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Junita Mohd Nordin

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LIST OF ABBREVIATIONS

APD	Avalanche Photo Detector
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CW	Continuous Wave
DCS	Dynamic Cyclic Shift
EDFA	Erbium Doped Fiber Amplifier
EDW	Enhanced Double Weight
FBG	Fiber Bragg Grating
FWM	Four Wave Mixing
Gb/s	Gigabit per second
GF	Galois Field
LAN	Local Area Network
LED	Light Emitting Diode
MAI	Multiple Access Interference
Mb/s	Mega bit per second
MDW	Modified Double Weight
MFH	Modified Frequency Hoping
MQC	Modified Quadratic Congruence
NDSF	Non Dispersion Shift Fiber
NRZ	Non Return to Zero
OOC	Optical Orthogonal Code
OCDMA	Optical Code Division Multiple Access
OOK	On-Off Keying

PIIN	Phase Induced Intensity Noise
PIN	Positive Intrinsic Negative
PMD	Polarization Mode Dispersion
PRBS	Pseudo Random Binary Sequence
PSD	Power Spectral Density
RD	Random Diagonal
RF	Radio Frequency
ROF	Radio Over Fiber
RZ	Return to Zero
SAC	Spectral Amplitude Coding
SCM	Subcarrier Multiplexing
SLD	Super Luminescent Diode
SMF	Single Mode Fiber
SNR	Signal to Noise-Ratio
SPC	Spectral Phase Coding
SPM	Self Phase Modulation
TDMA	Time Division Multiple Access
WDM	Wavelength Division Multiplexing
WDMA	Wavelength Division Multiple Access
ZCC	Zero Cross Correlation

Pembangunan Kod Baru untuk Sistem Subpembawa Multipleks – Pembahagian Kod Berbilang Capaian Optik

ABSTRAK

Pertumbuhan penggunaan aplikasi- aplikasi internet dan multi media yang mendambakan jalur lebar telah membawa kepada penyelidikan pembangunan yang besar dalam mengoptimakan kapasiti jalur lebar dalam perhubungan optik, terutamanya dalam Pembahagian Kod Optik Berbilang Capaian (OCDMA). Di dalam kerja ini, satu kod baru di dalam kumpulan pengkodan amplitud spektrum OCDMA telah dibangunkan sebagai satu usaha untuk menangani keterbatasan yang dihadapi oleh kod- kod lain yang sedia ada di dalam kelas yang sama. Kerja ini juga menyumbang kepada pembangunan model matematik subpembawa hibrid sistem multipleks OCDMA berdasarkan kod baru dan penilaian prestasi sistem ini. Gabungan SCM dan skim OCDMA boleh dianggap sebagai bidang penyelidikan baru yang masih di peringkat awal, kerana kerja-kerja yang sering dijalankan dalam SCM adalah memberi keistimewaan untuk gabungan dengan bahagian skim pemultipleksan gelombang (WDM). Gabungan ini menunjukkan peningkatan dalam penggunaan jalur lebar komunikasi optik. Secara terperinci, tesis ini bermula dengan pembinaan kod yang jelas, dinamakan sebagai kod kombinasi pengulangan (RC) yang direka untuk mempunyai silangan sekaitan yang minimum iaitu satu, dengan fleksibiliti untuk memilih parameter kod seperti pemberat kod dan bilangan jujukan kod, bersama panjang kod yang minima. Pembangunan kod yang ringkas adalah berdasarkan kaedah kombinasi matriks untuk mengekalkan hanya satu silangan sekaitan di antara jujukan kod bagi mengurangan gangguan berbilang capaian (MAI).Terbitan matematik telah dijanakan untuk teori prestasi kod bagi menganalisa pencapaiannya di dalam sistem OCDMA. Simulasi dijalankan bagi menilai dan mengoptimakan parameter-parameter untuk prestasi terbaik di dalam sistem. Kajian ini memberi tumpuan kepada kesan jarak, kadar bit, format modulasi data dan kuasa input terhadap prestasi sistem.Validasi keputusan teori dengan keluaran simulasi juga dijalankan. Dari analisa prestasi, kod ini mempamerkan prestasi yang lebih baik berbanding kod-kod lain di dalam kelas yang sama.Dari segi kardinaliti, kod ini mampu menampung sebanyak 105 pengguna serentak dengan kebenaran kadar ralat 10^{-9}. Dapat ditunjukkan bahawa menggunakan kod RC, SCM OCDMA boleh menampung sehingga 28 saluran subpembawa untuk BER lebih baik daripada 10^{-9}. Sebaliknya, kod MDW, hanya boleh menampung sehingga 20 saluran subpembawa. Model simulasi juga dibangunkan untuk sistem SCM OCDMA, di mana beberapa perbandingan dibuat bagi prestasi sistem tersebut. Kesimpulannya, sumbangan besar tesis ini terletak dalam pembangunan kod baru yang mempamerkan pembinaan kod yang sangat mudah dan sesuai bagi memudahkan pelaksanaan dalam rangkaian praktikal. Dengan menggunakan kod ini, menambah pengguna baru dalam rangkaian tidak memerlukan pengubahsuaian rangkaian yang sedia ada; nod boleh ditambah pada panjang gelombang yang ada seterusnya di sepanjang jalur lebar diduduki. Pada masa yang sama, menambah berat kod tidak akan mengubah apa-apa parameter lain. Dalam erti kata lain, reka bentuk kod ini mengekalkan keperibadian setiap parameter kod, oleh itu menjadikannya kod yang lebih fleksibel berbanding dengan yang lain. Selain daripada itu, model teori dan simulasi yang diperolehi untuk sistem hibrid subpembawa multipleks OCDMA berdasarkan kod RC telah merealisasikan pendekatan yang berpotensi dalam meningkatkan kecekapan penggunaan lebar jalur komunikasi optik.

