DESIGN AND PERFORMANCE ANALYSIS OF NOVEL SIGNATURE CODE IN TWO-DIMENSIONAL OPTICAL CDMA SYSTEMS

BY

Mengsu Zhang

A thesis submitted to
The University of Birmingham
for the degree of
MASTER OF PHILOSOPHY

COLLEGE OF ENGINEERING AND PHYSICAL SCIENCE
SCHOOL OF ELECTRONIC, ELECTRICAL AND COMPUTER ENGINEERING
March 2012

Abstract

As a scheme of multiple access, Optical Code Division Multiple Access (OCDMA) technology has many outstanding advantages such as large capacity, high security and excellent anti-interference ability, which make OCDMA a forefront topic of research in all-optic access networks. In this thesis, we introduce OCDMA technology in detail, especially 2-Dimensional (2D) OCDMA system. A novel signature code named nMPHC (new-Modified Prime-Hop Code) is designed for 2D system and its performance is analyzed in different system configurations under various circumstances against two similar-structured codes named PHC (Prime-Hop Code) and MPHC (Modified Prime-Hop Code). Results show that nMPHC can reduce the same amount of system complexity by decreasing less supported users than MPHC and nMPHC outperforms MPHC in most cases, it is proved that nMPHC is a good candidate for future 2D OCDMA system.

Acknowledgements

I would like to use this opportunity to express my sincere gratitude to my supervisor, Dr. Hooshang Ghafouri-Shiraz, for his continuous encouragement, advice and motivation that enabled me to achieve all goals to complete this research to the best of my standard. His insight and knowledge makes him a significant person to me. It is my great honour to be his student.

I have to specially thank my colleagues and friends Mohammad Hossein Zoualfaghari and Abubakar Tariq to give me helpful suggestions and constant encouragement during my research of this project.

Contents

List of Figures

List of Tables

List of Abbreviations

1D	1-Dimensional
2D	2-Dimensional
2G	Second Generation
3G	Third Generation
AC	Auto-Correlation
ASE	Amplified Spontaneous Emission
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BER	Bit-Error-Rate
BN	Beat Noise
CC	Cross-Correlation
CCR	Conventional Correlation Receiver
CDF	Cumulative Distribution Function
CDMA	Code-Division Multiple-Access
CL	Code-Length
CRC	Cyclic Redundancy Check
CW	Code-Weight
DARPA	Defence Advanced Research Projects Agency
DSSS	Direct Sequence Spread Spectrum
EDFA	Erbium-Doped Fibre Amplifier
EKL	Effective Key Length
EQC	Extended Quadratic Congruence
FBG	Fibre Bragg Grating
FDM	Frequency-Division Multiplexing
FDMA	Frequency-Division Multiple-Access
FEC	Forward Error Correction
FHSS	Frequency-Hopping Spread Spectrum
FIFO	First-In-First-Out
FTTH	Fibre-To-The-Home
GF	Galois Field
InP	Indium Phosphate
IP	Internet Protocol

LANs	Local Area Networks
LFSR	Linear Feedback Shift Register
MAC	Medium Access Control
MAI	Multi-Access Interference
MCP	Maximum Collision Parameter
MPHC	Modified Prime-Hop Code
MUI	Multi-User Interference
nMPHC	New-Modified Prime-Hop Code
OCDMA	Optical Code-Division Multiple-Access
OCS	One Coincidence Sequence
OOC	Optical Orthogonal Codes
OPC	Optical Prime Code
OTDL	Optical Tapped Delay Line
OTDM	Optical Time-Division Multiplexing
OWDM	Optical Wavelength-Division Multiplexing
PC	Prime Code
PDF	Probability Density Function
PER	Packet Error Rate
PHC	Prime-Hop Code
PIC	Parallel Interference Cancelation
PN	pseudo-noise
RIN	Relative Intensity Noise
SIC	Successive Interference Cancelation
SLD	Super-Luminescent Diode
SLMs	Spatial Light Modulators
SNR	Signal-to-Noise-Ratio
SOA	Semiconductor Optical Amplifiers
SONET	Synchronous Optical Network
SPC-OCDMA	Spectral Phase Coded Optical CDMA
SS	Spread Spectrum
TDM	Time-Division Multiplexing
TDMA	Time-Division Multiple-Access
THSS	Time-Hopping Spread Spectrum
TPC-OCDMA	Temporal Phase Coded Optical CDMA
WDM	Wavelength-Division Multiplexing
WHTS	Wavelength-Hopping/Time-Spreading

Chapter 1
Motivations and Objectives

1.1 Thesis Structure

This thesis will be constructed as following:

In Chapter 1, the motivations for the research of this project are stated, as well as the aims and objectives.

In Chapter 2, we introduce the principles of CDMA technology in modern communication systems and compare with FDM (Frequency-Division Multiplexing) and TDM (Time-Division Multiplexing) technologies in different aspects to show the reason why CDMA has became more attractive recently. The implementation of CDMA technology in all-optic networks is introduced and is compared to radio CDMA and wireless CDMA techniques to demonstrate how optical fibre communications bring CDMA enormous improvement and development. Current research concerns and challenges of OCDMA technology are reviewed.

In Chapter 3, we systematically describe an OCDMA system in several aspects. First of all, an intuitive cognition of OCDMA system is given by schematics and graphs. Then we discuss about coherent OCDMA and incoherent OCDMA systems to show that incoherent system is becoming the mainstream of OCDMA applications. Later, some key technologies in OCDMA system will be concerned, various address signature sequences and encoder/decoder structures are introduced and discussed with each other.

In Chapter 4, 2D OCDMA system and Wavelength-Hopping/Time-Spreading (WHTS) coding scheme will be introduced. Codes generated under the theory of WHTS are introduced, analyzed and compared with each other. In addition, some of the transceiver structures in 2D OCDMA system are introduced and their performances are analyzed.

In Chapter 5, a WHTS code named Prime-Hop Code (PHC) and its modification named Modified Prime-Hop Code (MPHC) are introduced, we analyze their properties and system performance to give the motivation of the design of a novel code named New-Modified Prime-Hop Code (nMPHC). The properties and performance of nMPHC are analyzed by a newly proposed mathematical model against PHC and MPHC.

In Chapter 6, the concept of IP routing over OCDMA networks is introduced, the possible noises involved in transmission are introduced. The system performances of MPHC and nMPHC in IP-over-OCDMA system are analyzed and compared in the presence of various noises under different network utilizations.

In Chapter 7, three network random access protocols are introduced for OCDMA system. The system throughputs by employing MPHC and nMPHC with Conventional

Correlation Receiver (CCR) are analyzed and compared.

In Chapter 8, the structure and the principles of a Parallel Interference Cancelation (PIC) receiver are introduced and tested with MPHC and nMPHC. The analysis results show that with the use of PIC nMPHC can greatly improve system performance.

In Chapter 9, conclusion is drawn and work for future researchers is suggested.

1.2 Challenges and Motivations

In incoherent OCDMA system, each data bit is sent as a sequence of optical pulses by a procedure called time-spreading (spread-spectrum communication). At the receiving end the data is retrieved by correlating the received signal with its own sequence. Many users can access the same channel simultaneously and asynchronously as CDMA assigns each user a specific and unique sequence. For the reason that data can be successfully deciphered at the receiver, the correlation properties of these sequences must be good enough to be observed. This will result very long and sparse sequences with poor cardinality (the largest user number that can be supported by the sequences) of the code family.

In order to obtain better throughput and larger cardinality it is possible to integrate CDMA with Wavelength-Division Multiplexing (WDM) which is an asynchronous technique as well. A hybrid system is built by applying the time-spreading pattern to a wavelength-hopping scheme, as a result the pulses transmit at different time slots and hop between various wavelengths conducting by a certain route simultaneously, hence this technique is labelled Wavelength-Hopping/Time-Spreading (WHTS).

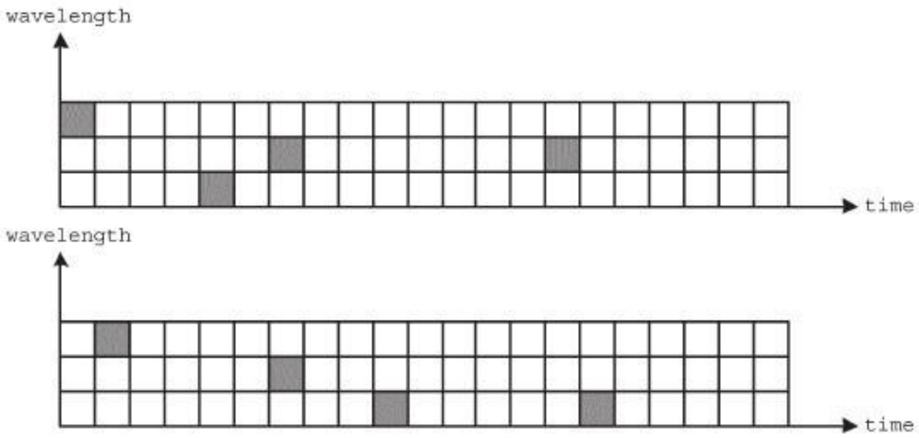


Figure 1 WHTS Sequences (from [15])

Figure 1 WHTS Sequences[15] shows 2 WHTS sequences with 21 time slots and 3 wavelengths. In comparison with time-spreading sequences without wavelength-hopping, more positions can be allocated for pulses, as a consequence the probability of interference between pulses in distinguishing sequences are reduced. For the same number of pulses WHTS has lower possibility to cause a collision, therefore the correlation properties have been improved. By remaining similar correlation properties to time-spreading sequences, code-length of WHTS sequences can be greatly reduced. Most of proposed WHTS codes have optimal correlation properties with Cross-Correlation (CC) equals to 1 and needle-shape Auto-Correlation (AC) peak with zero side-lobe. These were the origin to make efforts on WHTS sequences.

Hit probability of pulses between different sequences is directly related to system performance especially the Bit-Error-Rate (BER), little difference in average hit probability will result visible improvement in BER. In other words, for the same BER level (e.g. 10^{-9}) WHTS code accommodates more simultaneous users, that means the cardinality of the code family has also enlarged. In addition, the confidentiality of WHTS sequence is stronger than time-spreading sequences since the eavesdropper has to try $\binom{N_T}{w} \times w!$ possible code patterns to find the desired code in WHTS system but $\binom{N_T}{w}$ attempts are enough to compromise the system for time-spreading system. Where N_T is the number of time slots and w is the code weight.

To conclude, the motivation for researching on WHTS sequences is that it provides lower CC with zero AC side-lobe, larger cardinality at reduced code-length and better system performance (BER, confidentiality etc.).

1.3 Objectives

The objectives of this project:

a) Design of novel WHTS signature code by modification of existing time-spreading (wavelength-hopping) codes or by self-designed codes.

b) Performance analysis by comparing the newly designed code with similar-structured WHTS codes designed by previous researchers.

c) Apply the newly designed code in IP-over-OCDMA network to analyze its performance and to compare with previously proposed code, and to demonstrate the improvements in BER and Packet Error Rate (PER).

d) Examine the newly designed code by applying various random access protocols on it and compare the system performance with previously proposed code, and to verify the enhancement on system throughput.

e) Try the newly designed code with the transceiver structure introduced in [38] to minimize the interference between users, hence to maximize the improvement on system performance.

Chapter 2
Introduction

2.1 Overview of CDMA Technology

CDMA or Code Division Multiple Access is a type of communication using multiplexing. It provides a means of "multiple access to a physical medium". This medium can be a radio channel where a number of users use the medium simultaneously by utilizing different and unique orthogonal code sequences. The CDMA interface is related to the air interface only which is associated with the radio component of technology. CDMA facilitates the operators to offer network features as it finds suitable. CDMA best corresponds with data transfer where delays are expected and which possesses "burst behaviour" known as asynchronous data transfer. Various CDMA based technologies have been developed which help in radio transmission and wireless networks [1].

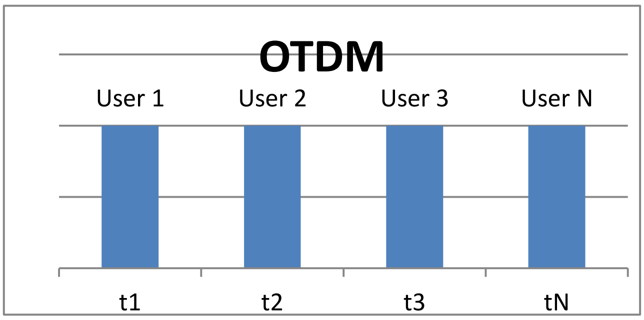
CDMA is also referred to as Spread Spectrum Multiple Access or SSMA. CDMA does not require the time synchronization for every user as required in Time-Division Multiple-Access (TDMA). It also does not require bandwidth allocation which is required by Frequency-Division Multiple-Access (FDMA). The advantage of CDMA is that the user has full bandwidth as well as full time available. But, the drawback is that the communication quality decreases as the number of users increase in the network. CDMA technology is widely used in communication systems using radio frequency like 3G and 2G networks for cellular telephone [2].

2.2 CDMA Implementation in Optical Fibre Networks

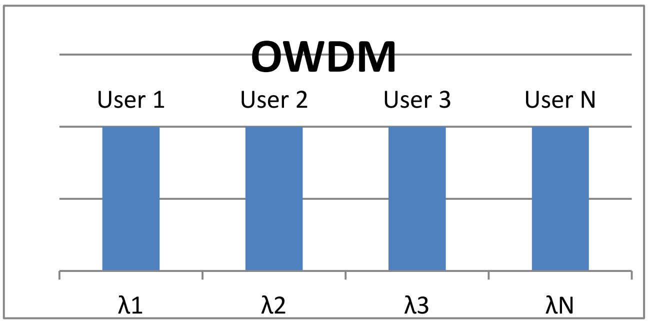
Optical communications has made rapid strides in recent years and the use of optical fibre telecommunication backbone trunks have revolutionized the field of telecommunication. OCDMA can be described as a “next generation CDMA” technology which uses fibre-optic technology [3]. Optical fibres use light pulse stream to transmit messages. Optical signal travel at much higher speed than electrical ones and give a higher bandwidth as well. The excess bandwidth offered by fibre-optic CDMA facilitates the conversion of low information rates of electrical data into high rate optical signals [4]. In earlier communication methods, different messages are divided from each other by a method known as WDM or Wavelength Division Multiplexing. In WDM, every message employs a separate wavelength of light. However, OCDMA uses a different approach. Here, every bit of information is encoded and spread across several time slots or hop across several wavelengths. On the receiving side, a key is used to decode the message and the original information is recreated. OCDMA does not require every user to use a separate wavelength. Earlier, existing optical fibre network backbones were accessed by users with the help of wireless or electronic connections which were much slower than the backbone. However, with the development of OCDMA devices it can become possible to connect to the network backbone by secure and fast link [5]. As in wireless applications, OCDMA can also transmit data asynchronously without packet collisions. Since OCDMA systems use the existing fibre-optic backbones, the implementation is relatively simpler than other technologies [2]. Table 2 shows comprehensive comparisons of OTDM (Optical Time-Division Multiplexing), OWDM (Optical Wavelength-Division Multiplexing) and OCDMA technologies.

OTDM	1, High bit-rate to bandwidth ratio; 2, Low non-linear influence on optical devices in transmission progress.	1, Low overall cost of equipments; 2, But low cost-effective because of low system capacity.	1, Extreme exact synchronization in high rate transmissions; 2, Low system capacity; 3, Low bandwidth efficiency.	Partially realized in practical applications.
OWDM	1, More matured techniques; 2, Very high bandwidth efficiency; 3, High system capacity; 4, 10Tbits/s rate can be achieved in a single fibre as from experiments.	1, High overall cost of equipments; 2, But high cost-effective because of great expansion of bandwidth.	1, Accurately adjustable laser source is needed; 2, Strict requirement on laser source synchronization; 3,Lack of low rate multiplexing points.	Backbone networks and main multiplexing technique used in optical communications currently.
OCDMA	1, Less optical-electronic-optical conversions; 2, High security and privacy in transmissions; 3, Asynchronous access; 4, High anti-interference ability; 5, No accurate synchronization needed; 6, Looser requirement for system components.	1, Less expensive in equipments and system supporting costs than OWDM system.	1, Few appropriate coding sequences and encoder/decoder in practice so far; 2, Few breakthrough improvements in realization progress.	Rarely practical implementations at this stage.

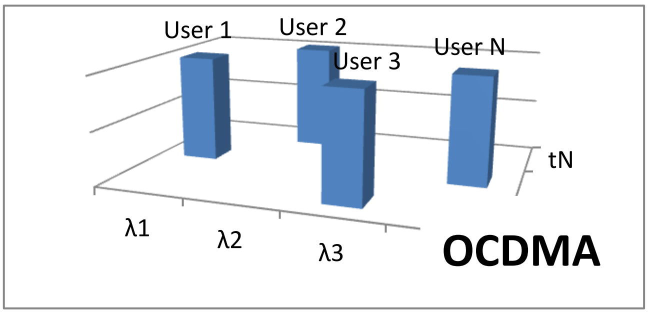
Table 1 Comparisons of OTDM, OWDM and OCDMA techniques.



(a)



(b)



(c)

Figure 2 Basic characteristics of OTDM (a), OWDM (b) and OCDMA(c).

Figure 2 shows the basic characteristics of OTDM, OWDM and OCDMA regarding different time slots and wavelengths. OCDMA can been seen as a combination of OWDM and OTDM, however, OCDMA encodes each user's data bit with sets of different time slots and different wavelengths rather than assigns each user with unique OWDM and OTDM channels. A communication system based on optical technology cannot transmit binary data streams consisting of +1 and -1 signals. It can only send binary data of the form 0 and 1. The reason is that an optical system is unable to distinguish between the various phases of light or optical signals. Therefore, an optical system can detect signals only by determining the power or energy of the light signals. However, a drawback is that there is considerable attenuation loss over long distances which have to be offset by using numerous repeaters on the optical trunk line. This is somewhat unavoidable since fibre-optic cables are almost always laid over large distances, sometimes even under the ocean [3].

OCDMA facilitates the simultaneous access of multiple users to the network asynchronously. It has gained a lot of popularity in recent times due to the fact that it is almost delay-free and it necessitates very less optical signal processing. OCDMA uses asynchronous data transmission which can make network control and management quite simple. Thus, OCDMA is well-suited for network applications like LANs (Local Area Networks). OOC (Optical Orthogonal Code) lets every node operate in an asynchronous mode without the requirement of a Global Clock. Since the number of network nodes is equal to the number of codes, the requirement of a central node for arbitration between channels is not there. Addition of new users is also quite easy provided that extra codes are available. In case, extra codes are not available, system upgradation to increase time slots and wavelengths can be carried out. OCDMA offers dynamic coding which makes the network connection very secure [3] [6]. That means the optical codes can be altered any time and since the frequencies that are used change frequently and rapidly, it becomes extremely tough for eavesdroppers to snoop into a transmission without having access to the key [5]. For instance, to check every possible combination of 961 chips or time slots and 41 wavelengths at the rate of 10^7 codes per second, it will take an eavesdropper more than a thousand years which makes the possibility of a security lapse extremely remote. OCDMA also provides service differentiation since different groups of multimedia can be classified by employing multi-rate OOC, where data rate is the number of transmitted data bits within a certain time duration. High rate codes can be used for video or audio information and low rate codes can be used for file transfer and e-mail [7].

2.3 Comparison of OCDMA and Radio/Wireless CDMA

A CDMA communication system based on optical codes is quite different from radio and wireless systems and possesses unique attributes and advantages. OCDMA possesses various advantages like employing optical processing to carry out certain network applications like routing or addressing without having to go through complex multiplexing and de-multiplexing. One of the unique attributes of optical communications is that the noises produced by optical communications have different properties and principles as compared to wireless or radio. These noisy elements are thermal noise, photo-detector shot noise, beat noise, etc. Optical communication systems employ different wavelengths to separate various signal channels whereas wireless communication systems employ different frequencies to separate various signal channels. Optical systems possess relatively more bandwidth than wireless or radio systems. Therefore, the concern of improvement of bandwidth efficiency becomes less important in an optical system as compared to other systems in which the spectral resource is saturated and more efforts have to be put to improve bandwidth efficiency.

In an optical system, the strength of signal is more stable than that in a wireless system because unlike the radio frequency signal, the optical fibre cable signal is not easily disturbed or affected by external disturbance. Therefore, optical fibre based technologies are well-suited for extremely high-quality transmissions. Optical fibre based communication is also an excellent candidate to conduct high security transmissions since the energy emissions to external environment is almost negligible, this is because the optical fibre cable can retain most of the transmitted power within itself. Furthermore, there is equivalent attenuation loss for various wavelengths in an optical system. In an optical system, system signal modelling is much easier than in a wireless system owing to that the optical system signal modelling is scalar-based rather than vector-based since signal detection is processed by scalar-based power or energy level detection [3].

Comparisons between OCDMA and radio CDMA reveals that the Signal-to-Noise-Ratio or SNR is very poor for radio CDMA whereas it is quite good for OCDMA [7]. The bit rate is very high for OCDMA whereas it is relatively low for radio CDMA. Radio CDMA is non-dispersive whereas OCDMA is dispersive in nature. Voice activity is easy to implement in radio CDMA whereas it is relatively difficult to implement in a “high bit-rate aggregated traffic”. With the help of Optical Orthogonal Codes (OOC), OCDMA can offer a large division of bandwidth. This helps the designers to manipulate spreading as per the needs of a particular system which is being designed [7].

2.4 Research Background and Challenges

Currently the aspects of OCDMA on which research efforts are being organized are (a) coding algorithms and techniques, (b) network architecture, scalability assessment, and applications, (c) advanced photonic encoding and decoding hardware and components. These are the thrust areas which will expand this technology to develop and implement an advanced and futuristic OCDMA system. Innovations in the field of ultrafast optical subsystems and components which include multi-wavelength laser sources, ultra-soft time slot tuners and all-optical de-multiplexers have also helped speed up research in OCDMA techniques [8]. There has been an effort to recreate the success of frequency hopping CDMA techniques of wireless networks in fibre-optic networks. However, this task has proved to be quite tricky as the capability of the current-day radio transmitters to rapidly alter transmission frequencies is lacking in fibre-optic networks. A clever solution to this challenge is the use of a number of gratings to produce a “hopping pattern” [9].

