



**Development of New Two Dimensional ZCC/MD
Spectral/Spatial Code for OCDMA System**

by

**RIMA MATEM
(1640812253)**

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LIST OF ABBREVIATIONS

APD	Avalanche Photodiode
ASE	Amplifier Spontaneous Emission
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
BLS	Broadband Light Source
CDMA	Code Division Multiple Access
DCS	Dynamic Cyclic Shift
DPD	Diluted Perfect Difference
DW	Double Weight
EDW	Enhance Double Weight
EOM	Electrical to Optical Modulator
FBG	Fiber Bragg Grating
FCC	Flexible Cross Correlation
FSO	Free Space Optics
FTTH	Fiber To The Home
Gbps	Gigabit per second
IM/DD	Intensity Modulation/Direct Detection
LAN	Local Area Network
LED	Light Emitting Diode
LPF	Low Pass Filter
MAI	Multiple Access Interference
Mbps	Mega bit per second
MD	Multi Diagonal
MDW	Modified Double Weight
MQC	Modified Quadratic Congruence
MS	Multi Service
MZM	Much-Zehender Modulator
NRZ	Non Return to Zero
OCDMA	Optical Code Division Multiple Access
OOC	Optical Orthogonal Code
OOK	On-Off Keying
PDC	Perfect Difference Code
PIIN	Phase Induced Intensity Noise

PIN	Positive Intrinsic Negative
PMD	Polarization Mode Dispersion
PON	Passive Optical Network
PRBS	Pseudo Random Binary Sequence
QGs	Quasi Group
QoS	Quality of Service
RD	Random Diagonal
RZ	Return to Zero
SAC	Spectral Amplitude Coding
SLD	Super-Luminescent Diode
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio
SPC	Spectral Phase Coding
TDMA	Time Division Multiple Access
TPC	Temporal Phase Coding
TSE	Temporal Spreading Encoding
T/S	Time/Spatial
W/T	Wavelegth/Time
WDMA	Wavelength Division Multiple Access
WHTS	Wavelength Hopping Time Spreading
ZCC	Zero Cross Correlation
1D	One Dimensional
2D	Two Dimentional

LIST OF SYMBOLS

w	Code Weight
$G(v)$	Power spectral density
w_1, w_2	2D ZCC/MD code weight
B_r	Electrical Bandwidth
R	Responsivity
k	Number of users
N	Spatial code length
M	Spectral code length
Δv	Bandwidth of the source
$d(k)$	Bit of data for the Kth user
λ_a	Auto correlation
λ_c	Cross correlation
X_g	Spectral encoding
Y_h	Spatial encoding
I	Average photocurrent
τ_c	Coherence time
e	Electron charge
K_b	Boltzmann's constant
T_n	Absolute receiver noise temperature
R_L	Receiver load resistor
ν_0	Central frequency
P_{sr}	Effective power of a broadband source at the receiver

