DEVELOPMENT OF NEW TWO DIMENSIONAL FCC-MDW CODE WITH WAVELENGTH/TIME SCHEME IN OPTICAL CODE DIVISION MULTIPLE ACCESS (OCDMA) NETWORK SYSTEMS

by

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LIST OF ABBREVIATIONS

APD	Avalanche Photodiode
ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
BLS	Broadband Light Source
CDMA	Code division multiple access
DCS	Dynamic Cyclic Shift
DPD	Diluted Perfect Difference
DS	Direct-Sequence
DW	Double Weight
EDFA	Erbium Doped Fibre Amplifier
FBG	Fiber Bragg Grating
FH	Frequency Hopping
FTTH	Fiber-to-the Home
FTTB	Fiber-to-the-Building
FTTC	Fiber-to-the-Curb
LAN	Local Area Network
LED	Light emitting diode
MAI	Multiple Access Interference
MDW	Modified Double Weight
MMC	M-Matrices Code
MQC	Modified Quadratic Congruence
NRZ	Non return-to-zero
OCDMA	Optical CDMA
OOK	ON-OFF Keying
OTDMA	Optical Time Division Multiple Access

PDC	Perfect Difference Code
PIIN	Phase Induced Intensity Noise
PLCs	planar lightwave circuits
PONs	Passive Optical Network
PSD	Power Spectral Density
QoS	Quality of Service
SAC	Spectral Amplitude Coding
SMF	Single Mode Fiber
SNR	Signal to Noise ratio
SPE	Spectral Phase encoding
SSFBG	Super-structured fiber Bragg gratings
TOFDLs	Tunable Optical Fiber Delay lines
TPE	Temporal Phase encoding
WDM	Wavelength Division Multiplexing
WDMA	Wavelength Division Multiple Access
WHTS	Wavelength Hopping Time Spreading
W/T	Wavelength/Time
ZCC	Zero Cross Correlation
1-D	One-dimensional
2-D	Two-dimensional

LIST OF SYMBOLS

Code Weight	w
2-D FCC-MDW code weight	k_1 , k_2
Power spectral density of the pulse	$S(f)$
Effective ionization ratio of the APDs	K_{eff}
Responsivity	$\Re$
Excess Noise Factor of APD	F
Optimum APD gain	G
Number of Users	K
2-D FCC-MDW number of user	W
Code length	N
Spectral Width	Δv
Bandwidth of the source	Δf
Bit of data for the *w*th user	$d(w)$
Cross-correlation	λ_c
Auto –correlation	λ_a
Number of wavelength	M
Spectral encoding	X_g
Spatial encoding	Y_h
Average photocurrent	I
Electrical Bandwidth	B
Coherence time	τ_c
Electron charge	e
Boltzman's constant	K_b
Absolute receiver noise temperature	T_n

Receiver load resistor	R_L
Central frequency	f_0
Effective power of a broadband source at the receiver	P_{sr}
Unit step function	$u(f)$
Noise equivalent electrical bandwidth of the receiver	B_r
Optical received power	P_r
Data transmission rate	R_b

Pembangunan Baru Kod Dua Dimensi FCC-MDW Dengan Skim Panjang Gelombang/Masa dalam Sistem Rangkaian Akses Pelbagai Pembahagian Kod Optik (OCDMA)