A particular DARPA (Defence Advanced Research Projects Agency) sponsored OCDMA project worked on the development of a single chip-scale OCDMA system. This involved focusing on various OCDMA technologies like Orthogonal Optical Coding, Indium Phosphate (InP) device fabrication OCDMA network architecture simulation and design. In this InP device, the following components were integrated on a common chip: phase coding device using a phase modulator, threshold detector in the form of SOA (Semiconductor Optical Amplifiers) based Mach-Zehder Interferometer, ultra-short pulse source in the form of Photonic Band-gap and a spread spectrum device in the form of Arrayed Wave-guide Grating (AWG). They used spectral phase encoding instead of temporal amplitude coding. The benefit of using this type of encoding is that the high-speed nature of the time-spreading signals is maintained all through the system. Therefore, in order to achieve encoding or decoding, signal bandwidth is not sacrificed with an increase of code complexity [3].

In 2004, an innovative system based on spectral OCDMA was developed by the University of Colorado at Boulder and Boulder Nonlinear Systems. This system had bipolar code capability which could be used in “ultra high speed communications applications”. This system uses liquid crystal Spatial Light Modulators (SLMs) to form a “reconfigurable two-user encoder-decoder system” which depends on a fibre test bed having liquid crystal SLMs arranged in three arrays. The spectral encoding and decoding was done by a broadband Super-Luminescent Diode (SLD) source which was amplified with the help of an Erbium-Doped Fibre Amplifier (EDFA). According to the Bit Error Rate (BER) measurements, this system has the capability to carry out Multiple Access Interference (MAI) rejection. It is possible for this system to retain its compactness despite being burdened with a large number of users. This is done with the help of two-dimensional, large format SLMs. Since this optical system can carry out two-dimensional operations and is programmable, it is well-suited for implementation of “optically transparent routings in an ultrafast Asynchronous

Transfer Mode (ATM) switch" [10].

Even though fibre-optic technology has the property of high bandwidth needed for backbone transmission in a super fast communication network, the development of a high bandwidth optical network has remained a challenge due to the fact that the following vital elements are not present simultaneously as part of a single technology. These critical elements are: (i) optical header recognition, (ii) high speed switching corresponding to an optical fibre's high data capacity, (iii) high speed optical memory, and (iv) expansion and integration of the afore-mentioned operations by WDM and CDMA [11].

However, there are certain technological barriers to general acceptance of OCDMA technology. One of these barriers is the shot and beat noise which results from optical power generated by other users operating on same wavelength channels. There is a linear increase of shot noise with a rise in the active user number. Thus, the scalability of OCDMA systems is somewhat limited due to this factor. One of the chief sources of noise in many OCDMA systems is the optical beat noise. However, effective manipulation of optical phase coherence can be employed to counter the effects produced by optical beat noise. In addition, optical FEC (Forward Error Correction) techniques can be used to cancel the effects produced by shot noise. Another technological barrier to the acceptance of OCDMA is the expensive optical hardware. An OCDMA system requires tuneable Fibre Bragg Grating (FBG) for the purpose of encoding data both at the head-end as well as the user-end of the OCDMA system. This makes the entire system quite bulky as well as expensive.

OCDMA systems also require Laser Diode Arrays and EDFAs, both of which are expensive. This problem can be mitigated to some extent through integration with other systems. Another barrier to the acceptance of OCDMA is the perception that it is inefficient and exotic and not really applicable in the practical or real-world and that it sounds good only theoretically [7].

However, OCDMA possesses a number of advantages, as discussed earlier, which make it a promising candidate for the multiple-access networks of the future. Most of the barriers to OCDMA acceptance have been found to be a matter of perception and not really severely limited by technology as technological advances are taking place rapidly and will be able to counter most of the disadvantages as seen today. The progress in the development of new architectures like optical Time Division Multiplexing (TDM) systems, photonic components and Wavelength Division Multiplexing (WDM) systems built on OCDMA technology will make these systems more functional and acceptable in the future [8]. Future commercially successful OCDMA systems based code-processing photonic devices need to be robust and cost-effective in order to be widely adopted in the communication arena [12].

2.5 Conclusion of Main Advantages of Optical CDMA System

i. All-optical Communications: OCDMA system encodes and decodes signals (data) from different users optically, the messages are converted to optical signals at the source end and are retrieved as electronic signals after transmission has completed. The electronic bottlenecks in transmitting and receiving ends are conquered in comparison with OWDM. Realization of photon to photon transmission actually enables all-optical communications.

ii. Security Performance: The signal transmitting in OCDMA networks is multiplexed signal of various users, the spread spectrum technology guarantees the received signal at any receiving end is multiplexed and can only be de-multiplexed when the address sequences are strictly matched.

iii. Anti-interference Ability: The bandwidth of transmitting signal is increased with the use of spread spectrum technology at encoding. Therefore OCDMA is not sensitive to wavelength drifting and the anti-interference ability is enhanced.

iv. Asynchronous Access: OCDMA system allows various users to access the same channel asynchronously. The signal of a new user adds directly onto the multiplexed signal vector, no synchronization between different users and wavelength adjustability needed. Moreover, the requirements of burst and high-rate transmissions in Local Area Networks (LANs) can be satisfied since the awaiting time before medium accessing is negligible.

v. Low Cost: OCDMA system adopts wideband optical source, the wavelength has not to be precisely manipulated. In addition, there is no particular requirements of optical fibre and fewer devices are used in constructing networks. Thus the overall cost is reduced, network management is simplified and the reliability is enhanced.

vi. Integrated Transmission Services: OCDMA can actually support multi-rate transmissions and various transmission services such as IP transmission, ATM (Asynchronous Transfer Mode) and SONET (Synchronous Optical Network) transmissions simultaneously.

vii. Easily Managed: OCDMA does not require precise synchronization management in time as well as in wavelength, instead OCDMA employs different address sequences to distinguish different users, therefore the network management is simplified.

Chapter 3
OCDMA Structure and Principles

3.1 Spread Spectrum Technology

Before we introducing the properties and principles of OCDMA system, a key and fundamental technology in modern communications should be introduced, named spread spectrum communication. It is the backbone technique in CDMA communications and the designs of code sequences and transceiver architectures are based on this.

Spread Spectrum (SS) technology is a type of information transmission technologies widely used in various communication systems, the bandwidth of the transmitting signal is much greater than the bandwidth that the information possesses. The spread of transmission bandwidth is achieved in the transmitter by applying a spreading signal as a carrier signal to the information signal and the received signal will be de-spread at the receiving end to recover the original signal. The spreading signal is high frequency and independent to the information signal and its envelope matches the waveform of the information signal. It is determined by a sequence of random pseudo-noise (PN) code as a modulation waveform to extend the information signal energy to a much greater level than the original signal. After transmission, receiver demodulates the information signal by applying a synchronized replica of the random PN code sequence to the spread signal [4].

This type of transmission is referred to as broadband communication, in contrast of narrowband transmission which is widely used in telephone networks and cable TV networks. The advantages of broadband transmissions or spread spectrum transmissions are high anti-interference ability and high resolution ranging, low probability of the occurrence of errors, low interference to various narrowband communication systems, multi-access attribute, as well as high security in transmission since the transmitted signal is hard to intercept [4]. According to different manners of spreading the spectrum of a signal, spread spectrum technology has the categories of Direct Sequence spread Spectrum (DSSS), Frequency-Hopping Spread Spectrum (FHSS), Time-Hopping Spread Spectrum (THSS), chirp modulation and hybrid spread spectrum.

3.2 Overview of OCDMA System

The method by which OCDMA systems work can be described as following: every user is allocated a unique code sequence which is multiplied with each bit. This particular code sequence is presented and recognized at the receiving end and is used to de-modulate the received data. This code sequence is the most important element for correct detection. This code sequence is expected to be ideally orthogonal and to have zero crosstalk with the code sequences of any other users. For spectrum coding, each of these code sequences represents a sequence of different wavelengths obtained from a "single broadband optical source" which is divided into numerous narrow optical wavelengths with the help of Wavelength Division Multiplexing (WDM). For time-spreading coding, each of the code sequences represents a sequence of positions of time slots for a given number of time slots. The entire encoding process can be divided into three steps: Source-Filter (or Delay Lines)-Modulator. OCDMA can be thought of as a broadcast technology through which information is transmitted to every part of the network. The spectrum filter or optical delay lines can be regarded as a sort of optical barcode which may be programmable or fixed. A receiver is installed at every terminating point. A star coupler depicted in Figure 4 is set up to connect all the active users, data stream within a star coupler is bi-directional. This helps to add users easily and economically. Wherever a receiver with a barcode matching one of the transmitters is positioned in the network, the matched signal is decoded and taken out from the network [2]. Figure 3 shows a typical OCDMA system in which each of these blocks represents a function unit in the system.

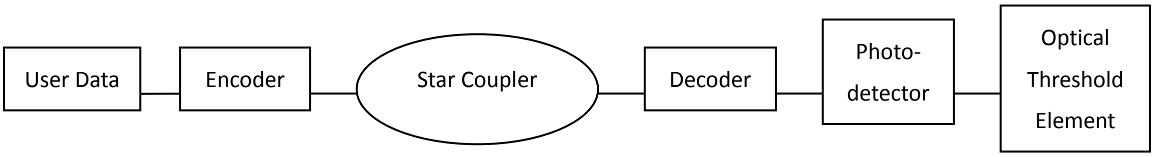


Figure 3 Typical OCMDA System Schematic

Multiplexing is achieved by going through the following steps: (a) every data stream is encoded by employing a unique code sequence for time spreading of each data bit and/or by spectrally encoding of each data bit; (b) all the encoded signals are fed into a star coupler simultaneously and asynchronously; (c) the mixed signal goes through the star coupler for a distance which is not fixed; (d) each of the encoded signals is decoded and de-spread at one of the receiving ends simultaneously with the help of a decoder whose function is basically the opposite of a corresponding encoder, thus the data signal is recovered from the encoded signal as detectable data bits [13]. The requirements of an OCDMA system are: (i) cost-effective and robustness of generating coded bits; (ii) suitable design of address signature code; (iii) suppression of Multi-Access Interference (MAI), which is the interference between users with different code sequences, and (iv) successful detection of data bits in a code-specific manner [14].

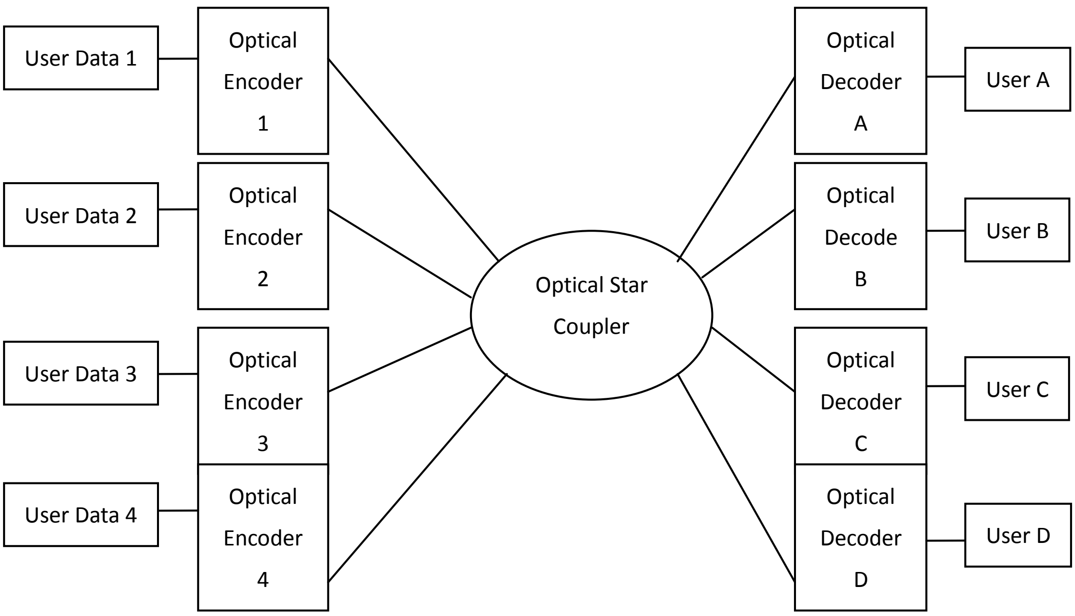


Figure 4 Topological Structure of OCDMA Access Network

3.3 Incoherent and Coherent OCDMA Systems

OCDMA systems can be placed in two categories depending on the method by which the optical signal is applied to a specific user's code sequence. These categories are coherent and incoherent OCDMA systems. In coherent OCMDA systems, a particular user's code sequence is usually applied through phase coding of optical signal field, which is generally achieved with the use of a mode-locked laser ("a highly coherent wideband source"). At the receiving end of a coherent OCDMA system, the original data is retrieved by the signal field's coherent reconstruction. Coherent OCDMA systems are further classified into several types, these are Spectral Phase Coded OCDMA (SPC-OCDMA) and Temporal Phase Coded OCDMA (TPC-OCDMA). An incoherent OCDMA system depends on amplitude-modulated codes instead of direct optical phase manipulation. Here, the decoding process at the receiving end is done through an "incoherent decoding and recovery process". Some incoherent OCDMA systems employ wideband incoherent sources like broadband Amplified Spontaneous Emission (ASE), while other incoherent OCDMA systems employ laser sources which are coherent [15].

Among these two categories, incoherent OCDMA has captured more attention due to the fact that it provides flexible bandwidth provisioning, phase insensitivity, asynchronous network access capability and robust performance. Incoherent OCDMA is expected to become the technology to fulfil the immense bandwidth demands of Fibre-To-The-Home (FTTH) services in the future. One of the 2D incoherent OCDMA systems named Wavelength-Hopping Time-Spreading (WHTS) system has been proved to have many advantages over other incoherent OCDMA techniques. WHTS spreads a user's data bit in wavelength domain and time domain simultaneously, this gives better system performance and better code-division flexibility [16]. We will consider incoherent OCDMA systems only in the following.

3.4 OCDMA Signature Codes

The practical application of OCDMA technology depends on the realization of incoherent optical system. The keys including design of appropriate address code sequences and transceiver architectures to suppress MAI.

Optical address code sequences should have the characteristic attributes of high autocorrelation peak and low cross-correlation to minimize the interference from other users and to acquire high SNR. In addition, for the reason of synchronizing transmitting end with receiving end, the autocorrelation side-lobes have to be as small as possible as well. Meanwhile, a good code cardinality is significant to accommodate a large number of users.

MAI is the main source of causing errors in transmission, a balanced detection technique at the receiving end has been proposed to eliminate MAI. An optical hard limiter can also inhibit errors caused by MAI when retrieving data and improve system performance [15].

Various codes have been designed for the use in OCDMA systems. They have two main categories: one is optical Prime Code (PC) while the other is Optical Orthogonal Code (OOC). In PC, a code function is determined in advance and is used to give the positions of each “1” in the code sequence, we use this function to analyze code correlation characteristics, MAI and BER etc. However, in OOC we assign the system parameters at first (Code-Length (CL), Code-Weight (CW, the number of "1"s in the code sequences) and cross-correlation etc.), and then determine the positions of “1”s under a given achievable aim by using a certain algorism. The regularity of PC design is easier to investigate than OOC and PC is easily to implement in encoding/decoding process and is conducive for fast reconstruction in case of damage. However, the correlation characteristics and capacity of PC are inferior to OOC, these characteristics are more important than the former properties and make PC rarely being applied in practice [15].

The most important property of OOC is the orthogonality between code sequences, but this orthogonality is quasi-orthogonal because that incoherent OCDMA system depends on optical field energy to transmit signal, which cannot be minus. Codes have been developed in order to comply with some prerequisites like non-zero shift cross-correlation and autocorrelation values which are bounded by one and a high autocorrelation peak which is comparable to the code weight. The use of Polarized-OOC has the capability of accommodating twice the number of users as compared with the normal OOCs [14].

3.5 OCDMA Encoding/Decoding

In general, OCDMA system has the following categories of coding approaches: (1) direct-sequence or temporal encoding; (2) spectral-amplitude-encoding; (3)spectral-phase-encoding (also known as spread-time encoding); (4) 2D spatial encoding (also known as spread-space encoding) and (5) hybrid coding approaches

[15]. The encoder/decoder structures used in OCDMA system can also be generalized in common: encoder/decoder based on optical delay line; (2) encoder/decoder based on diffraction gratings and spatially patterned mask; (3) FBG or Fibre Bragg Grating encoder/decoder; (4) AWG or Arrayed Waveguide Grating encoder/decoder etc.

3.6 Conclusion

In this chapter, we have introduced the spread spectrum technology as the fundamental in OCDMA technology, key features and properties of OCDMA technology have been discussed. Also two different types of OCDMA systems named coherent and incoherent systems have been reviewed, results show that the incoherent scheme is more applicable for realization. Two different code construction methods were introduced, there pros and cons in comparison with each other are discussed. Finally, various coding schemes for OCDMA system were briefly introduced.

Chapter 4

Introduction to 2D OCDMA System

4.1 Introduction

Recently the hybrid Wavelength-Hopping/Time-Spreading (WHTS) 2D coding attracted more and more attention owing to its good correlation properties comparing with 1D coding. A well designed 2D code can minimize the interference between users to a lowest level and enhance the BER substantially. Although the hybrid 2D system has not yet been intensively investigated, it is still a potential candidate for the next generation OCDMA system. In this Chapter, we will introduce the concept of 2D system and give an overview of 2D codes and 2D transceivers.

In 2D OCDMA system, we not only encode the data bit in time domain, but also in wavelength domain. By which different optical pulses are coloured with different time slots as well as different wavelengths, as demonstrated in Figure 5 [15].

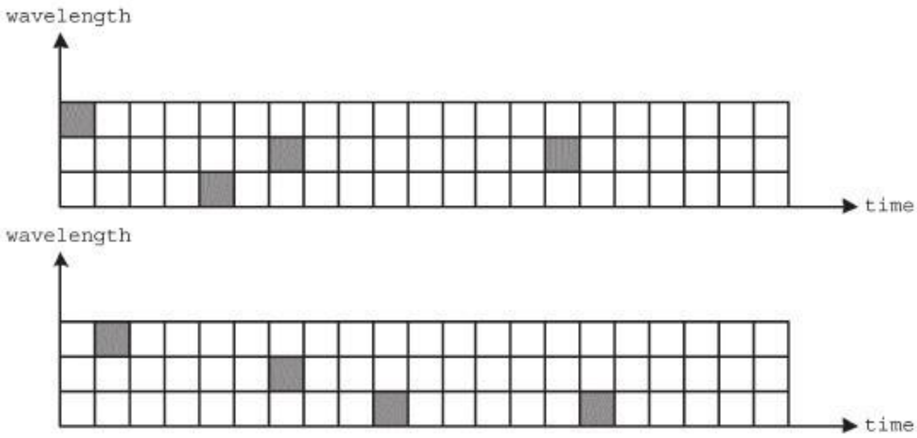


Figure 5 2D OCDMA Sequences (from [15])

2D OCDMA technology is a hybrid of time-spreading and wavelength-hopping communications. Hence 2D codes are generating from mixing of 2 different 1D codes which come from both OOC and codes based on prime sequence, one of them is still implemented as spreading code, the other one will be used as hopping code to colour the optical pulses within one code sequence to be centred at different wavelengths. Since 2D OCDMA system has not been investigating for a long time, most of 2D codes come from existing 1D codes. Although coding schemes of 2D OCDMA system can be various combinations of 1D coding schemes, such as spatial/time-spreading coding, spatial/wavelength-hopping coding, wavelength-hopping/time-spreading (WHTS) coding etc., the WHTS coding scheme is the most intensively investigated one since its high feasibility and high security and low cost.

In OCDMA system, three main factors are considered for evaluating a signature code, they are correlation properties, maximum supported user number and BER. These three properties are directly connected and restricted by each other. For a given

Code-Length, in order to maintain as many as possible users within an acceptable BER, correlation properties must be good enough, in other words, a good design of code is required. Another two are Code-Length (CL) and Code-Weight (CW), long CL will improve correlation properties and BER performance, also strengthen the security, however long CL will reduce the system throughput and increase the complexity of transceiver architecture. With certain CL large CW will worsen the correlation properties while raising the Signal-to-Noise-Ratio (SNR) at receiving end, therefore reduce the BER. All of these properties are influenced by the others, the reason we put all of these into consideration is that we want the signature code to support as many as possible users with as little as possible interference (MAI etc.) between users. It is impossible to design a signature code with all ideal properties, as mentioned improvement of one aspect will either improve or degrade the others, therefore we need to find a trade-off between all of these factors. In other words we need to find an optimized signature code by thinking over all of these and this optimized code can support as many as possible users with as little as possible interference (sometimes we need to consider also cost and security).

Comparing to 1D signature code, 2D code has great improvements on correlation properties, BER and maximum user number, this is the reason for researching on 2D signature code. However, 2D code is based on 1D code, it is the combination of two single 1D codes, design of 1D code with good properties is the basis of the design of 2D code.

4.2 Overview of 2D Codes and Receivers

Since all of 2D codes are based on 1D codes and most 2D codes come from OOC and 1D codes based on PC, we will discuss the constructions and properties of some 1D codes initially. The concept of OCDMA was firstly proposed in [17] and one of the basic uni-polar sequences in incoherent OCDMA systems named Optical Orthogonal Code (OOC) was also suggested. An $(\mathrm{F}, \mathrm{K}, \lambda_a, \lambda_c)$ OOC is a family of $(0,1)$ sequences of CL F and CW K with maximal CC and AC side-lobe equal to λ_c and λ_a. In the optimized case that $\lambda_a = \lambda_c = 1$ the largest user number that can be supported (cardinality) was given as $\mathrm{N} \leq \left\lfloor \frac{\mathrm{F}-1}{\mathrm{K}(\mathrm{K}-1)} \right\rfloor$. A general interference model between any two sequences in most incoherent OCDMA codes was given and the upper bound of hit probability (the probability of pulses overlapping between two sequences) was consequently determined as $\frac{\mathrm{K}^2}{2\mathrm{F}}$, where $\frac{1}{2}$ is the probability that the interfering user is transmitting data bit ‘1’. This is because that in F possible overlapping positions between two sequences, we have K^2 times that two pulses ("1"s) will overlap.