Pembangunan Dua Spektrum ZCC / MD Kod Spatial Baru untuk Sistem OCDMA

ABSTRAK

Kepentingan memperluas maklumat trafik membawa kepada peningkatan keupayaan dan fungsi sistem komunikasi. Atas sebab ini, pelbagai teknik pemultipleksan telah diperkenalkan dengan tujuan untuk membolehkan berbilang pengguna untuk berkongsi domain optik yang sama serentak di mana asas revolusi sistem adalah jalur lebar yang besar, penghantaran data dan keselamatan maklumat yang dihantar. Divisyen Kod Optik Pelbagai Akses (OCDMA) adalah teknik pemultipleks yang paling popular kerana kelebihanannya yang dapat memberikan kapasiti yang tinggi, jalur lebar yang fleksibel, kapasiti untuk meningkatkan keselamatan sistem, kardinaliti yang besar dan akses tak segerak yang berskala. Teknik ini, setiap pengguna diberikan oleh kod alamat unik dan khusus. Sistem OCDMA boleh dipengaruhi oleh dua cabaran utama iaitu Gangguan Akses Pelbagai (MAI) dan bunyi Intensiti Teras Fasa (PIIN). Oleh itu, kod yang sesuai dengan sifat rentas korelasi yang baik diperlukan untuk menekan kesan MAI dan mengurangkan PIIN. Berdasarkan pada anggapan ini, banyak kod 1D telah dibangunkan dalam domain yang berbeza (panjang gelombang, masa dan ruang), tetapi menggunakan kod 1D memerlukan panjang kod yang sangat panjang untuk meningkatkan jumlah pengguna serentak. Walau bagaimanapun, kod dua dimensi telah diperkenalkan dengan tujuan meningkatkan prestasi sistem dengan meningkatkan bilangan pengguna serentak dengan kod pendek berbanding kod 1D. Spektrum 2D / spatial adalah salah satu skema yang dibangunkan. Dalam tesis ini, kod hibrid 2D baru dicadangkan untuk skema spatial / spatial yang dipanggil kod 2D ZCC / MD untuk mengatasi masalah yang disebutkan. Pengembangan kod yang dicadangkan adalah berdasarkan kod ZCC dan MD di mana kod ZCC 1D digunakan untuk pengekodan spektrum dan sementara MD 1D digunakan untuk penyebaran spasial. Disebabkan gabungan ini, kesan MAI dapat ditindas sepenuhnya dan PIIN dikurangkan dan menawarkan kod yang dibangunkan sebagai sifat korelasi silang yang baik. Tambahan pula, analisis matematik dan simulasi disiasat. Derivasi persamaan matematik dimasukkan dari segi SNR dan BER takin menjadi pertimbangan bunyi yang berbeza di penerima, dan menggunakan perisian simulasi untuk pengesahan. Penemuan teoritis menunjukkan bahawa 2D ZCC / MD mempamerkan prestasi yang lebih baik daripada 2D FCC / MDW dan 2D DPDC dari segi kardinaliti. Telah didapati bahawa kod 2D ZCC / MD baru yang dicadangkan mencapai kardinaliti dan skalabilitas yang tinggi di mana ia mencapai 360 pengguna di BER standard dan nilai faktor penambahbaikan adalah 260%. Di samping itu, penyahkod sistem ZCC / MD 2D dicirikan oleh kesederhanaan kerana teknik pengesanan langsung yang digunakan pada penerima. Kajian ini membuktikan bahawa kod Spectral / spatial 2CC ZCC / MD berjaya meningkatkan prestasi sistem di mana penyelidikan simulasi mengesahkan bahawa kod 2CC ZCC / MD boleh digunakan dan dieksploitasi dalam rangkaian CDMA optik.

Development of New Two Dimensional ZCC/MD Spectral/Spatial Code for OCDMA System

ABSTRACT

The expanding interest in traffic information has led to an increase of the capacity and functionality of communication systems. For this reason, various multiplexing techniques have been introduced with the purpose of allowing multiple users to share the same optical domain simultaneously. The basis of the system revolution is large bandwidth, the data transmission and security of transmitted information. Optical Code Division Multiple Access (OCDMA) is the most popular multiplexing technique due to its advantages which include the ability to provide as high capacity, flexible bandwidth, and capacity to improve the system's security, large cardinality and scalable asynchronous access. In this technique, each user is assigned by a unique and specific address code. The OCDMA system can be affected by two major challenges which are Multiple Access Interference (MAI) and Phase Induced Intensity Noise (PIIN). Thus, a suitable code with a good cross-correlation property is needed in order to suppress the effect of MAI and mitigate PIIN. Based on this assumption, many 1D codes have been developed in different domain (wavelength, time and space), but using 1D codes require a very long code length in order to increase the number of simultaneous users. However, two-dimensional codes have been introduced with the purpose of enhancing the system performance by increasing the number of simultaneous users with short code length compared to 1D codes. The 2D spectral/spatial is one of the developed schemes. In this thesis, a new 2D hybrid code is proposed for the spectral/spatial scheme called 2D Zero Cross-correlation/Multi-Diagonal (ZCC/MD) code to overcome the mentioned deficiencies (MAI and PIIN). The development of the proposed code is based on ZCC and MD codes where the 1D ZCC code is used for the spectral encoding while 1D MD is used for spatial spreading. Due to this combination, the effect of MAI can be completely suppressed and the PIIN is mitigated and offer a developed code a good cross correlation property. In addition, the mathematical and simulation analysis have also been investigated. The mathematical equation derivation is presented in terms of SNR and BER by taking into consideration different noises at the receiver, and using the simulation software *OptiSystem*TM version 7.0 from *Optiwave* for the validation. The theoretical findings show that 2D ZCC/MD exhibits a better performance than the 2D Flexible Cross-correlation/Modified Double (FCC/MDW) and 2D Diluted Perfect Difference Code (DPDC), in terms of cardinality. It was found that the new proposed 2D ZCC/MD code achieves a high cardinality and scalability whereby it attains 360 users at the standard BER with an improvement factor value of 240%. In addition, the decoder of the 2D ZCC/MD system is characterized by simplicity, due to the direct detection technique used at the receiver. This study established that a 2D ZCC/MD spectral/spatial code can successfully improve the system performance, where the simulation finding validate that 2D ZCC/MD code can be used and exploited in the optical CDMA network.

