Optical Code Division Multiple Access

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"Optical Code Division Multiple Access"** was prepared by **ONG CHIA JYE** has met the required standard for submission in partial fulfillments of the requirements for the award of Bachelor (Hons.) of Electronic and Communication Engineering at University Tunku Abdul Rahman.

Approved by,

Signature : ___________________________

Supervisor : Mr Shee Yu Gang

Date : ___________________________

Specially dedicated to

my beloved parent who nurture me to who I am today

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In addition, I would also like to express my gratitude to my loving parent and friends who had helped and given me encouragement.

OCDMA
Optical Code Division Multiple Access

ABSTRACT

Optical communication for multiple access has become the mainstream for researchers as the utility rate in optical communication nowadays is increasing rapidly. As multiple accesses, the more users uses the network, date rate, capacity and security have become the critical issue for the optical system. The maturity of wireless communication with code-division multiple access (CDMA) technique have motivated the integration of CDMA technique in to optical network, as it is much more attractive since it allows multiple users in a local area network (LAN) environment to access the same fiber channel asynchronously at all times. Furthermore, the robustness of CDMA technique in wireless network is yet to prove that OCDMA offers security advantages over other multiple access systems by maintaining the quality of services.

In this thesis, the study on OCDMA is based on a conference paper that is mainly demonstrating an experiment on Optical Spectral-Amplitude Code (SAC) OCDMA structured with circulator free fiber bragg gratings array. It demonstrates a three-user SAC-OCDMA with the Walsh Hadamard code, by describing every detail in his experiment. That is why the first simulation on SAC-OCDMA is easily simulated. The simulation shows an error free transmission on all the three users, with a bit rate of 200mbps, and a transmission length that is up to 10km. From that I found out that the Fiber Bragg Gratings array shows an important role in the SAC-OCDMA network.

Finally, an increase of the number of users up to seven users in the SAC-OCDMA network, by changing the coding methods is achieved, studied and simulated. As the results came out are investigated and discussed.

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LIST OF SYMBOLS / ABBREVIATIONS

BER	Bit Error Rate
BERT	Bit Error Rate Tester
CDMA	Code Division Multiple Access
CW	Continuous-Wave
DS-OCDMA	Direct Sequence Optical Code Division Multiple Access
FBG	Fiber Bragg Grating
FDMA	Frequency Division Multiple Access
FE-OCDMA	Frequency Encoded Optical Code Division Multiple Access
FH-OCDMA	Frequency Hopped Optical Code Division Multiple Access
LED	Light Emitting Diode
NRZ	Non Return to Zero
OCDMA	Optical Code Division Multiple Access
OSA	Optical Spectrum Analyzer
RZ	Return to Zero
SMF	Single Mode Fiber
TDMA	Time Division Multiple Access
WDMA	Wave Division Multiple Access

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CHAPTER 1

INTRODUCTION

1.1 Background

In the ancient times, in order to increase the transmission speed of information, humans have started to learn how to use optical signals for communication. For instance, communicate using hand, smoke signals, semaphores, etc. However the utility of these methods are very limited due to the error rate is very high and it is very easy to be eavesdropped. Now optical communication involves optical fiber as the communication median as from one point to another uses light as a carrier. Optical fiber communication started in the early 1960s, when ruby laser is invented [1],togather with the propose of optical communication via dielectric waveguides or glass optical fibre by Kao and Hockham during 1966s [2]. Initial, optical fibre is not porpular, where the fibre exhibits very high attenaution than the coaxial cables. 1970s, Corning Company manufactured a fibre-optic with an attenuation of 17dB/km. The advantages of fibre-optics are mainly due to its enormous communation capacity, low transmission loss, Immunity to electromagnetic interference and etc. Togather with the numbers of advantages of fibre-optics many development, research and application on optical fibre communication system have came to a flourushing period.

The explosive growth of numbers of data being transferred and received has increased the demands of the bandwidth of the network. For every four to six months the internet traffic has been double, this causes a tremendous requirement for development of future optical networks. Wavelength division multiplexing (WDM), time division multiplexing (TDM) or hybrid approach is focused to achieve the

Tbit/s aggregate channel capacity. Multiplexing schemes are to manage the transmission link between one user, where else multiple access are to manage the transmission link between multiple users. Time Division Multiple Access (TDMA) is a multiple access method to divides time axis into different time slots; where each data packet or burst is assigned to a certain time slot. According to figure 1.1 the intervals length ΔT has to be inserted between successive slots in order to avoid interference. Frequency Division Multiple Access (FDMA) is the frequency axis is divided in to different sub band for the data is distributed on it [3].According to figure 1.2 N_f is the sub bands that is divided by the frequency axis. With the combination of TDMA and FDMA, Code Division Multiple Access (CDMA) is proposed by spectrally spread the data stream with specific sequences called spreading codes as CDMA allows simultaneous access on the channel in same frequency.

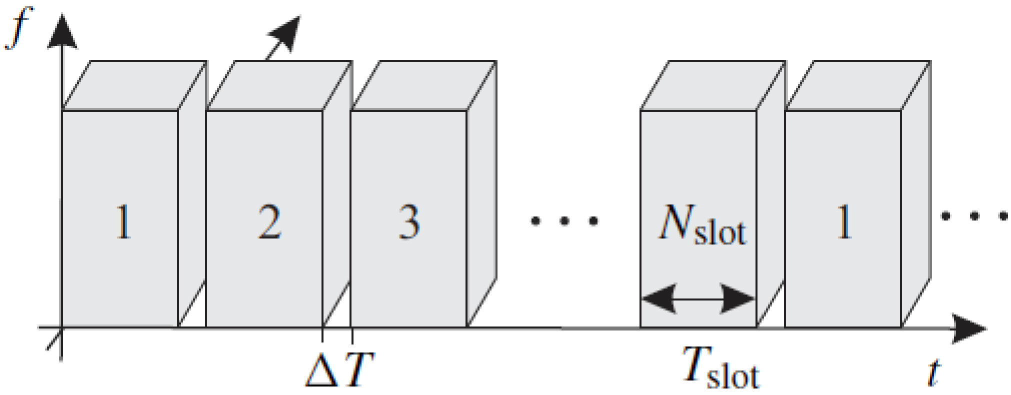


Figure 1-1 Schematic of TDMA

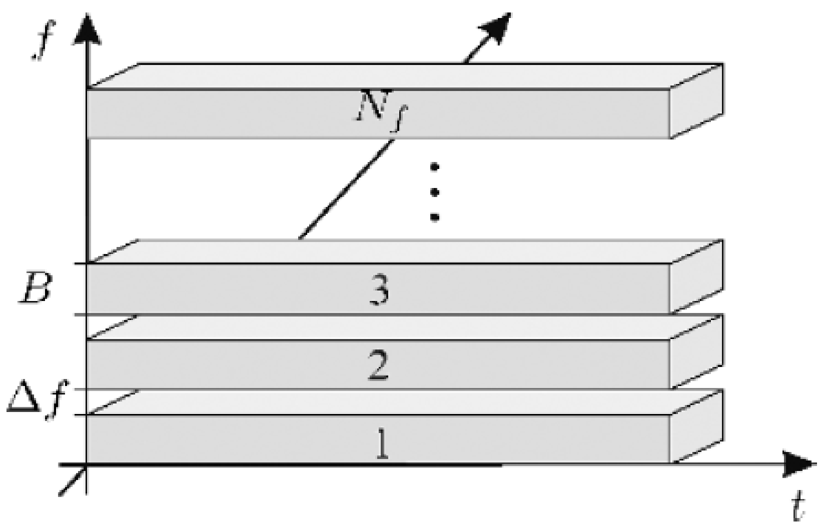


Figure 1-2 Schematic of WDMA

Investigation of CDMA for over 20 years of application in optical and wireless network, the multiplexing scheme could potentially achieve a throughput of the rate of Tbit/s. The roots of CDMA are found in Spread Spectrum communication techniques [4] . During World War , Spread Spectrum communication is applied on the military communication; as the information can be transmitted in a very rigid enviroment and mainly Spread Spectrum communication is very secure. Spread Spectrum was developed during the mid 1950s, where the transmission can overcome the rigid restrictions in radio bandwidth allocation [5] [6]. A normal Spread Spectrum communication started on transmitting a noise-like signal to the receiver which claims as a spreading action, and the received signal is hard to be recovered as if the receiver side is not authorized. That's why Spread Spectrum is widely being used on military application during the old days. Figure 1.3 shows a schematic drawing of a wireless spread spectrum network. The conventional PCN and GSM networks is replace by CDMA. By allocating a unique code to each individual user and distinguish them from other users CDMA is done by code division multiplexing and demultiplexing.

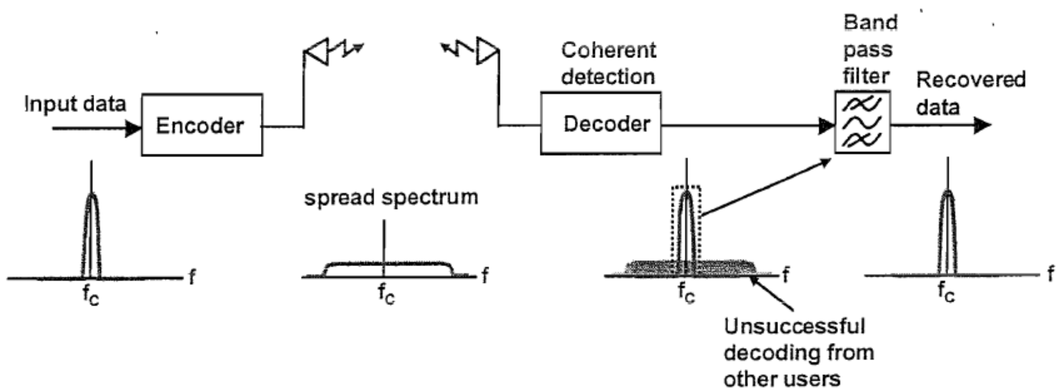


Figure 1-3 Spread Spectrum technique with CDMA network [7].

Optical CDMA started during the late 1970s in the area of fiber delays lines for optical processing that is based on incoherent and coherent optical match filtering [8]. Coherent OCDMA is based on using interference of the incoming optical signals to convert electric field values into intensity variations that can then be detected by a photo receiver [9].Thus it enables cancellation of the undesired user channels through destructive interference. Incoherent OCDMA detects the signals by superposition the incoming optical signal. Incoherent OCDMA is impossible to achieve perfect cancellation between interfering channels, as the optical intensity is a non-negative value. But the benefits of incoherent OCDMA is the system enables the use to inexpensive broadband source such as light emitting diodes (LED) and amplified spontaneous noise (ASE). Furthermore, it reduces the sensitivity to both environmental changes and polarization problems.

Optical encoding/decoding can be performed in frequency domain and time domain. As for the OCDMA that's performing in time domain, it is known as the frequency –hopping FH-OCDMA. A modulated information signal is changed over a wide set of discrete frequencies according to a well-defined pseudo random code sequence. In order to receive the signal, a narrowband frequency filter is incorporated within the receiver whose tuning sequence is synchronized to that of the transmitter.

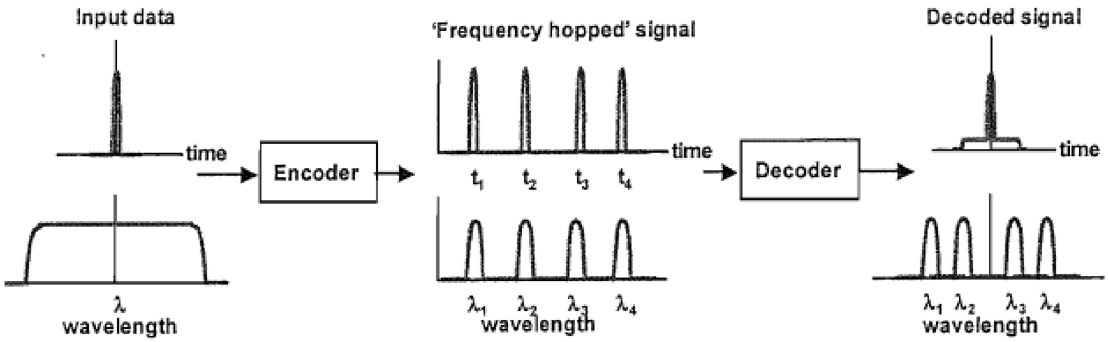


Figure 1-4 Coherent FH-OCDMA techniques [7]

Frequency encoded FE-OCDMA is which the broad spectral bandwidth of the information signals encoded in to code consisting of a number of discrete spectral components. This approach is also known as the spectral encoding OCDMA. From figure 1.5, an amplitude /phase modulated spectral code that is having individual frequency component is sliced from an input broadband signal. As result, high intensity input pulse is transform into a long duration, low intensity frequency encoded signal in time domain.