Continue with [17], the performance of OOC was further analyzed in accordance with the interference model proposed in [17] by [18]. The Probability Density Function (PDF) of interference from other users and the Cumulative Distribution Function (CDF) of BER were obtained in two cases: 1) Chip synchronous and 2) Ideal chip asynchronous, which represent the upper bound and lower bound that the BER can achieve. The PDF of interference for the chip synchronous case (the upper bound) is :

$$\mathrm{Pr}_{\mathrm{N}}(\mathrm{I}) = \binom{\mathrm{N}-1}{\mathrm{I}} \left(\frac{\mathrm{K}^2}{2\mathrm{F}}\right)^{\mathrm{I}} \times \left(1 - \frac{\mathrm{K}^2}{2\mathrm{F}}\right)^{\mathrm{N}-1-\mathrm{I}} \tag{4.1}$$

where N is the simultaneous active user number.

Formula (4.1) is a general and fundamental mathematical analysis model that can be adapted for most of codes in OCDMA. Also one of the interference cancelation techniques named Hard-limiting was briefly introduced and examined mathematically. In comparison with BER performance without Hard-limiting, improvement of one order of magnitude can be observed with the same decision threshold at receiver.

Furthermore, in [19] the structure and properties of $(\mathrm{F},\mathrm{K},1,1)$ OOC were systematically analyzed. The upper bound of simultaneous user number was amended as:

$$\begin{cases} \mathrm{N} \leq \left\lfloor \frac{\mathrm{F}-1}{\mathrm{K}(\mathrm{K}-1)} \right\rfloor & \text{for F is odd} \\ \mathrm{N} \leq \left\lfloor \frac{\mathrm{F}-2}{\mathrm{K}(\mathrm{K}-1)} \right\rfloor & \text{for F is even} \end{cases} \tag{4.2}$$

Several methods or algorithms were proposed to construct $(\mathrm{F},\mathrm{K},1,1)$ OOC including projective geometry, greedy algorithm, iterative constructions, algebraic coding theory, block design and various other combinatorial disciplines were discussed. This article also stressed the applications of OOC in many other fields such as mobile radio communications, spread-spectrum communications and radar and sonar signal design.

In the design of OOC, researchers pick up sequences from a space to consist a code-set according to the rule $(\mathrm{F},\mathrm{K},\lambda_a,\lambda_c)$. Under such a certain rule different code-set may create and the process is complicated. Another solution is to create a code function and use this function to generate sequences, as a result for a given code function and parameters the code-set is fixed. Prime Code (PC) generates sequences by employing such methodology to enable the process simplified while keeping the properties of all aspects similar to OOC (the code function for generating PC is: $a_{ij} = i \otimes_p j$ where $i = 0,1, \ldots, p-1; j = 0,1, \ldots, p-1; p$ is prime and $\otimes_p$ is modulo p operation of the product of $i \,\&\, j$). From another point of view PC is a kind of OOC with more straightforward constructing procedure but less optimized correlation properties comparing to $(F, K, 1,1)$ OOC.

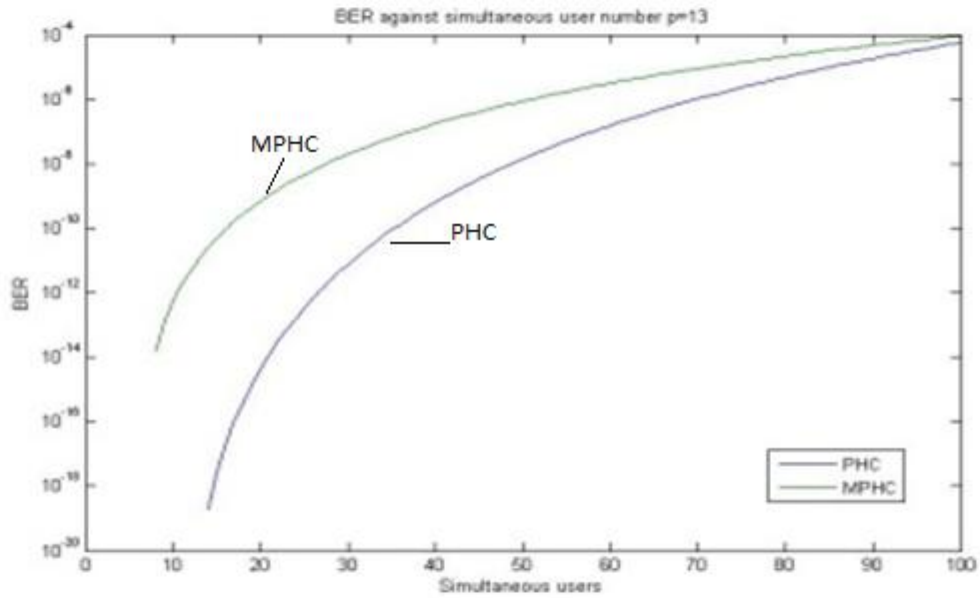
In comparison with 1D PC, for obtaining better BER performance and for supporting more simultaneous users, in [20] a 2D WHTS code structure was set up based on two identical PCs, named Prime-Hop Code (PHC). PHC utilizes PC as time-spreading pattern as well as wavelength-hopping scheme. PHC has the optimal correlation properties of uni-polar code that $\lambda_a = 0$, $\lambda_c = 1$, this greatly increased number of simultaneous users that can be supported over $(F, K, 1,1)$ OOC. In 1D code, all the pulses in a sequence are centred at the same wavelength, hence the optimal value of λ_a is 1. However, in 2D code, each pulse in a sequence can be centred at different wavelengths, if we have enough number of wavelengths which equals to the code weight, the optimal value of λ_a becomes 0. In addition, PHC was the first proposed WHTS code in 1994 and lots of WHTS code plans thereafter were based on this. In [21], the properties of PHC were further studied and its system performance was analyzed.

In [22], a similar 2D WHTS code was proposed by employing Extended Quadratic Congruence (EQC) sequences for time-spreading, PC and its cyclic shifts for wavelength-hopping named EQC/PC WHTS code(the code function for generating EQC is: $a_{ij} = i \otimes_p \frac{j(j+1)}{2}$ where $i = 1, \dots, p-1; j = 0,1, \dots, p-1;$ p is prime; a_{ij} is ith-row/jth-column element in the code matrix). According to the equality of CW and available wavelength number the categories of WHTS systems were discussed as symmetric system (CW = no. of wavelengths) and asymmetric (CW ≠ no. of wavelengths) system. Asymmetric system can be further classified into under-coloured asymmetric system (CW < no. of wavelengths) and overcolored asymmetric system (CW > no. of wavelengths). When the over-coloured asymmetric structure is considered EQC/PC can further increase the number of simultaneous user number while keeping the correlation properties the same as PHC. Another advantage of asymmetric system over PC/PC symmetric system is about security, analysis of the security properties of WHTS systems was presented both from the viewpoint of exhaustive search and from the viewpoint of chosen attack, investigations indicate that asymmetric system configuration provides higher level of protection against determined attack.

However, WHTS has more complex system configuration than time-spreading 1D system because the data bit is double encoded, hence components for both time domain encoding (delay lines) and wavelength domain encoding (gratings) are needed. [23] introduced a novel code named Modified Prime-Hop Code (MPHC), MPHC was derived from PHC by replacing the even columns of PHC by '0's. The system complexity was reduced by half while BER was remained similar to PHC as we can see from Figure 6 [23] (usually the maximal acceptable value of BER is 10^{-9}.)

Prime number	MPHCs Maximum number of users (BER ≤ 10^{-9})	Hardware requirement (number of tunable delay lines and filters)	PHCs Maximum number of users (BER ≤ 10^{-9})	Hardware requirement (number of tunable delay lines and filters)
$p=23$	182	12	231	23
$p=29$	407	15	446	29
$p=31$	508	16	536	31
$p=37$	898	19	866	37

(a)



(b)

Figure 6 Comparison of system complexity (a) and BER (b) performance of PHC and MPHC (from [23]).

A similar code was introduced in [24] by employing PC as time–spreading code and a new code, named One Coincidence Sequence (OCS), as wavelength-hopping code, and replacing the even columns by '0's. The OCS is generating from a Galois or Fibonacci Linear Feedback Shift Register (LFSR). Results show that BER performance of the new WHTS code is slightly better than PHC. This is reasonable because the new code employs an over-coloured structure, comparing to a PHC with the same

CW the new code has more available wavelengths.

As afore-mentioned, Hard-limiting is an effective method for compressing Multi-Access Interference (MAI) in receiver. Hard-limiting technique was firstly proposed by [25], a Hard-limiter is applied before the mixed signal arriving the receiving end, i.e. Hard-limiter is fixed at the forefront of the receiver. The role of Hard-limiting is to make optical intensity within each time slot in the mixed pulse sequence normalized. In other words, suppose there are more than one user interfering the same time slot, i.e. the optical intensity within this time slot of the mixed signal sequence is more than the optical intensity within a time slot of the original signal sequence, Hard-limiting will minimize the interference strength using the function:

$$\mathrm{g}(\mathrm{x}) = \begin{cases} 1, & \mathrm{x} \geq 1 \\ 0, & \mathrm{x} < 1 \end{cases} \tag{4.3}$$

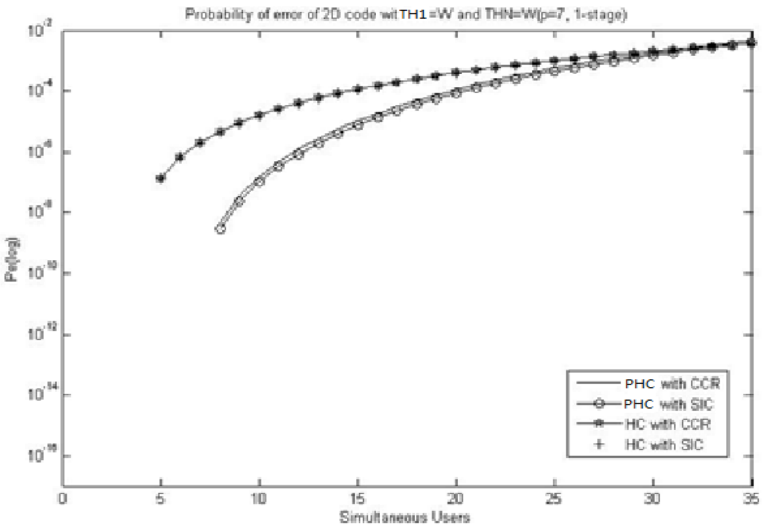
Where x is the power of received mixed signal within one time slot and we assume the power within one optical pulse of desired user's signal is 1.

Therefore Hard-limiter enables the received optical signal to give improved performance because interferences that heavily localized in a few time slots are eliminated. [26] further examined Hard-limiting technique by employing another WHTS code named Prime/OOC. The results present the BER of Prime/OOC with Hard-limiting can be improved by one order of magnitude in comparison with the BER without hard-limiting.

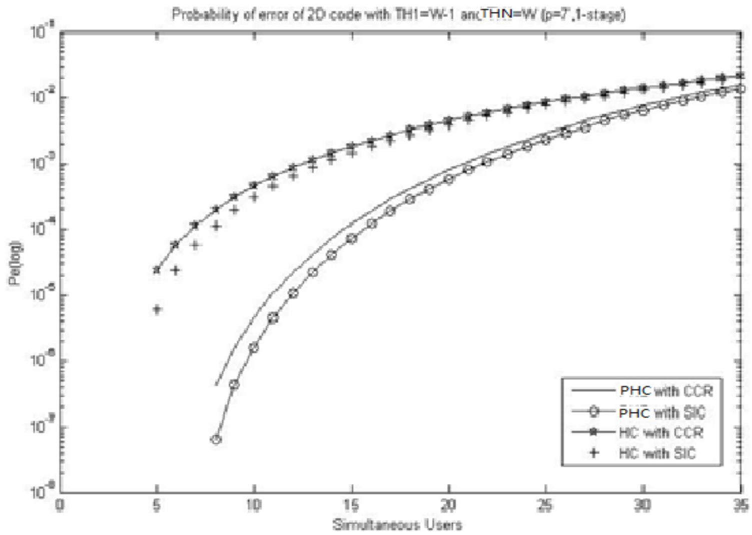
[27] introduced a general analytical interference probabilistic model for any asynchronous WHTS codes. Analysis employing this mathematical model using

Conventional Correlation Receiver (CCR) and Hard-limiting receiver was presented by relating code parameters to system performance. Results show that in WHTS systems, under certain number of time slots and certain number of wavelengths, the simultaneous or potential user number can be maximized and the Maximum Collision Parameter (MCP, the hit probability of pulses between different sequences) can be optimized by carefully selecting CW and several possible design rules were provided. Also the spectral efficiency limits using CCR and Hard-limiting receiver were studied.

In [28] another novel receiver structure named Successive Interference Cancelation (SIC) receiver was proposed. Just as the name implies, SIC compresses MAI in a different way in comparison with hard-limiter by placing the CCR of user N in front of the desired user, therefore before the CCR of the desired user receives the incoming signal the interference of user N can be detected and eliminated. Such a receiver structure is called 1-stage SIC receiver, in Figure 7 BER against simultaneous user number employing CCR and 1-stage SIC for TH1=W (a) and TH1=W-1 (b) respectively (TH1: threshold of CCR of the desired user; THN: threshold of the CCR of user N). Where More than one CCRs of other interfering users can be placed in series in front of the CCR of the desired user to detect and pre-eliminate the interference before arriving at the desired user’s CCR, i.e. multi-stage SIC receiver or N-stage SIC receiver. However, each of the N CCRs can cause an error and consequently interfere the following CCRs, this will give rise to BER recovery. As a result, supposing all of the interfering users' CCRs are placed successively in front of the desired user's CCR, the possibility that all the interference has been completely removed is extremely low.



(a)



(b)

Figure 7 BER against simultaneous user number employing CCR and 1-stage SIC for TH1=W (a) and TH1=W-1 (b) respectively (TH1: threshold of CCR of the desired user; THN: threshold of the CCR of user N).

[29] considered WHTS system from another aspect: the confidentiality. A

two-code-keying WHTS system was provided in which not only the bit '1' was encoded during transmission, but also bit '0'. A new term Effective Key Length (EKL) was proposed which is used for evaluating the robustness of codes against brute-force attacks:

$$\mathrm{EKL} = \log_2 \mathrm{C} \tag{4.4}$$

C is number of all possible code patterns that the eavesdroppers have to try when they are monitoring on the information of the desired user. Some practical approaches to compromise WHTS systems were introduced including single-wavelength detection, eye diagram observation and temporal recording. Correspondingly, methods to improve system's confidentiality performance were suggested such as M-Array modulation, chip slot overstepping and code conversion. Out of these three possible solutions applying the M-Array modulation in coding procedure seems like to be the most feasible and effective one.

4.3 Conclusion

In this Chapter, an overview of 2D OCDMA system has been given, codes and receivers in 2D OCDMA system and their performances have been reviewed, it has been shown that 2D codes have the privileges over 1D codes. Although a lot of 2D codes have been proposed by previous researcher, the 2D OCDMA system is still very immature and the codes which have been proposed are rarely feasible and practical in real world OCDMA communications, one of the inevitable weakness of 2D system is that the amount of electronic and optical devices used in the establishment of 2D network is huge. In other words, 2D network greatly increases the system complexity and cost. However, in 2D system reduction of system complexity means degradation of system performance, for consideration of finding out a balance or trade-off between system performance and complexity, we will propose a novel 2D code based on the codes previously proposed and will analyze its performance against the previous ones.

Chapter 5

new-Modified Prime-Hop Code

5.1 Design of new-Modified Prime-Hop Code

The new-Modified Prime-Hop Code (nMPHC) is derived from the WHTS codes PHC and MPHC both of which are based on 1D time-spreading code PC. The procedure of generating a set of PC sequences begins with a given Galois Field (GF):

$$\mathrm{GF}(p) = \{0,1,2,\dots,p\} \tag{5.1}$$

where p is a prime number. The function for generating a primary code-set as afore-mentioned in the previous section is described as:

$$a_{ij} = i \otimes_p j \tag{5.2}$$

where $i, j \in \mathrm{GF}(p)$, $\otimes_p$ is modulo p operation of the product of $i \,\&\, j$. A primary code-set is established by the above function (e.g. Table 2: Primary code-set of PC for p=5).

Table 2: Primary code-set of PC for p=5

S1	**0**	**0**	**0**	**0**	**0**
S2	**0**	**1**	**2**	**3**	**4**
S3	**0**	**2**	**4**	**1**	**3**
S4	**0**	**3**	**1**	**4**	**2**
S5	**0**	**4**	**3**	**2**	**1**

Consider each number in this code-set is a sub-codeword consisting of p time slots, the value of the number plus one is the location of the optical pulse which is represented by '1', the complete code-set of PC for a given p is constructed (e.g. Table 3: Complete code-set of PC for p=5).

Table 3: Complete code-set of PC for p=5

S1	**10000**	**10000**	**10000**	**10000**	**10000**
S2	**10000**	**01000**	**00100**	**00010**	**00001**
S3	**10000**	**00100**	**00001**	**01000**	**00010**
S4	**10000**	**00010**	**01000**	**00001**	**00100**
S5	**10000**	**00001**	**00010**	**00100**	**01000**

PC has the maximum cross-correlation $\lambda_c = 2$ and maximum auto-correlation side-lobe $\lambda_a = 1$ with $CL = p^2$, $CW = p$ and $\text{Cardinality}(C) = p$.

A PHC code-set is established by combining a complete PC code-set which is using for time-spreading pattern, and a primary PC code-set with the same p which is using for wavelength-hopping pattern. By replacing the '1's in the complete code-set by the corresponding values (plus one) in one of the primary code-set sequences in turn (excepting the first sequence in the primary code-set because that all the values are the same, therefore it cannot be used for wavelength-hopping), a PHC code-set for a given prime number p is obtained (e.g. Table 4: Code-set of PHC for p=5).

Table 4: Code-set of PHC for p=5

S11	10000	20000	30000	40000	50000
S12	10000	30000	50000	20000	40000
S13	10000	40000	20000	50000	30000
S14	10000	50000	40000	30000	20000
S21	10000	02000	00300	00040	00005
S22	10000	03000	00500	00020	00004
S23	10000	04000	00200	00030	00005
S24	10000	05000	00400	00030	00002
S31	10000	00200	00003	04000	00050
S32	10000	00300	00005	02000	00040
S33	10000	00400	00002	05000	00030
S34	10000	00500	00004	03000	00020
S41	10000	00020	03000	00004	00500
S42	10000	00030	05000	00002	00400
S43	10000	00040	02000	00005	00300
S44	10000	00050	04000	00003	00200
S51	10000	00002	00030	00400	05000
S52	10000	00003	00050	00200	04000
S53	10000	00004	00020	00500	03000
S54	10000	00005	00040	00300	02000

In Table 4, the numbers with values greater than 0 represent the positions of optical pulses in a sequence, the value of each number represents the wavelength that the pulse is centred respectively.

PHC has maximum cross-correlation $\lambda_c = 1$ between either same-spreading/different-hopping, different-spreading/same-hopping or different-spreading/different-hopping sequences and maximum auto-correlation side-lobe $\lambda_a = 0$ with $CL = p^2$, $CW = p$ and $\text{Cardinality}(C) = p \times (p-1)$.

A MPHC code-set is built on PHC code-set by simply replacing the sub-codewords on the even columns by p zeros (e.g. Table 5: Code-set of MPHC for p=5).

Table 5: Code-set of MPHC for p=5

S11	10000	00000	30000	00000	50000
S12	10000	00000	50000	00000	40000
S13	10000	00000	20000	00000	30000
S14	10000	00000	40000	00000	20000
S21	10000	00000	00300	00000	00005
S22	10000	00000	00500	00000	00004
S23	10000	00000	00200	00000	00005
S24	10000	00000	00400	00000	00002
S31	10000	00000	00003	00000	00050
S32	10000	00000	00005	00000	00040
S33	10000	00000	00002	00000	00030
S34	10000	00000	00004	00000	00020
S41	10000	00000	03000	00000	00500
S42	10000	00000	05000	00000	00400
S43	10000	00000	02000	00000	00300
S44	10000	00000	04000	00000	00200
S51	10000	00000	00030	00000	05000
S52	10000	00000	00050	00000	04000
S53	10000	00000	00020	00000	03000
S54	10000	00000	00040	00000	02000

The choice of "0" columns has been approved that can be random in [23], it does not affect system performance, any other choices of these two columns except the first column have equal performance to the one in Table 5.

MPHC has maximum cross-correlation $\lambda_c = 1$ and maximum auto-correlation side-lobe $\lambda_a = 0$ with $CL = p^2$, $CW = (p + 1)/2$ and $\text{Cardinality}(C) = p \times (p - 1)$. The requirement of delay lines and optical filters in the encoder and decoder of each user is reduced by $(p - 1)/2$, hence complexity of whole system is greatly reduced.

My proposed code has similar properties to MPHC, nMPHC code-set varies from MPHC by replacing the sub-codewords on odd columns in PHC excepting the first and last columns by p zeros (e.g. Table 6: Code-set of nMPHC for p=5).

