UNIVERSITI PUTRA MALAYSIA

ANALYTICAL SIMULATION OF NON-LINEARITY EFFECTS COMPENSATION IN ALL-OPTICAL ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING SYSTEMS

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By

ALI AZARNIA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of
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ANALYTICAL SIMULATION OF NON-LINEARITY EFFECTS COMPENSATION IN ALL-OPTICAL ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING SYSTEMS

By

ALI AZARNIA

August 2020

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All-Optical Orthogonal Frequency Division Multiplexing (AO-OFDM) modulation technique has attracted significant attention of the optical communication community for the high speed transmission systems. This research investigates the effects of the fiber nonlinear impairments on the performance of the AO-OFDM transmission systems and proposes three AO-OFDM systems which have high tolerance against the nonlinear impairments. The first AO-OFDM system employs Differential Quadrature Phase Shift Keying (DQPSK), while the second and third systems employ m-array Quadrature Amplitude Modulation (m-QAM), and Non Return to Zero (NRZ) DQPSK, respectively.

Each proposed system employs 29 subcarriers which are generated by an Optical Frequency Comb Generator (OFCG). The generated signals are transmitted over the transmission link and received by the coherent receiver. The analytical model of each system is developed to investigate the effects of various parameters such as the transmission distance, number of fiber spans, fiber dispersion, number of subcarriers, and power of subcarrier on the Nonlinear Phase Noise (NLPN) which induced by the fiber nonlinearity effects. The impacts of the NLPN due to Four-Wave Mixing (FWM), Self-Phase Modulation (SPM), and Cross-Phase Modulation (XPM) on the performance of the proposed systems are also investigated. The proposed systems are numerically simulated at the symbol rate of 25 Gsymbol/s. The optical multi-carrier signals were generated, modulated, de-correlated, and detected by the VPI transmission maker software 9.0. The received signals were linked to Matlab software and processed by using the Digital Signal Processing (DSP) algorithm in order to compensate the effects of the nonlinear impairments and improve the performance of the transmission system. The digital processing of the detected signals and Bit Error Rate (BER) calculation are performed by using DSP algorithm in Matlab software. In order to quantify the effectiveness of the proposed techniques, three AO-OFDM systems are demonstrated numerically before and after employing the nonlinearity mitigation techniques. The total phase noise variances, BER, and Error Vector Magnitude (EVM) are investigated to explore

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the effectiveness of the proposed technique. The results show that after using the phase noise mitigation technique, the EVM and BER are decreased by 20% and 7%, respectively. In addition, by employing the proposed technique the total phase noise variance is reduced by 50%. The simulation results clearly indicate that the constellation diagrams of the proposed system become more squeezed around the ideal constellation and the received signals are closer to the ideal point compared with the original system. That means, after employing the proposed techniques, the received signals have higher tolerance towards the fiber nonlinear impairments as compared to the original system. The obtained results show the significant improvements on the transmission performance of the proposed system after employing the post-compensation DSP or Optical Phase Conjugation (OPC) module.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ANALISIS SIMULASI PAMPASAN KESAN KETAKLINEARAN DALAM SISTEM SEMUA OPTIK-PEMULTIPLEKSAN PEMBAHAGIAN FREKUENSI ORTOGON (AO-OFDM)

Oleh

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Teknik modulasi semua optik-pemultipleksan pembahagian frekuensi ortogon (AO-OFDM) telah menarik perhatian penting komuniti komunikasi optik untuk sistem penghantaran berkelajuan tinggi. Penyelidikan ini mengkaji kesan kemerosotan gentian tidak linear terhadap prestasi sistem penghantaran AO-OFDM dan mencadangkan tiga sistem AO-OFDM yang mempunyai toleransi yang tinggi terhadap kemerosotan tidak linear. Sistem AO-OFDM yang pertama menggunakan Kebezaan Kudratur Kekunci Anjakan Fasa (DQPSK), manakala sistem kedua dan ketiga menggunakan modulasi Kuadratur Amplitud Susunan (m-QAM), dan tidak kembali ke sifar (NRZ) DQPSK, masing-masing.