Direct sequence DS-OCDMA is an alternative to the FH-OCDM A and FE-OCDMA that performed in the time domain. In DS-OCDMA, a sequence of pulse is to define each data bit that is transmitted. The individual pulses comprising the coded bit are commonly referred to as chips. The user might need a receiver that is designed to unambiguously recognize data bits of the given specific address code, while the coded bits are broadcast on to the network. Figure 1.6 shows the direct sequence encoder is defined from the encoded “time spread” signal comprises of a sequence of pulses according to the code sequence.

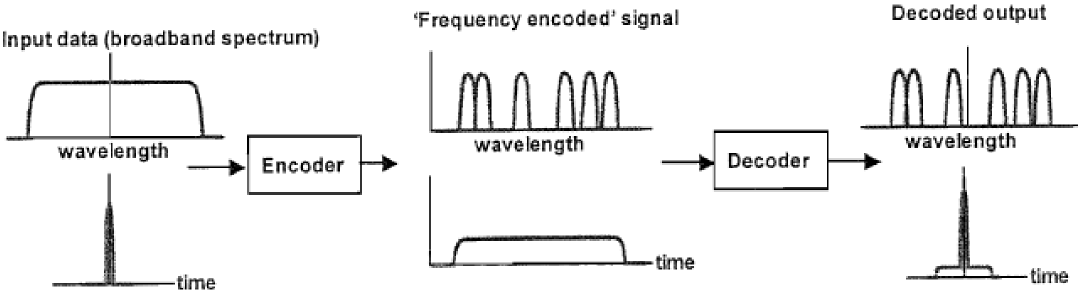


Figure 1-5 FE-OCDMA technique [7].

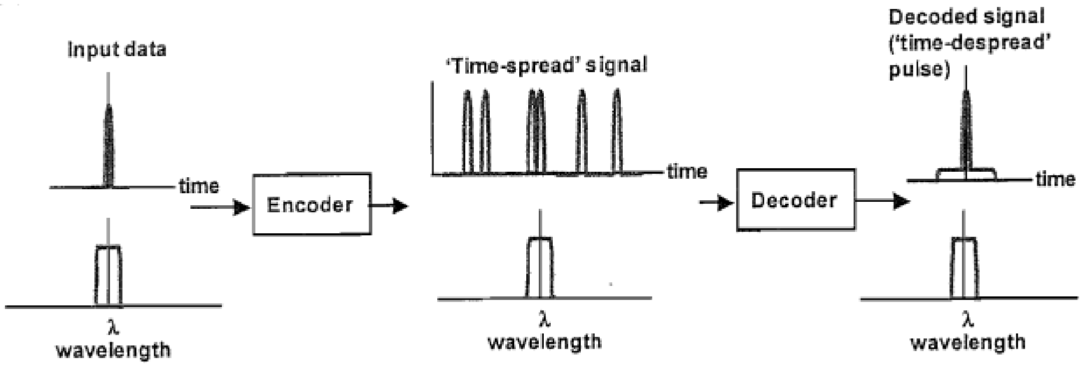


Figure 1-6 DS-OCDMA technique [7].

The main advantage of an OCDMA network is the OCDMA system is totally asynchronous, that does not require any clock signals for synchronization in the network. Hence, OCDMA provide a network that is simpler and offers the potential for scalability to higher levels of connectivity. Furthermore, the OCDMA encoding /decoding process also provides a level of security directly implemented in the physical layer. Finally OCDMA enables high spectral efficiency to be achieved, enabling such optical network to achieve throughputs in excess of Tbit/s by making efficient use of fiber bandwidth.

1.2 Motivation

Fiber Optics technology has becomes the new leads for digital communication during this decade. From communication systems that's hybrid between optical domain and electrical domain, till a full communication system undergoes only optical domain humans tends to puts a lot of effort on researching, testing and implementing. As is the demand for speed, data rate, throughput growth rapidly.

As many researches are conducted throughout the world, optical fibre communication has become the renowned technology. As an undergraduate student, I'm keen to learn on the Optical Code Division Multiple Access as before I have a simple background on Code Division Multiple Access. OCDMA reception is based on optical light (intensity) converted to an electrical signal in a photo-detector rather than amplitude (electric field) detection as in radio CDMA.

`For a well-designed OCDMA network, it eliminates channel contention. This mean that the upstream and downstream connection can be established asynchronously with no collision or blocking and the interference is well controlled. Besides that, the OCDMA network is able to supports a large number of users than TDMA or WDMA that exploit just time or wavelengths dimension, especially for 2D-OCDMA system exploit time and wavelength dimension that having a larger number codes. Furthermore, OCDMA network may accommodate additional users with less cost and complexity. Finally, OCDMA exhibits a higher level of security, where the encryption is done on the optical domain and not at the electrical level.

1.3 Aims and Objective

In fibre optics communication system, various OCDMA systems have been proposed and improved. In this report, three main objectives are listed as:

- To study and understand the operating principles of OCDMA mainly on SAC-OCDMA.
- To study and understand the two coding methods used in incoherent FE-OCDMA system such as the m-sequence code and Walsh – Hadamard code.

- To simulate FE- OCDMA base on two kinds of coding methods in Optisystem and perform the full characterization on both coding methods.

1.4 Problem Statement

Designing various OCDMA formats is the main objective, to perform the OCDMA system, an adequate and insight knowledge has to be strong. Therefore the basic operating principles of OCDMA must be studied and understood.

The concept and operating principle of FE-OCDMA or spectral- amplitude coding (SAC- OCDMA) is studied. A full characterization of the FE- OCDMA is simulated, in the sense of optical fiber length, Fiber Bragg-grating condition, various types of coding methods and also number of users in the network.

With the help of the simulation tools, Optisystem, it tends to faster the speed of investigation of various situations and environment of OCDMA. From that the simulation software Optisystem, need to be familiarized. Finally the various architecture of OCDMA will be simulated and studied.

1.5 Dissertation Outline

Chapter one gives a brief introduction to optical communication system. Short introduction on multiple access communication system background and Optical Code Division Multiple Access communication system background is introduced and illustrated with diagrams. With relevant to the report, the motivation, aim and objective, and problem statement are discussed based on personal finding.

Chapter two will focus on literature review- introduces the basic concept on fiber optic communication in term of the OCDMA system. The basic characteristic of intensity modulation formats and OCDMA system and optical codes are briefly described.

Chapter three will then focus on methodology. Optisystem is the software used to simulate the intensity modulation network and SAC-OCDMA network. In this chapter, the studied of SAC OCDMA network is implemented with a schematics diagram with a full configuration consisting optical encoder and decoder, formation of optical codes.

Chapter four consists of results and discussion of the studied SAC-OCDMA system. The SAC OCDMA system is characterized in different kinds of situation. For example number of users, coding methods, Fiber Bragg Grating situation, and etc.

Chapter five discuss about the conclusion and recommendation of the whole simulation and the thesis. Basically the characterization of SAC-OCDMA system are concluded and ways to improve my understanding on OCDMA system.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

The main focus of this chapter is to introduce optical communication systems including the basic intensity modulation optical communication based on only one transmitter and one receiver. For multiple access networks part, chapter two mainly focusing on OCDMA networks on various methods and principle and summarized of various optical codes and their characteristic.

2.2 Intensity Modulation (IM) Formats

Intensity modulation is a very basic optical communication system where the data is carried in the intensity of light. Digital signal of binary '1' and '0' is represented by the changing of high to low power from the light source. Two types of optical modulation formats in intensity modulation are the Non-return to Zero On/Off Keying (NRZ-OOK) and Return to Zero On/Off Keying (RZ-OOK). Both of these modulations are introduced on the next section.

2.2.1 Non-return to Zero On/Off Keying (NRZ-OOK)

The simplest way to generate an optical modulation is using NRZ-OOK. It is normally known as NRZ. Figure 2.1 illustrates the basic schematic configuration of a NRZ transmitter, whereby the input signal data is modulated in to the optical laser with an external intensity modulator. The intensity modulator can be either Mach-Zehnder or electro- absorption modulator, which converts the electrical signal to optical signal at the same date rate.

Figure 2.1a shows the basic block diagram configuration for NRZ transmitter, whereby the signal is modulated into the laser source with a Mach-Zehner Modulator (MZM). MZM converts the electrical signal to optical with the same data rate.

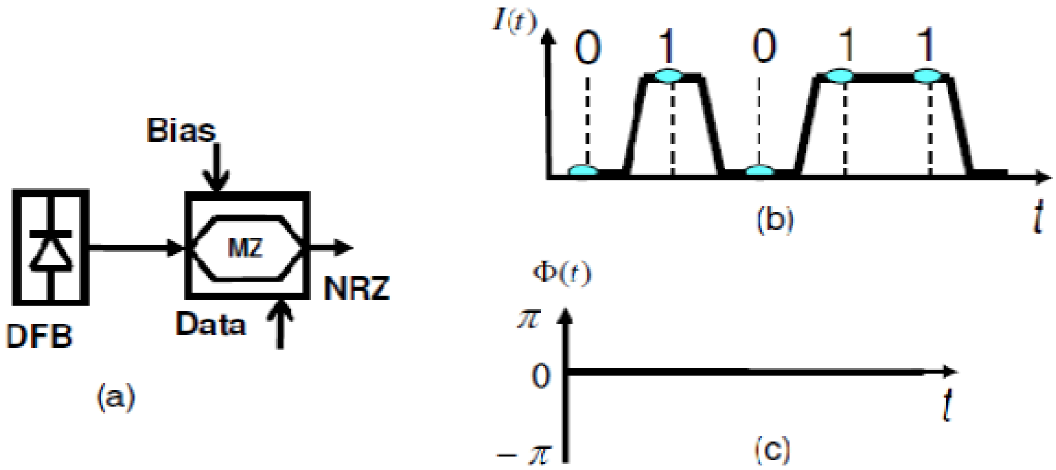


Figure 2-1 NRZ modulation scheme: a) Block diagrams of NRZ transmitter (b) waveform for intensity I(t), (c) phase

For the receiver part of IM system, a direct detection is used. Where a photodiode is used to detect the intensity of the optical signal; and converts optical signal to electrical signal.

2.2.2 Return to Zero On/Off Keying (RZ-OOK)

Return to Zero (RZ) optical modulation format show a smaller bit period of optical signal. Usually a clock signal with the same data rate as electrical signal is used to carve RZ shape of optical signals.

Figure 2.2a shows the basic block diagram configuration for NRZ transmitter, the RZ optical signal is generated by two cascading MZMs, whereby the first MZM modulate the optical light source with data to generate NRZ optical signal; where else the second MZM modulated the NRZ optical signal with a pulse carver to generate the RZ optical signal. From figure 2.2(b) we observe that the main difference between NRZ signal and RZ signal is when the representation of binary '11'. The electrical signal of NRZ (figure 2.1(b)) will remain the same amplitude, while the electrical signal of RZ (figure 2.2(b) its amplitude will drop to zero before presenting the next binary '1'.