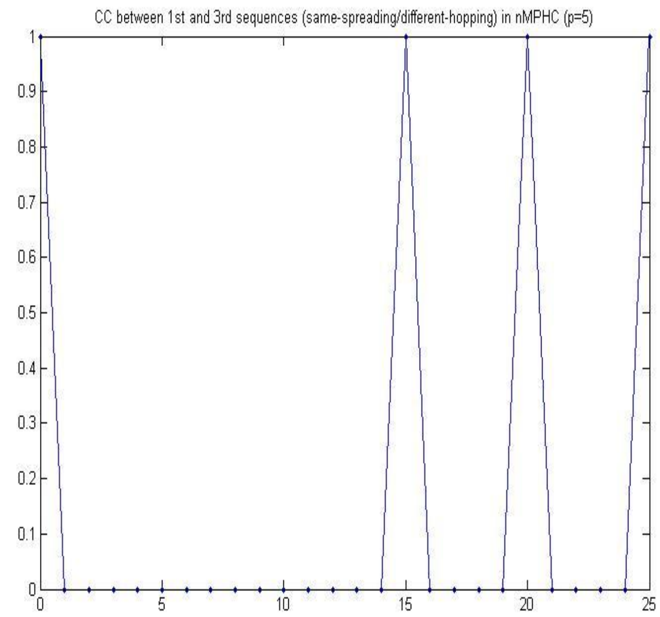
Table 6: Code-set of nMPHC for p-5

S11	10000	20000	00000	40000	50000
S12	10000	30000	00000	20000	40000
S13	10000	40000	00000	50000	30000
S14	10000	50000	00000	30000	20000
S21	10000	02000	00000	00040	00005
S22	10000	03000	00000	00020	00004
S23	10000	04000	00000	00030	00005
S24	10000	05000	00000	00030	00002
S31	10000	00200	00000	04000	00050
S32	10000	00300	00000	02000	00040
S33	10000	00400	00000	05000	00030
S34	10000	00500	00000	03000	00020
S41	10000	00020	00000	00004	00500
S42	10000	00030	00000	00002	00400
S43	10000	00040	00000	00005	00300
S44	10000	00050	00000	00003	00200
S51	10000	00002	00000	00400	05000
S52	10000	00003	00000	00200	04000
S53	10000	00004	00000	00500	03000
S54	10000	00005	00000	00300	02000

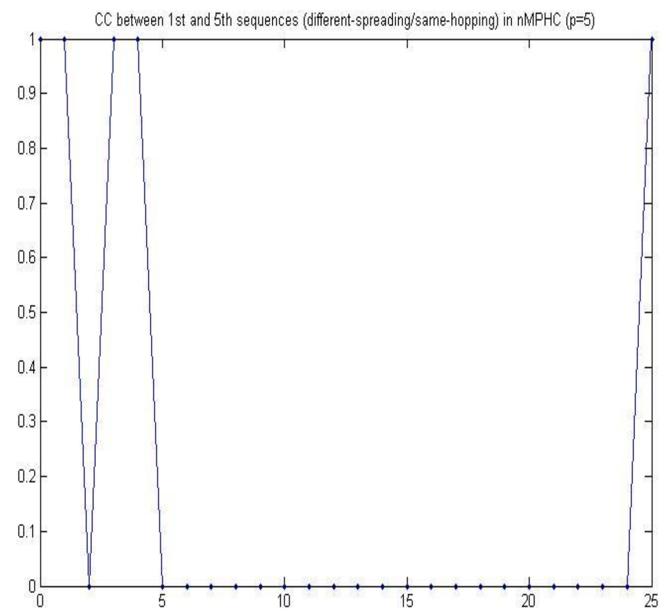
According to [23], any and only one of these columns (not only the middle one) can be removed except the first column and this does not affect system performance. For analysis purpose, we choose to replace the odd columns except the first and last columns of PHC.

It can be noticed that for a given number p, the code weights of PHC, MPHC and nMPHC are different because that different elements are removed, this will affect MAI. It is obvious MPHC has the lowest hit probability. However, by choosing different thresholds in performance analysis (their code weights), making PHC, MPHC and nMPHC with the same p to be comparable is still sensible, especially the BER performance.

Because the correlation properties of PHC has been verified by previous researchers, as some of the pulses in PHC has been removed in nMPHC, the correlation properties of nMPHC must be the same or better than PHC, hence MPHC has maximum cross-correlation $\lambda_c = 1$ (Figure 8 and Figure 9(a)) and maximum auto-correlation side-lobe $\lambda_a = 0$ (Figure 9(b)) with $CL = p^2$, $CW = (p+3)/2$ and $\mathrm{Cardinality}(C) = p \times (p-1)$, which have also been approved by computer-aided simulation. Comparing with PHC, the system complexity is reduced by $(p-3)/2$, and one unit increment in comparison with MPHC.

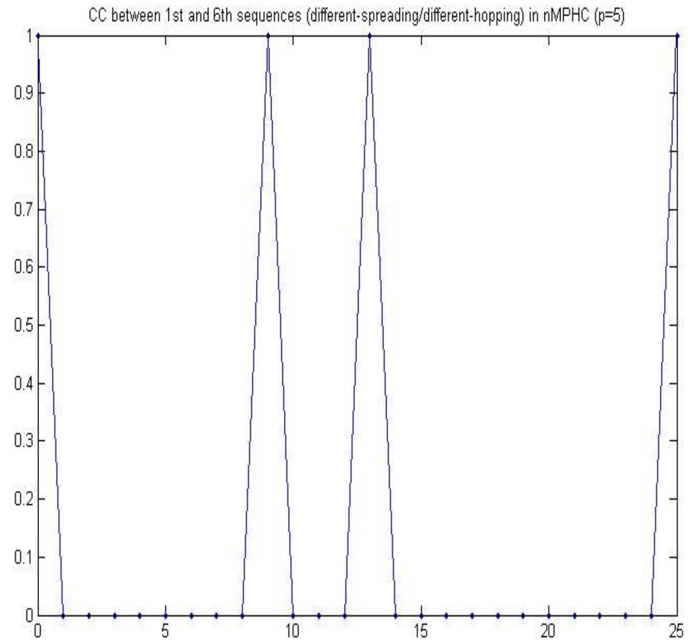


(a)

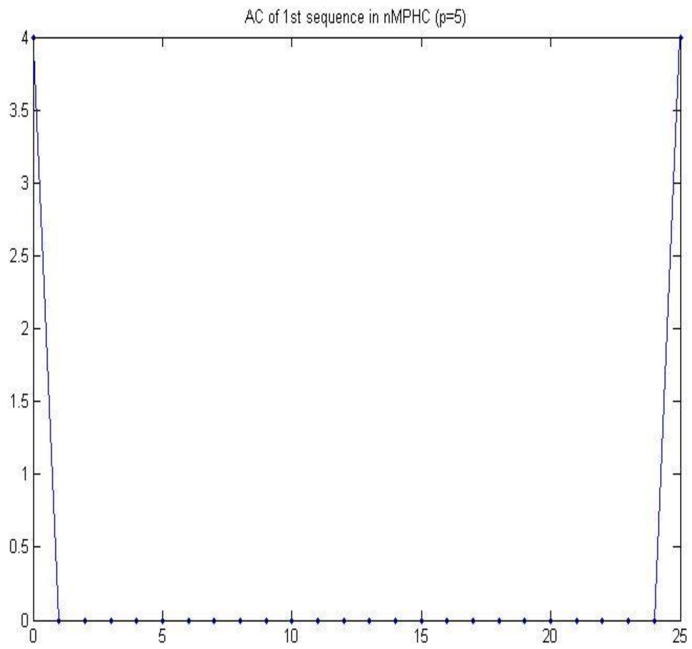


(b)

Figure 8 CC between 1st (a) and 3rd (b) (same-spreading/different-hopping) sequences and CC between 1st and 5th (different-spreading/same-hopping) sequences in nMPHC (p=5)



(a)



(b)

Figure 9 CC between 1st (a) and 6rd (b)(different-spreading/different-hopping) sequences and AC of 1st sequence in nMPHC (p=5)

A comprehensive comparison of PHC,MPHC and nMPHC in their code structures, correlation properties and system complexity is presented in Table 7.

Table 7: Comparison of PHC, MPHC and nMPHC on code properties

	CL	CW	C	λ_c	λ_a	Improvement on Complexity
PHC	p^2	p	$p \times (p + 1)$	1	0	0
MPHC	p^2	$(p + 1)/2$	$p \times (p + 1)$	1	0	$(p - 1)/2$
nMPHC	p^2	$(p + 3)/2$	$p \times (p + 1)$	1	0	$(p - 1)/2$+1

The superiority of MPHC over PHC is its reduction in system complexity by $(p - 1)/2$. However, the system complexity of nMPHC is poorer than PHC by one unit. In the next section, it will be proved that the proportion of improvement of BER performance of nMPHC is larger than the proportion of reduction of system complexity, and a novel analysis methodology will be proposed in details.

System complexity in this thesis is considered to be the same as code weight, this is because code weight reflects the required amount of OTDLs and gratings in both transmitter and receiver for a single user. Once the code weight is reduced, the required optical devices for each transceiver is reduced, this is the original intention of the designs of MPHC [23] and nMPHC. The build of OCDMA network is different from OWDM and OTDM networks, it requires lagers amount of optical devices which will increase power loss and cost and difficulty in network constructing and maintenance substantially, this is the reason that OCDMA technology has rarely been realized in real world application. Based on this, reduction of system complexity of OCDMA network becomes an important issue and receives more and more attentions recently [23].

We can see from Table 7 that comparisons of PHC, MPHC and nMPHC in this thesis are based on a given prime number p, although these three codes have different code weights. This is because in performance analysis, especially BER and PER (Packet Error Rate) analysis, threshold of the comparator in the receiver is sensitive and needed to be set carefully to achieve optimal performance, this threshold is directly related to the decision of data bit, once the electronic current from the photo-detector is greater than the threshold data bit "1" is detected, otherwise data bit "0" is detected. For CCR(Conventional Correlation Receiver), we choose the threshold of the comparator to be the same as code weight to achieve optimal performance, because if the threshold is chosen to be smaller than the code weight less interferers will cause an error, on the other hand if the threshold is chosen to be larger than the code weight bit "1" has the opportunity to be erroneously detected which will not happen if we choose the threshold to be the same as code weight, for both cases system performance degrades. This is the reason we assign different thresholds for PHC, MPHC and nMPHC in performance analysis to give optimal performance for these three codes. Although the code weights of these three codes for a given p are different, i.e. the hit probabilities between sequences (or MAIs) are different (PHC>nMPHC>MPHC), however in performance analysis the thresholds are different as well (PHC>nMPHC>MPHC), in other words larger code weight will increase the SNR(Signal-to-Noise-Ratio) in receiving end and will give raise to system performance, according to this the choice of a given p for comparison of performance analysis is sensible.

If we choose for a given code weight (or complexity) for comparison, the code lengths of MPHC and nMPHC will become much longer than PHC, hence the hit probabilities (or MAIs) of MPHC and nMPHC become much smaller than PHC, and in performance analysis these three code have the same thresholds, hence they become uncomparable, this will lead to that the performances of MPHC and nMPHC are much better than PHC which is not reasonable. Moreover, system throughputs of PHC, MPHC and nMPHC become different and uncomparable. IF we choose for a given supported user number (cardinality) for comparison, code weight and code length may vary from one to another, codes become uncomparable, which is not sensible as well.

5.2 BER Performance Analysis of nMPHC

In OCMDA system the Multi-Access Interference (MAI) is the major factor limiting the system performance even with the presence of optical beat noise between pulses of the same wavelength from different users. In the following analysis MAI is considered as the only cause to compromise system performance. Generally the probability for the occurrence of an error is expressed as:

$$\mathrm{Pe} = \Pr(\mathrm{Z} \geq \mathrm{TH}|\mathrm{b} = 0) \times \Pr(\mathrm{b} = 0) + \Pr(\mathrm{Z} < TH|\mathrm{b} = 1) \times \Pr(\mathrm{b} = 1) \qquad (5.3)$$

where Z is the integral of intensity of correlated signal after correlation processing, TH is the threshold of the receiver of the desired user, b is the bit value intended to be received by the desired user. Error occurs when the transmitting bit is '0' but the interference from other users makes the receiver of the desired user to detect '1' (intensity of received signal is greater than threshold), or when the transmitting bit is '1' but the intensity of the received signal is less than the threshold. The latter case will not happen when threshold is set to be less than or equal to CW. However, when threshold is set to be less than CW the probability that the former case takes place increases as less interfering users can cause an error. Therefore CW is set as the optimal threshold value. Knowing that the probabilities of that '1' is transmitting and '0' is transmitting are equal:

$$\Pr(\mathrm{b} = 0) = \Pr(\mathrm{b} = 1) = \frac{1}{2} \qquad (5.4)$$

because it can be seen as random to transmit bit '1' or '0' on system level. The expression for probability of error is then simplified as:

$$\mathrm{Pe} = \frac{1}{2} \times \Pr(\mathrm{Z} \geq \mathrm{CW}|\mathrm{b} = 0) \qquad (5.5)$$

The binomial distribution function for calculating the upper bound (chip synchronous assumption) of the probability of interference on a certain user with a given active user number N and a given interfering user number I in asynchronous system, i.e. the probability that I users out of N active users will interfere with the desired user, is given in [17] as:

$$\Pr_{\mathrm{N}}(\mathrm{I}) = \binom{\mathrm{N}-1}{\mathrm{I}} \left(\frac{\mathrm{CW}^2}{2\mathrm{CL}}\right)^{\mathrm{I}} \times \left(1 - \frac{\mathrm{CW}^2}{2\mathrm{CL}}\right)^{\mathrm{N}-1-\mathrm{I}} \qquad (5.6)$$

where $\frac{\mathrm{CW}^2}{2\mathrm{CL}}$ is the probability that one of the active users will overlap with the desired user at one pulse position for 1D OOC. Since $(\mathrm{CL}, \mathrm{CW}, 1,1)$ OOC is considered, the probability of overlaps at more than one pulse positions is zero. $\frac{\mathrm{CW}^2}{2\mathrm{CL}}$ indicates that out of $2\mathrm{CL}$ possible coupling positions of two sequences CW^2 positions will cause an overlap. In PHC system, because different pulses in the same sequence possess different wavelengths, therefore out of $2\mathrm{p}^2$ possible coupling positions only p positions will cause an overlap, the Probability Density Function (PDF) of interference in PHC system is:

$$\mathrm{Pr_N(I)} = \binom{\mathrm{N}-1}{\mathrm{I}}\left(\frac{\mathrm{p}}{2\mathrm{p}^2}\right)^{\mathrm{I}} \times \left(1-\frac{\mathrm{p}}{2\mathrm{p}^2}\right)^{\mathrm{N}-1-\mathrm{I}} = \binom{\mathrm{N}-1}{\mathrm{I}}\left(\frac{1}{2\mathrm{p}}\right)^{\mathrm{I}} \times \left(1-\frac{1}{2\mathrm{p}}\right)^{\mathrm{N}-1-\mathrm{I}} \tag{5.7}$$

In a PHC code-set each sequence employs the same wavelengths, as a result the probability of occurrence of one overlap is fixed to be $\frac{1}{2\mathrm{p}}$. However, in MPHC and nMPHC systems the wavelengths employed by sequences vary from one to another for the reason that some of the wavelengths of a sequence in PHC have been removed and these wavelengths are different for distinct sequence. Therefore it is necessary to calculate the average number of collisions with the desired user in MPHC and nMPHC systems. The sequences of the code-set of MPHC or nMPHC excepting the sequence of the desired user can be divided into $\mathrm{p}-1$ groups, each group contains p ($(\mathrm{p}-1)$ for the first group) different-spreading/same-hopping sequences, the number of identical wavelengths of ith group comparing with the desired user is written as $\mathrm{hit_i}$ ($\mathrm{hit_1} = \frac{\mathrm{p}+1}{2}$ because the first group is the group that the desired user is in), hence the formula for calculating average number of collisions in MPHC system is given as:

$$\overline{\mathrm{H}} = \frac{\frac{p+1}{2}\times(p-1)+\sum_{i=2}^{p-1}\mathrm{hit}_i\times p}{p^2-1} \tag{5.8}$$

and for nMPHC system:

$$\overline{\mathrm{H}} = \frac{\frac{p+3}{2}\times(p-1)+\sum_{i=2}^{p-1}\mathrm{hit}_i\times p}{p^2-1} \tag{5.9}$$

The average number of collisions with various p for MPHC and nMPHC are listed in Table 8 and Table 9 respectively.

Table 8: Average number of collisions with various $\mathbf{p}$ for MPHC

Prime number	Average value	Prime number	Average value	Prime number	Average value	Prime number	Average value
$\mathbf{p=5}$	1.974	$p=13$	3.98	$p=23$	6.489	$p=37$	9.985
$\mathbf{p=7}$	2.46	$p=17$	4.966	$p=29$	7.991	$p=41$	10.987
$\mathbf{p=11}$	3.477	$p=19$	5.486	$p=31$	8.491		

Table 9: Average number of collisions with various $\mathbf{p}$ for nMPHC

Prime number	Average value	Prime number	Average value	Prime number	Average value	Prime number	Average value
$\mathbf{p=5}$	3.2105	$p=13$	5.0321	$p=23$	7.5198	$p=37$	11.0128
$\mathbf{p=7}$	3.6341	$p=17$	6.0257	$p=29$	9.0160	$p=41$	12.0116
$\mathbf{p=11}$	4.5780	$p=19$	6.5234	$p=31$	9.5151		

By substituting $\overline{\mathrm{H}}$ into $\Pr_N(I)$, the PDF of interference in MPHC and nMPHC systems is:

$$\Pr_N(I) = \binom{N-1}{I}\left(\frac{\overline{H}}{2p^2}\right)^I \times \left(1-\frac{\overline{H}}{2p^2}\right)^{N-1-I} \tag{5.10}$$

The probability that the intensity of signal after correlation processing is greater than the threshold is the probability that more than $\frac{p+1}{2}$ ($\frac{p+3}{2}$ for nMPHC) users are interfering the desired user:

$$\Pr(Z \geq CW|b=0) = \sum_{I=CW}^{N-1}\binom{N-1}{I}\left(\frac{\bar{H}}{2p^2}\right)^{I} \times \left(1-\frac{\bar{H}}{2p^2}\right)^{N-1-I} \quad (5.11)$$

and the BER for a given active user number N is:

$$Pe_N = \frac{1}{2} \times \Pr(Z \geq CW|b=0) = \frac{1}{2} \times \sum_{I=CW}^{N-1}\binom{N-1}{I}\left(\frac{\bar{H}}{2p^2}\right)^{I} \times \left(1-\frac{\bar{H}}{2p^2}\right)^{N-1-I} \quad (5.12)$$

By using the average number of collisions $\bar{H}$ the BER can be calculated against active user number. A more accurate and more reasonable method is to consider the probabilities of different cases (different number of collisions) respectively and finally add them together.

As mentioned above, the sequences in the code-set of a nMPHC excepting the sequence of the desired user can be divided into $p-1$ groups, each of which has p ($(p-1)$ for the first group) sequences which are employing the same wavelengths. These groups can be further merged to a smaller number of groups, each of which contains the sequences having the same number of collisions with the desired user and the numbers of sequences in these groups are represented by $C_3, C_4, \dots, C_{\frac{p+3}{2}}$, where the subscript indicates the number of collisions that a certain group has with the desired user and $C_3 + C_4 + \cdots + C_{\frac{p+3}{2}} = C - 1$, where C is the cardinality of the code-set. For a given number of active users N, supposing there are $N_3, N_4, \dots, N_{\frac{p+3}{2}}$ users from the groups having $3,4,\dots,\frac{p+3}{2}$ collisions with the desired user and $\sum_{i=3}^{\frac{p+3}{2}} N_i = N-1$, the probability for each different combination of $N_3, N_4, \dots, N_{\frac{p+3}{2}}$ is given as $\frac{\prod_{i=3}^{\frac{p+3}{2}} C_{C_i}^{N_i}}{C_{C-1}^{N-1}}$, where C_n^k is n-choose-k operation. Similarly for a given number of interfering users I, the probability that $I_3, I_4, \dots, I_{\frac{p+3}{2}}$ users are from

$N_3, N_4, \dots, N_{\frac{p+3}{2}}$ respectively is given as $\prod_{i=3}^{\frac{p+1}{2}}(C_{N_i}^{I_i} \times (\frac{H_i}{2\times p^2})^{I_i} \times (1-\frac{H_i}{2\times p^2})^{N-1-I_i}))$, where H_i is the number of collisions that ith group has with the desired user. Finally the probability that I users out of N active users are interfering the desired user for nMPHC using the novel analysis method is written as:

$$Pr_N(I) =$$

$$\sum_{N_3,N_4,\dots,N_{\frac{p+3}{2}}(N_3+N_4+\dots+N_{\frac{p+3}{2}}=N-1)}\left(\frac{\prod_{i=3}^{\frac{p+3}{2}} C_{C_i}^{N_i}}{C_{C-1}^{N-1}} \times \sum_{I_3,I_4,\dots,I_{\frac{p+3}{2}}(I_3+I_4+\dots+I_{\frac{p+3}{2}}=I)} \prod_{i=3}^{\frac{p+3}{2}} C_{N_i}^{I_i} \times (\frac{H_i}{2\times p^2})^{I_i} \times (1-\frac{H_i}{2\times p^2})^{N_i-1-I_i}\right) \quad (5.13)$$

and the BER:

$$Pe_N = \frac{1}{2} \times \sum_{I=\frac{p+3}{2}}^{N-1} Pr_N(I) \quad (5.14)$$

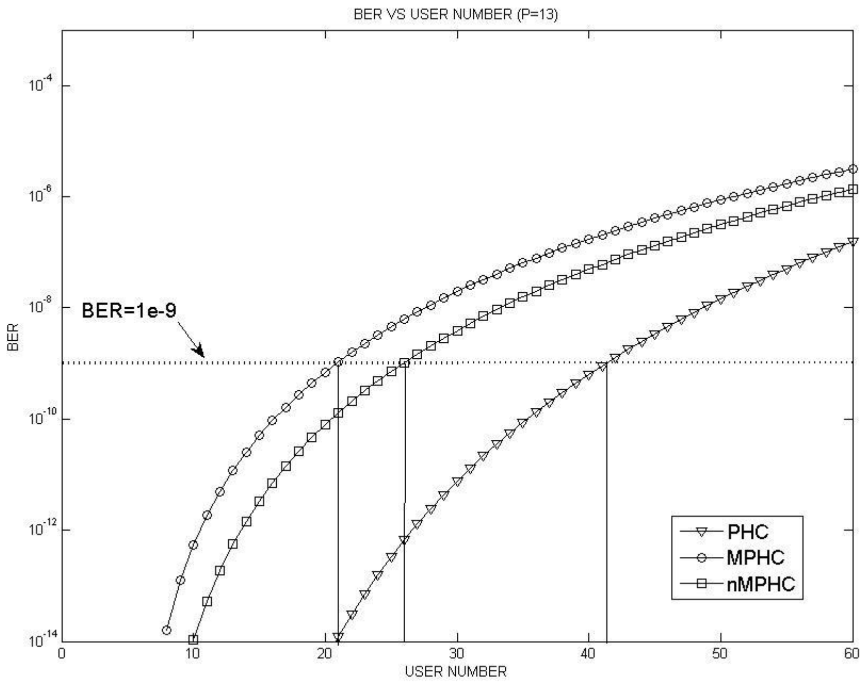
For MPHC:

$$Pr_N(I) =$$

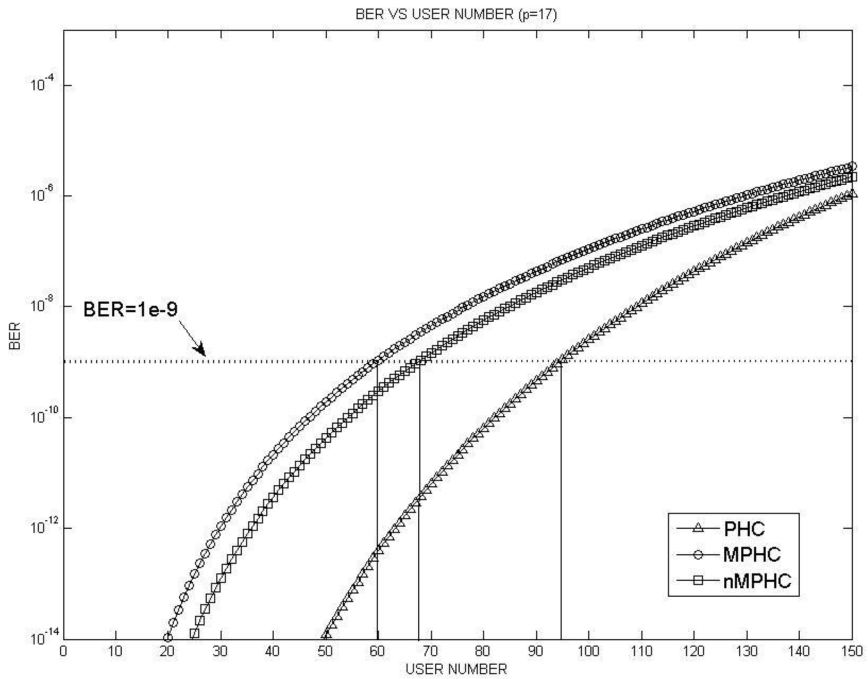
$$\sum_{N_1,N_2,\dots,N_{\frac{p+1}{2}}(N_1+N_2+\dots+N_{\frac{p+1}{2}}=N-1)}\left(\frac{\prod_{i=1}^{\frac{p+1}{2}} C_{C_i}^{N_i}}{C_{C-1}^{N-1}} \times \sum_{I_1,I_2,\dots,I_{\frac{p+1}{2}}(I_1+I_2+\dots+I_{\frac{p+1}{2}}=I)} \prod_{i=1}^{\frac{p+1}{2}} C_{N_i}^{I_i} \times (\frac{H_i}{2\times p^2})^{I_i} \times \left(1-\frac{H_i}{2\times p^2}\right)^{N_i-1-I_i}\right) \quad (5.15)$$

$$Pe_N = \frac{1}{2} \times \sum_{I=\frac{p+1}{2}}^{N-1} Pr_N(I) \quad (5.16)$$

By employing the above formulas, the comparisons of BER performance against active user number between MPHC and nMPHC are presented with $p = 13, p = 17, p = 19, p = 23, p = 29$ and $p = 31$ (Figure 10, Figure 11 and Figure 12) through Matlab simulations.

