
4.3.1. The Sufficient Statistics Used in the Decision Rule of PCC-OFDM Receiver.....	81
4.3.2. BPSK Modulation.....	82
4.3.2.1. Conditional Probability of Error.....	82

4.3.2.2. The Average Probability of Error over Nakagami-m Fading Channel	88
4.3.3. QPSK Modulation.....	95
4.3.3.1. Conditional Probability of Error.....	95
4.3.3.2. The Average Probability of Error over Nakagami-m Fading Channel	100
4.4. Exact Analysis of Ameliorated ICI Cancellation OFDM System Subjected to CFO over Nakagami-m Fading Channel.....	107
4.4.1. The Sufficient Statistics Used in the Decision Rule of Ameliorated ICI Cancellation OFDM Receiver.....	107
4.4.2. BPSK Modulation.....	109
4.4.2.1. Conditional Probability of Error.....	109
4.4.2.2. The Average Probability of Error over Nakagami-m Fading Channel	112
4.4.3. QPSK Modulation.....	115
4.4.3.1. Conditional Probability of Error.....	115
4.4.3.2. The Average Probability of Error over Nakagami-m Fading Channel	118
4.5. Conclusion.....	122

CHAPTER 5 - DIVERSITY RECEPTION OF OFDM SYSTEMS.....123

5.1. Introduction.....	123
5.2. Introduction to Diversity Reception.....	123
5.2.1. The Diversity Concept.....	123
5.2.2. The Diversity Techniques.....	124
5.2.2.1. Space Diversity.....	124
5.2.2.2. Frequency Diversity.....	124
5.2.2.3. Time Diversity.....	125
5.2.3. The Diversity Combining Methods.....	125
5.2.3.1. Pure Combining Methods.....	125
5.2.3.2. Hybrid Combining Methods.....	127
5.2.4. The Impact of Fading Correlation.....	128
5.2.4.1. Dual Correlation Model.....	128
5.2.4.2. Constant Correlation Model.....	129
5.2.4.3. Exponential Correlation Model.....	129
5.3. Diversity Reception of PCC-OFDM.....	130
5.3.1. Diversity Reception of PCC-OFDM Subjected to CFO with Uncorrelated MRC Branches.....	130
5.3.1.1. BPSK Modulation.....	131
5.3.1.2. QPSK Modulation.....	137

5.3.2. Diversity Reception of PCC-OFDM Subjected to CFO with Correlated MRC Branches.....	142
5.3.1.1. BPSK Modulation.....	143
5.3.1.2. QPSK Modulation.....	147
5.4. Conclusion.....	150
 CHAPTER 6 – THESIS CONCLUSION & FUTURE WORK.....	 151
6.1. Thesis Conclusion.....	151
6.2. Thesis Contributions.....	152
6.3. Future Work.....	153
 REFERENCES.....	 154