Setiap sistem yang dicadangkan menggunakan 29 sub-pembawa yang dihasilkan oleh satu Penjana Sisir Frekuensi Optik (OFCG). Isyarat yang dihasilkan dihantar melalui pautan penghantaran dan diterima oleh penerima koheren. Model analisis setiap sistem dibangunkan untuk mengkaji kesan pelbagai parameter seperti jarak penghantaran, bilangan jarak gentian, penyebaran gentian, bilangan sub-pembawa, dan kuasa sub-pembawa ke atas Hingar Fasa Tidak Linear (NLPN) yang disebabkan oleh kesan gentian tidak linear. Kesan NLPN disebabkan oleh Pencampuran Empat Gelombang (FWM), Modulasi Fasa Kendiri (SPM), dan Modulasi Fasa Silang (XPM) ke atas prestasi sistem yang dicadangkan juga disiasat. Sistem yang dicadangkan disimulasikan secara berangka pada kadar simbol 25 Gsimbol/s. Isyarat pelbagai-pembawa optik dijanakan, dimodulasi, de-korelasi, dan dikesan oleh perisian VPI transmission maker. Isyarat-isyarat yang diterima dihubungkan ke perisian Matlab dan diproses dengan menggunakan algoritma Pemprosesan Isyarat Digit (DSP) untuk mengimbangi kesan tidak linear dan meningkatkan prestasi sistem penghantaran. Pemprosesan digit isyarat yang dikesan dan pengiraan Kadar Ralat Bit (BER) dilakukan dengan menggunakan algoritma DSP dalam perisian Matlab. Untuk mengukur keberkesanan teknik yang dicadangkan, tiga sistem AO-OFDM ditunjukkan secara berangka sebelum dan selepas

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menggunakan teknik pengurangan tidak linear. Jumlah varians hingar fasa, BER dan Ralat Magnitud Vektor (EVM) disiasat untuk meneroka keberkesanan teknik yang dicadangkan. Keputusan menunjukkan bahawa selepas menggunakan teknik pengurangan hingar fasa, EVMs menurun sebanyak 20% dan BER menurun sebanyak 7%. Sebagai tambahan, varians kebisingan fasa tidak linear menurun sebanyak 50%. Hasil simulasi dengan jelas menunjukkan bahawa gambarajah gugusan sistem yang dicadangkan menjadi lebih tertumpu di sekitar gugusan unggul dan isyarat yang diterima lebih dekat ke titik unggul berbanding dengan sistem asal. Ini bermakna, selepas menggunakan teknik yang dicadangkan, isyarat yang diterima mempunyai toleransi yang lebih tinggi terhadap kemerosotan gentian tidak linear berbanding dengan sistem asal. Hasil yang diperolehi menunjukkan peningkatan yang ketara terhadap prestasi penghantaran sistem yang dicadangkan selepas menggunakan modul pasca-pampasan DSP atau konjugat fasa optik (OPC).

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ACE	Active Constellation Extension
ADC	Analog to Digital Converter
AO-OFDM	All-Optical Orthogonal Frequency Division Multiplexing
ASE	Amplified Spontaneous Emission
AWG	Array Waveguide Grating
AWGR	Arrayed-Waveguide Grating Routers
BER	Bit Error Rate
BLPF	Bessel Low Pass Filter
BPF	Band Pass Filter
CD	Chromatic Dispersion
CFO	Carrier Frequency Offset
CO-OFDM	Coherent Optical OFDM
CP	Cyclic Prefix
CS	Coherent Superposition
CW	Continuous Wave
DAC	Digital to Analog Converter
dB	Decibel
dBm	Decibel milliwatts
DBP	Digital-Back-Propagation
DCF	Dispersion Compensation Fiber
DCM	Dispersion Compensation Module
DD	Direct Detection
DFT	Discrete Fourier Transform

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DI	Delay Interferometer
DML	Directly Modulated Laser
DQPSK	Differential Quadrature Phase Shift Keying
DSP	Digital Signal processing
EAM	Electro-Absorption Modulator
EDFA	Erbium-Doped Fiber Amplifier
EVM	Error Vector Magnitude
FBG	Fiber Bragg Grating
FFT	Fast Fourier Transform
FSR	Free Spectral Range
FWM	Four Wave Mixing
GBPS	Giga Bit per Second
GHz	Giga Hertz
Gsymbol/s	Giga symbol per second
GVD	Group Velocity Dispersion
HNLF	Highly Non-Linear Fiber
ICI	Inter-Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IF	Intermediate Frequency
IFFT	Inverse Fast Fourier Transform
IM/DD	Intensity Modulation with Direct Detection
IM	Intensity Modulator
ISI	Inter-Symbol Interference
LO	Local Oscillator
LPF	Low Pass Filter