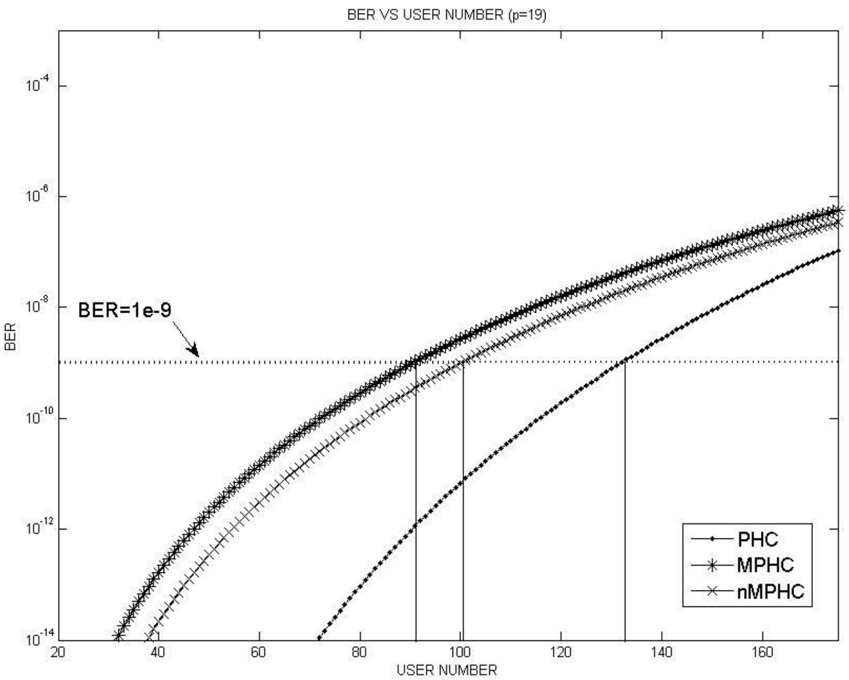


(a)

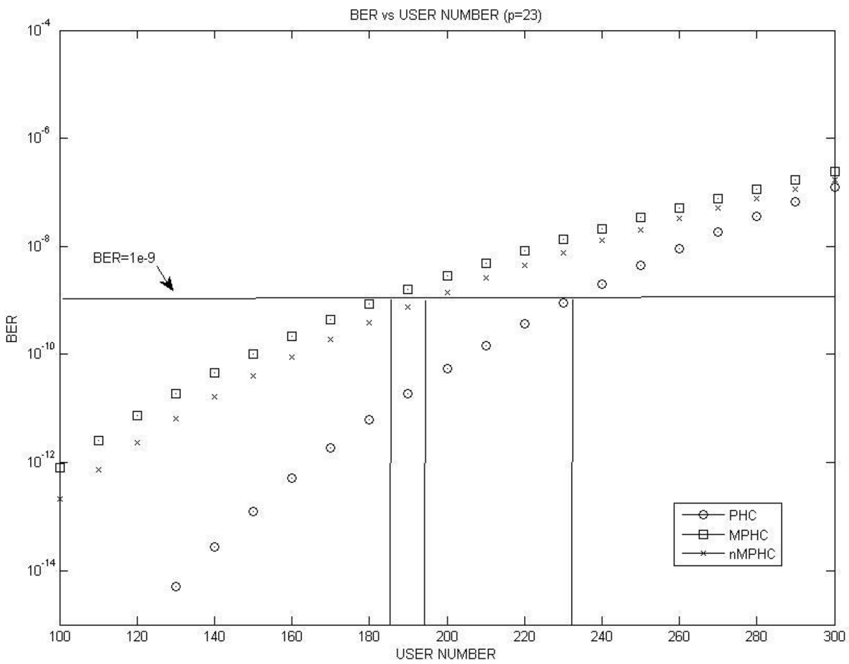


(b)

Figure 10 BER against active user number for p=13 (a) and p=17 (b)

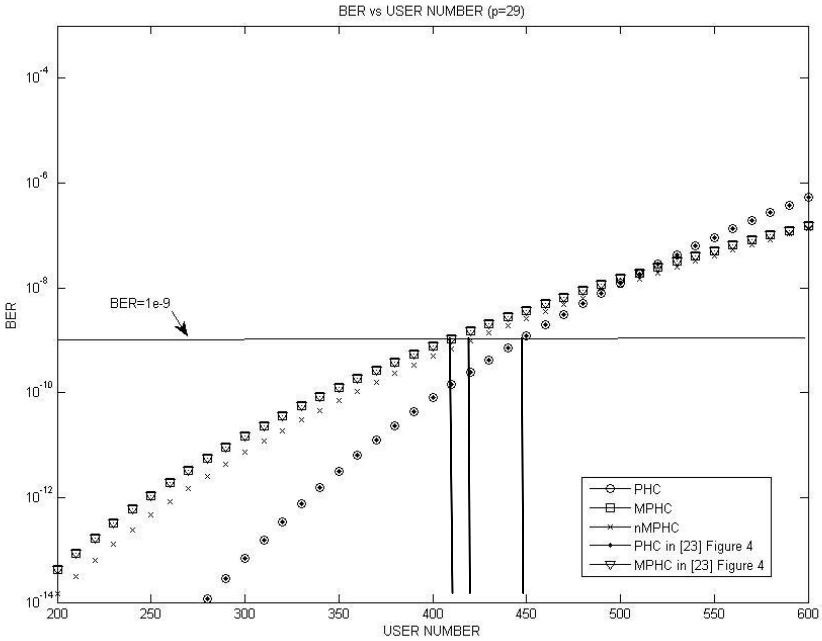


(a)

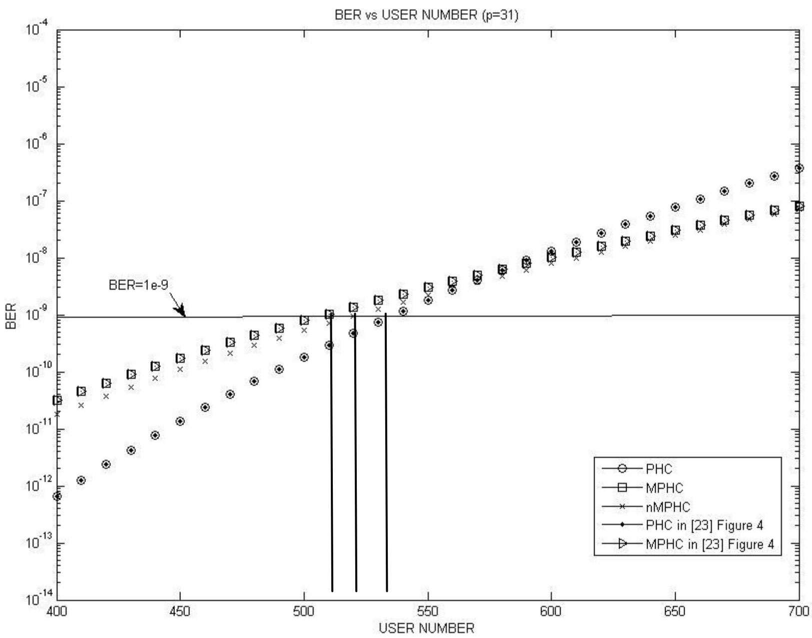


(b)

Figure 11 BER against active user number for p=19 (a) and p=23 (b)



(a)



(b)

Figure 12 BER against active user number for p=29 (a) and p=31 (b)

In Figure 12, we compare the performances of PHC and MPHC using the newly derived analysis approach with the performances of PHC and MPHC in [23] by employing p=29 and 31, it can be seen that they are completely overlapped and we can only see two curves for the performances of PHC and MPHC, this demonstrates that the newly derived approach has been proved to be feasible and correct.

As mentioned in the previous section, nMPHC has one unit increment of system complexity in comparison with MPHC. However, from the figures above it can be seen that the maximum user number that can be accommodated with $\mathrm{BER}=10^{-9}$ (which is a limitation in most analysis) for nMPHC is more than MPHC. Further investigation is concluded in Table 8 which shows the ratios between the reduction of system complexity and the reduction of maximum supported user number referring to PHC for MPHC and nMPHC employing various p.

This ratio is a good merit for codes like MPHC and nMPHC because that this kind of codes aim to reduce system complexity, however, they have to keep BER acceptable (acceptable BER is that at a certain level of BER, the supported user number is acceptable). Therefore the ratio between the reduction of system complexity and the reduction of maximum supported user number is a good means to valuate these codes.

Table 10: Ratios between the reduction of system complexity and the reduction of maximum supported user number referring to PHC for MPHC and nMPHC employing various $\mathbf{p}$

	$\mathbf{p=13}$	$\mathbf{p=17}$	$\mathbf{p=19}$	$\mathbf{p=23}$	$\mathbf{p=29}$	$\mathbf{p=31}$
nMPHC	0.3125	0.3182	0.2581	0.2703	0.4643	0.8235
MPHC	0.2857	0.2286	0.2195	0.2245	0.3590	0.5357

From the table above, the ratios of nMPHC are always greater than MPHC which indicates that the sacrifice of maximum supported user number per unit of reduction in system complexity in nMPHC is less than in MPHC. In other words, nMPHC can reduce the same units of system complexity as MPHC by sacrificing less users.

5.3 Improvement on Confidentiality

In this section, a new method of improving system confidentiality for MPHC and nMPHC is proposed. CDMA in radio communication was firstly proposed for military purpose because of its high security. OCDMA provides optical layer security which realizes data security on the lowest layer of optical network. Security in communications engineering has many aspects including confidentiality, integrity, availability and authentication etc., among all of these properties confidentiality is the most important one which guarantees system security in the transmission process. Ways to enhance system confidentiality come from its encoding/decoding and multiplexing processes.

Approaches to compromise WHTS systems by eavesdroppers include single-wavelength detection, eye-diagram observation and temporal recording etc. Correspondingly, methods for enhancing system confidentiality were developed by researchers such as: 1) 2-code-keying by which not only the data bit ‘1’ is encoded, but also ‘0’; 2) chip slot overstepping which spreads some user’s sequences in multiple bit intervals (different bit intervals for different sequences); 3) Dynamic code conversion which reconfigures pulse positions and wavelength channels both in temporal domain and wavelength domain by an additional WHTS encoder which is activated by a particular key.

Another effective but easy-to-realize method for improving system confidentiality is to apply M-Array modulation in the encoding process by assigning each user with M sequences to represent $\log_2 \mathrm{M}$ bits in one code symbol interval. Dividing the sequences in one code-set into M groups and assigning each user with one of these groups greatly reduces the cardinality and possible simultaneous user number. However, by selecting another $\mathrm{M}-1$ similar-structured code-sets and by picking one sequence from each of the M code-sets as signature code for one user, the correlation properties can maintain at the same as before.

For nMPHC, another $\mathrm{p}-1$ code-sets are established by cyclic shifting the original code-set $\mathrm{p}-1$ times. For representing n bits ($\mathrm{n} \geq 2$) in one code symbol interval, $\mathrm{p} \geq 2^{\mathrm{n}}$ is needed for constructing the original code-set. One of the sequences in the original code-set and its $\mathrm{M}-1$ shifted versions are assigned to one user for representing M different combinations of n bits. In the case $\mathrm{p} > 2^{\mathrm{n}}$, selection of M sequences out of p sequences can be pre-determined or dynamic controlled. The cross-correlation between sequences from different code-set remains the same as nMPHC since they originate from different sequences in nMPHC which has maximum phase shift cross-correlation of one.

From the view point of eavesdroppers, for compromising M-Array modulated WHTS system they need to try $\mathrm{p}^2 \times (\mathrm{p}-1)$ possible code patterns instead of $\mathrm{p} \times (\mathrm{p}-1)$

under the assumption that they know the code structure. Furthermore they have to know the number of bits in one code symbol interval and have to find the M sequences associated with the desired user. Therefore, by applying M-Array modulation in encoding process data is double encrypted while system performance maintains the same as nMPHC.

5.4 Conclusion

After the study on the design of WHTS code and the review of many existing codes a novel WHTS code named nMPHC was proposed and examined against the previously proposed codes MPHC and PHC. The analysis of the code structure of nMPHC indicates its simplification in system implementation. The methodology of BER analysis for WHTS code has been systematically studied and applied on the novel proposed code, a more reasonable and accurate method for evaluating BER of over-coloured WHTS system was proposed. By applying the new method in the BER analysis of MPHC and nMPHC, it shows that nMPHC can reduce the same units of system complexity as MPHC by sacrificing less number of users. Finally this chapter commented on the confidentiality of WHTS system and a feasible and effective approach was suggested for the newly designed code nMPHC. In the next chapter, we will further examine this newly proposed code by applying this code and the previously proposed code MPHC in IP-over-OCDMA environment to verify its improvement in contrast with MPHC. In the previous analysis we consider only MAI as MAI is the most important interference source in OCDMA communications, since in realistic IP network we have to consider more rather than just MAI, it is necessary to include noises in performance analysis to give more precise and accurate results.

Chapter 6
IP Routing by 2D OCDMA Network

6.1 Overview of IP-over-OCDMA System

The concept of the application of OCDMA technology in IP network was firstly proposed in [30] by employing spectral-amplitude-coding and further developed in [31] and [32] by using direct time spreading sequence. In last two decades, the Internet Protocol (IP) has became the dominating telecommunication protocol for data transmission network. However, the slow processing speeding of IP routing which operates electrically in network layer cannot match the network capacity offered by fibre-optic system. The OCDMA system provides the network with asynchronous, simultaneous and secure access, hence it is worthwhile to investigate the feasibility of implementing OCDMA system in IP network.

When IP network is directly loaded to the OCDMA system, to avoid burst traffic the designed peak transmission rate should be greater than the average output bit rate, that means at certain time the network is not fully utilised. Then we have the definition of network utilisation as:

$$\text{utilis} = \frac{\text{average output bit rate}}{\text{peak transmission rate}} \tag{6.1}$$

Or we can name the network utilisation as network burst:

$$\text{burst} = \frac{\text{peak bit rate}}{\text{average bit rate}} \tag{6.2}$$

When the network is not fully utilized, the number of active users who are sending bit "1" varies when different network utilisation applied. Normally the probability of a user who is sending a bit "1" is $\frac{1}{2}$ which follows a binomial distribution, by taking consideration of the network utilisation, that probability becomes $\frac{u}{2}$. Since in OCDMA system the system performance is direct related to the number of active users, the network utilisation impacts the system performance significantly. It is obvious that lower network utilisation provides the system a better performance in BER. However it has also been shown that given a fixed average output bit rate, an optimal utilisation can be found to give the best system performance.

The structure of a typical IP-over-OCDMA system is shown is Figure 13 [30]. When the incoming IP traffic arrives at the IP address recognition unit, the IP address recognition unit will identify the header of the each IP packet and transmit the packet to the buffer, the buffer is divided into N subparts to store the IP packets for different destination, the IP packets with the same destination are saved in the same subpart. At the same time the IP address recognition unit will inform the control unit that an IP packet has been transferred to one of the N subparts. Each of the N subparts has a threshold which is controlled by the control unit, once the threshold is reached the control unit will notice the buffer to release the packet, this buffer is a First-In-First-Out (FIFO) buffer. Meanwhile the control unit will tell the tuneable

OCDMA encoder to adjust the parameters of its Optical Tapped Delay Line (OTDL) or/and gratings according to the destination's signature sequence. After that the encoded IP packet is sending to the optical star coupler, the optical star coupler will mix the signals from all of the N transmitters and transmit the mixed signal to each receiver at the receiving end. The MUI-cancellation OCDMA decoder will correlate the received mixed signal and retrieve the information. The structure of the MUI-cancellation OCDMA decoder is shown in Figure 14 [30], the reference decoder performs a complementary decoding scheme[33]. When 2 or more IP packets with the same destination arrive at the same time, the code sense unit will prevent this from happening, also the code sense unit is used to check if the tuneable OCDMA encoder is adjusted correctly and a feedback will be send to the control unit in the transmitter.

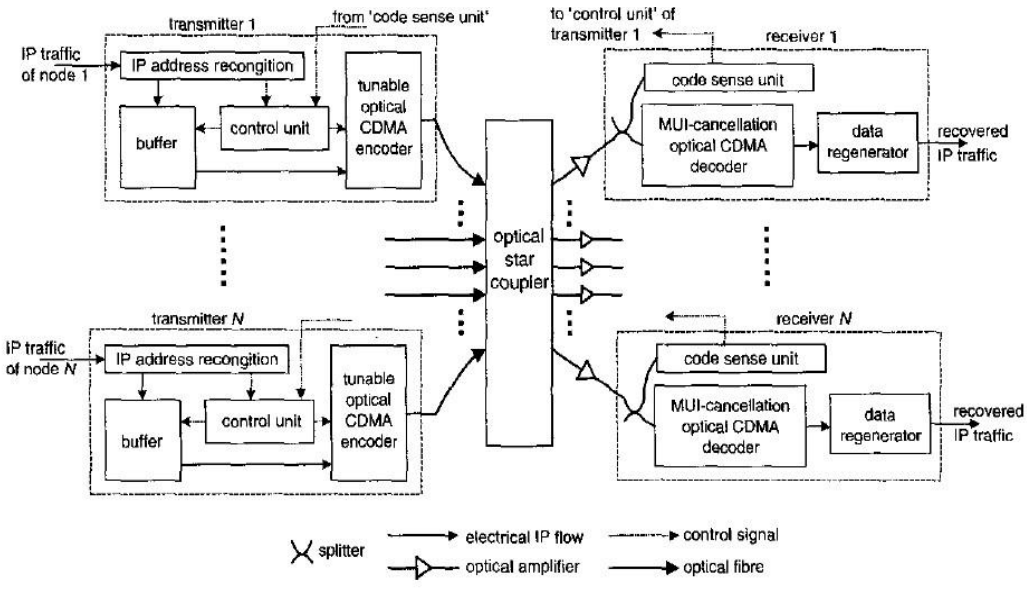


Figure 13 IP-over-OCDMA network structure (from [30])

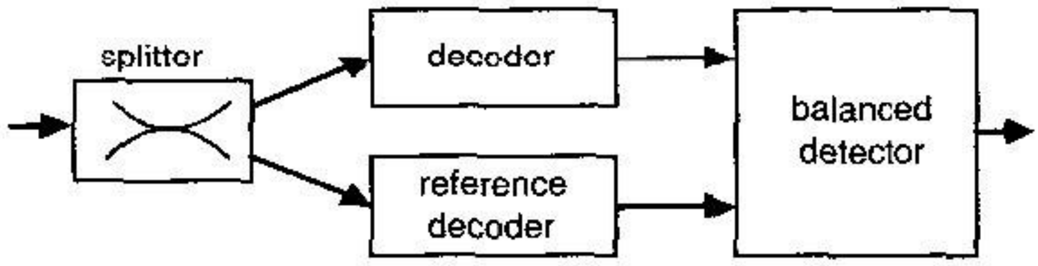


Figure 14 Structure of MUI-cancellation OCDMA decoder (from [30])

It should be noticed that the tuneable OCDMA encoder does not adjust for a single IP packet, but for a group IP packets in one of the N subparts of the buffer at the transmitter. When one of the N subparts reaches its threshold, it will send all the IP packets contained in the subpart in turn. The purpose is to avoid tuning the encoder for each IP packet separately, but for a number of packets, hence the requirement of the encoder tuning speed is relieved. However, when the threshold is higher, delays in the buffer are longer, that means packets have to queue longer time to be transmitted, at this moment the delays become the dominating reason for the degradation of system throughput. Therefore a proper threshold for each subpart in the buffer is important and is necessary to be adjusted according to the network traffic.

6.2 Noises Affecting System Performance

The performance of OCDMA system is affected by a combination of noises at physical level, the predominant affected noises are MAI and Beat Noise (BN).

BN is the most important noise affecting system performance due to the essence of fibre-optic communications, it occurs when two or more optical pulses with the same wavelength incident simultaneously at the same photo-detector, owing to the square law detection of the photo-detector there is beating between these optical pulses to give rise to BN.