ABSTRAK

Peningkatan secara besar-besaran khususnya daripada pengguna internet di seluruh dunia menggalakkan pembekal perkhidmatan bersama-sama dengan para penyelidik untuk meneroka teknologi telekomunikasi yang sesuai dan bermanfaat kepada pengguna. Uniknya, berbanding dengan teknik akses pelbagai yang lain, teknik Akses Pelbagai Pembahagian Kod (OCDMA) boleh digunakan dalam rangkaian akses optik dengan perkhidmatan mengikut permintaan, seperti protokol internet, video atas permintaan, tele-kehadiran dan audio berkualiti tinggi. Walaupun terdapatnya keutuhan di dalam OCDMA, kewujudan gangguan capaian pelbagai (MAI) dan hingar fasa intensiti teraruh (PIIN) dalam sistem menjejaskan prestasinya. Malah, MAI terkenal sebagai faktor utama kemerosotan prestasi dalam sistem OCDMA itu. Atas alasan tersebut, di dalam tesis ini, siasatan telah dijalankan untuk meneroka kod tersendiri yang boleh mengurangkan MAI dan PIIN. Motivasi lain kajian ini adalah untuk mendapatkan kod tersendiri yang boleh menampung sejumlah besar pengguna serentak yang selaras dengan tuntutan semasa. Maka, kod dua dimensi (2-D) fleksibel korelasi silang- berat berganda diubahsuai (FCC-MDW) dengan skim panjang gelombang/masa (W/T) dicadangkan dan didemonstrasikan. Pada asasnya, pembangunan kod 2-D FCC-MDW dibentuk dengan menggabungkan dua kod satu dimensi (1-D) OCDMA yang dikenali sebagai kod 1-D FCC dan 1-D MDW. Pembangunan kod bermula dengan menetapkan kod 1-D MDW sebagai corak gelombang pengekodan dan urutan kod 1-D FCC sebagai corak penyebaran masa. Lebih lagi, dalam usaha untuk mengurangkan MAI, pengekod dan penyahkod baru 2-D FCC-MDW adalah direka berdasarkan kepada pengesanan seimbang berganda. Tesis ini menyediakan analisis matematik dan simulasi untuk menyiasat prestasi kod baru 2-D FCC-MDW. Gabungan domain panjang gelombang dan domain masa membawa kepada hak korelasi silang yang baik. Hasilnya, pengurangan MAI dengan bantuan reka bentuk penyahkod pengesanan keseimbangan berganda, penindasan PIIN boleh dicapai secara optimum. Penemuan yang paling jelas dari kajian ini adalah prestasi kod 2-D FCC-MDW mengatasi kod yang lain, iaitu 1-D FCC, 1-D MDW, 2-D perbezaan sempurna (PD) dan kod 2-D perbezaan cairkan sempurna (DPD) dari segi BER, kekardinalan, kuasa yang berkesan, kadar penghantaran data, kecekapan spektrum dan jarak fiber optik. Telah didapati bahawa cadangan kod baru mencapai kekardinalan tinggi dan berskala yang mana kod dicadangkan 2-D FCC-MDW mencapai 150 pengguna serentak pada BER 10^{-9} manakala kod 2-D PD dan kod 2-D DPD masing-masing hanya boleh mencapai 90 dan 135 pengguna serentak. Secara khususnya, kardinaliti kod 2-D FCC-MDW dapat menandingi kod PD 2-D dan 2-D kod DPD sebanyak 66.67% dan 11% masing-masing pada kadar data 622 Mbps. Kuasa berkesan minimum, P_{sr} bagi kod baru ini boleh dicapai pada -24dBm berbanding kod 2-D DPD yang memerlukan sebanyak -16dBm bagi merealisasikan keperluan penghantaran optik minimum. Secara keseluruhannya, 2-D FCC-MDW telah berjaya meningkatkan prestasi sistem secara keseluruhan. Penilaian dan pengesahan antara simulasi dan keputusan teori mendedahkan bahawa kod 2-D FCC-MDW dapat direalisasikan dalam rangkaian OCDMA.

Development of New Two Dimensional FCC-MDW Code with Wavelength / Time Scheme in Optical Code Division Multiple Access (OCDMA) Network Systems

ABSTRACT

A massive grown specifically for internet users worldwide encourages the service provider along with the researchers to explore an appropriate telecommunication technology that is beneficial to the users. Uniquely, as compared to other multiple access techniques, Optical Code Division Multiple Access (OCDMA) technique can be utilized in optical access network with full services on demand, such as internet protocol, video on demand, tele-presence and high quality audio. In spite of the robustness of OCDMA, the existence of Multiple Access Interference (MAI) and Phase Induced Intensity Noise (PIIN) in the system affects its performance. In fact, MAI is well known as a key factor of performance deterioration in the OCDMA system. For that reason, in this thesis, an investigation was conducted to explore on signature code that can minimize the MAI and PIIN. Another motivation of this study is to discover a signature code that can accommodate a huge number of simultaneous users which is in line with the recent demands. Consequently, two-dimensional (2-D) Flexible Cross Correlation-Modified Double Weight (FCC-MDW) code with Wavelength/Time (W/T) scheme is proposed and demonstrated. Basically, the construction of 2-D FCC-MDW code is formed by merging of two one-dimensional (1-D) OCDMA code known as 1-D FCC and 1-D MDW codes. The development of the code begins by assigning 1-D MDW code as a wavelength encoding pattern and 1-D FCC code sequences as time-spreading patterns. Furthermore, in order to mitigate MAI, the encoder and decoder of new 2-D FCC-MDW is designed based on double balanced detection. This thesis provides mathematical and simulation analysis in order to investigate the performance new 2-D FCC-MDW. The combination of wavelength domain and time domain leads to the good property of cross correlation. As a result, mitigation of MAI by the help of double balance detection decoder design, PIIN suppression can be achieved optimally. The most obvious finding to emerge from this study is that the performance of 2-D FCC-MDW code outperformed other codes, namely 1-D FCC, 1-D MDW, 2-D Perfect Difference (PD) code and 2-D Dilute Perfect Difference (DPD) code in terms of BER, cardinality, effective power, data transmission rate, spectral efficiency and fiber distance. It was found that the new proposed code achieves high cardinality and scalability whereby it attains 150 simultaneous users at the standard BER threshold of 10^{-9} while 2-D PD and 2-D DPD code can only achieve 90 and 135 simultaneous users respectively. Specifically, the cardinality of 2-D FCC-MDW code outshines the 2-D PD code and 2-D DPD code by the increment of 66.67% and 11% respectively at data rate 622 Mbps. The minimal effective power, P_{sr} of new proposed code can be achieved at -24dBm in comparison with 2-D DPD code requires -16dBm to realize the minimum optical transmission requirement. On the whole, 2-D FCC-MDW has been successfully improved the overall system performance. The evaluation and validation between simulation and theoretical results reveal that 2-D FCC-MDW code can be realized in the OCDMA network.

