

**PERFORMANCE IMPROVEMENT IN ORTHOGONAL
FREQUENCY DIVISION MULTIPLEXING BASED
OPTICAL COMMUNICATION SYSTEMS**

A THESIS

submitted by

PRAVINDRA KUMAR

*for the award of the degree
of*

DOCTOR OF PHILOSOPHY



**SCHOOL OF COMPUTING AND ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY MANDI, H.P.**

DECEMBER 2016

ॐ सरस्वती मया दृष्ट्वा, वीणा पुस्तक धारणीम् ।
हंस वाहिनी समायुक्ता मां विद्या दान करोतु मे ॐ ॥

Dedicated to

My Parents, Brother

Who taught me the value of study and perseverance ethic and have given me endless
support

My Wife and Daughter

Who encouraged me in the odds during Ph.D work

Declaration

I hereby declare that the entire work embodied in this thesis is the result of investigations carried out by me in the **School of Computing and Electrical Engineering**, Indian Institute of Technology Mandi, under the supervision of **Dr. Satyajit Thakor**, and that it has not been submitted elsewhere for any degree or diploma. In keeping with the general practice, due acknowledgments have been made wherever the work described is based on finding of other investigators.

Kamand, 175005

Pravindra Kumar

Date:

THESIS CERTIFICATE

This is to certify that the thesis titled **PERFORMANCE IMPROVEMENT IN ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING BASED OPTICAL COMMUNICATION SYSTEMS**, submitted by **Pravindra Kumar**, to the Indian Institute of Technology Mandi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a bonafide record of the research work done by him under my supervision. The content of this thesis, in full or in parts, have not been submitted to any other institute or university for the award of any degree or diploma.

Kamand, 175005

Date:

Dr. Satyajit Thakor

(Supervisor)

Acknowledgments

This Thesis work is the outcome of the combinational work of me, my computer and the efforts of remarkable individuals who I wish to acknowledge. First and foremost, I owe my deepest gratitude to my supervisor Dr. Satyajit Thakor and former supervisor Prof. Anand Srivastava. Their guidance, support and patience have made this research possible. They always been there not to spoon-feed but to guide and encourage in just the right amounts. I really thank him for patiently reviewing several drafts of my papers and thesis to improve those.

I would like to extend my sincere gratitude to all the members of doctoral committee that of Dr. Anil K. Sao, Dr. Samar Agnihotri, Dr. Arnav Bhavsar, and Dr. Syed Abbas for their valuable inputs in my research work. Let me take the opportunity to thank Prof. Ramesh Oruganti, and Prof. B. D. Chaudhary for their several supports academically as well as administratively. I want to vote my gratitude to Prof. Sukumar Bhattacharya, Dr. Bharat Singh Rajpurohit, Dr. Satinder Kumar Sharma, and Dr. Arti Kashyap for their valuable discussions regarding research. I also would like to thank Prof. Timothy A Gonsalves, the director of IIT Mandi for giving all the facilities for research.

I want to express my gratitude to Srimanta Mandal and Pankaj Narula for being valuable roommates during my stay in IIT Mandi, and for keeping a positive atmosphere around me during gloomy time. I want to appreciate Pulkit Sharma and Vinayak Abrol for all their supports, for keeping me cheering through their sense of humor, and for keeping a good research environment in Lab.

Above everything, I owe my gratitude to my *Father, Mother, Brother*, and other family members for their endless supports, care, blessings in my entire journey. I can never thank them enough in words. Importantly, I would like to thank my wife Preety Verma and daughter Vaanya Verma for being their with me in my ups and downs, for keeping me motivated, and taking care of me in the odds during my Ph.D work in IIT Mandi. Thank you all your support in all forms. Last but not the least, there are persons not mentioned here but, deserve my token of appreciation, I want to thank them all.

Pravindra Kumar

ABSTRACT

Keywords: *Passive optical network (PON), free space optical (FSO) link, OFDM, CDM-OFDM, square root module (SRM) device, three time slotted analog network coding (3T-ANC), transmit frequency diversity, receive space diversity, minimum Euclidean distance (MED), MeijerG-function.*