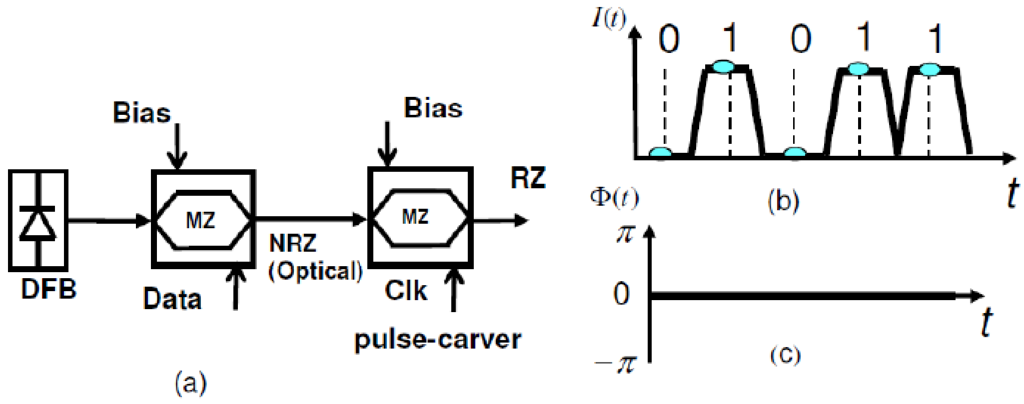


Figure 2-2 RZ modulation scheme: a) Block diagrams of NRZ transmitter (b) waveform for intensity I(t), (c) phase

The receiver part for RZ modulation is same with the NZR modulation. As the RZ format require a slightly more complex transmitter structure but are generally more robust to Intersymbol interference (ISI) [10]. For RZ modulation it is better on long distance, due to the 'return – to-zero' characteristic, RZ format exhibits better tolerance to nonlinearity than NRZ format due to the narrow pulse width that the RZ format is having.

2.3 OCDMA Encoding methods

The encoding theory and encoding technology of OCDMA have been studied and developed thoroughly and many research accomplishments have been made, since the mid 1980's [11]. The encoding approaches of OCDMA can be divided into categories based on the choice of different light sources, different detection schemes and encoding approaches. For light sources there is coherent and incoherent light source, narrow and broadband light source. OCDMA can be divided into two broad categories, which are coherent OCDMA system and incoherent OCDMA system.

2.4 OCDMA match filtering and coherent coding/ decoding

Around the 70's coherent optical coding and decoding was first introduced to illustrate that such network can be intergraded in optical processing [12]. Coherent coding and decoding is based on the network architecture of Ladder network encoder. The ladder network is an incoherent network and will be discuss on the next subsection.

The main difference between both networks is that the phase of the optical pulses is now very much of interested and the decoder network is matched to the desired encoder by less than the coherence length of the source. Under these conditions the optical pulses are summed up coherently at the decoder output. The phases of the individual pulses emerging from the individual pulses emerging from the encoder, and the phase changes induced when the pulses pass through the decoder, determine the interference at the optical detector and hence the resulting detected signal amplitudes [13]. The correlation process in the decoder yields the same pulse location as in incoherent CDMA but the amplitudes are different. The central autocorrelation peak amplitude is P^2, which are P times higher than the incoherent counterpart. Conversely it has been shown that the ratio power in the central autocorrelation peak to the side lobes is higher when compared to the same code used in an incoherent system. It should be stressed that the signal coming from the co-users are summed up incoherently since the encoders are not matched up to the particular decoder. Figure 2.3 shows a schematic drawing of a coherent network of only 1 channel.

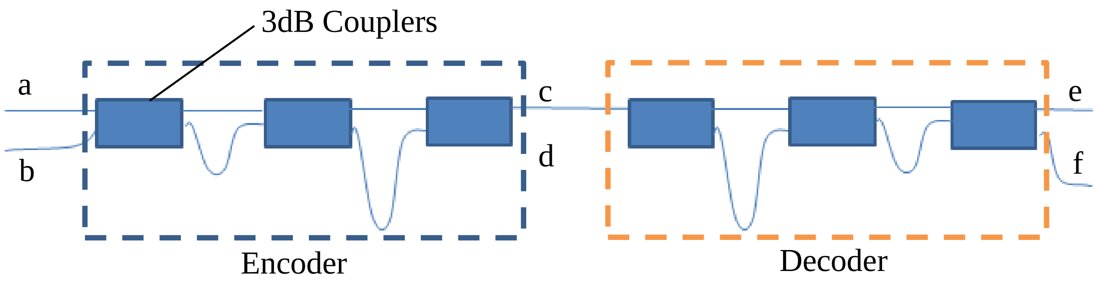


Figure 2-3 1-channel coherent decoding network

Coherent network that involved the usage of both channels is named as 2-channel coherent decoding or inverse decoding where figure 2.4 illustrated. Inverse decoding is done by using two fibers themselves as two spatial channels or by launching the signal from the two outputs of the encoder to the two polarization states of a single mode fiber by means of a polarization beam splitter (PBS) [14]. A PBS will split the signal that is from 2 polarization channels to the 2 inputs of the decoder.

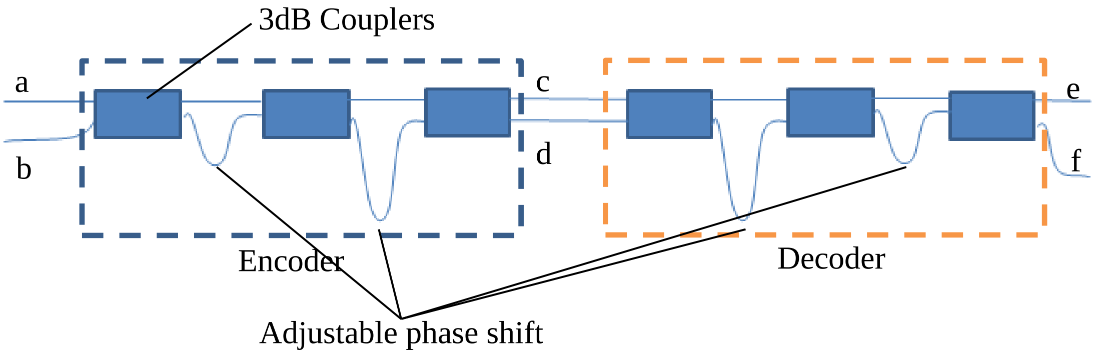


Figure 2-4 2-channel coherent decoding network

The main advantages of inverse decoding are the autocorrelation peak is $4P^2$, which reflects an increase by 4 in comparison to the single channel and the signals from the 2 spatial or polarization channels cancel each other by causing the autocorrelation side lobes disappear [15] [16].

A perfect and lossless reconstruction of the pulse fed to the encoder is gain from the network. In fact, inverse decoding provides a mechanism whereby a transmission to matched receiver occurs as if the encoding or decoding process did not take place. For the case of the 1-channel scheme, cross correlation will remain the same as in the incoherent scheme. Whereas for the 2-channel scheme, twice as many pulses is received as the incoherent scheme or the 1-channel scheme, the cross correlation will be 4 times larger in term of power. In other words, coherent decoding enhances largely the autocorrelation process of the receiver, while maintaining the crosstalk at comparatively low levels, and therefore it exhibits higher SNR. Overall the SNR in the inverse decoding scheme will be $4P^2$ better than the incoherent approach. This shows the performance of coherent network is potentially better than the incoherent counterpart. This is due to substantial improvement to the autocorrelation characteristic of the receiver [13]. This is show on table 2.1 on how the increase of the autocorrelation peak results in higher SNR [15] [16].

Table 2-1 Comparison of Ladder CDMA network using Coherent and Incoherent Decoding

Scheme	*Autocorrelation peak energy*	*Autocorrelation side lobes*	*Cr. variance/ Cr var (Incoh)*	*SNR*
Incoherent	P	P-1	1	1
1-Ch. Coherent	P^2	1	1	P^2
2-Ch.Coherent	$4P^2$	0	4	$4P^2$

Code length of 2n bits need to be employed for the ladder network of these schemes. New phase code also designed for the phase encoding, for more detailed analysis of the design and properties of the new code, although the initial code shows a promising result [17].

2.5 OCDMA match filtering and Incoherent Network

In the mid-1980's incoherent Optical CDMA was proposed to use with asynchronous transmission [18]. The idea was to extend to the optical regime the techniques of pulse coding and spread spectrum which are so successful at radio frequencies. RF techniques are coherent while the initial optical work is incoherent, cause the major differences.

The phases of light signals are not important in incoherent OCDMA, as they are summed on the basis of power rather than electric field. In all passive schemes, the encoder uses a passive optical network to generate an impulse response which is a train of P pulses, delayed scaled replicas of input laser pulse which are called as chips. The receiver's specific sequences are recognized by performing the operation of correlation with other sequences.

Incoherent OCDMA consider as the most attracted research part in the OCDMA research group. This is due to the practical ease of implementing direct optical detection based system. Several version of incoherent system have been proposed, and progressively these systems improve from the original idea. The designs of codes and encoders/ decoders are the main effort that has been focus on. Few incoherent OCDMA schemes are the Delay Line Network, Ladder Network encoders and Tunable Delay Lines network. They are all introduced and discussed in the following sections.

2.5.1 Delay Line Network

The most common approach is to uses arrays of discrete optical waveguide based delay lines too temporally, or sometimes spectrally, manipulate the individual data bits in order to perform the coding and decoding process. Simple optical fibers of different lengths appropriately coupled together using fiber couplers were implemented by delay lines. This was 1st proposed during the mid-1980s by Prucnal and co-workers, to develop a purely asynchronous multiple access network [19]. The delay line network was illustrated on figure 2.5.

Figure 2.5 shows that the encoder and decoder consist of a delay line network. At the encoder part, the incident laser pulse splits and produce a train of P pulses which are appropriately delayed within the data bit period according to the length of each fiber. While the decoder, it has a reverse impulse response from the encoder, by reconstruct the data pulse. The highest in the series of output pulses are the reconstructed pulses, the represents the autocorrelation peak of the matched reception. There are few issues on this delay network.

First is the main restriction of incoherent techniques that is based on direct photo detection that cannot perform bipolar correlation. This is due to the bipolar correlation function is equivalent to the X-NOR logical operation, followed by integration over the data bit period [4]. Therefore the incoherent CDMA uses the unipolar correlation where the system is based on power summation.

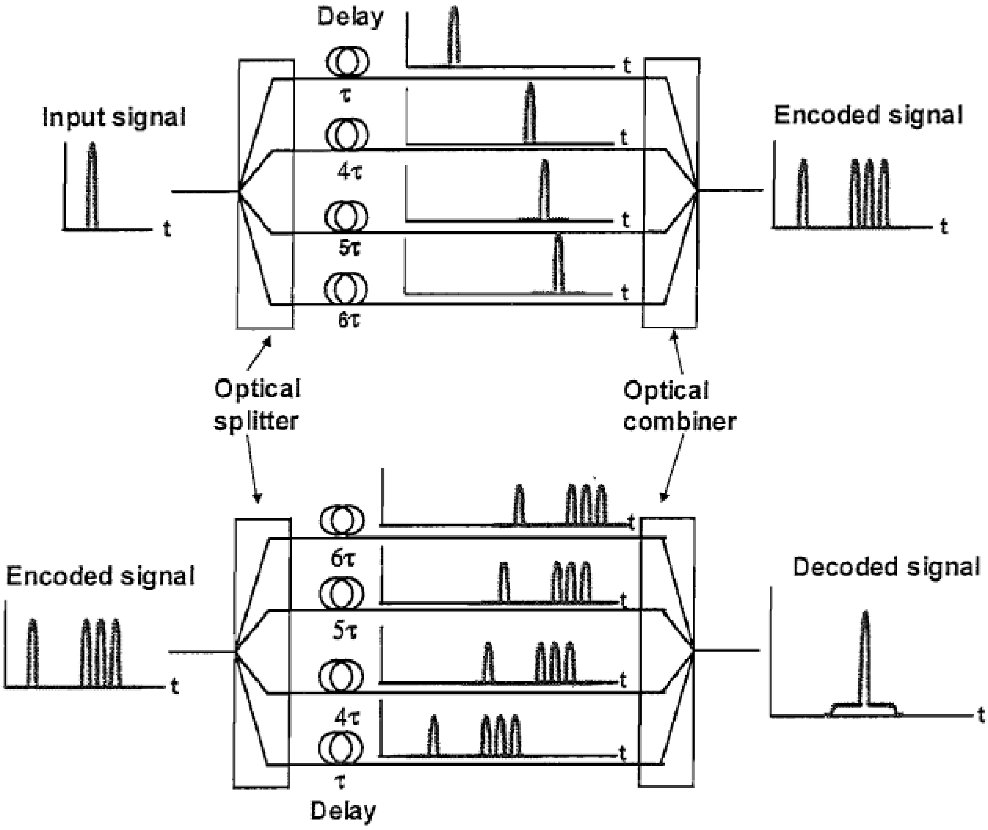


Figure 2-5 Fiber Delay Lines based optical encoder and decoder for DS-OCDMA

Second, the main issue is to maintain the accurate delays that constitute the code sequence and compensation of the changes in fiber lengths due to environmental conditions. Few methods have proposed to overcome this problem. A multistage Mach-Zander interferometer chain fabricated on a silica planar waveguide to overcome this issue and the receiver used balanced detection scheme to enhance the code recognition recovery [20]. Arrayed waveguide gratings with a phase filter also proposed to overcome the issue [21].