Development of New Code for Subcarrier Multiplexed – Optical Code Division Multiple Access System

ABSTRACT

The growing utilization of bandwidth hungry applications of the internet and multimedia applications has lead to tremendous research development in optimizing the bandwidth capacity in optical communication, particularly in Optical Code Division Multiple Access (OCDMA). In this work, a new code in the family of Spectral Amplitude Coding (SAC) OCDMA has been developed in an attempt to overcome the limitations faced by other existing codes of the same class. This work also contributes to the development of mathematical model of hybrid subcarrier multiplexed OCDMA system based on the new code and its performance evaluations. The combination of Subcarrier Multiplexing (SCM) and OCDMA scheme can be regarded as a new research area which is still in its infancy, since most work on SCM gives privilege to the combination with Wavelength division multiplexing (WDM) scheme. This combination demonstrates an improvement in bandwidth utilization of optical communication. In particular, this thesis begins with an explicit construction of the code, namely the Recursive Combinatorial (RC) code that is designed to have a minimum cross correlation of one, with the flexibility of choosing the code's parameter, such as the code weight and number of code sequences, with minimum code length. The simple code development are based on the matrix combinatorial method to maintain the cross correlation of one between the code sequences, that reduces the Multiple Access Interference (MAI). The mathematical derivation of this code's performance is then generated to analyze its performance in the OCDMA system. Simulations are carried out to evaluate and optimize the parameters for best performance in the system. The study focuses on the effect of distance, bit rate, data modulation format and input power on the systems performance. Validations of theoretical results by simulations are also conducted. It is shown from the performance analysis that this codes exhibits better performance compared to other codes in the same class. It is shown in term of cardinality; this code could accommodate up to 105 users simultaneously at a permissible bit error rate of 10^{-9}. In the hybrid SCM OCDMA using RC code, this system could accommodate up to 28 subcarrier channels for BER better than 10^{-9}. On the other hand, the MDW code, as compared, can only accommodate up to 20 subcarrier channels. A simulation model is also developed for the SCM OCDMA system, where some comparisons are being made on its performances. In short, the significant contribution of this thesis lies in the development of a new code exhibiting a very simple code construction, which is suitable for the ease of implementation in a practical network. Adding new users in the network using this code does not require modifying the existing network; nodes can be added at the next available wavelength along the bandwidth occupied. At the same time, adding up the code weight will not change any other parameters. In other words, this code design retains the individuality of each code parameter, hence making it a more flexible code compared to others. Apart from that, the theoretical and simulation model derived for a hybrid system of subcarrier multiplexed OCDMA based on RC code has realized a potential approach in improving the bandwidth utilization efficiency of optical communication.