Orthogonal frequency division multiplexing (OFDM) technique gives improved performance in passive optical network (PON) system and free space optical (FSO) communication link due to its dispersion compensation capability, high bandwidth efficiency, flexibility on both multiple services and dynamic bandwidth allocation (DBA), narrow-band interference, and increased tolerance capacity against fading. The increasing demand for high bandwidth or more capacity and world wide connectivity for data and other multimedia rich application from private and business users, can be fulfilled by OFDM based PON/FSO (OFDM-PON/FSO) system at every scale, from core to metro, access networks and in-building or in-house networks. The light wave system, with prodigious bandwidth of several hundred terahertz (THz) in the infrared light wave region, can provide a staggering capacity of 100 Tb/s and beyond. Thus, the optical communication systems have become indispensable as the backbone of the modern-day information infrastructure. The PON features a point-to-multipoint (P2MP) architecture to provide broadband access that becomes the most popular solution for fiber-to-the-home (FTTH) deployment among operators. PON-based FTTH has been widely deployed ever since 2004 and is defined in ITU-T G.984 series. FSO communication link with its high data rate, capacity same as of optical fiber and secure communication over an unlicensed spectrum have become a promising technique where the installation of optical fiber is not possible. This thesis focuses on the performance improvement in terms of bit-error-rate (BER), receiver sensitivity, link length, spectral efficiency, transmission capacity or maximum achievable rate. In particular, our focus is to obtain lower complexity optical OFDM architecture in PON and FSO transmission system.

To increase the number of customers or access distance in PON/FSO link and to reduce the number central offices (COs) in any PON system, high optical power budget is required. To improve the optical power budget, we propose to use three dimensional OFDM (3-D OFDM) technique that increase minimum Euclidean distance (MED) and performance improvement as a result. In 3-D OFDM technique, 3-D signal mapper and 2-D IFFT is used. The performance can further be improved using forward error correction (FEC) codes.

To provide the security on physical layer in OFDM-PON and OFDM-FSO link, reduced optical beating interference (OBI) among different optical network units (ONUs) in upstream direction in PON system, performance improvement in presence of multi-user interference (MUI), reduced required electrical bandwidth, and reduced inter-carrier interference (ICI), we propose to use PON and FSO architecture based on combination of OFDM and CDMA known as CDM-OFDM that gives enhanced optical power budget and reduced OBI among different ONUs because of high cross-correlation among different spreading codes. This architecture provides security on physical layer due to individual user defined spreading codes. In spite of using CDM, there is a significant saving in bandwidth thereby decreasing computational complexity in digital signal processing.

To compensate the problem for non-linear behaviour of chromatic dispersion in PON system, non-linear behaviour of temporal dispersion in FSO link, due to square-law characteristic of photo-detector (PD), we propose to use square root module (SRM) device, placed after PD, in the receiver architecture. The SRM device does the inverse function of the square-law characteristic performed at the PD diode and helps to improve the performance in terms of chromatic dispersion tolerance in PON system, temporal dispersion in FSO link.

Finally, we address the non-line-of-sight (NLoS) situation of FSO link in which communication breakdown between two users. To make possible the information exchange, a relay can be used but at the cost of less achievable rate or throughput and increased electrical power. In this work, we propose to use three time slotted analog network coding (3T-ANC) scheme that gives improved error performance and increased throughput. The 3T-ANC scheme has no optical-to-electrical and electrical-to-optical conversion interface at the relay resulting into reduced cost, complexity, and less required electrical power.

Contents

Abstract	i
List of Tables	ix
List of Figures	xi
Glossary	xv
List of Notations and Symbols	xix
1 Introduction	1
1.1 Problem Statement	3
1.1.1 Security Risk on Physical Layer	3
1.1.2 Optical Beating Interference (OBI)	3
1.1.3 Optical Power Budget	4
1.1.4 High Electrical Bandwidth	4
1.1.5 Non Linearity due to Square Law Behavior of Photo-detector Diode	4
1.1.6 Non Line-of-Sight (NLoS) Situation	5
1.2 Motivation	5
1.3 Objective of This Thesis	6
1.4 Scope and Contributions	7
1.4.1 Scope	7
1.4.2 Contributions	7
1.5 Organization of The Thesis	8
2 Fundamental Theory and Literature Review	11
2.1 Optical Fiber Communication System and its Evolution	11
2.1.1 Spectrum For Optical Communication	11
2.1.2 Block Diagram of Optical Fiber Communication (OFC) System	13
2.1.3 Evolution of OFC System	13
2.1.4 Optical Fiber	15
2.1.4.1 Types of Fiber	16
2.1.5 Signal Distortion (Degradation) Due to Transmission Over Optical Fiber	17
2.1.5.1 Signal Attenuation (Loss)	17
2.1.5.2 Linear Distortion	18
2.1.5.3 Non-Linear Distortion	19
2.1.6 Optical Transmitter	19