2.5.2 Ladder Network Encoder

Every communication network will face with the power budget problem, where this is also a main problem of the delay line encoder. Due to the use of 3-dB couplers in the delay line network it waste a large amount of optical power. An alternative to this approach has been proposed, where a ladder network replaces the parallel delay line architecture [22].

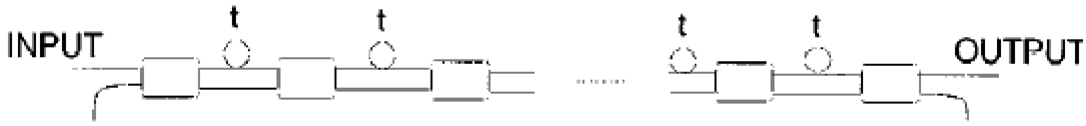


Figure 2-6 Ladder Network Encoder [13]

Figure 2.6 shows an illustration on a normal ladder network encoder. The figure shows an *n* stage network consist of *n+1* 3-dB couplers connected in cascade by n double fiber links. This combination is assumed to be incoherent. The fiber delay in each arm of the ladder network reflecting the position of 1's in the code, causing the separation of the pulses. Due to the configuration of the encoder, 2n pulses are produced from a single pulse passing through the encoder. Due to the autocorrelation peak is now only 4*P* times less than the original pulse. However, the requirements for 2^n first in the code period seems to restrict very much the design of suitable codes for ladder network. Clearly, the ladder network seems to be working worse than those systems using delay line encoder in term of number of users. Therefore Tunable delay lines were the next scheme for incoherent network.

2.5.3 Tunable Delay Lines

Based on the architecture of ladder network, the idea of tunable delay lines (TDL) is proposed. TDL is a network where the fiber couples were replaced by 2 x 2 optical switches that can guide the optical power to the upper or lower branch of the switch. As the illustration if a tunable delays is a show on figure 2.7. So, at a particular time slot the switches are arranged so as to delay the optical pulses according to the position each pulse should occupy in the code word.

The receiver part will in a form of delay lines. Due to the system need synchronization of receiver switches with ones of the transmitter, therefore the receiver is excluded. The main advantage of tunable delay line is that the whole transmitter configuration become programmable and be able to generate any kind of block code, since with the employment of the electro optic switches.

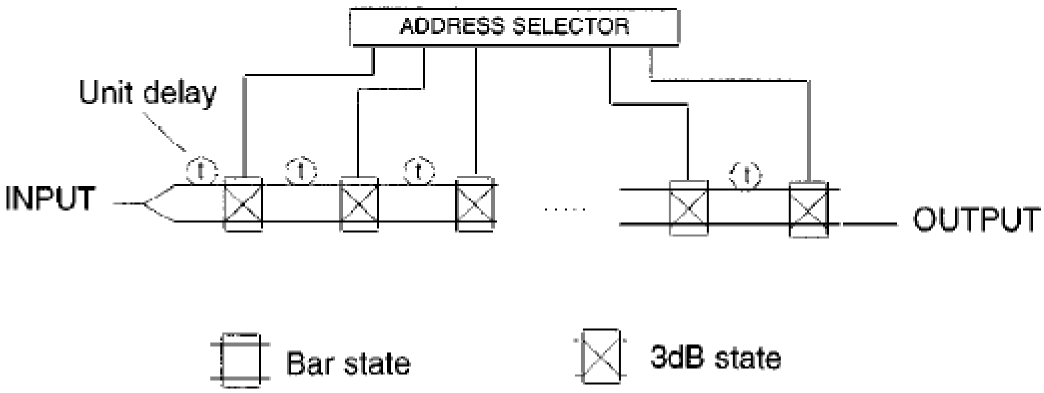


Figure 2-7 OCDMA network using tunable delay lines [13].

2.6 Implementation of Fiber Bragg Grating technology in OCDMA

In OCDMA, passive ‘single beam’ encoding and decoding schemes based on Fiber Bragg grating (FBG) technology have been proposed and demonstrated . FBG is implemented on incoherent WH/TH optical encoder network and also on Spectral Amplitude Incoherent Optical Encoder/Decoder.

2.6.1 Incoherent WH/TH Optical Encoder and Decoder Using FBGs

FBG is used to comprise the incoherent wavelength-hopping or time-spreading (WT/TS) encoder and decoder, where the FBG is adopt with a series [23] of parallel [24] structure in the network to reflect the optical signal with different wave length.

The fixed optical encode and decoder using a series structure are shown in figure 2.8. A broadband light source or a multi-wavelength light source is used for the output of short pulse trains with the repetition rate *1/T* and the width τ, which are modulated by the input data in an optical modulator. The modulated narrow pulses are fed into port one of the optical circulator. The optical signals output from port two of the circulator are reflected back by FBGs with different wavelengths. Meanwhile two adjacent FBGs are connected with the delay lines with different lengths in order to implement the desired delays in terms of the requirement of a WH/TS code word.

The operating principle of the optical decoder is similar to its correspondent encoder. Where the FBGs is put in a reverse order and the delays of fiber optics delay lines that lay between the two adjacent FBGs is changed, in order to make their delay values be complementary values of those in its corresponding encoder. The delay parameters are shows on figure 2.8(b).

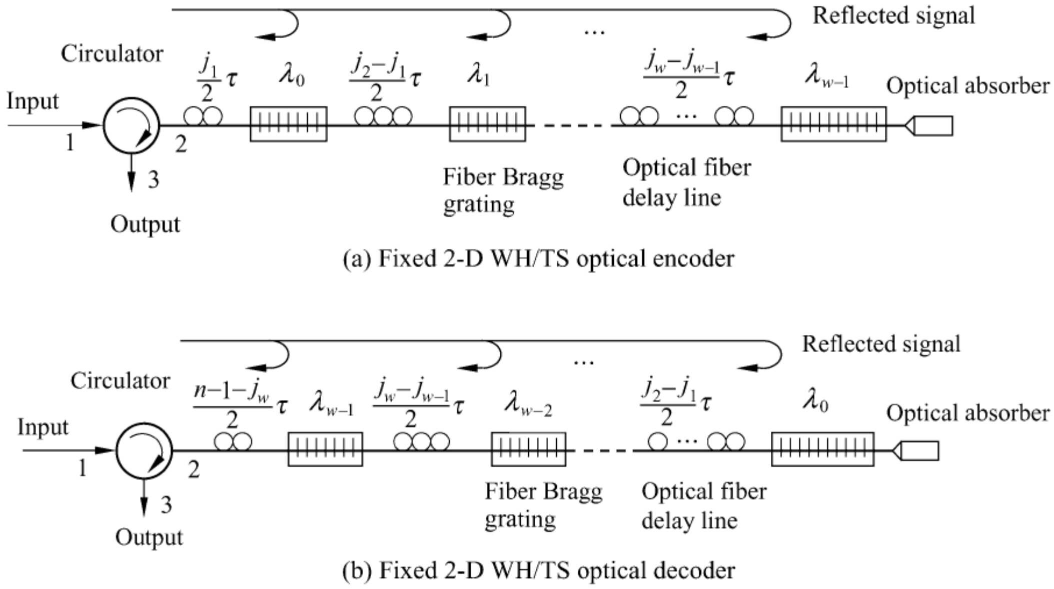
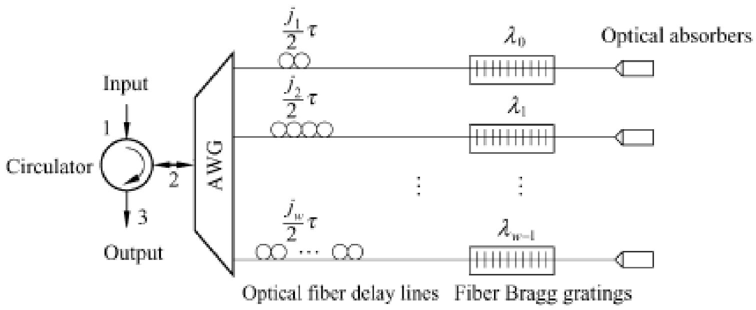


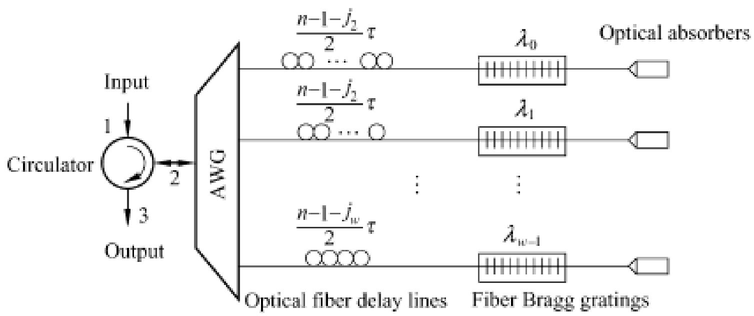
Figure 2-8 Fixed WH/TS optical encoder/decoder based on serial FBG [25]

WH/TS network with optical encoder and decoder using parallel FBGs structure, it consist an arrayed waveguide grating (AWG) wavelength–division de-multiplexer. Figure 2.9 show that have the schematic of the parallel FBGs based WH/TS encoder /decoder. Modulated broadband light source goes through a circulator to the AWG to decompose the optical signals in to parallel output. Optical signals pass through the fiber delay lines with different lengths and are reflected by FBGs with different wavelengths, and return into the AWG again. Both encoder and decoder operating principles are similar and it the component involves in shown on figure 2.9.

Both of the WH/ TS encoder that adopts a series or parallel structure is able to replace the fiber delay lines with the tunable optical delay line that implement the required delays determined by the code words under the control of users [26]. Figure 2.10 shows that the replacement of fiber delay lines.



(a) Fixed 2-D WH/TS optical encoder based on parallel FBGs



(b) Fixed 2-D WH/TS optical decoder based on parallel FBGs

Figure 2-9 WH/ TS encoder/ decoder based on parallel FBGs [25]

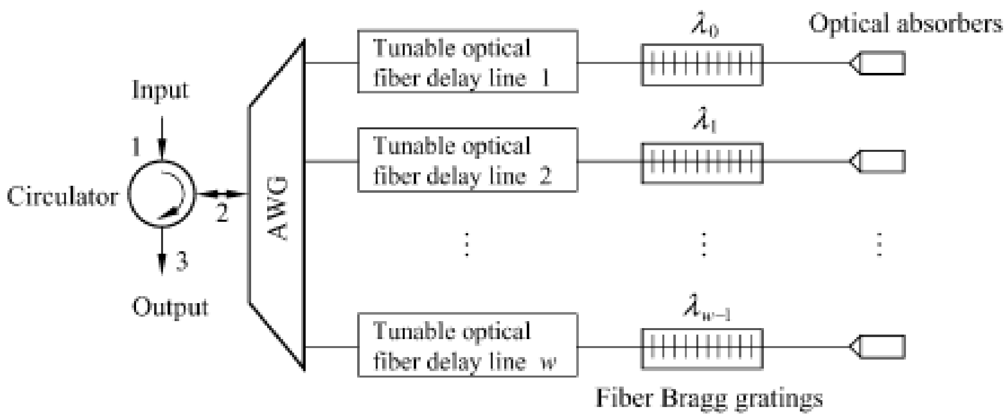


Figure 2-10 Tune able WH/TS encoder/ decoder based on parallel FBGs [25]

However, with the replacement of tunable delay lines; it would result in large optical power loss. Hence, such a structure is only suitable for the implementation of fixed encoder/decoder. Of course, although the encoder/decoder may be tuned by the piezoelectricity component to strain the fiber Bragg gratings and fiber optic delay lines to control the reflected wavelengths and delays theoretically, the tuned range is severely limited as a matter of fact [25].