For 2D OCDMA system, beating happens when two or more optical pulses from different users with the same wavelength and located in the same slot are received in the optical-electrical conversion process. Beating can take place between the desired signal and interferer's signal, or/and between interferer's and interferer's signals. When data bit "1" is transmitting, BN includes data-crosstalk beating and crosstalk-crosstalk beating if there are more than one interferers. When "0" is transmitting, BN is only the beating between crosstalk users' signals.

The electrical Signal-to-Noise-Ratio (SNR) by taking BN into account in the receiver for bit detection at the instance of autocorrelation peak has been given by [34] for bit "1" and bit "0" respectively:

$$\mathrm{SNR_1(k)} = \frac{(p_s P_d + kP_c - p_s P_d D)^2}{2kP_d P_c + 2\frac{1}{p_s} P_c P_c \binom{k}{2}} \tag{6.3}$$

$$\mathrm{SNR_0(k)} = \frac{(p_s P_d D - kP_c)^2}{2P_c P_c \frac{1}{p_s} \binom{k}{2}} \tag{6.4}$$

Where p_s is the autocorrelation peak i.e. code-weight, k is the number of interferers, P_d is the normalized electrical power received for the desired signal, P_c is the normalized electrical power received for the interferer's signal and D is the threshold level for bit detection. The term $p_s P_d$ is the power of the desired signal, kP_c is the power for interferer's signal, $2kP_d P_c$ is the energy of data-crosstalk BN and $2P_c P_c \frac{1}{p_s} \binom{k}{2}$ is the crosstalk-crosstalk BN energy. As mentioned above, the data-crosstalk BN does not exist any longer in the second expression since when "0" is sending there is no energy for the desired signal.

Besides the BN, some of other noises can interfere the data signal as well, such as thermal noise, photo-detector shot noise and Relative Intensity Noise (RIN) which is caused by the instability at the power level of a laser. The expressions of the received energy for these noises are given in [35]:

$$\sigma_{th}^2 = \frac{4K_B T B_e}{R_L} \tag{6.5}$$

$$\sigma_{sh/s}^2 = 2q(s p_s P_d + kP_c)B_e \qquad \forall s = 0,1 \tag{6.6}$$

$$\sigma_{RIN/s}^2 = RIN(s p_s P_d + kP_c)^2 B_e \quad \forall s = 0,1 \tag{6.7}$$

Where K_B is the Boltzman's constant, B_e is the receiver's electrical equivalent bandwidth, T is the absolute temperature in Kelvin, R_L is the receiver's load resistance, RIN is the relative intensity noise parameter (dB/Hz) and q is electron charge. s represents the data bit of desired signal.By taking into account the thermal noise, shot noise and RIN, we can re-write the SNR functions above as:

$$SNR_1(k) = \frac{(p_s P_d + kP_c - p_s P_d D)^2}{2kP_d P_c + 2\frac{1}{p_s} P_c P_c \binom{k}{2} + \frac{4K_B T B_e}{R_L} + 2q(p_s P_d + kP_c)B_e + RIN(p_s P_d + kP_c)^2 B_e} \tag{6.8}$$

$$SNR_0(k) = \frac{(p_s P_d D - kP_c)^2}{2P_c P_c \frac{1}{p_s}\binom{k}{2} + \frac{4K_B T B_e}{R_L} + 2qkP_c B_e + RIN(kP_c)^2 B_e} \tag{6.9}$$

In the previous analysis in Chapter 5, we considered the MAI as the sole interference affecting BER, by considering the noises in the performance analysis, the SNR becomes the significant factor in determining the BER.

6.3 Performance Analysis of nMPHC

Continue with the performance analysis in Chapter 5, by introducing the network utilisation into Formula (5.12) and still consider the MAI only, the error probability function for MPHC or nMPHC becomes:

$$Pe_N = \sum_{I=CW}^{N-1}\binom{N-1}{I}\left(\frac{u}{2}\right)^I\left(1-\frac{u}{2}\right)^{N-I}\sum_{J=CW}^{I}\binom{I}{J}\left(\frac{\bar{H}}{2p^2}\right)^J \times \left(1-\frac{\bar{H}}{2p^2}\right)^{I-J} \quad (6.10)$$

Where u is the network utilisation, N is the number of active users, CW is the threshold for bit detection i.e. code-weight, I is the number of active users who are sending bit "1" and J is the number of users who are interfering with the desired user, $\bar{H}$ is the average hit probability between any 2 sequences as described in Chapter 5, $\frac{u}{2}$ is probability that an active user is sending a bit "1".

Furthermore, by taking into account the noises and using Gaussian approximation, the error probability function can be expressed as:

$$Pe_N = \sum_{I=1}^{N-1}\binom{N-1}{I}\left(\frac{u}{2}\right)^I\left(1-\frac{u}{2}\right)^{N-I}\sum_{J=CWD}^{I}\binom{I}{J}\left(\frac{\bar{H}}{2p^2}\right)^J \times \left(1-\frac{\bar{H}}{2p^2}\right)^{I-J} \times \frac{1}{2}\left(Q\left(\sqrt{SNR_1(k)}\right) + Q\left(\sqrt{SNR_0(k)}\right)\right) =$$

$$\sum_{I=1}^{N-1}\binom{N-1}{I}\left(\frac{u}{2}\right)^I\left(1-\frac{u}{2}\right)^{N-I}\sum_{J=CWD}^{I}\binom{I}{J}\left(\frac{\bar{H}}{2p^2}\right)^J \times$$

$$\left(1-\frac{\bar{H}}{2p^2}\right)^{I-J}\frac{1}{2}\left(Q\left(\sqrt{\frac{(p_sP_d+kP_c-p_sP_dD)^2}{2kP_dP_c+2\frac{1}{p_s}P_cP_c\binom{k}{2}+\frac{4K_BTB_e}{R_L}+2q(p_sP_d+kP_c)B_e+RIN(p_sP_d+kP_c)^2B_e}}\right)+\right.$$

$$\left.Q\left(\sqrt{\frac{(p_sP_dD-kP_c)^2}{2P_cP_c\frac{1}{p_s}\binom{k}{2}+\frac{4K_BTB_e}{R_L}+2qkP_cB_e+RIN(kP_c)^2B_e}}\right)\right) \quad (6.11)$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty}\exp\left(-\frac{y^2}{2}\right)dy \quad (6.12)$$

and "erfc" is the error function, the threshold for bit detection becomes CWD where D is the threshold level defined in the expression of $SNR_1(k)$ and $SNR_0(k)$.

In the numerical analysis of error probability, we assume that $P_d = P_c = 1\mu W, B_e = 100MHz, R_L = 1K\Omega, RIN = -120dB/H$ and $D = \frac{1}{2}$ which has been verified to be the optimum value for fixed threshold receiver in [36].

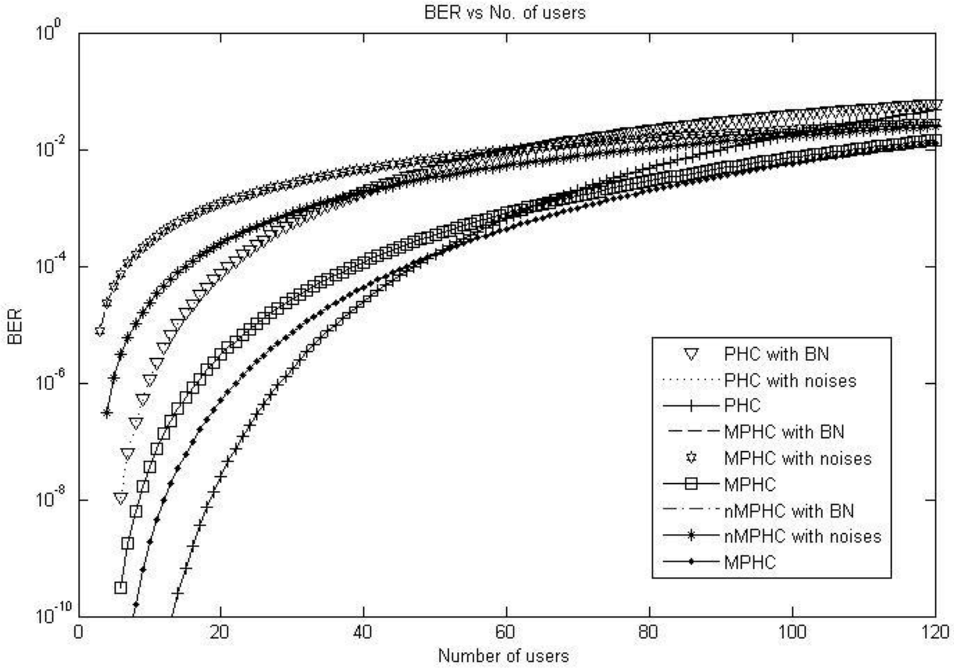


Figure 15 BER against active user number for PHC, MPHC and nMPHC with network utilisation equals to 1 and various noises for p=11

Figure 15 calculates the error probability of PHC, MPHC and nMPHC for p=11 against the user number with BN and other noises in a fully utilized network with the use of Matlab. Firstly we can see the performance of PHC, MPHC and nMPHC without any noise are the same to the result in Chapter 5. Since the curves with BN for these three codes are overlapped with those which have taken into account all kinds of noises, we can see the BN is the dominant interference except MAI, and the thermal noise, photo-detector shot noise and RIN are negligible when comparing with BN. When active user number is less than 40, PHC outperforms MPHC and nMPHC and nMPHC outperforms MPHC with or without noises, the trend is similar to previous analysis. When the user number reaches 40 and above, the nMPHC outperforms PHC and MPHC, however we can see BER performances of these three codes in this region have became unacceptable, this is because that p is too small to provide acceptable performance, in real world application p=11 is not possible to be used for constructing a code, here for demonstration purpose we employ a small value of p=11. This results the nMPHC is not only superior in system complexity, but also performs better in BER in noisy network. The PHC performs better than nMPHC in ideal environment, but its complexity determines that it has more BN generated during the receiving process.

Regarding the performance analysis of IP network, Packet Error Rate (PER) is generally used as a measurement rather than BER, PER in IP traffic is defined as:

$$\mathrm{PER(N)} = 1 - (1 - \mathrm{BER(N)})^{\mathrm{w}} \tag{6.13}$$

Where w is the number of bits contained in a packet, in the analysis we assume the longest packet length is 1500 octet bytes, each byte is consisted of 8 bits, hence the packet length is 12000bits. We analyze the PER of MPHC and nMPHC in IP traffic using the same manner as we analyzed the BER but with various network utilisations.

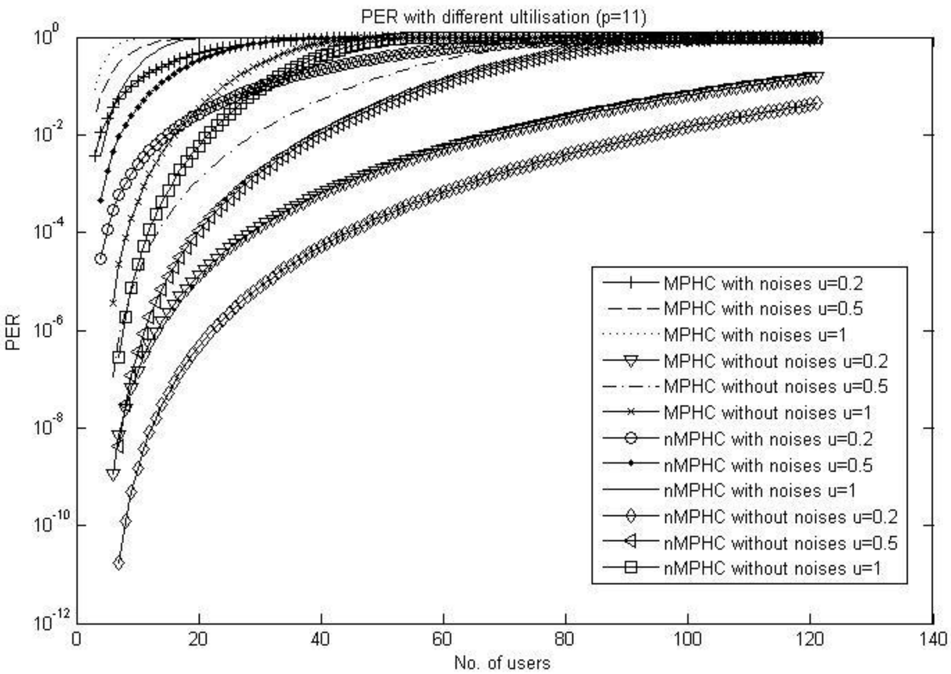


Figure 16 PER against active user number for MPHC and nMPHC with various network utilisation and various noises for p=11

Figure 16 calculates the PER performance of MPHC and nMPHC for p=11 against the active user number with network utilisation u=0.2, 0.5 and 1 and with BN and other noises by the use of Matlab. We did not consider PHC in the PER analysis since in this thesis we mainly concern the performance of MPHC and nMPHC, this is because MPHC and nMPHC are designed for the same purpose and they are the most comparable codes. Usually the highest acceptable value of PER is 10^{-5}, we can see from Figure 16 most of the PER values are unacceptable, this is because that p is too small to provide acceptable performance, in real world application p=11 is not possible to be used for constructing a code, here for demonstration purpose we employ a small value of p=11. **As just mentioned the thermal noise, shot noise and RIN have little effect on system performance and is negligible. As discussed in the previous section, for IP traffic without fixed average output bit rate, lower network**

utilisation leads to better system performance. When the network utilisation is low, nMPHC outperforms MPHC even better than when the network utilisation is high, this is because when traffic is low the effect of MAI becomes less severe, but the nMPHC has higher threshold for bit detection and higher autocorrelation peak, this results a higher SNR than MPHC, even with the presence of other noises.

6.4 Conclusion

In this chapter, we numerically analyzed the BER performance (for PHC, MPHC and nMPHC) and PER performance (for MPHC and nMPHC) with p=11 in a IP-over-OCDMA system, results show that by applying nMPHC in IP-over-OCDMA system, it is again proved the possibility of IP routing over OCDMA network. We can see nMPHC still performs better than MPHC, under certain circumstances the superiority becomes more obvious. In the real world noisy environment, nMPHC can perform better than PHC with reduced system complexity when the user number is large. These have demonstrated that nMPHC is a more practical and potential candidate for 2D OCDMA system than the previous one in some aspects. In the next chapter, we will apply nMPHC in three different OCDMA random access protocols to testify if we can improve the system throughput by employing nMPHC.

Chapter 7
OCDMA Random Access Protocols

7.1 Introduction

The capacity of OCDMA packet network in the link layer cannot always meet the needs of the large amount of users and bursty traffic, when the active user number exceeds the number of available code sequences, a random access protocol is needed which is similar to the Medium Access Control (MAC) in IP networking. In [37] three different OCDMA random access protocols were proposed, two of them need pre-transmission coordination by which a control packet is sent before the data is transmitting to pre-set the encoder and decoder, the third one of them does not need pre-transmission coordination.

Owing to the need of pre-transmission coordination for the first two protocols, a control message is sent before data is launched to adjust the transmitter and receiver, which requires both transmitter and receiver to be tuneable, i.e. the optical encoder and decoder have to have the ability to tune their signature code according to the control message at any time. However, the third protocol does not require the OTDL or/and gratings to be tuneable and is simpler to implement.

When data is received by the receiver, a Cyclic Redundancy Check (CRC) is performed to examine if the data is retrieved correctly, if the result is negative a feedback message is sent to the transmitted asking for re-transmission. After the transmitter has received the feedback message it will re-transmit the erroneously detected packet which is save in the buffer of the transmitter after an average time delay, rather than re-generate the packet, because re-generating (in which case the error message will send to the end user to tell the end user that transmission has failed and request the end user to re-generate and re-transmit the lost packet.) of packet will give rise to the traffic in the channel and cause increment of interference. The packet is stored in the buffer of the transmitter until the transmitter receives a positive acknowledgement from the destination receiver which tells the transmitter the packer has been successfully detected.

The OCDMA system has the property of a bursty network in which the users are not always active, hence we allow the number of user accommodated in the network exceeds the capacity of the OCDMA signature code.

One of the measurements for evaluating a random access protocol is system throughput by which the number of successfully received packets per time slot is shown. The other one is average time delay which tells after how many time slots a packet can be successfully received by the destination receiver on average. In the following analysis we consider Conventional Correlation Receiver (CCR) only, and for the interference causing system degradation we take into account only the MAI without other noises.

7.2 Three Random Access Protocols

7.2.1 Protocol 1

We consider all the available sequences of an OCDMA code as an pool (Figure 17 [37]), when one of the user accommodated in the network becomes active and needs to transmitted a packet, the system will randomly pick up and assign the user with a signature sequence from the pool. After all of the available sequences have been assigned to the users, i.e. $\mathrm{N} > |\mathrm{C}|$ (N is the number of users who intend to transmit a packet, $|\mathrm{C}|$ is the capacity of the OCDMA code), the next user who is intending to transmit a packet has to wait until one of the users who are currently assigned codes from the pool finishes transmitting and sequences are available again from the pool. In other words, there is no more sequence available to assign the user and the user has to keep trying to transmit at subsequent time slots.

For Protocol 1 pre-transmission coordination is needed, a control message is sent before transmitting because the system assigns sequences randomly from the pool to users, the transmitter does not know its destination address before transmitting, the receiver does not know the packet encoded with which signature sequence it should receive as well. The control packet is broadcasting to all the users accommodated in the network to inform them their address and the destination address and the signature sequence for transmitting, every user in the network has a pre-allocated period at the head of each time slot or a pre-allocated channel with specific wavelength, every user listens to its own message from its pre-allocated channel and establish connection. After the transmitter and receiver have been informed with their signature sequences, they adjust their encoder/decoder according to the sequence by tuning the OTDL and gratings and start transmitting.

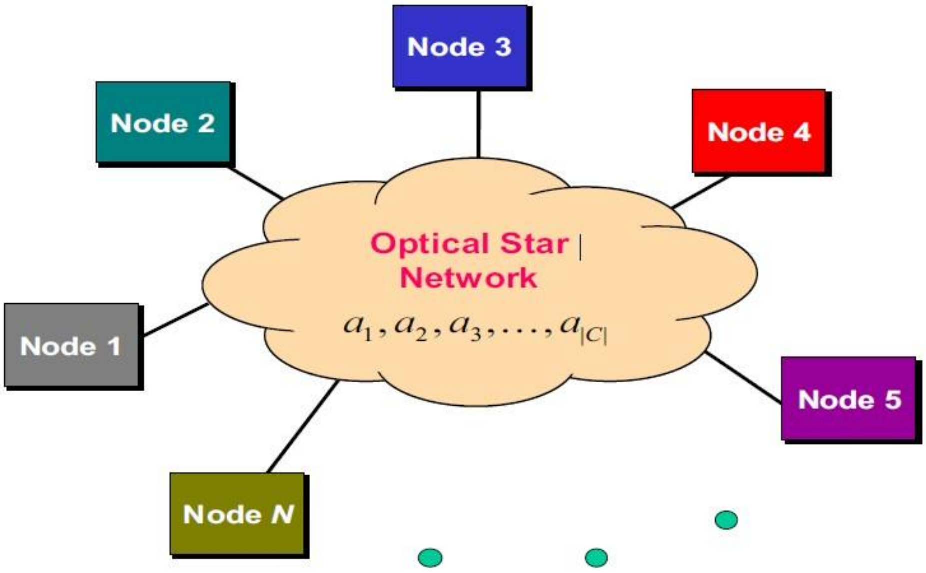


Figure 17 An OCDMA network (from [37])

7.2.2 Protocol 2

The principle of Protocol 2 is slightly different from Protocol 1. After all the signature sequences from the pool have been assign to $|C|$ users, the next user who is intending to transmit a packet can still be assigned a signature sequence by the system randomly, i.e. when $N > |C|$ the user with intention to transmit does not have to keep trying in the subsequent time slots and wait until the appearance of next available sequence. Hence all the users can always find a code to transmit their packets. Obviously by doing this the interference in transmission will increase dramatically since some of the sequences from the pool are used more than once. However, the enhancement on network traffic will give rise to the system throughput.

In addition, for suppression of the interference among users, a randomly cyclic shifted sequence of itself will be assigned to the next user with intention to transmit if this sequence has been selected previously and is still in use when $N > |C|$. In Protocol 2, pre-transmission coordination is still needed and a control message is broadcasting in the same manner as Protocol 1 before transmitting.

7.2.3 Protocol 3

In Protocol 3, every user is allocated with a fixed signature sequence when it is connected to the network, therefore there is no needs for pre-transmission coordination. Similar to Protocol 2, after the accommodated users have reached the limit of the capacity of the OCDMA code $|C|$, a randomly shifted sequence of one of the sequence in the pool will be allocated to the user who has just subscribed to the network randomly.

In theoretical analysis we assume that the control message is always transmitted successfully and there is no delays caused by the control message, therefore Protocol 3 performs similarly to Protocol 2 in numerical analysis because we discard pre-transmission coordination, hence we consider Protocol 2 and Protocol 3 as one Protocol in the following analysis. If we take the delay caused by erroneously received control message into account, Protocol 3 will outperform Protocol 2 in system throughput and average delay for success of packet transmission.

In Protocol 1, the interference among users is minimized in comparison with Protocol 2 because when all sequences in the pool are subscribed no more cyclic shifted sequences of existing sequences will be involved in the transmission, this will enhance the probability of a successful transmission of packet. However, the offered load of Protocol 2 within a time slot is higher than Protocol 1, by which the system throughput is probabilistically enhanced. In the following analysis, we will theoretically analyze the system throughput of Protocol 1 and Protocol 2 (as we consider Protocol 2 and Protocol 3 as the same protocol) by employing MPHC and nMPHC, CCR will be used as the receiver and MAI will be the only interference source of performance degradation for consideration.