CHAPTER 1

INTRODUCTION

1.1 Project Background and Motivations

Recent years have seen the rapid growth of bandwidth hungry broadband access network for applications such as internet, High Definition TV (HDTV), triple play services, multimedia applications and gaming, which keeps the network, and service providers busy finding ways of connecting the network up to the last mile solutions. Conventional communication links such in wireless communication and satellite communications are already left with the bandwidth constraints to provide high speed data for various new services over the communication network.

Optical communications came along taking the attention more than two decades ago because of the huge amount of bandwidth it offers. Optical fiber has then been widely deployed in long haul networks which carry a huge amount of information over long distances. However, to provide high speed data to the increasing broadband populations, the research and development in the optical communications are focused on the techniques for providing bandwidth efficient multiple access formats and protocols (Fouli & Maier, 2007, Kwong, 2005). In the optical communication, there are three major multiple accesses, which are the Optical Code Division Multiple Access (OCDMA), Wavelength Division Multiple Access (WDMA) and Time Division Multiple Access (TDMA). Even their combination is proposed and improved.

In TDMA, the concept is to increase the bit rate carried by a single optical wavelength, where high bit rates are achieved by using very short pulses. This technique, however, are sensitive to dispersion (due to the wide bandwidth nature of the

signal) and nonlinearities. As technology grew, WDMA seems the best solution. WDMA principle makes better use of the optical fiber bandwidth by allocating each user a single wavelength. One advantage of WDMA over TDMA is that it usually uses lower bit rates and optical power in each channel, yet achieving higher network capacity. However, WDMA is also limited by some factors such as limited wavelengths when it comes to large number of users. Hence, unfortunately, it is obvious that both multiple access present significant drawbacks in local area systems requiring large number of users (P. Prucnal, Santoro, & Ting, 1986; P. R. Prucnal, 2006). Also, the maximum transmission capacity for TDMA and WDMA depends on the total number of time slots and wavelength channels respectively (Yin & Richardson, 2007).

The most popular multiple access technique nowadays is the OCDMA (Fadhil, H.A., 2012; Eltaif, Shalaby, Shaari, & Hamarsheh, 2009; Lin, Huang, & Yang, 2007; Weng & Wu, 2001) due to its advantages over WDMA and TDMA. In OCDMA, users are distinguished by assigning them an unique optical code. Hence each data bits are signed by this optical code to differentiate it from other users. This coding scheme allows users to share the same wavelength with asynchronous operation. In addition, it offers resilience against eavesdropping because of the coding (Spuensens, 2008). In term of scalability, OCDMA can accommodate higher number of subscribers compare to TDMA or WDMA. Multi rate OCDMA scheme allows the low and high bit rate channels transmitting on the same OCDMA network. Hence, the current demand of variable bit rates operation can thus be fulfilled. The OCDMA also does not require centralized network control. A self-routing is coded with assigned users where bandwidth is effectively utilized. Due to this, the complicated routine algorithm such in other multiple access schemes is reduced. In term of information security, the information data are protected in both the code level and transmission medium level in

OCDMA. It is free from packet collisions, resulting in very low latencies. Eavesdroppers could not intercept the information data without knowledge of which code is being used to send the particular data to a particular user. Unlike TDMA, an asynchronous access protocol permits OCDMA to be randomly and simultaneously accessed without timing synchronization. A dynamic bandwidth allocation and soft capacity on demand makes it flexible wavelength control, with adding and removing subscribers (Dexter, et al., 2009; Yin, Liang, Ma, & Qin, 2009). The advantages and disadvantages of these three schemes are summarized in Table 1.1.

Table 1.1: Comparison of Common Optical Multiple Access Schemes (Yin & Richardson, 2007).

Multiple Access Schemes	Advantages	Disadvantages
1. TDMA	a. Dedicated channels provided b. High throughput c. Deterministic access	a. Accurate synchronization needed. b. Bandwidth wasted c. Channel not efficiently used d. Deterioration of performance as number of users increases.
2. WDMA	a.Dedicated channels provided b. Simultaneous users allowed c. High bandwidth efficiency d. Simultaneous users allowed	a. Channel crosstalk b. Channel idle most of the time c. Non-linear effects
3. OCDMA	a. Simultaneous users allowed b. Asynchronous access c. No delay or scheduling d. High bandwidth efficiency e. Efficient for bursty traffic. f.Dedicated channels provided	a. Performance degrades with increase the number of simultaneous users.