2.7 Spectral–Amplitude Incoherent Optical Encoder and Decoder

With development and maturation of FBGs, they can be employed as the choosing wavelength filters to implement in the Spectral Amplitude Encoding (SAE). In chapter 1 it is introduce that the SAE is also a Frequency Encoded –OCDMA (FE-OCDMA). The implementation of SAE OCDMA is to overcome the disadvantage of the bulk-optic spectral amplitude encoder/ decoder. Figure 2.11 illustrate a bulk-optic spectral amplitude encoder/decoder. The SAE OCDMA employing the FBGs in series or the linear array of FBGs and the superposition FBGs, is extensively investigated and demonstrated [27].

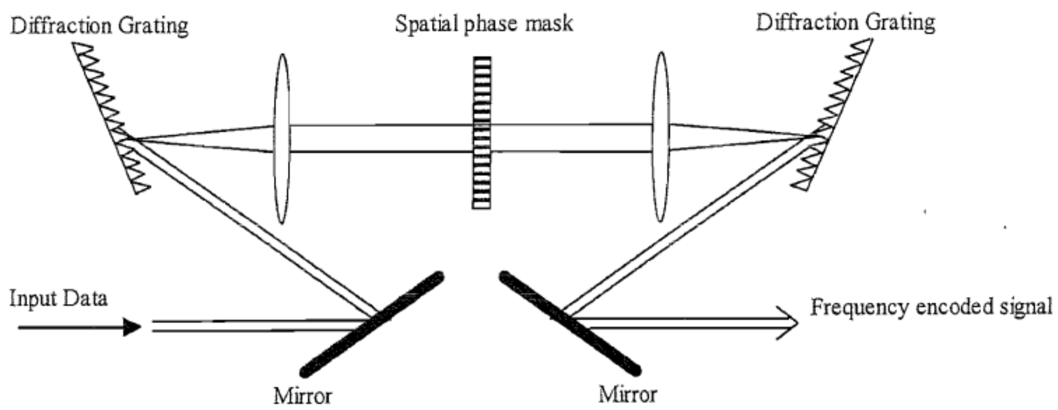


Figure 2-11 FE-OCDMA implementation using bulk optics [25]

The spectral amplitude operates where the optical pulse from a broadband light source is modulated by data; go through the FBGs with different wavelength to determine the chosen user's address code word. Figure 2.12 shows the block diagram of OCDMA system of spectral amplitude encoding with FBGs. The purpose of using a 1: α coupler in figure 2.12 is to make MUI (multiple user interference) received by the photo diode one (PD_1) to be equal to MUI received by PD_2, so that they counteract with each other. Figure 2.12(b), shows the reflection spectrum of FBGs that is represented as *A (ω)* in the figure, as the transmission of spectrum of FBGs is known as the *A (ω) symbol*.

Figure 2.13(a) shows the spectral amplitude encoder is formed base on the array of FBGS. A broadband optical pulse inputs from port 1 of the circulator and outputs from port 2, and then enters the first array of FBGs. The spectral components corresponding to *A(ω)* are reflected back and output from port 3, and then enter the second optical circulator. After reflected by the second array of FBGs, they output from port 6 of the second optical circulator at last. In doing so, the spectral amplitude encoding based on FBGs is achieved. The order of wavelengths reflected by the second array of FBGs is just opposite to that of wavelengths reflected by the first array of FBGs in order to compensate the delay differences caused by the different times of different wavelengths reflected by the first array of FBGs. In this way, the encoded optical pulses of all wavelengths reflected can be guaranteed to reassemble into a bigger optical pulse onto the same slot.

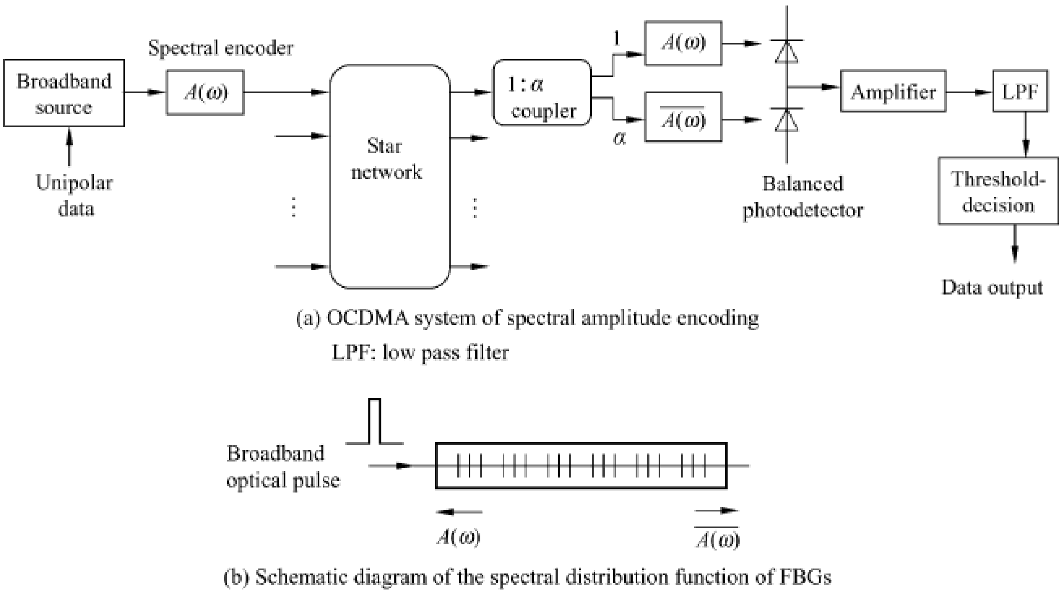


Figure 2-12 Block diagram of Spectral amplitude encoding OCDMA system with FBGs [25].

Figure 2.13 (b) illustrate the spectral amplitude decoder. For multiple user access network the FBGs in the network should be tunable, that is the center wavelength of reflected spectrum of each FBG should be able to be tuned. Such a tunable FBG can be implemented by employing a piezoelectricity device to strain the FBG or by using a heater to adjust the temperature of the FBG. The tunable FBGs are applicable to both encoder and decoder. The MUI can be counteracted by employing the transmission spectrum of the first FBG and the balanced detection. In this spectral amplitude encoding OCDMA system based on the en/decoder of the arrays of FBGs, the data rate is no longer limited by the length of the array of FBGs because the delay of each spectral component is the same after the delay is compensated. Therefore, the bit rate is mainly confined by the maximal modulation rate of the broadband light source and the bandwidth of photo-detector applied to the balanced detection.

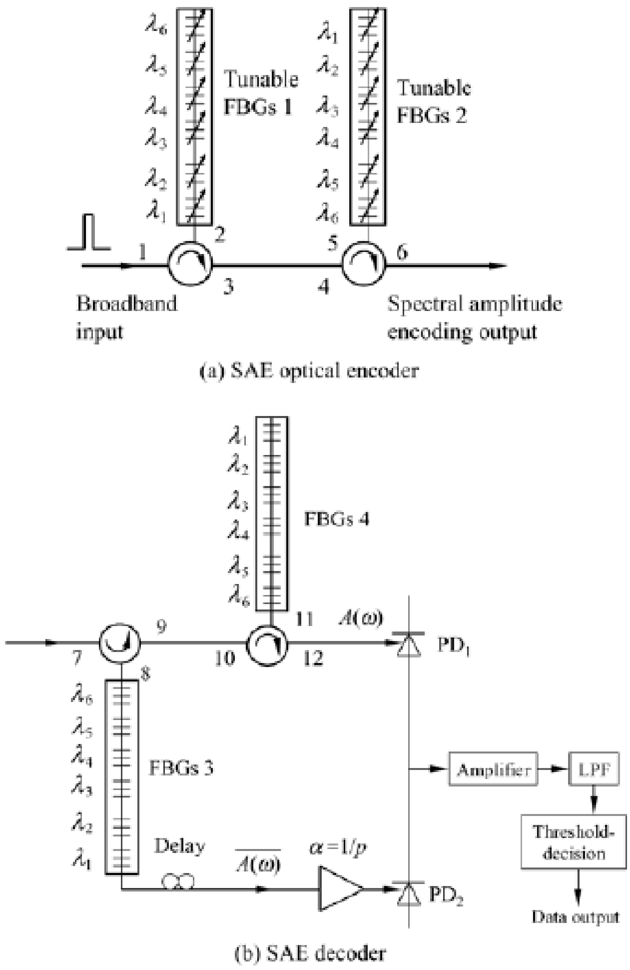


Figure 2-13 Encoder and decoder using a linear array of FBGs for SAE OCDMA [25]

2.8 OCDMA Optical Code

In OCDMA network, the transmission signal over a fiber-optic channel is formed by the superimposing of pseudorandom OCDMA signals encoded from multiple channels. The receiver in the network decodes the signal that is broadcasted from the transmitter. In order to implement OCDMA communication network, address codes with sufficient performance are required. When a set of code is chosen, a code should be constructed that has many code words as necessary and good enough auto- and cross-correlation so that accurate synchronization can be implement and the multiple access interference (MAI) from other codes can be suppressed effectively by decoding the signals. Optical coding for OCDMA network is mainly categorized in to two parts, unipolar codes and bipolar codes.

Unipolar codes is only suitable for incoherent OCDMA network, that is Optical orthogonal codes (OOC), Prime codes (PC), Quadratic congruence codes (QCC) and Hyperbolic congruence codes (HCC). Where else, for bipolar codes it suits both coherent and incoherent OCDMA network. The optical codes are m sequence, Gold Code and Walsh Hadamarad Codes.

2.9 Prime codes

Prime code (PC) is a typical linear congruence code that is generated using a prime number using a specific algorithm [28].

$C_i = (C_{i,0}, C_{i,1}, \ldots., C_{i,k}, \ldots.., C_{i(n-1)})$ $i = 0,1, \ldots.. P-1, n=p^2$

The code length and code weight of the prime code are $n = p^2$. The number of available address is again equal to the generating prime number, while the number of active users for a given Bit Error rate (BER) depends upon the correlation properties of these codes. The autocorrelation peak of PC is obviously P, while the cross-correlation is always less than two.

From table 2-2 [25] it can be seen that each code word in a prime code can be divided into p subsets with the length p for each subset. There is exactly one "1" in each subset and the position of this "1" is determined by the element in the corresponding prime sequence. The advantage of the prime code is that its generation algorithm is very simple and the shortcomings are that it has larger autocorrelation side lobes equal to $P-1$; its cross-correlation is not equal to 1 and the cardinality of the prime code is only equal to its weight

Table 2-2 Prime codes for P=5

Prime Sequence S_i	***Prime code C_i***
S_0 =(00000)	10000 10000 10000 10000 10000
S_1 =(01234)	10000 01000 00100 00010 00001
S_2 =(02413)	10000 00100 00001 01000 00010
S_3 =(03142)	10000 00010 01000 00001 00100
S_4 =(04321)	10000 00001 00010 00100 01000

2.10 M- Sequence code

M- Sequence is a bipolar code that is able to apply in both coherent and incoherent OCDMA system using different detection. M-sequence is also known as the maximal-length sequence in long. Because the bipolar codes are having the negative components in the code word there for it is better than unipolar codes.

The m-sequence is a pseudorandom sequence in the most common use, which can be generated by the feedback-shift-registers and has the maximal period. Therefore, it is called the maximal linear feedback-shift-register sequence. The period of an m-sequence is not only associated with the number of stages of shift-registers, but is also related to the linear feedback logic [29]. When an r-stage shift-register is employed, the period is n=2'-1. The linear feedback logic is determined by the equation below.

$$f(x) = \sum_{i=0}^{r} c_i x^i$$

The m-sequence can be generated by the r-stage linear feedback shift register. Figure 2.14 shows the r-stage shift register, in which a_{r-1} denotes the state if the $(r-i)^{th}$ shift register and $C_i(i=0,1,\ldots\ldots,r)$ indicates the link state of the feedback line in the shift-register, where $c_i = 1$ represents the line connected, otherwise $c_i = 0$ represent the line disconnected.