CHAPTER 1 : INTRODUCTION

1.1 Overview

The optical fiber communication system is a recent type of communication systems, where the information is transported using an optical wave as a carrier and fiber optics as the transmission medium. Many recompenses can be offered by optical communication systems such as a long transmission distance, saving energy, and transmitting a massive amount of information at one time, where a large number of users can receive the required information at the same time with a fast communication speed (Yin & Richardson, 2008; Senior & Jamro, 2009; Venghaus, 2012). As a transmission channel, optical fiber is characterized by a wide bandwidth, small size and weight, low loss, signal security, and electrical isolation. Thus, it is a rich and potentially low cost resource, where means it can be classified as the best candidate to transport broadband access for a long distance (Noé, 2010; Agrell, Alvarado, Kschischang, & Agrell, 2016). As data transmission increases and the traffic is heavier, the need for a high rate transmission technology is increasing with the target of high speed and high capacity transmission. These requirements are achieved using numerous different multiple access schemes, such as OCDMA, Time Division Multiple Access (TDMA) and Wavelength Division Multiple Access (WDMA) for multiplexing and de-multiplexing of the information stream (Senior & Jamro, 2009; Nordin et al., 2013).

In TDMA, all users in the system share the entire bandwidth W , but transmit signals in a chronological sequence, with no interference between any two users, namely orthogonality. However, TDMA requires synchronization to maintain a common timing

reference. Another challenge faced by the TDMA technique is that it is subject to multipath distortion, referred as nonlinearities, where it is difficult to transmit the wideband signal, which requires equalization to reduce the inter-symbol interference. As technology grows, WDMA seems the best solution. In WDMA, the available spectrum is divided into physical channels of equal bandwidth. Each physical channel is allocated per subscriber which makes better use of the optical fiber bandwidth. One advantage of WDMA over TDMA is that it usually uses lower bit rates of optical power in each channel, yet achieves higher network capacity. However, one of the challenges of WDMA is the limitation of the wavelengths when the number of users becomes large. Therefore, unfortunately, it is obvious that both these multiple access techniques present significant drawbacks in local area systems requiring a large number of users (P. Prucnal & Santoro, 1986; P. R. Prucnal, 2006; Walther & Fry, 2016). Moreover, the maximum transmission capacity for TDMA and WDMA depends on the total number of time slots and wavelength channels respectively (Yin & Richardson, 2008; Agrawal, 2016) .

OCDMA is currently the most well-known multiple access technique (Fadhil, Aljunid, Ahmed, & Alkhafaji, 2012; Rana & Gupta, 2016). Since optical CDMA (OCDMA) was introduced and has attracted researchers, due to its ability to enhance the system's performance and information security, and improve the spectral efficiency, as well as increasing the flexibility of the bandwidth (Ghafouri-Shiraz & Karbassian, 2012; Kaur, Goyal, & Rani, 2017). OCDMA is a multiplexing technique that uses an approach different from TDM and WDM where the principal of the OCDMA technique is to allow many subscribers to share the optical network simultaneously and asynchronously by assigning a distinguish code to each user. At the transmitter, the information bit stream of every client is optically encoded according to a unique assigned code sequence for