OCDMA is basically distinguished by the coding domain, which is time, wavelength or both. They are also differentiate by the coding principle, which is either coding is in optical intensity or in the optical field. In time domain implementations, the coding rate has to be higher than the data rate, thus requiring a high speed data rate even to transmit data at a moderate rate. Subsequently, high speed electro-optics equipment which is generally expensive, are required, thus leaving the time domain implementation not to be very popular for access networks. Wavelength domains are split into two, which are the coherent and incoherent implementations. The coherent wavelength domain implementation applies phase shifts on spectral components of an optical pulse. These systems require accurate phase control which makes them expensive (Spuensens, 2008).

In the incoherent wavelength domain implementation several frequency bins from a broadband source are dedicated to the users. Incoherent OCDMA systems are known not just for their cost-effective implementation, but also for their sensitivity to multiple access interference (MAI), that results when large number of simultaneous users transmit at the same time and on the same common channel (Aljunid, Ismail, et. al, 2004). In addition, there are other noises arising from the physical effect of the system design itself, such as Phase Induced Intensity Noise (PIIN), thermal noise, and shot noise (Fadhil, H.A. et. al, 2009a; Shin-Pin & Jingshown, 2010)**.** Here, the overlapping spectra from diverse users creates cross correlation function that relates the PIIN with the MAI (Aljunid, Ismail, et al., 2004; Fadhil, H.A.,et. al 2012)**.** These drawbacks leave a challenge to OCDMA's researchers to find ways on reducing the MAI and also the PIIN noise.

Among all the OCDMA approaches the Spectral Amplitude Coding OCDMA (SAC-OCDMA) technique attracts much attention due to its capability to remove the

MAI completely by spectral coding (Kavehrad & Zaccarin, 1995). Theoretically, the MAI can be removed when using code with fixed in phase cross-correlation (Shin-Pin & Jingshown, 2010). Hence, an intelligent design of code sequence is necessary to eliminate the effect of MAI in OCDMA systems (Stok & Sargent, 2000). It is desirable to design a code that exhibits a low cross correlation characteristic between its code sequences, which in turn minimized the overlapping bits between the codes.

Although some few codes have been developed to restrain the PIIN noise or to remove the MAI for SAC OCDMA, these codes still suffer from some limitations. They suffer from high cross correlation values, e.g. Hadamard (Li & Chan, 1997) and Random Diagonal (H.A. Fadhil, Aljunid & Ahmad, 2009c), exist for only certain parameters, for example in Modified Quadratic Congruence, MQC (Zou, Ghafouri-Shiraz & Shalaby, 2001a) only exist for prime numbers, and prime power in Modified Frequency Hopping, (MFH) (Zou & Ghafouri-Shiraz, 2002a), only double weight in Double Weight (DW) code, an even number or odd number of weight in Modified Double Weight, MDW (Aljunid, Ismail, et al., 2004; Aljunid, Zan, Anas, & Abdullah, 2004), and Enhanced Double Weight, EDW (Abdullah, Hasoon, Aljunid, & Shaari, 2008); and also long code lengths such as Optical Orthogonal code (J. A. Salehi, 1989a), Prime code (G. C. Yang & Kwong, 1995) and Zero Cross Correlation (ZCC) code (Anuar et. al, 2007). Long code length requires a very wide bandwidth sources, hence it is considered a disadvantage in the code design implementation. Hence, there are still rooms of improvement in the OCDMA research and development to find a better code design that could overcome the limitations of the existing codes.

Another challenge in the key design issues of OCDMA lies in the spread spectrum nature of the OCDMA, making it an access scheme with lower spectral efficiency (Yan, 2008) compared to WDMA. Hence, one way of increasing the spectral efficiency of

OCDMA is by having hybrid system such as the OCDMA - WDMA (Kitayama & X. Wang, 2006; Galli, 2008; Djordjevic, 2004) or combining it with subcarrier multiplexing (SCM) scheme. In multi-service environments of high density communication network such in metropolitan area, the transmission capacity and the number of simultaneous users can be enlarged by using the subcarrier multiplexing (SCM) scheme that enables multiple RF signals to be transmitted simultaneously over the fiber-optic links (Kim, K. et.al., 2010).