LIST OF FIGURES

Fig 1.1 FDM and OFDM SCs.....	3
Fig 2.1 SCs in Time Domain.....	7
Fig 2.2 OFDM Spectrum.....	8
Fig 2.3 Simple OFDM Structure.....	9
Fig 2.4 FFT/IFFT in OFDM System.....	11
Fig 2.5 Multipath Fading Environment.....	12
Fig 2.6 Signal Time Dispersion.....	14
Fig 2.7 ISI.....	15
Fig 2.8 Nakagami PDF for $\Omega = 1$ and different m	19
Fig 2.9 Cyclic Prefix in OFDM.....	22
Fig 2.10 OFDM Block Diagram.....	24
Fig 3.1 CFO Problem in OFDM.....	28
Fig 3.2 The OFDM Symbol.....	34
Fig 3.3 The Spectrum of OFDM Symbol around NSC.....	36
Fig 3.4 Cost Function $J(\omega)$ with Multiple Minima.....	36
Fig 3.5 ICI Coefficient, $N = 64$	40
Fig 3.6 Higher Order Cancelation.....	41
Fig 4.1 OFDM-BPSK; CFO = 0.1; BER vs. E_b/N_0	55
Fig 4.2 OFDM-BPSK; Different CFO; BER vs. E_b/N_0	56
Fig 4.3 OFDM-BPSK; $E_b/N_0=10\text{dB}$; BER vs. CFO.....	57
Fig 4.4 OFDM-BPSK; CFO = 0.1; BER vs. E_b/N_0 ; Different m ..	62
Fig 4.5 OFDM-BPSK; Different CFO; BER vs. E_b/N_0 ; Half Gaussian Channel.....	63
Fig 4.6 OFDM-BPSK; $E_b/N_0=10\text{dB}$; BER vs. CFO; Half Gaussian Channel.....	64
Fig 4.7 OFDM-BPSK; Different CFO; BER vs. E_b/N_0 ; Rayleigh Channel.....	65
Fig 4.8 OFDM-BPSK; $E_b/N_0=10\text{dB}$; BER vs. CFO; Rayleigh Channel.....	66
Fig 4.9 OFDM-QPSK; Different CFO; SER vs. E_b/N_0	70
Fig 4.10 OFDM-QPSK; $E_b/N_0=10\text{dB}$; SER vs. CFO.....	71
Fig 4.11 OFDM-QPSK; CFO = 0.1; SER vs. E_b/N_0 ; Different m	76
Fig 4.12 OFDM-QPSK; Different CFO; SER vs. E_b/N_0 ; Half Gaussian Channel.....	77

Fig 4.13 OFDM-QPSK; $E_b/N_0=10\text{dB}$; SER vs. CFO; Half Gaussian Channel.....	78
Fig 4.14 OFDM-QPSK; Different CFO; SER vs. E_b/N_0 ; Rayleigh Channel.....	79
Fig 4.15 OFDM-QPSK; $E_b/N_0=10\text{dB}$; SER vs. CFO; Rayleigh Channel.....	80
Fig 4.16 OFDM BPSK with and without Cancellation – BER vs. at Different CFO.....	86
Fig 4.17 OFDM BPSK with and without Cancellation – BER vs. CFO at $E_b/N_0 = 10\text{dB}$	87
Fig 4.18 OFDM BPSK with and without Cancellation – BER vs. E_b/N_0 ; CFO = 0.1; Different m	91
Fig 4.19 OFDM BPSK with and without Cancellation – BER vs. E_b/N_0 at Different CFO; Half Gaussian Channel	92
Fig 4.20 OFDM BPSK with and without Cancellation – BER vs. CFO at $E_b/N_0=10\text{dB}$; Half Gaussian Channel.....	93
Fig 4.21 OFDM BPSK with and without Cancellation – BER vs. E_b/N_0 at Different CFO; Rayleigh Channel.....	94
Fig 4.22 OFDM BPSK with and without Cancellation – BER vs. CFO at $E_b/N_0=10\text{dB}$; Rayleigh Channel.....	95
Fig 4.23 OFDM QPSK with and without Cancellation – SER vs. E_b/N_0 at Different CFO.....	99
Fig 4.24 OFDM QPSK with and without Cancellation – SER vs. CFO at $E_b/N_0 = 10\text{dB}$	100
Fig 4.25 OFDM QPSK with and without Cancellation – SER vs. E_b/N_0 ; CFO = 0.1; Different m	103
Fig 4.26 OFDM QPSK with and without Cancellation – SER vs. E_b/N_0 at Different CFO; Half Gaussian Channel	104
Fig 4.27 OFDM QPSK with and without Cancellation – SER vs. CFO at $E_b/N_0 = 10\text{dB}$; Half Gaussian Channel.....	105
Fig 4.28 OFDM QPSK with and without Cancellation – SER vs. E_b/N_0 at Different CFO; Rayleigh Channel.....	106
Fig 4.29 OFDM QPSK with and without Cancellation – SER vs. CFO at $E_b/N_0 = 10\text{dB}$; Rayleigh Channel.....	107
Fig 4.30 OFDM BPSK with and without Cancellation – BER vs. E_b/N_0 at CFO = 0.1; Ameliorated & PCC-OFDM.....	111
Fig 4.31 OFDM BPSK with and without Cancellation – BER vs. E_b/N_0 at CFO = 0.1; Different m ; Ameliorated & PCC-OFDM...	114
Fig 4.32 OFDM QPSK with and without Cancellation – SER vs. E_b/N_0 at CFO = 0.1; Ameliorated & PCC-OFDM.....	117