7.3 System Model and Theoretical Analysis

Assume N is the number of users accommodated in the network, each user has a probability of A to transmit a packet at the beginning of a time slot. A packet contains K bits which is the duration of a time slot as well. A user who becomes active and intends to transmit a packet with probability A is allocated with a signature sequence according to the random access protocol used (e.g. Protocol 1 or Protocol 2). After the packet arrives at the destination receiver the receiver will send back an acknowledgement to inform the transmitter if the packet has received successfully. If the transmission was unsuccessful the sending user enters a backlog mode and the same packet will be re-transmitted after d time slots on average (or with a probability of $\frac{1}{d}$ to re-transmit). Assuming the number of backlogged user at a certain time slot is n, the traffic load and system throughput is given by [37]:

$$G(n) = (N-n)A + \frac{n}{d} = NA - (A - \frac{1}{d}) \qquad (7.1)$$

$$\beta(n) = \begin{cases} \sum_{j=0}^{N-n}\sum_{i=0}^{n}\big((i+j)\wedge|C|\big)P_s\big((i+j)\wedge|C|\big)P_{bl}(i|n)P_{th}(j|n); & \text{for Protocol 1} \\ \sum_{j=0}^{N-n}\sum_{i=0}^{n}(i+j)P_s(i+j)P_{bl}(i|n)P_{th}(j|n); & \text{for Protocol 2} \end{cases}$$

(7.2)

Where $x \wedge y$ denotes the minimum value between x and y, $|C|$ in the code cardinality. $P_{bl}(i|n)$ is the probability of i backlogged users being active for a given number of backlogged users n and $P_{th}(j|n)$ is the probability of j thinking users who are intending to transmit a new packet being active for a given number of backlogged users n:

$$P_{bl}(i|n) = \binom{n}{i}\left(\frac{1}{d}\right)^{i}(1-\frac{1}{d})^{n-i} \tag{7.3}$$

$$P_{bl}(i|n) = \binom{N-n}{j}(A)^{j}(1-A)^{N-n-j} \tag{7.4}$$

$P_s(r)$ is the probability that a packet is successfully received by the receiver for a given number of active user r.

In 2D OCDMA codes, the maximum cross-correlation between any two sequences is 1, therefore any two sequences can either interfere with each other by 1 chip or w chips (w is the code-weight). Or we can say the interferers can interfere the desired user with 0, 1 or w chips, because the interferers can either use a cyclic shift of the other codes or a cyclic shift of the desired user's code, in the former case interferer will interfere the desired user with either 0 or 1 chips, in the latter case interferer will interfere the desired user with either 0 or w chips. Let p_w to be the probability that the desired user is interfered by w chips with one of the interferers and $p_1$to be the probability that the desired user is interfered by 1 chip with the interferer, for MPHC and nMPHC:

$$p_w = \begin{cases} 0 & \text{for Protocol 1} \\ \frac{1}{p^2}\frac{\frac{r}{p(p-1)}-1}{r-1} & \text{for Protocol 2} \end{cases} \tag{7.5}$$

$$p_1 = \begin{cases} \frac{\bar{H}}{p^2} & \text{for Protocol 1} \\ \frac{\bar{H}}{p^2}\left(1 - \frac{\frac{r}{p(p-1)}-1}{r-1}\right) & \text{for Protocol 2} \end{cases} \tag{7.6}$$

Where p is the prime number for constructing MPHC and nMPHC and $\bar{H}$ is the average hit probability as mentioned in Chapter 5, and r is the number of active user number. Because the active user number is r, then we have 1 desired user and $r-1$ other users. We can divide the $r-1$ users into 3 groups: a) Users having no interference with the desired user; b) Users interfering the desired user by 1 Chip; c) Users interfering the desired user by w chips. Assume the number of the active users who are interfering with the desired user by 1 chip is l and the number of the active users who are interfering with the desired users by w chips is m, bit "1" and bit "0" have equal probability to be transmitted which is $1/2$. The CCR decides a data bit to be "1" if the received number of pulses reaches the threshold w (i.e. the code-weight), or bit "0" is decided. Therefore the conditional bit-correct probability $P_{bc}(l,m)$ can be expressed as:

$$P_{bc}(l,m) = \Pr\{\text{a bit success}|l,m\} = \frac{1}{2}\Pr\{\text{a bit success}|l,m,1\} + \frac{1}{2}\Pr\{\text{a bit success}|l,m,0\} = \frac{1}{2} + \frac{1}{2}\frac{1}{2^m}\frac{1}{2^l}\sum_{i=0}^{w-1}\binom{l}{i} \tag{7.7}$$

Consequently, the conditional packet success probability is:

$$P_s(r|l.m) = (P_{bc}(l,m))^K = \left(\frac{1}{2} + \frac{1}{2}\frac{1}{2^m}\frac{1}{2^l}\sum_{i=0}^{w-1}\binom{l}{i}\right)^K \tag{7.8}$$

Eventually the packet success probability $P_s(r)$ for CCR is:

$$P_s(r) = \sum_{l=0}^{r-1}\sum_{m=o}^{r-1-l}\frac{(r-1)!}{l!m!(r-1-l-m)!}p_1^l p_w^m (1-p_1^l-p_w^m)^{r-1-l-m}\left(\frac{1}{2} + \frac{1}{2}\frac{1}{2^m}\frac{1}{2^l}\sum_{i=0}^{w-1}\binom{l}{i}\right)^K \tag{7.9}$$

In the numerical analysis of the steady-state system throughput by employing MPHC and nMPHC, we assume that a thinking user (a user who has a packet which is about to be transmitted in the first time) and a backlogged user have the same probability to become an active user i.e. $A = \frac{1}{d}$, we set the system parameters as $p = 5, N = 50$ and $K = 127$ which is the length of a packet or the duration of a time slot. Because $A = \frac{1}{d}$, the number of backlogged user n is not necessary to be given since any value of n leads to the same results.

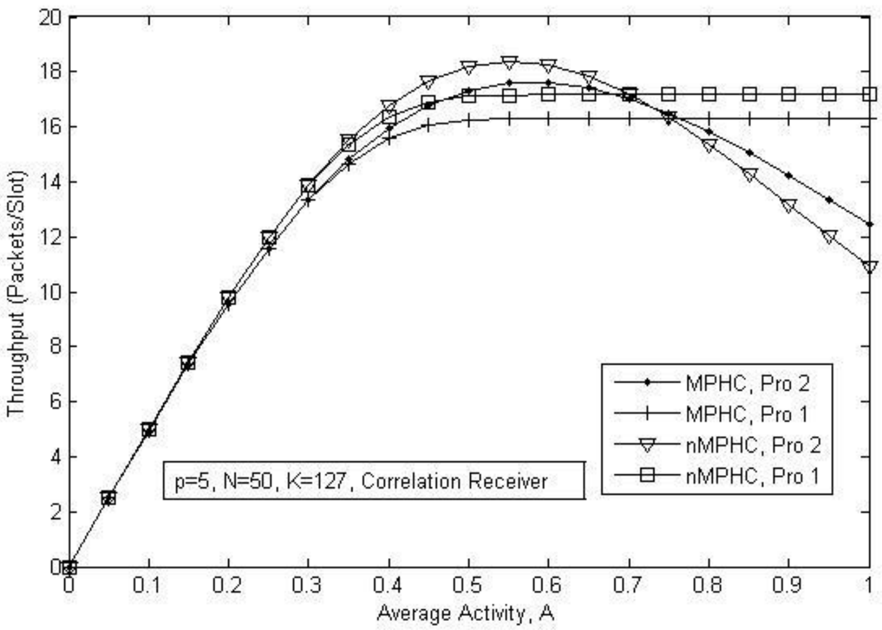


Figure 18 System throughput against average activity A for p=5, N=50, K=127 employing MPHC and nMPHC

Figure 18 calculates steady-state system throughput against average activity for user number $N = 50$, packet length $K = 127$ employing MPHC and nMPHC with $p = 5$ by the use of Matlab. For Protocol 1, when the average activity is low MPHC and nMPHC have the same system throughput, when the average activity is greater than 0.3, nMPHC performs approximately 1.5 packets/slot higher on system throughput than MPHC. For Protocol 2, the performance of MPHC and nMPHC remain the same when A is less than 0.3, between 0.3 and 0.7, nMPHC outperforms MPHC, when A is higher than 0.7, MPHC becomes superior to nMPHC.

7.4 Conclusion

In this chapter we introduced three different OCDMA random access protocols, we applied these three protocols on MPHC and nMPHC to examine the feasibilities of these protocols and to analyze the performances of MPHC and nMPHC. To conclude, for Protocol 1, when average activity is low, either MPHC or nMPHC can provide an acceptable system throughput, however, when offered traffic is high, nMPHC should be a better choice than MPHC. For Protocol 2, when average activity is low, the analysis results are similar to Protocol 1, with medium average activity nMPHC provides higher throughput, but with higher activity MPHC is better than nMPHC to alleviate the heavy traffic. We can see in most cases nMPHC outperforms MPHC regarding system throughput, it is proved again that nMPHC can be a potential candidate for OCDMA packet network.

In the next Chapter, we will introduce a novel receiver architecture named Parallel Interference Cancellation (PIC) receiver rather than CCR, by applying PIC in 2D OCDMA system with the use of nMPHC, the system performance can be improved greatly.

Chapter 8
Parallel Interference Cancellation Receiver

8.1 Introduction to Parallel Interference Cancellation

The schematic of Parallel Interference Cancellation (PIC) receiver is depicted in Figure 19 [38]:

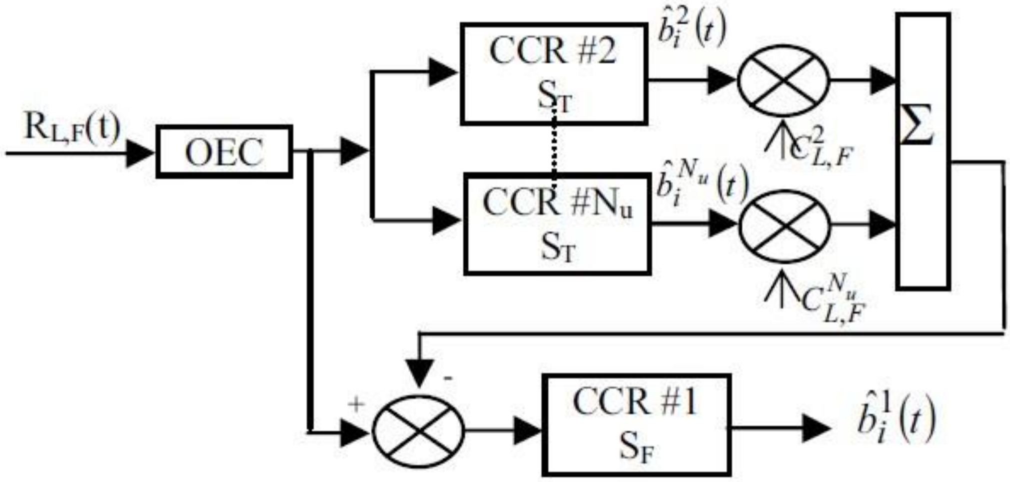


Figure 19 Schematic of a typical PIC receiver (from [38])

For an OCDMA network accommodated with N_u users, A PIC receiver is consisted of N_u different CCRs correlating with the N_u different sequences of an OCDMA code.

We assume user #1 to be the desired user, the CCRs of the non-desired users are connected in parallel and then connected to the CCR of user #1 in serial. The incoming mixed signal is divided into two streams after optical-electrical conversion, one of which is directly going to the CCR of the desired user with a time delay while the other stream is heading to the parallel structure of the non-desired users' CCRs. The CCRs #2 to #N_u perform as reference decoders to remove the interference signals from the mixed incoming signal, the interference signals are supposed to be detected in the parallel structure and spread by its own sequence again, and then to be transmitted to adder and removed from the mixed signal. The objective of a PIC receiver is to separate the interfering signal from the received mixed signal and then remove it to offer the destination user the desired signal without interference. The $N_u - 1$ reference CCRs are set with a threshold of S_T, each of the $N_u - 1$ CCRs gives an estimation $\hat{b}_i^j(t)$ of the data bit of its corresponding user #j, then the data is spread again with the signature sequence $c_j(t)$ of user #j. Finally the interference from user the $N_u - 1$ users is re-constructed and removed from the received mixed signal $r(t)$. The bit detection of the desired user #1 is done by the CCR of the desired user with a threshold S_F, the signal at the entry of CCR #1 can be described as [38]:

$$s(t) = r(t) - \sum_{j=2}^{N_u} \hat{b}_i^j(t) c_j(t) = b_i^1(t) c_1(t) + \sum_{j=2}^{N_u} (b_i^j(t) - \hat{b}_i^j(t)) c_j(t) \qquad (8.1)$$

8.2 Theoretical Analysis

In this section, the BER expressions of MPHC and nMPHC with PIC are theoretically deduced. As mentioned above, we assume that the threshold level of the $N_u - 1$ reference receivers is S_T where $0 < S_T < w$ (w is the code-weight of MPHC or nMPHC) and the threshold of the desired user's receiver is S_F where $0 < S_F < w$.

In the following two cases receiver #1 will erroneously detects a data bit:

Case(1): $b_i^1 = 0$ and $\hat{b}_i^1 = 1$

Case(2): $b_i^1 = 1$ and $\hat{b}_i^1 = 0$

Since bit "1" and bit "0" are transmitted equally in probability therefore the error probability can be expressed as:

$$P_{EPIC} = \frac{1}{2}P\left(\hat{b}_i^1 = 1 \middle| b_i^1 = 0\right) + \frac{1}{2}P\left(\hat{b}_i^1 = 0 \middle| b_i^1 = 1\right) \quad (8.2)$$

and the decision variable:

$$Z_i^1 = wb_i^1 + \sum_{j=2}^{N_u}(b_i^j - \hat{b}_i^j)\int_0^T c_1(t)c_j(t)dt \quad (8.3)$$

Then we can re-write the Case(1) and Case(2) as:

Case(1): $b_i^1 = 0$ and $Z_i^1 = \sum_{j=2}^{N_u}(b_i^j - \hat{b}_i^j)\int_0^T c_1(t)c_j(t)dt = I \geq S_F$

Case(2): $b_i^1 = 1$ and $Z_i^1 = wb_i^1 + \sum_{j=2}^{N_u}(b_i^j - \hat{b}_i^j)\int_0^T c_1(t)c_j(t)dt = w + I < S_F$

Where $I = \sum_{j=2}^{N_u}(b_i^j - \hat{b}_i^j)\int_0^T c_1(t)c_j(t)dt$ is the interference term. Therefore the interference of #j user is $I_i^j = (b_i^j - \hat{b}_i^j)\int_0^T c_1(t)c_j(t)dt$. Consider the interference of #j user on the desired user for the following cases:

1) When $\int_0^T c_1(t)c_j(t)dt = 0$, no interference of #j user on #1 user, $I_i^j = 0$.

2) When $\int_0^T c_1(t)c_j(t)dt = 1$, the interference depends on $(b_i^j - \hat{b}_i^j)$.

2.1) When $b_i^j = 1$, $\hat{b}_i^j = 1$ because CCR can never erroneously detect a bit "1", therefore $(b_i^j - \hat{b}_i^j) = 0$, and $I_i^j = 0$.

2.2) When $b_i^j = 0, \hat{b}_i^j$ can either be recognize as "1" or "0".

2.2.1) If $\hat{b}_i^j = 0, (b_i^j - \hat{b}_i^j) = 0$ and $I_i^j = 0$, hence no interference incurred.

2.2.2) If $\hat{b}_i^j = 1, (b_i^j - \hat{b}_i^j) = -1$ and $I_i^j = -1$, therefore the interference of #j on #1 is -1 and the value of the decision variable Z_i^1 is reduced by 1.

Because $I = \sum_{j=2}^{N_u} I_i^j$, the value of the interference term is always minus or zero. Consequently, because $Z_i^1 = wb_i^1 + \sum_{j=2}^{N_u}(b_i^j - \hat{b}_i^j)\int_0^T c_1(t)c_j(t)dt$,

Case(1): $Z_i^1 = -|I| < S_F$, there is no error occurs because Z_i^1 is either zero or minus, and S_F must be greater than zero.

Case(2): $Z_i^1 = w - |I|$, an error is possibly occurs when $Z_i^1 = w - |I| < S_F$, i.e.

$$|I| \geq w - S_F + 1 \tag{8.4}$$

According to the above analysis, we can tell that for the PIC receiver, when data bit "0" is received the data bit will not be erroneously detected, when data bit "1" is received there can be an error, which is contrary to CCR, thus Formula (8.2) can be re-write as:

$$P_{EPIC} = \frac{1}{2}P\left(\hat{b}_i^1 = 0 \middle| b_i^1 = 1\right) \tag{8.5}$$

Therefore in the following analysis we consider the case $b_i^1 = 1$ only. In addition, we can deduce from the above analysis that a non-desired user who is sending a bit "1" cannot interfere the desired user for decision making.

For the deduction of the expression for error probability of PIC, we divide the $N_u - 1$ non-desired users into three groups:

Group 1: The users who are sending a bit "1" and are not interfering with the desired user. However, the users in Group 1 can interfere the decision making of the non-desired users who are sending bit "0" in the reference receivers. Assume the number of users in Group 1 is N_1. To form an error of the non-desired users who are sending bit "0", N_1 has to be greater than or equal to $S_T - 1$ because we already knew that the desired user was sending a bit "1". The probability of N_1 users $\#j_1$ out of $N_u - 1$ non-desired users being sending bit b_i^{j1}=1 is:

$$P_1 = \binom{N_u-1}{N_1}(\frac{1}{2})^{N_1} \tag{8.6}$$

Group 2: The users who are sending bit "0" and are interfering the decision making of the desired user. If one of the non-desired users is interfering the desired user, it must satisfy two conditions: 1) This user must be interfered by the non-desired users who are sending bit "1" and an error occurs when this user makes its own decision; 2) This user's signature sequence must have non-zero cross-correlation with the sequence of the desired user and have overlapping of pulses with the desired user at the auto-correlation peak when the desired user makes its decision. Assume the number of users in Group 2 is N_2, for creating an error of the desired user, N_2 must be greater than or equal to $w + 1 - S_F$ as in Formula (8.4). Thus for a given N_1 we have $w + 1 - S_F \le N_2 \le N_u - 1 - N_1$. The probability of N_2 users $\#j_2$ out of $N_u - 1 - N_1$ non-desired users being sending bit b_i^{j2}=0 is:

$$P_2 = \binom{N_u-1-N_1}{N_2}(\frac{1}{2})^{N_2} \tag{8.7}$$

Group 3: The users who are sending bit "0" but are belonging to Group 2. For given N_1 and N_2, the number of users in Group 3 is $N_u - 1 - N_1 - N_2$. The probability of $N_u - 1 - N_1 - N_2$ users being sending bit "0" is:

$$P_3 = (\frac{1}{2})^{N_u-1-N_1-N_2} \quad (8.8)$$

After we have divided the non-desired users into these three groups above, we now can derive the expression for the probability of a user in Group 2 being interfering the decision-making of the desired user (i.e. the probability of a user being in Group 2). As mentioned above, a user who is sending a bit "0" must meet two conditions to interfere the desired user: 1) $\int_0^T c_1(t)c_{j_2}(t)dt = 1$; 2) $b_i^{j_2}$=0 but $\hat{b}_i^{j_2}$=1. Thus the expression can be derived as:

$$P_I = P((\hat{b}_i^{j_2} = 1 \cap \int_0^T c_1(t)c_{j_2}(t)dt = 1)|(b_i^{j_2} = 0 \cap b_i^1 = 1) \quad (8.9)$$

If $\int_0^T c_1(t)c_{j_2}(t)dt = 1$ the first condition is satisfied, also $\int_0^T c_1(t)c_{j_2}(t)dt = 1$ means the desired user is interfering the decision making of user $\#j_2$ in the reference receiver $\#j_2$, thus Formula (8.9) can be expressed by another way:

$$P_I = P(\int_0^T c_1(t)c_{j_2}(t)dt = 1) \times P(Z_i^{j_2} \geq S_T|b_i^{j_2} = 0 \cap b_i^1 = 1 \cap \int_0^T c_1(t)c_{j_2}(t)dt = 1) \quad (8.10)$$

Given that $b_i^{j_2} = 0$, $b_i^1 = 1$ and $\int_0^T c_1(t)c_{j_2}(t)dt = 1$,

$$Z_i^{j_2} = wb_i^{j2} + b_i^1 \int_0^T c_1(t)c_{j_2}(t)dt + \sum_{j=2,j\neq j_2}^{N_u} b_i^j \int_0^T c_j(t)c_{j_2}(t)dt =$$

$$1 + \sum_{j=2,j\neq j_2}^{N_u} b_i^j \int_0^T c_j(t)c_{j_2}(t)dt \geq S_T \quad (8.11)$$

The probability of two sequences being overlapping with one pulse for MPHC and nMPHC are easily found in Chapter 5:

$$P\left(\int_0^T c_1(t)c_{j_2}(t)dt = 1\right) = \frac{\overline{H}}{2p^2} \quad (8.12)$$

Where $\overline{H}$ is the average hit probability between any two sequences and p is the prime number for constructing the code.

Therefore:

$$P_I = \frac{\overline{H}}{2p^2} \times P(\sum_{j=2,j\neq j_2}^{N_u} b_i^j \int_0^T c_j(t)c_{j_2}(t)dt \geq S_T - 1) \tag{8.13}$$

The error of $\#j_2$ is caused by the desired user and the users in Group 1, therefore for generating an error, owing to the threshold of bit detection S_T, the interfering users number in Group 1 must be greater than or equal to $S_T - 1$, thus:

$$P(\sum_{j=2,j\neq j_2}^{N_u} b_i^j \int_0^T c_j(t)c_{j_2}(t)dt \geq S_T - 1) = \sum_{n_1=S_T-1}^{N_1} \binom{N_1}{n_1} \left(P\left(\int_0^T c_1(t)c_{j_2}(t)dt = 1\right)^{n_1} P\left(\int_0^T c_1(t)c_{j_2}(t)dt = 0\right)^{N_1-n_1}\right) = \sum_{n_1=S_T-1}^{N_1} \binom{N_1}{n_1} (\frac{\overline{H}}{2p^2})^{n_1}(1 - \frac{\overline{H}}{2p^2})^{N_1-n_1} \tag{8.14}$$

Thus the probability that a user belongs to Group 2 is :

$$P_I = \frac{\overline{H}}{2p^2} \times \sum_{n_1=S_T-1}^{N_1} \binom{N_1}{n_1} (\frac{\overline{H}}{2p^2})^{n_1}(1 - \frac{\overline{H}}{2p^2})^{N_1-n_1} \tag{8.15}$$

Then we can deduce the probability that a user who is sending a bit "0" belongs to Group 3 to be $(1 - P_I)$. For the given numbers N_1 and N_2, the probability of N_2 users interfering the desired user simultaneously is $(P_I)^{N_2}$, and the probability of $N_u - 1 - N_1 - N_2$ users belonging to Group 3 is $(1 - P_I)^{N_u-1-N_1-N_2}$. Finally we have the error probability function of PIC for the desired user #1:

$$P_{EPIC} = \frac{1}{2}\sum_{N_1=S_T-1}^{N_u} \sum_{N_2=w+1-S_F}^{N_u-1-N_1} P_1P_2P_3(P_I)^{N_2}(1 - P_I)^{N_u-1-N_1-N_2} = (\frac{1}{2})^{N_u} \sum_{N_1=S_T-1}^{N_u} \sum_{N_2=w+1-S_F}^{N_u-1-N_1} \binom{N_u-1}{N_1}\binom{N_u-1-N_1}{N_2}(P_I)^{N_2}(1 - P_I)^{N_u-1-N_1-N_2} \tag{8.16}$$

From the two limits for N_1 and N_2 mentioned previously ($w + 1 - S_F \leq N_2 \leq N_u - 1 - N_1$ and $N_1 \geq S_T - 1$), we can infer that if $w + 1 - S_F > N_u - S_T$ or $w + 1 - S_F + S_T > N_u$, the transmission of the desired user is error free.