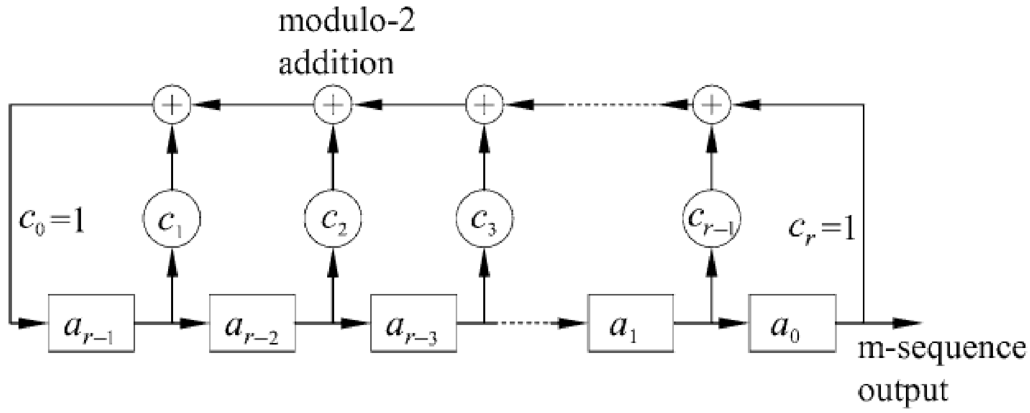


Figure 2-14 r-stage linear feedback shift register

2.11 Walsh-Hadamard Codes

Walsh-Hadamard code is also one of the bipolar codes. Walsh-Hadamard consists of the row vector of a Walsh code matrix arranged according to the order of Hadamard. It is also called Walsh code. The elements of this Walsh matrix are ∓ 1, which can be rapidly generated from the following recursion relation:

$$H(i+1) = \begin{bmatrix} H(i) & H(i) \\ H(i) & -H(i) \end{bmatrix}$$

$i = 0,1,2 \ldots.; H(O) = +1$ Using the recursion expression, we can deduce:

$$H(1) = \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix}$$

$$H(2) = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}$$

It can be seen that *H (i)* is a 2^i x 2^i square matrix consisting of elements +1 and -1. For 2 x 2 dimension Hadamard matrix it is call as H matrix.

2.12 Fiber Bragg Gratings

Fiber Bragg Grating (FBG) is a periodic perturbation of the refractive index along the fiber length which is formed by exposure of the core to an intense optical interference pattern. The formation of permanent gratings in an optical fiber was first demonstrated by Hill *et al.* in 1978 at the Canadian Communications Research Centre (CRC), Ottawa, Ont., Canada [30]. This was done with a Germania-doped fiber with an intense Argon-ion laser radiation runs into it. The observation was done by seeing an increase power with the reflected light intensity until almost all the light was reflected from the fiber. From that, it leads to the intensive researches on the photosensitivity of fiber and the development of FBG.

The FBG written by ultraviolet light (UV) into the core of an optical fiber has developed into a critical component for many applications in fiber-optic communication and sensor systems. When ultraviolet light radiates an optical fiber, the refractive index of the fiber is changed permanently; the effect is termed photosensitivity. The change in refractive index is permanent in the sense that it will last for decades (life times of 25 years are predicted) if the optical waveguide after exposure is annealed appropriately, that is by heating for a few hours at a temperature of 50 C above its maximum operating temperature [31]. Advantages of fiber gratings over competing technologies include all-fiber geometry, low insertion loss, high return loss or extinction, and potentially low cost. But the most distinguishing feature of fiber gratings is the flexibility they offer for achieving desired spectral characteristics. Numerous physical parameters can be varied, including: induced index change, length, apodization, period chirp, fringe tilt, and whether the grating supports counter-propagating or co-propagating coupling at a desired wavelength. The illustration for the variation of the induced index change along the fiber axis is shown on figure 2-15.

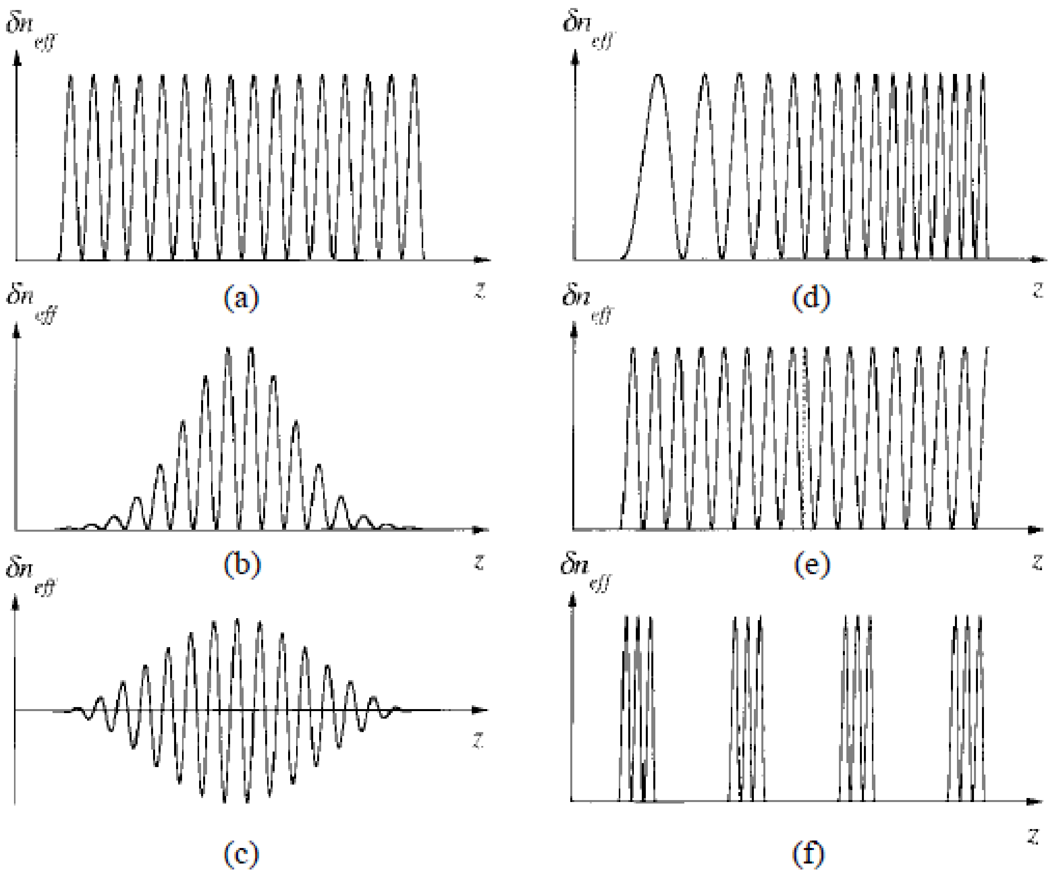


Figure 2-15 Common types of fiber gratings as classified by variation of the induced index change along the fiber axis, including (a) uniform with positive-only index change, (b) Gaussian-apodized, (c) raised-cosined-apodized with zero-dc index change, (d) chirped, (e) discrete phase shift (of π), and (f) superstructure.

CHAPTER 3

METHODOLOGY

3.1 Overview

In this chapter, the setup of optical communication network of Intensity modulation and SAC-OCDMA network is shown. Both of the simulations are done based on 3 users and 7 users SAC-OCDMA. All the simulation this is demonstrated in the environment of Optisystem is shown and described.

3.2 OptiSystem

In an industry where cost effectiveness and productivity are imperative for success, the award winning OptiSystem can minimize time requirements and decrease cost related to the design of optical systems, links, and components. OptiSystem is an innovative, rapidly evolving, and powerful software design tool that enables users to plan, test, and simulate almost every type of optical link in the transmission layer of a broad spectrum of optical networks from LAN, SAN, MAN to ultra-long-haul. It offers transmission layer optical communication system design and planning from component to system level, and visually presents analysis and scenarios. Its integration with other Optiwave products and design tools of industry leading electronic design automation software all contribute to OptiSystem speeding your product to market and reducing the payback period.

OptiSystem enables users to plan, test, and simulate:

- WDM/TDM or CATV network design
- SONET/SDH ring design
- Transmitter, channel, amplifier, and receiver design
- Dispersion map design
- Estimation of BER and system penalties with different receiver models
- Amplified System BER and link budget calculation

OptiSystem is a comprehensive software design suite that enables users to plan, test and simulate optical links in the transmission layer of modem optical networks. A comprehensive GUI controls the optical component layout and net list, component model, and user component.

The OptiSystem Component Library includes hundreds of components that enable you to enter parameters that can be measured from real devices. It integrates with test and measurement equipment from different vendors. Users can incorporate new components based on subsystems and user-defined libraries, or utilize co-simulation with a third party tool such as MATLAB or SPICE.

User can select component ports to save the data and attach monitors after the simulation ends. This allows you to process data after the simulation without recalculating. You can attach an arbitrary number of visualizers to the monitor at the same port.

To make a simulation tool flexible and efficient, it is essential to provide models at different abstraction essential to provide models at different abstraction levels, including the system, subsystem, and component levels. OptiSystem features a truly hierarchical definition of components and systems, enabling you to employ specific software tools for integrated and fiber optics at the component level, and allowing the simulation to be as detailed as the desired accuracy dictates.

3.3 Intensity Modulation Network

Intensity modulation is an optical system whereby data is carried in the intensity of light. Normally the light source uses in basic intensity modulation is continuous wave (CW) laser. For digital data, intensity of the laser represents the digital signal of '1' and '0'.

In this simulation a normal Mach-Zehner Modulator is used for intensity modulation. The schematic diagram of IM modulation is show on figure 3.1 and figure 3.2. Both figures come with different modulation formats. This is done is to show which modulation formats it more suitable for OCDMA network. From the figure, it shows that the modulated signal is sent through a Single Mode Fiber (SMF), where at the receiver part the modulated signal is received and detected by the photo detector; where at the electrical part, the data is yet still unable to be retrieve as the receive data is very noisy, therefore the receive data is passed by a 0.75GHz low pass filter. This is often known as autocorrelation in communication network.

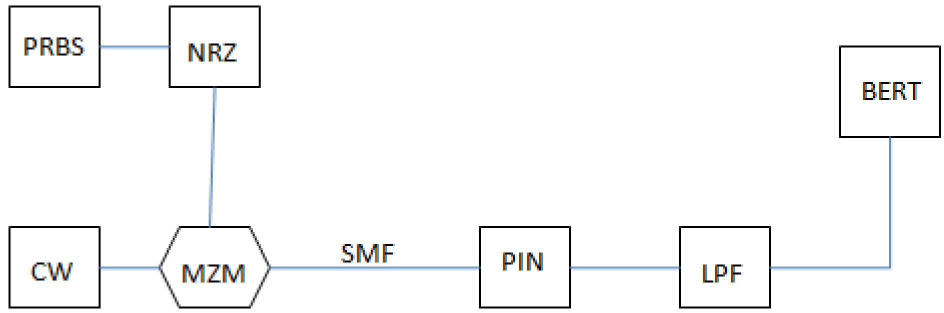


Figure 3-1 Intensity Modulation Network with NRZ modulation format

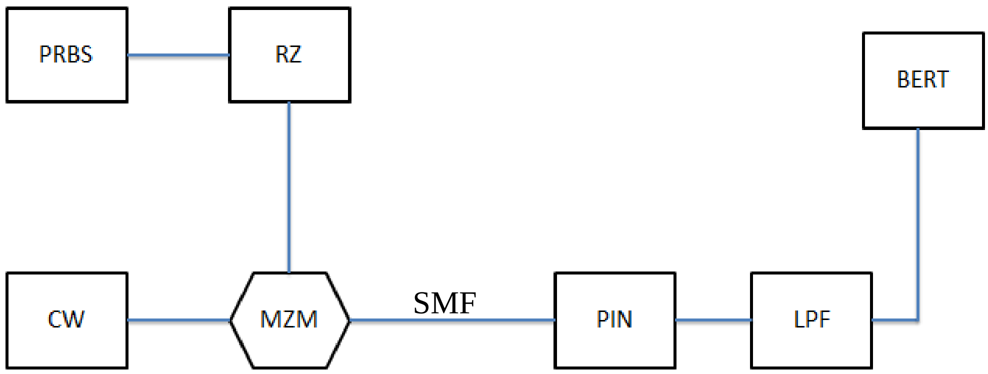


Figure 3-2 Intensity Modulation Network with RZ modulation format

Besides that, simulation on changing the CW light source to broadband light source is done. Based on both simulation schematic diagram of figure 3.1 and figure 3.2, the CW is changed with white light source. This simulation is done to prove that how suitable is the white light source in intensity modulation network.