each client, then transmitted via the optical fiber system asynchronously. At the receiver, knowing the code sequence of each client, an optical decoder is designed to decode the desired transmitted optical signal and convert it to electronic data to recover the original signal. Various parameters including the data rate, number of simultaneous users, transmission power, receiver power and the type of codes determine the performance of OCDMA networks. However, the types of codes and rate of transmitted data are crucial parameters, as they determine the numbers of subscribers who can simultaneously access the optical network (Zou & Ghafouri-Shiraz, 2002; S. A. Aljunid, Ismail, Ramli, Ali, & Abdullah, 2004; Arief, Aljunid, Anuar, Junita, & Ahmad, 2013; Kaur et al., 2017).

1.2 Problem Statement

The Internet is defined as the worldwide interconnection of individual networks operated by government, industry, academia, and private parties. Originally the Internet served to interconnect laboratories engaged in government research, and since 1994 it has been expanded to serve millions of users and a multitude of purposes in all parts of the world. In 2015, the International Telecommunication Union estimated that about 3.2 billion people, or almost half of the world's population, would be online by the end of the year (IWorld Internet Users Statistics and 2016 World Population Stats, 2016). Of these, about 2 billion people would be from developing countries, including 89 million from the least developed countries (SANOU, 2015). The enormous increase in the percentage of internet users has prompted service providers and researchers to explore the appropriate telecommunication technology that would be beneficial to the users (Nurol et al., 2014). For efficient use of the optical bandwidth, OCDMA techniques have been introduced, which allows many users to share the available bandwidth and transmission link

simultaneously. Each subscriber in OCDMA is represented by a unique code (Kaur et al., 2017).

OCDMA is an advanced multiple access technique that offers high security and large capacity, since each data bit is sent as a sequence of optical pulses. At the receiving end, data will be recovered back by correlating the received signal with its own sequence (N Din Keraf, Aljunid, Arief, & Ehkan, 2015). Based on the property of its respective optical signal, the OCDMA system can be classified as coherent or incoherent (R.A. Kadhim, Fadhil, Aljunid, & Razalli, 2015). Incoherent OCDMA only manipulates power in the encoding and decoding process and discards the coherence of the light source. The incoherent system receiver utilize the direct detection technique: the photo detector gives the output current I_D which is relative to the average power of the receiver's optical power (Kaur et al., 2017). The principle of coherent OCDMA is to encode signals by changing the phase of the light source, which it is difficult in terms of realization (Arief et al., 2011).

Despite the advantages that a coherent OCDMA system offers such as better receiver sensitivity and the ability to use different kinds of modulation scheme (exp: FSK, PSK), it is exposed to disadvantages as it is difficult to implement and expensive. For this reason, the incoherent system has attracted a lot of attention, due to its simplicity, and because it is economical and more practical. However, there are a large number of published studies (Danideh & Sadeghzadeh, 2013) describing certain challenges that the incoherent OCDMA system encounters at the implementation level. The key factor in the deterioration in system performance are the multiple access interference (MAI) of the overlapping chips, an increased number of simultaneous users and a low bit rate, in order

to compensate for increases in code length and weight. MAI is the interference due to the chips overlapping with the those of the other users transmitting on the same wavelengths at the same time (Bazan, 2017). It should note that, the incoherent OCDMA system provides access for various users, each with their specific and unique sequence, to the same channel, simultaneously and asynchronously (Mengsu, 2012). Consequently, the code sequences need good correlation properties, especially with low cross-correlation, with the purpose of reducing MAI (Bazan, 2017). Moreover, the system's performance can be affected by several noises originating from the physical effect of the system design itself, such as Phase Induced Intensity Noise (PIIN), thermal noise and shot noise (Rad & Salehi, 2006). PIIN is the most dominant noise close to MAI from overlapping (cross-correlation function) of the spectra from different users (Panda, 2017; Alderson, 2018; Mishra, Ravikumar, Tripathy, & Palai, 2018).