The SCM is an attractive technique where it provides the independency of different channels. This allows for great flexibility in the choice of modulation schemes. With this technique, the information signals are modulated onto different electrical subcarriers in the radio or microwave domain and combined together to modulate the intensity of an optical carrier (Khaleghi & Kavehrad, 1995). At the receiving part, a photo detector will convert the optical signal into an electric current. To retrieve the original signal, the electric current will then be demultiplexed and demodulated using a conventional method. One significant benefit of SCM is that the electrical components and equipments are far less expensive than its optical counterparts are. In fact, the low implementation cost of SCM system has been proposed to transmit multi channel digital optical signals for LAN (Rongqing, et al., 2002).

The research on SCM in optical system has mostly been on the combination with WDMA scheme and been used for Radio-over-Fiber (RoF) or Fiber-Wireless (Fi-Wi) networks. To date, there are quite a number of published works done on the Fi -Wi or RoF networks architecture, mostly proposing on the WDM architecture on the optical side (Ghazisaidi and Maier, 2009 & 2011; Lim et. al, 2000, 2001 & 2003; Koonen, 2006; Wen et.al, 2003; and Opatic, 2009). Figure 1.1 illustrates a typical SCM-WDM architecture.

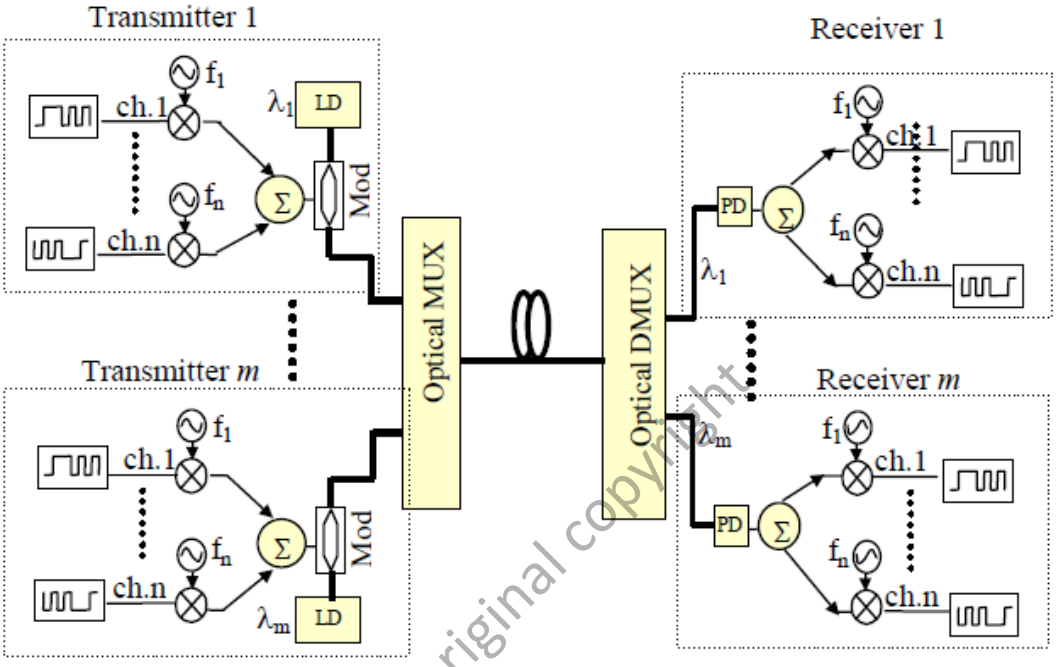

Figure 1.1: SCM/WDM basic architecture (Hui, R. et. al., 2004).

On the other hand, related work on the area of SCM-OCDMA has only been found in (Sahbudin et al., 2009; Sahbudin et al., 2011), where the authors evaluated the performance of this hybrid technique based on different detection techniques using one of the existing codes. Yet, the work on hybrid SCM-OCDMA technique still requires more attention. Considering this, in this thesis, a new code for the OCDMA is proposed and the hybrid SCM-OCDMA system based on this new code is developed theoretically and in simulation to investigate the system performance with various design parameters.

1.2 Research Objectives

Following the project motivations described in the previous subsection, this dissertation is orientated by the following research objectives:

i. To develop a new Spectral Amplitude Coding OCDMA code that have the following properties: minimum cross correlation of one with minimum code