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MCM	Multi Carrier Modulator
M-PSK	M-array-Phase Shift Keying
M-QAMM-array	Quadrature Amplitude Modulation
MSSI	Mid-Span Spectral Inversion
MZI	Mach Zehnder Interferometer
MZM	Mach Zehnder Modulator
NLPN	Nonlinear Phase Noise
NLSE	Nonlinear Schrodinger Equation
NRZ	Non-Return-to-Zero
OBPF	Optical Band-Pass Filter
O-DQPSK	Optical-Differential Quadrature Phase Shift Keying
OFCG	Optical Frequency Comb Generator
OFDM	Orthogonal Frequency Division Multiplexing
OFFT	Optical Fast Fourier Transform
OIDFT	Optical Inverse Discrete Fourier Transformation
OIFFT	Optical Inverse Fast Fourier Transform
O-OFDM	Optical Orthogonal Frequency Division Multiplexer
OOK	On-Off Keying
OPAPR	Optical Peak-to-Average-Power Ratio
OPC	Optical Phase Conjugation
OSNR	Optical Signal to Noise Ratio
PAPR	Peak-to-Average-Power Ratio
PCM	Pulse Code Modulation
PCTWs	Phase-Conjugated Twin Waves
PD	Photo-Detectors

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PM	Phase Modulators
PMD	Polarization Mode Dispersion
PN	Phase Noise
PRBS	Pseudo-Random Bit Sequence
PRT	Phase Rotate Term
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RZ	Return-to-Zero
SBS	Stimulated Brillouin Scattering
SE	Spectral Efficiency
SMF	Single-Mode Fiber
SNR	Signal to Noise Ratio
SOA	Semiconductor Optical Amplifiers
SPC	Serial-to-Parallel Converter
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
SMF	Single Mode Fiber
SSMF	Standard Single Mode Fiber
Tbps	Tera bit per second
TDM	Time Division Multiplexer
WDM	Wavelength Division Multiplexer
WSS	Wavelength Selective Switch
XPM	Cross Phase Modulation

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter begins with an introduction to the background of the study containing describing the optical communication networks and reviews the recent progress in the high bit rate transmission systems. It provides an overview of the existing optical communication techniques, covering conventional Optical Orthogonal Frequency Division Multiplexing (O-OFDM), and All-Optical OFDM (AO-OFDM) techniques. In addition, this chapter explores the impairments which limit the performance of the AO-OFDM transmission systems and demonstrates various methods to improve the performance of the transmission system.

1.2 Background of Study

System vendors and the network operators are trying to increase the Spectral Efficiency (SE), channel capacity, and the flexibility of the optical networks to produce high-speed transmission applications. The optical transmission systems can gain this demand due to the ability to transmit the signal with the required data rate, specifically with evolving the multichannel optical communication systems such as Time-Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM), and Orthogonal Frequency Division Multiplexing (OFDM). TDM, WDM, and OFDM are three common multiplexing schemes in the fiber communication systems, which are employed in many transmission applications (Yao et al., 2015). The OFDM systems split a high data rate data-stream into multiple low-rate data-streams that can be transmitted simultaneously over both the wired and wireless transmission links. The OFDM systems are able to transmit a high bit rate signal over long distance and they have high interest between the other multichannel systems due to high SE. OFDM is one of the most successful technologies for high-speed optical communication systems due to its high tolerance against dispersion (Hillerkuss et al., 2011). This modulation technique attracted significant attention from the optical communication community to use in large capacity transmission networks. OFDM is used to divide a high data rate signal into multiple lower speed signals which leads to the Inter-Symbol Interference (ISI) reduction and decreases the complexity of the receiver (Hillerkuss et al., 2011).

The OFDM modulation scheme has considerable advantages such as immunity to Polarization Mode Dispersion (PMD) and Chromatic Dispersion (CD). The OFDM subcarriers are orthogonal to each other, which make OFDM systems more spectrally efficient than other types of communication techniques. In addition, due to employing the high number of subcarriers in OFDM systems, these systems can transmit the high speed signals over the longer transmission distances as compared with WDM or TDM systems (Hillerkuss et al., 2011).

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Although OFDM systems have many advantages, they suffer from various impairments such as the Phase Noise (PN), carrier frequency offset, and high Peak-to-Average Power Ratios (PAPR). These impairments destroy the orthogonality between subcarriers, which results in Inter-carrier Interference (ICI). For instance, PN makes phase rotation between subcarriers which leads to destroy the orthogonality between them and decrease the SE in OFDM systems. Because of the high resilient to channel dispersion, this technology has been proposed to use in the optical communication systems. Up to date, two types of the OFDM systems have been implemented in the optical domain. The first type is conventional optical OFDM systems, and the other one is called AO-OFDM systems.