3.4 Spectral Amplitude Coding (SAC) OCMDA

The simulation of OCDMA is done base on a conference paper on the topic of "Optical Spectral-Amplitude Coder/Decoders Structure with Circulator-Free Fiber-Grating Array." By Jen-Fa Huang et al [32].

The OCDMA system proposed by Jen Fa Huang is based on an incoherent OCDMA that uses an incoherent optical light source that offers broadband spectrum, high emitting power, and lower cost due to high yields in packaging technology. Figure 3.3 shows the FBG-based optical decoder and encoder network that is proposed by Jen Fa Huang. The encoder shows on figure 3.3(a) consist a broadband light source that goes through an intensity modulator and goes through a series of FBGs. The broadband source is modulated with the information data using Amplitude Shift Keying (ASK) modulation scheme.

Figure 3.3 (b) show the receive end of the network or also known as the decoder part. The decoder part consist of a 1x2 power splitter , a pair of series FBGs, photo detectors on each end of the series of FBGs, and an Bit Error rate detector (BERT). Both series of Bragg gratings are respectively fabricated in a single fiber to make CDMA spectral chip pulses. The spectral frequency pattern, with spectral chips centered about the grating frequencies, is determined by the OCDMA signature address codes properly written in the FBGs [32].

An OCDMA code will be encoded by the encoder FBGs to form a trans-missive light field, where the code is denote by the code vector $X_k = \left(X_{k,0}, X_{k,1}, \dots . X_{k,N-1}\right)$; N is the sequence length of the address code. When there are k users in the OCDMA network, a pair of Nx1 and 1xN passive couplers is used to connect the local area network (LAN) user in the system. The transmitter broadcast all the encoded data to all the receivers in the network. The receiver applies a correlating decoder to the incoming signal to extract the desired bit stream. To reduce the undesirable effects caused by multiple-access interference (MAT) coming from the other users in the same OCDMA network, an FBG decoder scheme is configured on the basis of the correlation subtractions of nearly orthogonal maximal-length sequence (M-sequence) codes or Walsh-Hadamard codes. When the summed encoded broadband signal is sent to each receiving decoder, the received optical signal is divided into two branches equally. It is obtained X_k (λ) in the upper branch and $X_k(\lambda)$ in the lower branch.

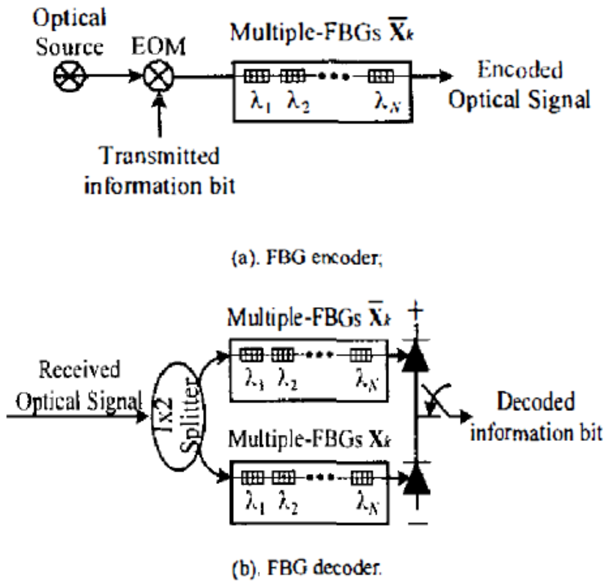


Figure 3-3 FBG encoder and decoder in the OCDMA network
(a) FBG Encoder (b) FBG Decoder [32]

The receiver part of the FBG encoder/ decoder scheme uses a correlation subtraction scheme $R_{X_kV}(\lambda) - R_{\bar{X}_kV}(\lambda)$. The OCDMA network is an incoherent OCDMA; which means both unipolar and bipolar coding is applicable. Figure 3.4 shows a schematic drawing of a 3 user OCDMA network. Figure 3.5 shows a schematic drawing of a 7 users OCDMA network.

For an OCDMA network that is having 7 subscribers (user), the code word has to be change and the Nx1 and 1xN passive couplers have to be change to fit the number of user.

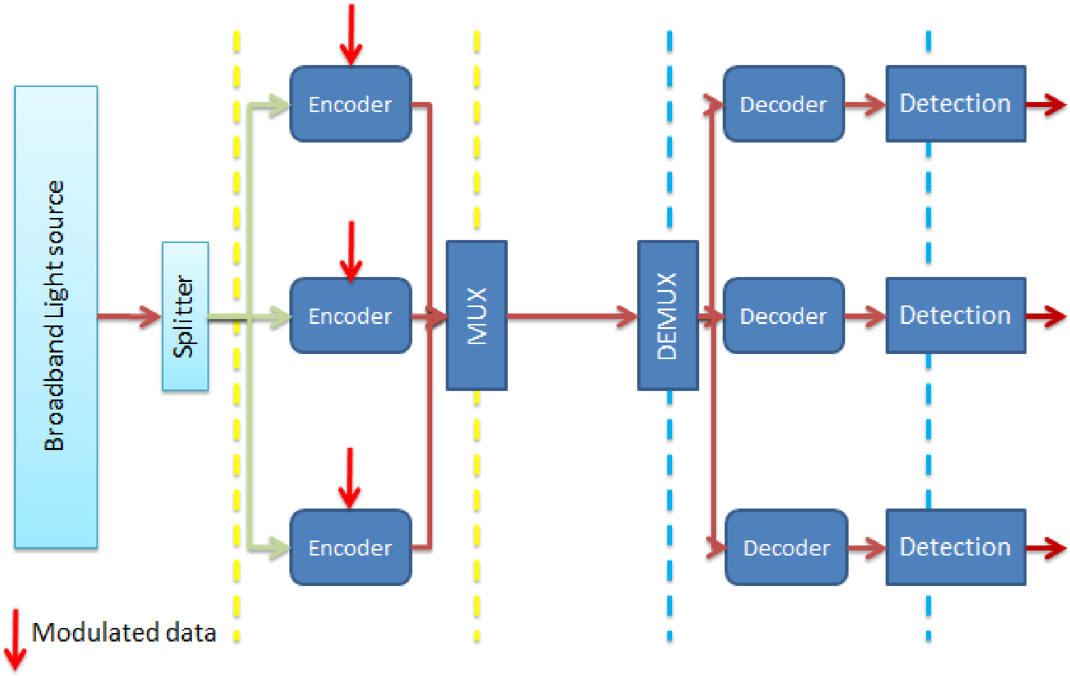


Figure 3-4 SAC OCDMA 3 users network

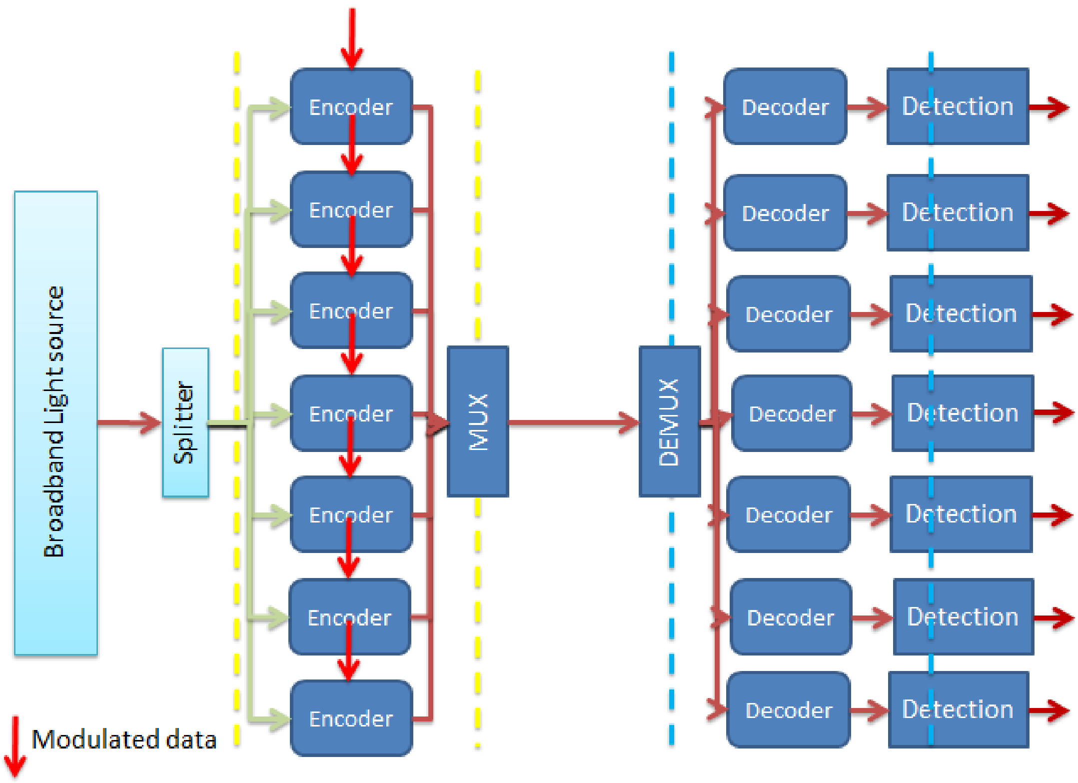


Figure 3-5 SAC OCDMA 7 users network

Figure 3.6 shows an overview of the Optical code division multiple access system that are proposed and experimented. The highlighted part is the main content in this thesis.