In the numerical analysis we set the two thresholds as $S_T = w$, and $S_F = 1$.

Because in CCR, lowest BER is obtained when threshold equals to code-weight, and for the desired user's CCR, because the interference is always negative, therefore the ideal value for S_F is the smallest positive number.

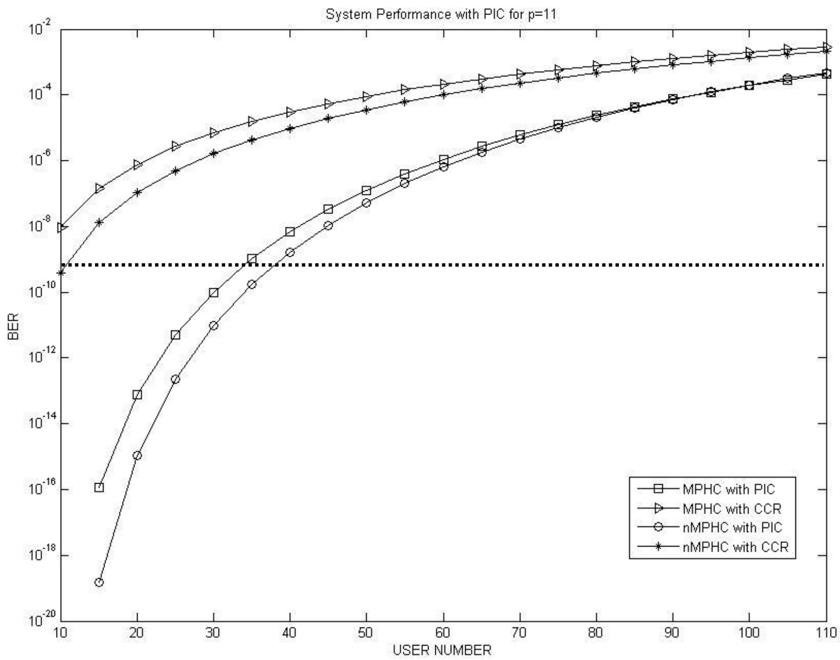


Figure 20 BER against active user number of MPHC and nMPHC with CCR and PIC respectively for p=11

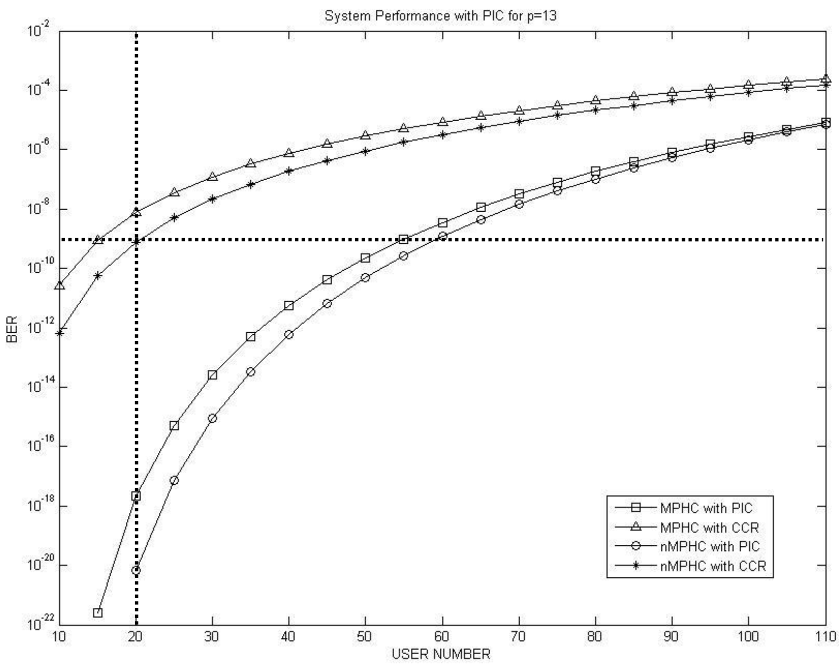


Figure 21 BER against active user number of MPHC and nMPHC with CCR and PIC respectively for p=13

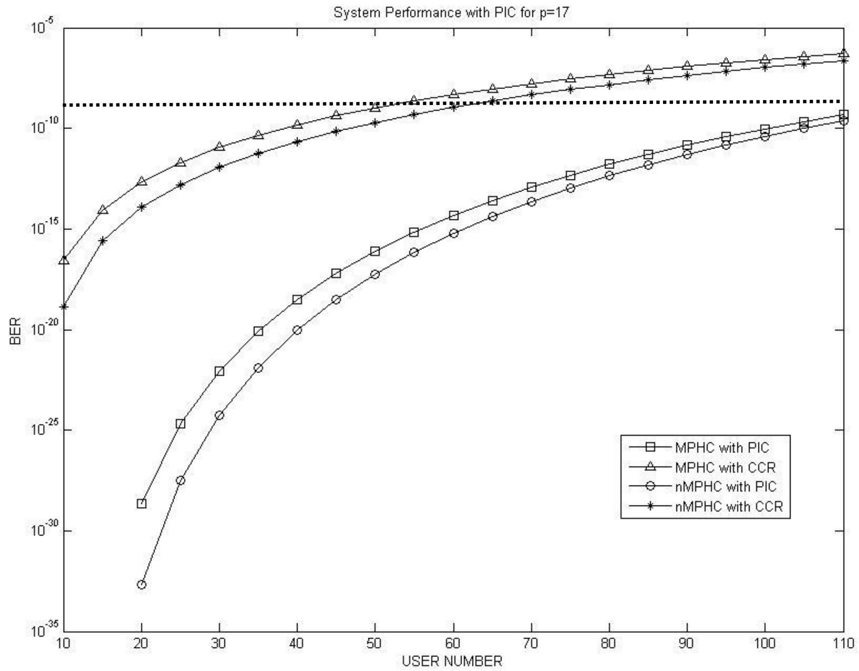


Figure 22 BER against active user number of MPHC and nMPHC with CCR and PIC respectively for p=17

Figure 20, 21 and 22 depicted the BER performance against active user number employing MPHC and nMPHC with the use of CCR and PIC for p=11, 13 and 17 respectively by Matlab. We set the maximum active user number to be 110. With the use of PIC, the BER performances of both MPHC and nMPHC are greatly improved. For example, for p=13 at $\mathrm{BER} = 10^{-9}$ the supported user number of nMPHC increases from 12 (CCR) to 40 (PIC), for p=17 at $\mathrm{BER} = 10^{-9}$ the supported user number of MPHC increases from 50 (CCR) to 110 (PIC). In addition, the enhancement of BER performance of nMPHC in contrast with MPHC has been enlarged with the use of PIC, for instance, when p=13 the enhancement increases from 1 magnitude to more than 2 magnitudes for user number 20. However, as the user number increases, the enhancement of nMPHC in comparing with MPHC becomes inconspicuous.

8.3 Conclusion

In this Chapter, a new receiver structure rather than CCR was introduced, named PIC. The schematic of a typical PIC has been given and the principles have been explained in detail in section one. Theoretical analysis of the performance of PIC has been taken place in section two, the expression of error probability for PIC was finally deduced and examined with MPHC and nMPHC. The analysis results show that with the use of PIC the BER performances of both MPHC and nMPHC can be improved substantially, when user number is small the enhancement on BER of nMPHC in comparison with MPHC has been enlarged. We can conclude that the PIC has the attributes to provide the system with a less interfering environment, especially with the use of the proposed code, nMPHC.

Chapter 9
Conclusion and Future Work

In this thesis, we firstly introduced the concept of CDMA technology and its principles. We compared the properties of CMDA with TDM and WDM techniques to summarize its pros and cons. Then we introduced the application of CDMA technology in fibre-optic networks, we discussed the advantages of OCDMA over Radio/Wireless CDMA technologies. Finally the research concerns and challenges of OCDMA technology nowadays are reviewed. In Chapter 3 we reviewed the application of CDMA technology in fibre-optic networks, we compared two different optical sources named coherent optical source and incoherent optical source and we found out that the incoherent optical source is more appropriate for practical realization. The overview of OCDMA signature codes and coding schemes were described at the end of Chapter 3. In Chapter 4, 2D OCDMA system was introduced and reviewed, various 2D codes proposed by previous researcher were discussed including transceiver architectures. In Chapter 5, a novel 2D code was proposed based on the previously proposed PHC and MPHC, which is named nMPHC. Its code properties and system performance were intensively analyzed and compared with PHC and MPHC, results show that the newly proposed nMPHC can reduce the same amount of system complexity as MPHC by sacrificing less number of accommodated users. In Chapter 6 the concept and principles of IP routing over OCDMA network was introduced. Noises involved in the transmission of packet network were numerically analyzed and the expressions were given. A new concept in IP network called network utilisation was introduced. The newly designed code was examined in IP-over-OCDMA system for the use of packet transmission. System performance of nMPHC including both BER and PER were performed with different network utilisation in the presence of MAI and beat noise etc. against PHC and MPHC. The results shown that nMPHC is a proper 2D signature code for packet transmission over OCDMA network and is superior to PHC and MPHC in some aspects. In Chapter 7, we applied the nMPHC to three different OCDMA random access protocols for traffic control, steady-state system throughput of nMPHC was analyzed against the performance of MPHC, the results shown nMPHC outperforms MPHC in most cases. In Chapter 8 we introduced a new receiver architecture rather than CCR name PIC, the principles of PIC were intensively analyzed and the expression for the estimation of error probability for PIC was given. The BER performance of nMPHC was evaluated again with the use of PIC against MPHC, the results shown that BER performance of MPHC and nMPHC can be greatly improved by employing PIC as receiver, and the enhancement of nMPHC against MPHC was enlarged when user number is not too large.

To conclude, the proposed code nMPHC is a good candidate for 2D OCDMA system, it reduces the system complexity by nearly half while keeping the system performance at an acceptable level, its outstanding performance over the previously proposed MPHC is obvious during our analysis. The reduction of system complexity greatly lowers the cost of network establishment and brings convenience to network rebuild. It is a feasible and practical scheme for future OCDMA network.

However, although nMPHC greatly reduced the system complexity, its system performance is inevitably inferior to the code with large code-weight since the SNR at the receiving end is suppressed, the concern of future researchers should be focusing on seeking solutions regarding this problem. An optimal trade-off between system complexity and system performance is necessary to be found out. In addition, design of novel transceiver architecture for 2D OCDMA system is another issue to be considered, a successful design of an efficient receiver structure can reduce the interference and improve system performance greatly. Furthermore, it is worth to research on the system security and confidentiality of 2D OCDMA system due to some of the unique attributes of 2D OCDMA system.

References

[1] N. A. n. d. "*Didn't know what is CDMA: Now you will know.*" URL:http://www.mgovworld.org/techbytes/didn-t-know-what-is-cdma-now-you-will-know;

[2] George Partasides. n. d. "*Optical CDMA*". University at Buffalo. URL:www.ee.buffalo.edu/faculty/paololiu/566/op_cdma.ppt

[3] S. J. Ben Yoo, et. al. n. d. "*Optical CDMA Technology*." URL:http://www.citris-uc.org/research/projects/optical_cdma_technology_

[4] Karbassian. M. Massoud. "Optical CDMA Networks." University of Birmingham. URL:http://postgrad.eee.bham.ac.uk/karbassm/OCDMA_Concept.pdf_

[5] John Edwards. *"Telecosmos: The Next Great Telecom Revolution."* John Wiley and Sons. p. 1. 2005

[6] Enrico Forestieri. "*Optical Communication Theory and Techniques*". Springer. p. 104. 2005

[7] Nasir D. Gohar. n. d. "*Optical CDMA- An Introduction.*" URL:http://www.honet.niit.edu.pk/presentations/Session6/Dr%20Gohar/Optical%20CDMA-An%20Introduction_nD_gohar.pdf

[8] I. Glesk; V. Baby; C. S. Bres; L. Xu; P. R. Prucnal; W. C. Kwong. *"A Design of a wavelength-hopping time-spreading incoherent optical code division multiple access system"*. Acta Physica Slovaca, vol. 55, no. 2, p. 220. 2005

[9] N. A. n. d. *"Enhanced optical fast frequency hopping-CDMA by means of over-spreading and interleaving*." URL:http://www.wipo.int/pctdb/en/wo.jsp?IA=WO2004030254&DISPLAY=DESC

[10] Xiaowei Xia. *"Optical CDMA Systems in High-Speed Telecommunications."* Mar 2005
URL:http://www.stormingmedia.us/87/8711/A871134.html

[11] Ravinder Kachru. "*High Bandwidth Optical Switching Technology for Optical Fiber Communication*." Sept 1998
URL:http://www.stormingmedia.us/24/2445/A244553.html?searchTerms=optical~CDMA

[12] Yue-Kai Huang; Ivan Glesk; Camille-Sophie Bres. et. al. "*Novel Multicode-Processing Platform for Wavelength-Hopping Time-Spreading Optical CDMA: A Path to Device Miniaturization and Enhanced Network Functionality."*
URL:http://www.lightsmyth.com/downloads/articles/STQEv13p1471.pdf

[13] N. A. n. d. *"Enhanced optical fast frequency hopping-CDMA by means of over-spreading and interleaving."*
URL:http://www.wipo.int/pctdb/en/wo.jsp?IA=WO2004030254&DISPLAY=DESC

[14] Tarhuni, N; Elmusrati, M; Korhonen T. "*Polarized optical orthogonal code for optical division multiple access systems."* Progress in Electromagnetic Research, PIER, vol.65, no. 2. 2006

[15] Paul R. Prucnal. "*Optical Code Division Multiple Access."* CRC Press. 2006

[16] Yue-Kai Huang; Ivan Glesk; Camille-Sophie Bres. et. al. "*Novel Multicode-Processing Platform for Wavelength-Hopping Time Spreading Optical CDMA: A Path to Device Miniaturization and Enhanced Network Functionality.* "
URL: http://www.lightsmyth.com/downloads/articles/STQEv13p1471.pdf

[17] Salehi, J.A.; , "*Code division multiple-access techniques in optical fiber networks. I. Fundamental principles*," Communications, IEEE Transactions on , vol.37, no.8, pp.824-833, Aug 1989
doi: 10.1109/26.31181
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=31181&isnumber=1344

[18] Salehi, J.A.; Brackett, C.A.; , "*Code division multiple-access techniques in optical fiber networks. II. Systems performance analysis*," Communications, IEEE Transactions on , vol.37, no.8, pp.834-842, Aug 1989
doi: 10.1109/26.31182
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=31182&isnumber=1344

[19] Chung, F.R.K.; Salehi, J.A.; Wei, V.K.; , "*Optical orthogonal codes: design, analysis and applications*," Information Theory, IEEE Transactions on , vol.35, no.3,

pp.595-604, May 1989
doi: 10.1109/18.30982
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=30982&isnumber=1333

[20] Tancevski, L.; Andonovic, I.; , "*Wavelength hopping/time spreading code division multiple access systems*," Electronics Letters , vol.30, no.17, pp.1388-1390, 18 Aug 1994
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=326326&isnumber=7741

[21] Tancevski, L.; Andonovic, I.; Tur, M.; Budin, J.; , "*Hybrid wavelength hopping/time spreading code division multiple access systems*," Optoelectronics, IEE Proceedings, vol.143, no.3, pp.161-166, Jun 1996
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=503665&isnumber=11120

[22] Tancevski, L.; Andonovic, I.; , "*Hybrid wavelength hopping/time spreading schemes for use in massive optical networks with increased security*," Lightwave Technology, Journal of , vol.14, no.12, pp.2636-2647, Dec 1996
doi: 10.1109/50.545782
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=545782&isnumber=11950

[23] Wen, J.-H.; Lin, J.-Y.; Liu, C.-Y.; , "*Modified prime-hop codes for optical CDMA systems*," Communications, IEE Proceedings , vol.150, no.5, pp. 404-8, 14 Oct. 2003
doi: 10.1049/ip-com:20030478
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1251689&isnumber=28024

[24] Ji Jianhua; Xu Ming; Zhang Zhipeng; Yang Shuwen; , "*A New Family of two-dimensional Optical Orthogonal Codes EPC/OCS Based on Extend Prime Code and One-coincidence Sequence*," Communications, Circuits and Systems Proceedings, 2006 International Conference on , vol.3, no., pp.1856-1859, 25-28 June 2006
doi: 10.1109/ICCCAS.2006.285034
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4064260&isnumber=4064154

[25] Azizoglu, M.; Salehi, J.A.; Li, Y.; , "*Optical CDMA via temporal codes*," Communications, IEEE Transactions on , vol.40, no.7, pp.1162-1170, Jul 1992
doi: 10.1109/26.153360
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=153360

&isnumber=4002

[26] Shengpeng Wan, Sailing He, Yu Hu, *"Time-spreading wavelength-hopping 2D-OCDMA system with optical hard limiter"*, Optik - International Journal for Light and Electron Optics, Volume 118, Issue 8, 7 August 2007, Pages 381-384, ISSN 0030-4026,
doi: 10.1016/j.ijleo.2006.04.016.
URL:http://www.sciencedirect.com/science/article/B7GVT-4MC0X55-1/2/93bde3b472f0dbbcb1f0ac2be5af41bc

[27] Saghari, P.; Omrani, R.; Willner, A.E.; Kumar, P.V.; , "*Analytical interference model for two-dimensional (time-wavelength) asynchronous O-CDMA systems using various receiver structures*," Lightwave Technology, Journal of , vol.23, no.10, pp. 3260- 3269, Oct. 2005
doi: 10.1109/JLT.2005.856290
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1522413&isnumber=32558

[28] Mrabet, H.; Dayoub, I.; Attia, R.; Haxha, S.; , "*Performance Improving of OCDMA System Using 2-D Optical Codes With Optical SIC Receiver,*" Lightwave Technology, Journal of , vol.27, no.21, pp.4744-4753, Nov.1, 2009
doi: 10.1109/JLT.2009.2026293
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5153301&isnumber=5233077

[29] Wang, Z.; Chang, J.; Prucnal, P. R.; , "*Theoretical Analysis and Experimental Investigation on the Confidentiality of 2-D Incoherent Optical CDMA System,*" Lightwave Technology, Journal of , vol.28, no.12, pp.1761-1769, June15, 2010
doi: 10.1109/JLT.2010.2048199
URL: http://www.ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5453003&isnumber=5473167

[30] Zou Wei; Ghafouri-Shiraz, H.; , "*IP routing by an optical spectral-amplitude-coding CDMA network*," Communications, IEE Proceedings- , vol.149, no.56, pp. 265- 269, 2002
doi: 10.1049/ip-com:20020611
URL:
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1176172&isnumber=26399

[31] Karbassian, M.M.; Ghafouri-Shiraz, H.; , "*IP Routing and Traffic Analysis in Coherent Optical CDMA Networks*," Lightwave Technology, Journal of , vol.27, no.10, pp.1262-1268, May15, 2009
doi: 10.1109/JLT.2008.2007574

URL:
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4907479&isnumber=4840636

[32] Karbassian, M.M.; Ghafouri-Shiraz, H.; , "*IP Routing and Transmission Analysis in Optical CDMA Networks: Coherent Modulation With Incoherent Demodulation,*" Lightwave Technology, Journal of , vol.27, no.17, pp.3845-3852, Sept.1, 2009
doi: 10.1109/JLT.2009.2016581
URL:
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4895236&isnumber=5196856

[33] Zou Wei; Ghafouri-Shiraz, H.; Shalaby, H.M.H.; , "*New code families for fiber-Bragg-grating-based spectral-amplitude-coding optical CDMA systems,*" Photonics Technology Letters, IEEE , vol.13, no.8, pp.890-892, Aug. 2001
doi: 10.1109/68.935838
URL:
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=935838&isnumber=20254

[34] Tancevski, L.; Rusch, L.A.; , "*Impact of the beat noise on the performance of 2-D optical CDMA systems*," Communications Letters, IEEE , vol.4, no.8, pp.264-266, Aug 2000
doi: 10.1109/4234.864189
URL:
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=864189&isnumber=18722

[35] T. Bazan; D. Harle; I. Andonovic; ," *Effect of beat noise on the performance of two-dimensional time-spreading/wavelength-hopping optical code-division multiple-access systems,"* Journal of Optical Networking, OSA, Vol.4, No.3, pp.121-129, Mar 2005

[36] Legg, P.J.; Tur, M.; Andonovic, I.; , "*Solution paths to limit interferometric noise induced performance degradation in ASK/direct detection lightwave networks,*" Lightwave Technology, Journal of , vol.14, no.9, pp.1943-1954, Sep 1996
doi: 10.1109/50.536961
URL:
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=536961&isnumber=11497

[37] Shalaby, H.M.H.; , "*Optical CDMA random access protocols*," Computers and Communication, 2003. (ISCC 2003). Proceedings. Eighth IEEE International Symposium on , vol., no., pp. 907- 912 vol.2, 30 June-3 July 2003

doi: 10.1109/ISCC.2003.1214232
URL:
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1214232&isnumber=27298

[38] Morelle, M.; Goursaud, C.; Julien-Vergonjanne, A.; Aupetit-Berthelemot, C.; Cances, J.; Dumas, J.; Guignard, P.; , "*2-Dimensional Optical CDMA System Performance with Parallel Interference Cancellation*," Computers and Communications, 2006. ISCC '06. Proceedings. 11th IEEE Symposium on , vol., no., pp. 634- 640, 26-29 June 2006
doi: 10.1109/ISCC.2006.5
URL:
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1691098&isnumber=35645