1.2.1 Conventional Optical OFDM Systems

The key idea behind O-OFDM technology is to split a high data rate stream into multiple low rate data-streams in optical domain which are transmitted simultaneously over an optical fiber transmission link (Omiya et al., 2013). In O-OFDM transmission systems, all the subcarriers are generated electronically and modulated in the optical domain (Omiya et al., 2013). The bit rates of the O-OFDM transmission systems are limited by electronics process speed and bandwidth of the Digital to Analog and Analog to Digital (DAC/ADC) conversions. The O-OFDM systems have high tolerance towards linear fiber impairments such as PMD and CD, but they highly suffer from electronic speed limitations (Hillerkuss et al., 2011).

1.2.2 AO-OFDM Systems

In order to avoid the electronic bottleneck and overcome the bandwidth limitation in the conventional O-OFDM systems, the AO-OFDM technique has been proposed for high-speed optical data transmission. The AO-OFDM systems are employing the Optical Fast Fourier Transform (OFFT) instead of electrical FFT, and the Optical Inverse Fast Fourier Transform (OIFFT) is implemented in the optical domain (Hichem et al, 2018). In the AO-OFDM systems, the subcarriers are generated, modulated, and also transmitted in the optical domain. It leads to overcome the electronics speed limit which exists in the conventional O-OFDM systems. The AO-OFDM technique also can overcome the system capacity limit which exists in the conventional O-OFDM. Therefore, AO-OFDM systems can transmit the high-speed signals over the long distances, and they are more spectrally efficient compared to conventional OFDM systems. In the AO-OFDM transmission systems, the sub-channels are generated directly in the optical domain with larger power efficiency compared to the conventional O-OFDM systems. In the AO-OFDM systems, the OFDM subcarriers are optically generated by utilizing the optical components such as the Optical Frequency Comb Generator (OFCG) and each subcarrier is modulated by an external modulator such as Differential Quadrature Phase Shift Keying (DQPSK), Quadrature Amplitude Modulation (QAM), and On-Off Keying (OOK) (Shahad et al., 2020). Although the AO-OFDM systems have several advantages for the high-speed optical data transmission, they highly suffer from nonlinear impairments such as Nonlinear Phase Noise (NLPN).

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1.3 Problem Statement

In optical communication systems, the nonlinear effects occur at the transmitter, fiber channel, and receiver. At the transmitter side, when a Mach–Zehnder Modulator (MZM) is used to modulate the optical subcarrier by the electrical data, its transfer function is not linear. When the signal is propagating through the transmission link, several nonlinear impairments such as the Kerr effect and inelastic scattering are originated in the optical fiber link and degrade the performance of the transmission system.

The performance of an AO-OFDM system is determined by the orthogonality among the subcarriers. In an AO-OFDM system, the NLPN creates a Phase Rotate Term (PRT) on each subcarrier and the PRT leads to the destruction of the orthogonality among subcarriers. Therefore, in order to improve the performance of the transmission system, the NLPN must be mitigated. In addition, at the receiver side, the nonlinearity may occur in the photo-detector. The NLPN is the main problem facing the researchers in AO-OFDM transmission systems, which is caused by the nonlinear fiber impairments such as the Self Phase Modulation (SPM), Cross-Phase Modulation (XPM), and Four-Wave Mixing (FWM). The NLPN significantly limits the bit rate, system capacity, and performance of the transmission system. This research evaluates the parameters such as the transmission distance, laser phase noise, number of subcarriers, the power of subcarriers, and number of amplifiers which govern the nonlinear impairments by using the numerical simulation. In this research, three efficient AO-OFDM schemes with the nonlinear mitigation techniques are proposed for the high-speed optical transmission system. In order to improve the performance of the AO-OFDM transmission systems, a new approach is proposed for mitigating the nonlinear fiber impairments and demonstrates the proposed system setup by aiding the numerical simulation using the Virtual Photonics Integrated (VPI) software 9.0.

1.4 Motivation of the Study

Nonlinear impairments limit the performance of the optical transmission systems and degrade the quality of the transmitted signals. In order to improve the performance of the optical transmission systems, the effects of the nonlinear impairments must be mitigated. The purpose of this research is to explore the effects of the nonlinear fiber impairments on the quality of the transmitted signals in the AO-OFDM transmission systems. This study aims to estimate the impacts of the fiber nonlinear impairments on the performance of various AO-OFDM schemes, and presents a technique to mitigate the fiber nonlinear impairments in the AO-OFDM transmission systems. In addition, three AO-OFDM schemes are demonstrated by employing the proposed techniques. This research also intends to analyze the effects of the nonlinear impairments on the performance of the proposed AO-OFDM systems in order to explore the efficiency of the proposed techniques in mitigating the nonlinear fiber impairments.