CHAPTER 1

INTRODUCTION

1.1 Demand for OCDMA Technology

Code division multiple access (CDMA) is originally based on the spread-spectrum communications used for military applications due to its inherent low probability of intercept. Later, this kind of multiple access is used in commercial mobile communications and satellite. Alternatively, optical CDMA (OCDMA) was introduced and fascinated the researchers due to its potential for enhancement in information security, improved spectral efficiency as well as increased flexibility of bandwidth (Shiraz & Karbassian, 2012). Recently, remarkable demand for multiple access has grown up, especially OCDMA for their flexibility and scalability (Kitayama Ken-ichi, 2014) albeit being outside the mainstream of optical communication research and development three decades ago. The key factor is due to the immaturity of optical devices which are proprietary to the OCDMA such as the optical en/decoder an optical thresholding device. However, with the amazing progress has been made in device technology, OCDMA becomes the promising multiple access technology for addressing the bandwidth and flexibility compared to other multiple access technology. As compared to others multiple access technologies, OCDMA technology can be utilized in optical access network with full services on demand, such as internet protocol, video on demand, tele-presence and high quality audio.

1.2 Problem Statement

The rise of the on-demand economy worldwide has massively grown specifically for internet users. There were 2.8 billion internet users as of 2014 compared to only 35 million users in 1995 or in percentage, 0.6 percent to 39 percent of the world's population (Gannes, 2015). The extreme increase in the percentage of internet users encourages the service provider and researcher to explore the appropriate telecommunication technology that is beneficial to the users. OCDMA is one of the multiple access technique that offers high security and large capacity since each data bit is sent as a sequence of optical pulses and the data will retrieve back at the receiving end by correlating the received signal with its own sequence. However, there is a large volume of published studies (Shiraz & Karbassian, 2012) describing that in the incoherent OCDMA system, the key factor of deterioration in the system performance is Multiple Access Interference (MAI). MAI is the hit probabilities between sequences that arise from dark pulses of interfering users, which replicate the signature sequence of the user (Sayed, Jolly & Khot, 2014). Noted that in the incoherent OCDMA system, various users with their specific and unique sequence can access the same channel simultaneously and asynchronously (Zhang, 2012). For that reason, the code sequences with good correlation properties or particularly with low cross-correlations need to be observed in order to minimize MAI.

The Spectral Amplitude Coding (SAC) technique was introduced to suppress the influence of the MAI effect by employing codes with fixed in-phase cross correlation, λ_c. Hence, several numbers of one dimensional (1-D) codes using SAC techniques have been proposed such as modified quadratic congruence (MQC) code (Wei & Shiraz, 2002), m-sequence code (Huang, 2006), MDW (Aljunid, Ismail, Ramli, Borhanuddin

& Abdullah, 2004) and ZCC (Anuar, Aljunid, Saad & Hamzah, 2009) to overcome the MAI effect from the system. However, the performance of the spectral-amplitude-encoding OCDMA system also is affected by the Phase Induced Intensity Noise (PIIN) (Shiraz & Kabassian, 2012). The incoherent lights are mixed and incident on the photo detector causes arise of PIIN. It should also be noted that the previous studies of 1-D codes revealed some other limitation such as a long code length of 1-D MDW and ZCC code resulting the increasing of MAI in the system. Previous researches have also shown that 1-D codes with good correlation properties still suffer from the low cardinality. Obviously, the cardinality or the number of users that can be supported affects the system capacity while the correlation properties of the signature codes can influence the BER of the system.