2.1.6.1	Optical Source	20
2.1.6.2	Optical Modulator	20
2.1.7	Optical Receiver	21
2.1.8	Optical Amplifier	21
2.2	Passive Optical Network (PON) and its Evolution	23
2.2.1	Passive Optical Network (PON) and its Different Architectures	23
2.2.2	Next Generation PONs	24
2.2.3	Various PON Architecture	25
2.2.3.1	TDM-PON	25
2.2.3.2	WDM-PON	25
2.2.3.3	OCDM-PON	26
2.2.3.4	OFDM-PON	26
2.3	Free Space Optical (FSO) Communication system	27
2.3.1	Block Diagram of FSO Communication System	29
2.3.1.1	Optical Transmitter	30
2.3.1.2	Optical Receiver	30
2.3.1.3	Atmospheric Channel	30
2.3.2	Challenges with FSO Link	31
2.3.2.1	Atmospheric Turbulence	31
2.3.2.2	Weather Condition	32
2.3.2.3	Pointing Acquisition and Tracking (PAT)	32
2.3.2.4	Blocking Due to Object	32
2.3.2.5	Source of Noise	32
2.3.2.6	Eye Safety	33
2.3.2.7	Beam Divergence (Beam Spreading)/Geometrical Losses	33
2.3.2.8	Imperfect Lenses	33
2.3.2.9	Multi-User Interference (MUI)	34
2.3.2.10	Non-Line of Sight (NLoS) Situation	34
2.4	Orthogonal Frequency Division Multiplexing (OFDM) Technique	34
2.4.1	Historical View of Optical OFDM	34
2.4.2	Basics of OFDM	35
2.4.2.1	Definition of OFDM	35
2.4.2.2	Mathematical Framework	35
2.4.2.3	Minimum Frequency Separation For Orthogonality Condition	39
2.4.2.4	Cyclic Prefix (CP) in OFDM	39
2.4.3	Types of Optical OFDM	41
2.4.3.1	Direct Detection Optical OFDM (DDO-OFDM)	41
2.4.3.2	Coherent Optical OFDM (CO-OFDM)	41
2.4.4	Properties of OFDM	42
2.4.4.1	Symbol and Bit Rate	42
2.4.4.2	Bandwidth of OFDM Signal	43
2.4.4.3	Bandwidth Efficiency	44
2.4.5	Advantages of Optical OFDM	44
2.4.6	Problem with Optical OFDM	45
2.4.6.1	Peak-to-Average Power Ratio (PAPR)	46
2.4.6.2	Frequency Offset and Phase Noise Sensitivity:	49

3 OFDM-PON System and its Performance Improvement with Three Dimensional (3-

D) Mapping	51
3.1 Introduction	51
3.2 Problem Statement, Motivation, Related work, and Contributions	52
3.2.1 Problem Statement	52
3.2.2 Motivation	53
3.2.3 Related Work	53
3.2.4 Contributions	54
3.3 Architecture of CO-OFDM-PON System	54
3.3.1 The CO-OFDM Transmitter Architecture	55
3.3.2 The CO-OFDM Receiver Architecture	57
3.3.2.1 Reduced Required Bandwidth	60
3.3.3 Bandwidth Efficiency	60
3.4 Three-dimensional (3-D) Optical OFDM Communication System	61
3.4.1 Principle of 3-D OFDM System	63
3.4.2 Minimum Euclidean Distance (MED) for 3-D Constellation	64
3.5 Impairments and Noise Sources	65
3.5.1 Effect of Cyclic Prefix, Unused Sub-carriers and Pilot Sub-carriers on Error Performance	65
3.5.1.1 Effect of Cyclic Prefix on E_s/N_0	66
3.5.1.2 Effect of Unused Sub-carriers on E_s/N_0	68
3.5.1.3 Effect of Pilot Sub-carriers on E_s/N_0	68
3.5.2 Impairments Due to Frequency Offset and Phase Noise Sensitivity	68
3.5.2.1 Frequency Offset	68
3.5.2.2 Phase Noise	70
3.5.3 Noise Sources	70
3.6 Signal-to-Noise Ratio (SNR), Bit-Error Rate (BER), and Error Vector Magnitude (EVM) Formulation	73
3.6.1 Signal-to-Noise Ratio (SNR)	73
3.6.2 Bit-Error Rate (BER)	74
3.6.3 Error Vector Magnitude (EVM)	80
3.7 Forward Error Correction (FEC) Code	82
3.7.1 Uncoded and Coded Transmission System:	83
3.7.2 Convolutional Coding	84
3.7.3 Viterbi Decoding	87
3.7.3.1 BER using Hard Decision Decoding	87
3.7.3.2 BER using Soft Decision Decoding	87
3.8 Results and Discussion	87
3.9 Chapter Summary	97
4 OBI Reduction and Optical Power Budget Enhancement in OFDM-PON System using Spreading Code in Electrical Domain	99
4.1 Introduction	99
4.2 Problem Statement, Motivation, Related work, and Contribution	100
4.2.1 Problem Statement	100
4.2.2 Motivation	101
4.2.3 Related work	101
4.2.4 Contributions	102
4.3 Architecture of DDO-OFDM-PON System	102