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1.5 Objectives of the Study

This study proposes the new and efficient techniques to mitigate the nonlinear impairments and improve the performance of the AO-OFDM transmission systems. This study embarks on the following objectives:

a) To implement three efficient schemes of the AO-OFDM transmission systems and investigate the performance of the systems in presence of the fiber nonlinear impairments.

b) To develop the analytical model of the DQPSK AO-OFDM, 4/16 QAM AO-OFDM, and Non Return to Zero (NRZ)-DQPSK AO-OFDM systems.

c) To investigate the nonlinear impairments and mitigate the effects of phase noise in the AO-OFDM transmission systems.

1.6 Scope of the Study

This research explores the fundamental principles of the existing multichannel optical communication methods and introduces various schemes of the AO-OFDM systems. It reviews the recent advances in compensating the fiber nonlinearity in the optical transmission systems and presents various existing techniques on mitigation of the nonlinear fiber impairments in the AO-OFDM systems. It analyses the effectiveness of the reported techniques on mitigation of the fiber nonlinear impairments in the AO-OFDM systems. It investigates the effects of various parameters such as the transmission distance, dispersion, number of subcarriers, and the power of subcarrier on the performance of the AO-OFDM systems. This research explains how to investigate the proper phase correction factor in order to compensate the effects of the NLPN on the performance of the AO-OFDM systems electrically. Therefore, an efficient nonlinearity mitigation technique is proposed, and the system setup is numerically simulated by using the VPI transmission maker software 9.0. The investigations of the proposed techniques are carried out for both the DQPSK and m-array Quadrature-Amplitude Modulation (m-QAM) modulation formats. In order to show the efficiency of the proposed techniques to improve the performance of the AO-OFDM system, the AO-OFDM transmission system is simulated before and after employing the proposed techniques and the obtained results are compared to each other.

1.7 Thesis Organization

This research is organized into five chapters where

Chapter 1 introduces the basic principle of the AO-OFDM systems and explores various types of the impairments. This chapter evaluates the effects of the fiber impairments on the capacity and performance of the AO-OFDM transmission systems. Also, the problem statement, research objectives, motivation of study, and scope of study are presented in this chapter.

Chapter 2 explores the fundamental principles of the optical communication techniques, which have been reported in recent years. In addition, this chapter introduces various schemes of the AO-OFDM systems, which have been proposed in the recent years. In this chapter, the nonlinear fiber impairments are briefly discussed, and several approaches to mitigate the nonlinearity in the AO-OFDM transmission systems are explored. This chapter briefly explores the effects of the nonlinear fiber impairments on the transmitted signals in the AO-OFDM transmission systems. Moreover, this chapter introduces various evaluation methods to investigate the effects of the nonlinear impairments on the performance of the AO-OFDM systems. This chapter also explores several techniques to investigate the efficiency of the nonlinearity compensation techniques in mitigating the effects of the nonlinear fiber impairments on the performance of the AO-OFDM systems.

Chapter 3 presents three efficient schemes of the AO-OFDM systems and proposes two techniques to mitigate the effects of the phase noise on the performance of the systems. This chapter describes the proposed system setups containing the schematic diagrams of the transmitter, fiber link, and receiver. The proposed AO-OFDM transmission systems are successfully demonstrated by simulating the schematics. For each proposed AO-OFDM system, the numerical simulation is performed by VPI software 9.0. The signals are generated, modulated, transmitted, and received by using VPI software. Afterwards, the received signals were linked and analyzed with Matlab software in order to process the signals and perform BER calculation. In addition, the phase correction algorithm and phase conjugation techniques have been proposed in order to improve the performance of the AO-OFDM systems. The proposed techniques are demonstrated analytically by Matlab software.

Chapter 4 presents the obtained simulation results before and after employing the nonlinearity mitigation techniques, and investigates the performance of the implemented AO-OFDM systems by the numerical simulation. The obtained simulation results are analyzed to explore the efficiency of the proposed techniques. This chapter also estimates the phase noise variances, Bit Error Rate (BER), and Error Vector Magnitude (EVM) in order to quantify the effectiveness of the proposed phase noise mitigation technique.

Chapter 5 contains the conclusion, future works, and contribution of the research field.

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