One of the promising solutions for this drawback is to employ two dimensional (2-D) code in OCDMA system. In 2-D encoding system, both, the flexibility of code design and the cardinality of the code can be improved significantly. The significant difference about the 2-D optical CDMA system from the 1-D counterpart is that every pulse in the spreading codeword is transmitted at a unique wavelength (Ni, 2005). In order to match the transmitter in frequency domain, each delay line at the receiver is equipped with a band-pass filter (BPF) to allow only a specific wavelength go through. Hence, the intention of this research is to propose the 2-D code with good correlation properties by using W/T method as well as to demonstrate this 2-D code has good code cardinality with satisfactory performance. The relevance of correlation properties of the system performance, especially the Bit Error Rate (BER) is very clear. A little difference in average hit probability of pulses between different sequences will result in visible improvement in BER (Zhang, 2012). In other words, BER, cross correlation and cardinality are interrelated to each other. Furthermore, Prucnal (2006) highlighted the

advantage of 2-D W/T schemes that offer the scalability and flexibility as well as provides a lower probability of interception.

1.3 Research Objectives

This research was undertaken to present a new 2-D OCDMA coding system that can enhance the system performance as well as the cardinality of the OCDMA network. The primary aim of this research is to design a spreading code with significant correlation properties to suppress MAI effectively. This new 2-D signature code is developed by combining of two 1-D code (1-D MDW and 1-D FCC codes), namely 2-D FCC-MDW. Particularly, the objectives of this research covers:

- Development of 2-D FCC-MDW code with W/T scheme in OCDMA system.
- Analyze the theoretical performance and simulated performance of proposed 2-D FCC-MDW code as well as comparing its system performance with the existing similar structured codes at the standard BER.
- Validate the proposed 2-D FCC-MDW code by comparing the results from the mathematical derivation and simulation data.

1.4 Scope of Works

The scope of this study involves with the capability of 2-D code by using W/T methods to suppress the influence of the MAI effect in the incoherent SAC-OCDMA system. A number of studies have examined the relationship between the MAI effect and the degradation of system bit error rate (BER) (Shiraz & Karbassian, 2012; Yin & Richardson, 2007). This newly proposed 2-D signature code can be obtained by

combining of 1-D MDW (Aljunid *et. al*., 2004) and 1-D FCC (Rashidi, Aljunid, Ghani, Fadhil, Anuar, & Arief, 2014) codes known as 2-D FCC-MDW. The scheme used is based on wavelength and time encoding decoding process. Each user will be assigned a hybrid signature code where the optical pulses will be first encoded in the wavelength domain using MDW code scheme and later the FCC code will be encoded in the time domain. The serious issues to deal with when designing the code in OCDMA system with satisfactory performance is that the correlation properties and the number of users can be supported (Chen, 2007). Hence, to demonstrate the potential of this approach and its suitability for the application, the mathematical derivation is investigated. A simulation which uses OPTISYS simulation software Version 7.0 used to simulate the data which practically replicate a real system. The comparison will be carried out between the theoretical (mathematical analysis) and simulation data. In order to verify the analytical methods, all the mathematical development based on 2-D FCC-MDW code will be compared with the existing similar structured 2-D codes.

1.5 Research Contribution

The important contributions drawn from this research include:

i) A new mathematical algorithm of the SNR and BER for 2-D OCDMA code system by employing wavelength-time technique/scheme was developed.

ii) A new 2-D FCC-MDW code in OCDMA was thoroughly analyzed and compared with existing 2-D code.

iii) New design of encoder-decoder for a 2-D OCDMA network system based on the double balanced detection scheme is developed.

iv) Realization of new 2-D OCDMA system of high capacity transmission on optical platform.

1.6 Thesis Structure

This thesis focuses on developing a new theoretical algorithm and simulation techniques to enhance the performance and cardinality in OCDMA networks. A 2-D spreading sequence is proposed for OCDMA systems by employing the wavelength-time scheme. In particular, the 2-D FCC-MDW algorithm not only comparable performance with other existing systems, but it allows an increased number of simultaneous users to be generated. It begins with demands of OCDMA technology in the current trend of telecommunications system. The challenges of OCDMA system that clarify the motivating aspect together with the objectives of this research, scope of work and research contribution are included in Chapter 1.

Chapter 2 will present the background of OCDMA in a multiple access scheme, the progress of OCDMA technology during the past three decades and the classification of OCDMA system.

Chapter 3 provides the methods used to design and analyze the 2-D incoherent OCDMA codes. The principal aims to provide the general overview required to understand some mathematical theory of the other existing 2-D code sequences in OCDMA system. Moreover, the parameters used for analyzing the performance of 2-D code sequences are also presented. Together with this, it is an introduction to the OptiSystem simulator package as a simulation tool in this research.

Chapter 4 presents the explicit constructions of new 2-D FCC-MDW code sequences based on the combination of 1-D FCC and 1-D MDW codes. Derivation of a