The incoherent OCDMA system can be implemented in one-dimensional (1-D), or two-dimensional (2-D) encoding over a spatial domain, spectral domain or hybrid spectral-spatial domain simultaneously (Jamil Abdullah, 2012; Jellali, Najjar, Ferchichi, & Rezig, 2017b). Various schemes have been proposed for one-dimensional incoherent OCDMA including Time Spreading (TS) and Spectral Amplitude Coding (SAC-OCDMA), where the codes are implemented in the time or frequency domains, respectively (Chung, Salehi, & Wei, 1989; Weng & Wu, 2001; Kadhim et al., 2015). The Spectral Amplitude Coding (SAC) technique was introduced in order to eliminate the influence of the MAI effect and further reduce the impact of the noises at the receiver as Phase Induced Intensity Noise (PIIN) by using codes with fixed in-phase cross-correlation, λ_c and by keeping it as small as possible (J. Y. Lee & Hwang, 2008; J M Nordin et al., 2012). An huge number of codes have been developed for the SAC-

OCDMA system including Modified Quadratic Congruence code (MQC) (Zou & Ghafouri-Shiraz, 2002; Shi & Ghafouri-Shiraz, 2016), Modified Double Weight code (MDW) (S. A. Aljunid et al., 2004; S. Aljunid & Zan, 2004; Salah & Alhassan, 2017), M-sequence code (SHAH, 2003; Huang & Yang, 2006; Moghaddasi, Mamdoohi, Noor, Hitam, & Anas, 2016) and Zero Cross Correlation code (ZCC) (Anuar, Aljunid, Saad, & Hamzah, 2009; Bakshi & Sarangal, 2016) to overcome the MAI effect. The previous studies of 1D codes exposed some limitations, such as a long code length and the increasing presence of MAI in the system. Wide bandwidth sources are required to accommodate more subscribers in the network that reducing the spectral efficiency (Arief, Aljunid, Anuar, Junita, et al., 2013; R.A. Kadhim et al., 2015; Kumawat & Kumar, 2017).

An alternative approach to increase sequence cardinality is by introducing 2-D OCDMA systems. 2D codes have been proposed to overcome the limitations of 1D codes through the combination of two resources (time, wavelength, spatial). The advantage of 2-D codes is due to their large cardinality with shorter code length, which allows a large number of simultaneous users to be supported by spreading the code in two domains. The 2-D scheme provides better performance in comparison to 1-D at the expense of greater complexity (Jamil Abdullah, 2012). The three schemes presented in this approach are wavelength hopping time spreading (WHTS), spectral/spatial and time/spatial. The 2D approach has the ability to reduce the effects of MAI and PIIN, accommodate a large number of active users at high data rates and increase spectral efficiency. For this reason, various codes have been proposed such as 2D MDW code (Arief, Aljunid, Anuar, Junita, et al., 2013; Jellali, Najjar, Ferchichi, & Janyani, 2018), 2D Flexible Cross Correlation Modified Double Weight (FCC/MDW) hybrid code (Nui Din Keraf, Aljunid, Ehkan, &

Safar, 2016), 2D Diluted Perfect Difference (DPD code) (H. Singh, Sheetal, & Singh, 2016; B. C. Yeh, Lin, Yang, & Wu, 2009), 2D MQC/M-sequence (C C Yang, Huang, & Chiu, 2007; Nui Din Keraf et al., 2016). However, these approaches can eliminate MAI by using the double balanced detection technique decoder. Nevertheless, the effect of PIIN still limits the system performance and the code length needs to be very long to accommodate a large number of users. (Jellali et al., 2017b). As a result, a new code with large cardinality, providing the ability to cancel the influence of MAI and to mitigate the PIIN effect with less complexity in the design, is required.

1.3 Research Objectives

The present work was introduced to develop a new 2D OCDMA coding system. The construction of the new 2D signature code is based on the combination of two 1D codes (1D ZCC and 1D MD codes), namely 2D ZCC/MD. The new 2D code is design to enhance the system performance as well as the cardinality of the OCDMA network. The basic fundamental of this exploration is to design a spreading code with significant correlation properties to suppress MAI effectively.

The objectives of this work can be summarized as follows:

1. To develop a new 2D spectral/spatial OCDMA code known as Two-dimensional Zero Cross-correlation Multi diagonal (2D ZCC/MD) code based on the ZCC and MD code families.