Fig 4.33 OFDM QPSK with and without Cancellation – SER vs. E_b/N_0 at CFO = 0.1; Different m ; Ameliorated & PCC-OFDM.....	121
--	-----

Fig 5.1 PCC-OFDM BPSK; BER vs. E_b/N_0 at CFO = 0.1; Dual Diversity; Distinct Fading & Distinct E_b/N_0	134
Fig 5.2 PCC-OFDM BPSK; BER vs. E_b/N_0 at CFO = 0.1; L Branch Diversity; Half Channel.....	135
Fig 5.3 PCC-OFDM BPSK; BER vs. E_b/N_0 at CFO = 0.1; L Branch Diversity; Rayleigh Channel.....	136
Fig 5.4 PCC-OFDM QPSK; SER vs. E_b/N_0 at CFO = 0.1; Dual Diversity; Distinct Fading & Distinct E_b/N_0	140
Fig 5.5 PCC-OFDM QPSK; SER vs. E_b/N_0 at CFO = 0.1; L Branch Diversity; Half Channel.....	141
Fig 5.6 PCC-OFDM QPSK; SER vs. E_b/N_0 at CFO = 0.1; L Branch Diversity; Rayleigh Channel.....	142
Fig 5.7 PCC-OFDM BPSK; BER vs. E_b/N_0 at CFO = 0.1; L Branch Diversity; Correlated Half Guassian; Channel.....	145
Fig 5.8 PCC-OFDM BPSK; BER vs. E_b/N_0 at CFO = 0.1; L Branch Diversity; Correlated Rayleigh Channel.....	146
Fig 5.9 PCC-OFDM QPSK; SER vs. E_b/N_0 at CFO = 0.1; L Branch Diversity; Correlated Half Guassian; Channel.....	148
Fig 5.10 PCC-OFDM QPSK; SER vs. E_b/N_0 at CFO = 0.1; L Branch Diversity; Correlated; Rayleigh Channel.....	149

LIST OF SYMBOLS

N	Number of SCs
τ_{RMS}	RMS Delay Spread
f_d	Doppler Frequency Shift
m	Nakagami-m Parameter
ε	Normalized CFO
$S(i)$	ICI Coefficient
P_{be}	Bit Error Probability
P_{se}	Symbol Error Probability
γ	E_b/N_o (Bit Energy to Noise Spectral Density)
$M_\gamma(x)$	Moment Generating Function of γ
$Q(x)$	Gaussian Q Function
$n(k)$	Additive White Gaussian Noise
$\phi(\omega)$	Characteristic Function
σ^2	Noise Variance
$\Gamma(x)$	Gamma Function
${}_2F_1(a,b;c;d)$	Guasshypergeometric Function
L	Number of Diversity Branches
ρ	Correlation Coefficient

LIST OF ABBREVIATIONS

ADSL	Asymmetric Digital Subscriber Line
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
CFO	Carrier Frequency Offset
CHF	Characteristic Function
DAB	Digital Audio Broadcasting
DFT	Discrete Fourier Transform
DVB	Digital Video Broadcasting
EGC	Equal Gain Combining
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
GA	Gaussian Approximation
GSC	Generalized Switched Combining
ICI	Inter-Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Inter-Symbol Interference
LOCZ	Location of Channel Zeros
LOS	Line of Sight
MGF	Moment Generating Function
MLE	Maximum Likelihood Estimation
MRC	Maximum Ratio Combining
NSCs	Null Subcarriers
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak to Average Power Ratio
PCC	Polynomial Cancellation Coding
Pdf	Probability Density Function
PSAM	Pilot Symbol Assisted Modulation
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RMS	Root Mean Square
SCs	Subcarriers
SCC	Symmetric Cancellation Coding
SER	Symbol Error Rate
SINR	Signal to Interference plus Noise Ratio