4.3.1	The Transmitter Architecture	102
4.3.2	The Receiver Architecture	103
4.4	Frequency Diversity based Architecture of OFDM-PON System	104
4.4.1	Frequency Diversity based Transmitter Architecture for DDO-OFDM-PON and CO-OFDM-PON System	104
4.4.2	Frequency Diversity based Receiver Architecture for DDO-OFDM-PON and CO-OFDM-PON System	105
4.5	Architecture of CDM-OFDM-PON System	105
4.5.1	The Transmitter Architecture for CDM-OFDM-PON System	108
4.5.2	The Receiver Architecture for CDM-OFDM-PON System	110
4.5.3	Reduced Required Bandwidth	111
4.6	Optical Beating Interference (OBI) Noise	112
4.7	Signal-to-Noise Ratio (SNR), and Bit-Error Rate (BER)	114
4.7.1	Signal-to-Noise Ratio (SNR)	114
4.7.2	Bit-Error Rate (BER)	114
4.8	Results and Discussion	115
4.9	Chapter Summary	122
5	OFDM-FSO Multi-user Communication System with Combined Transmit Frequency Diversity and Receive Space Diversity	123
5.1	Introduction	123
5.2	Problem Statement, Motivation, Related Work, and Contributions	124
5.2.1	Problem Statement	124
5.2.2	Motivation	125
5.2.3	Related Work	125
5.2.4	Contributions	126
5.3	Architecture of Conventional OFDM-FSO Link	126
5.3.1	The Transmitter Architecture	126
5.3.2	The Receiver Architecture	127
5.3.2.1	Reduced Required Bandwidth	129
5.4	Architecture of CDM-OFDM-FSO Link	129
5.4.1	The Transmitter Architecture	129
5.4.2	The Receiver Architecture	130
5.4.2.1	Reduced Required Bandwidth	131
5.5	FSO Channel Model and its Characteristic	131
5.5.1	Absorption and Scattering in FSO Channel	132
5.5.2	FSO Channel Model	134
5.6	Signal-to-Interference-Noise Ratio (SINR) and Bit-Error Rate (BER) Formulation	135
5.6.1	Signal-to-Interference-Noise Ratio (SINR)	135
5.6.2	Bit-Error Rate (BER)	137
5.6.2.1	For TDM case	137
5.6.2.2	For OFDM case	138
5.7	Results and Discussion	139
5.8	Chapter Summary	143
6	OFDM based PON and FSO System with Square Root Module (SRM) Device	145
6.1	Introduction	145
6.2	Problem Statement, Motivation, Related Work, and Contributions	146

6.2.1	Problem Statement	146
6.2.2	Motivation	146
6.2.3	Related work	146
6.2.4	Contributions	147
6.3	Chromatic Dispersion (CD)	147
6.4	Temporal Dispersion	148
6.5	Square Root Module (SRM) Device	149
6.6	Results and Discussion	151
6.7	Chapter Summary	154
7	Analog Network Coding Based NLoS-OFDM-FSO System	155
7.1	Introduction	155
7.2	Problem Statement, Motivation, Related Work, and Contributions	156
7.2.1	Problem Statement	156
7.2.2	Motivation	156
7.2.3	Related Work	156
7.2.4	Contributions	157
7.3	Network Coding Schemes	158
7.3.1	Digital Network Coding (DNC) Scheme	159
7.3.2	Physical Layer Network Coding (PLNC) Scheme	160
7.3.3	Analog Network Coding (ANC) Scheme	161
7.3.4	3 Time Slotted ANC (3T-ANC) Scheme	161
7.4	Mathematical Model for ANC and 3-T ANC	162
7.5	Achievable Rate and Bit-Error Rate(BER)	164
7.5.1	Achievable Rate	164
7.5.2	Bit-Error-Rate (BER) Formulation	167
7.6	Results and Discussion	168
7.7	Chapter Summary	171
8	Conclusions and Future Work	173
8.1	Conclusions	173
8.2	Future Work	175
8.2.1	Light Fidelity (Li-Fi)	175
8.2.2	Rateless Codes for FSO Link	176
8.2.3	Hybrid FSO/RF Link	177
8.2.4	Cooperative FSO (C-FSO) Communication	177
A		179
A.1	PAPR for single sinusoidal and for complex sinusoidal signal	179
A.1.1	PAPR for single sinusoidal signal	179
A.1.2	PAPR for complex sinusoidal signal	179
A.2	Probability that at least one branch has $\text{PAPR} > \zeta_p$	180
A.3	MeijerG-function	181
	References	183
	List of Publications	207