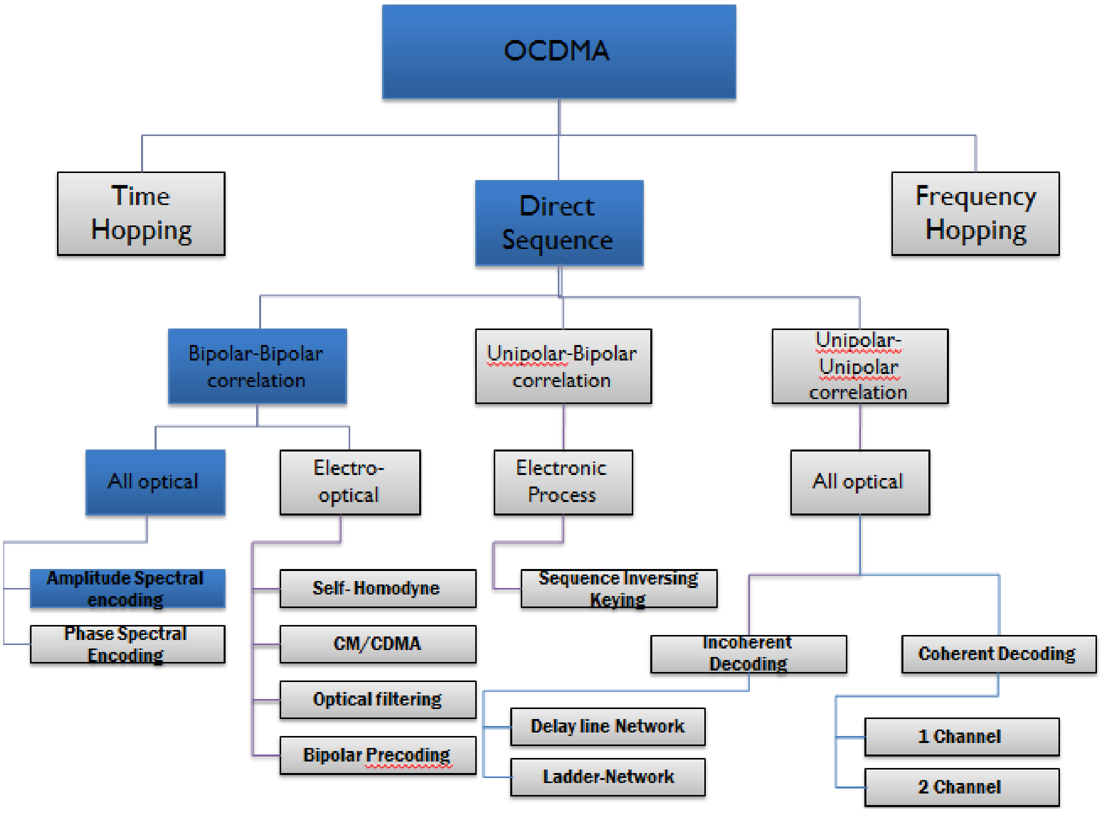


Figure 3-6 Classification of OCDMA networks

3.5 SAC Optical coding and decoding

According to the SAC-OCDMA proposed by Jen Fa Huang, it encodes based on the passing through of a data modulated broadband light source through a series of multiple FBGs wavelength with a specified code sequence in order to accomplish the coding pattern. For decoding the coded broadband signal that is sent to the receiving part of the decoder; the optical signal is divided into two branches equally with an 1x2 power splitter. The upper part is a series of FBGs that's corresponding to the encoder code vector, while the lower part is also a series of FBGs that is inversely followed the encoder code vector. While at the detection part, the subtraction between both upper and lower part of the decoder is brought out and passing it through the photo-detector; as it is known as match filtering detection.

Furthermore, for SAC-OCDMA for 3 users' network, Walsh Hadamard codes are used; as there is a 4x4 Hadamard matrix code vector available. Where else, for 7 users' network, M-sequence and Walsh Hadamard codes are used.

3.5.1 Walsh Hadamard code

Walsh-Hadamard consists of the row vector of a Walsh code matrix arranged according to the order of Hadamard. It is also called Walsh code. The elements of this Walsh matrix are ∓ 1, which can be rapidly generated from the following recursion relation:

$$H(i+1) = \begin{bmatrix} H(i) & H(i) \\ H(i) & -H(i) \end{bmatrix}$$

For 3 users OCDMA network, the code word of H(2) is used. Where else, for 7 users OCDMA network, the code word of H(3) is used. H(2) is a 4x4 Walsh matrix; while H(3) is a 8x8 Walsh Matrix. But the 1st line of the code from both matrixes is consisting of a group of logic "1". The row of logic "1" is not in used, as though the decoding processing, the data will be extracted out by the FBGs. That why both H(2) and H(3) matrixes only able to provide 3 users and 7 users in the SAC-OCDMA network.

$$H(2) = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}$$

Figure 3-7 Walsh Hadamard matrix codes for 3 users OCDMA network

$$H(3) = \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 & +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 & +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 & +1 & -1 & -1 & +1 \\ +1 & +1 & +1 & +1 & -1 & -1 & -1 & -1 \\ +1 & -1 & +1 & -1 & -1 & +1 & -1 & +1 \\ +1 & +1 & -1 & -1 & -1 & -1 & +1 & +1 \\ +1 & -1 & -1 & +1 & -1 & +1 & +1 & -1 \end{bmatrix}$$

Figure 3-8 Walsh Hadamard matrix codes for 7 users OCDMA network

Figure 3.6 and 3.7 shows the code word of both Walsh Hadamard codes for 3 users and 7 users. Walsh Hadamard code is a unipolar code, but to implement into the SAC-OCDMA network, a bipolar is needed. This means the unipolar Walsh Hadamard codes have to be converted into a bipolar code. To make the conversion happens, the “-1” is changed to a logical “0”. Table 3-1 show the Bipolar Walsh Hadamard code with a code length of 4 and showing which wavelength should be chosen to cut off by the FBGs. Table 3-2 show the Bipolar Walsh Hadamard code with a code length of 8 and showing which wavelength should be chosen to cut off by the FBGs.

Table 3-1 Bipolar Walsh Hadamard code with length of 4

Walsh Hadamard codes for 3 Users	Cut Off Wavelengths
1010	$\lambda_1\lambda_3$
1100	$\lambda_2\lambda_3$
1001	$\lambda_1\lambda_2$

Table 3-2 Bipolar Walsh Hadamard code with length of 8

Walsh Hadamarad Code	Cut Off Wavelenghts
10101010	$\lambda_1\lambda_3\lambda_5\lambda_7$
11001100	$\lambda_2\lambda_3\lambda_6\lambda_7$
10011001	$\lambda_1\lambda_2\lambda_5\lambda_6$
11110000	$\lambda_4\lambda_5\lambda_6\lambda_7$
10100101	$\lambda_1\lambda_3\lambda_4\lambda_6$
11000011	$\lambda_1\lambda_3\lambda_4\lambda_5$
10010110	$\lambda_1\lambda_2\lambda_4\lambda_7$

3.5.2 M-Sequence Code

The m-sequence is a pseudorandom sequence in the most common use, which can be generated by the feedback-shift-registers and has the maximal period. Therefore, it is called the maximal linear feedback-shift-register sequence.

To get a code length, n of 7, the number of sequence is from$n = 2^r - 1$, from the equation we can get the number of stages r is equal to 3 stages. The 3-stage primitive polynomial, $(x) = x^3 + x + 1$; where else the inversely polynomial $f(x^{-1}) = x^3 + x^2 + 1$. Figure 3.8 shows the 3 stage linear feedback shift register for generating an m-sequence code with a code length of 7.

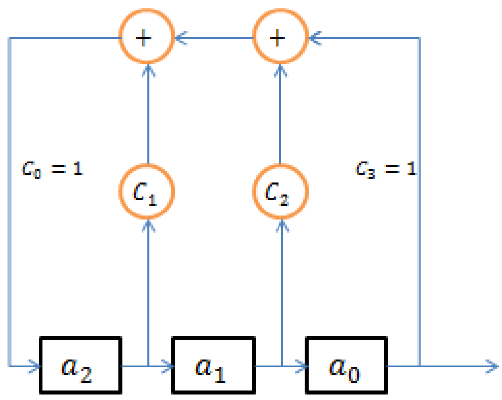


Figure 3-9 3 stage linear feedback shift register

With the M-sequence having a code length of 7, and yielding (+1 +1 +1 -1 +1 -1 -1) the m-sequence is sequence cyclically six times and a cyclic shift sequence can be produced from every cyclic shift. Therefore, it is able to obtain a six cyclic shift sequence in all. By including the original sequence, a total of seven M- sequence code is generated for the 7 users OCDMA network.

Table 3-3 M-sequence with length 7

M-sequence Code	Cut Off Wavelengths
1110100	$\lambda_3\lambda_5\lambda_6$
0111010	$\lambda_0\lambda_4\lambda_6$
0011101	$\lambda_0\lambda_1\lambda_5$
1001110	$\lambda_1\lambda_2\lambda_6$
0100111	$\lambda_0\lambda_2\lambda_3$
1010011	$\lambda_1\lambda_3\lambda_4$
1101001	$\lambda_2\lambda_4\lambda_5$

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Overview of Result and Discussion

In this chapter, a full characterization of SAC-OCDMA system is simulated and discussed. The full characterization is done on a 3-users Walsh Hadamard coded SAC-OCDMA, 7-users Walsh Hadamard coded SAC-OCDMA and a 7-users M-sequence coded SAC-OCDMA. The full characterization covers on no of users, different FBG bandwidth, vary of temperature, FBG reflectivity and FBG deflects. For an error free optical transmission, the BER is always to be lower than 10^{-9}. Before conducting simulation on SAC-OCDMA few of small simulations are done for the confirmation of how optical communication takes place in OCDMA.

4.2 Intensity modulation

In optical communication network, Intensity modulation is the most basic communication network. Intensity modulation uses ASK modulation scheme for optical communication. Intensity modulation comes with RZ and NRZ modulation formats. Bit error rate (BER) is the probability number of bit errors in one data stream over a communication channel. When the BER is zero means there is zero error over the data stream, if the BER is one means the probability to get 1 error is 1. This means by sending 1 bit, it will get 1 bit error; means communication breakdown on the system. For an error free transmission, is it important to get a log10 BER of lower than 10^-9.

4.2.1 Compare between the RZ and NRZ modulation format

According to table 4-1, we can notice that during short distance IM transmission using RZ modulation format, the BER shows a better result if compare with transmission using NRZ modulation. But for long distance transmission, transmission using RZ modulation format totally cannot perform at all, where else, the NRZ modulation format still able to perform optical transmission; although the BER is not on the error free range.

Table 4-1 BER for both RZ and NRZ for different optical fiber length

Modulation scheme	*BER*
RZ	0
NRZ	0
RZ (10m)	0
NRZ (10m)	4.45E-292
RZ (100m)	1
NRZ (100m)	0.006566

This is due to during long distance the dispersion of the optical signal is high, but due to the NRZ code length is longer than the RZ format; NRZ performs betters than the RZ format. Figure 4.1 shows the graph of table 4-1. Table 4-2 shows the eye diagram of each result that is taken from the table 4-1. In term of length of the fiber, for both modulation format longer distance the eyes close smaller. For the RZ format modulation, during 100km transmission, we can observe from that eye diagram; the eye is totally run off by showing a BER of 1. This means during the simulation, it is better to chooses NRZ modulation format than RZ modulation format, as the NRZ shows a better result that the RZ modulation format.

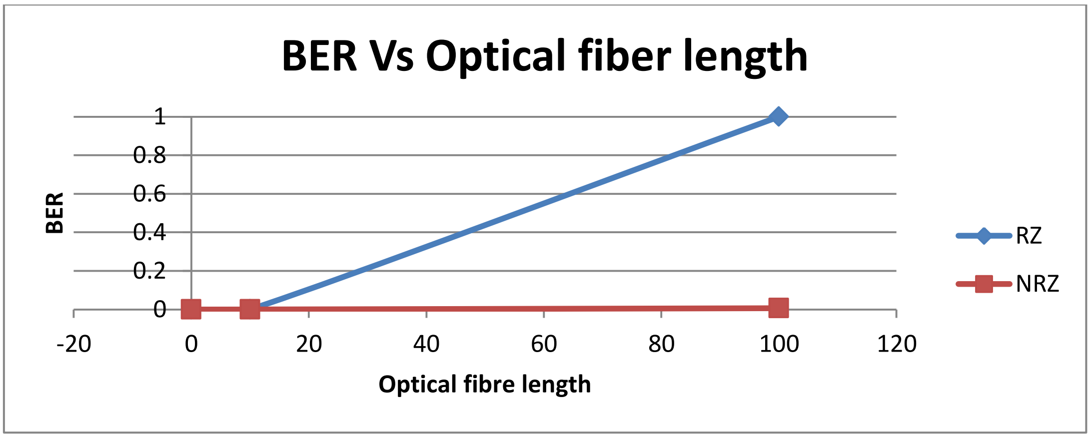
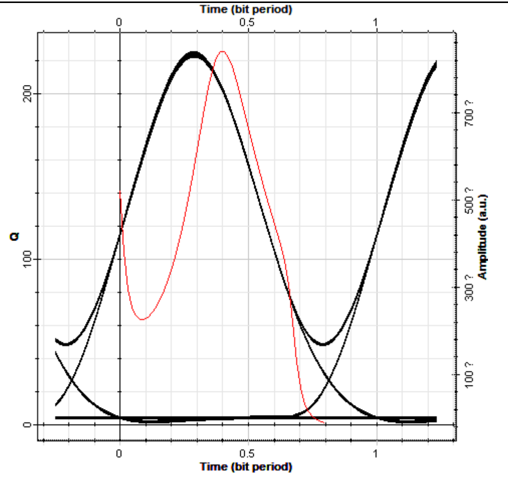
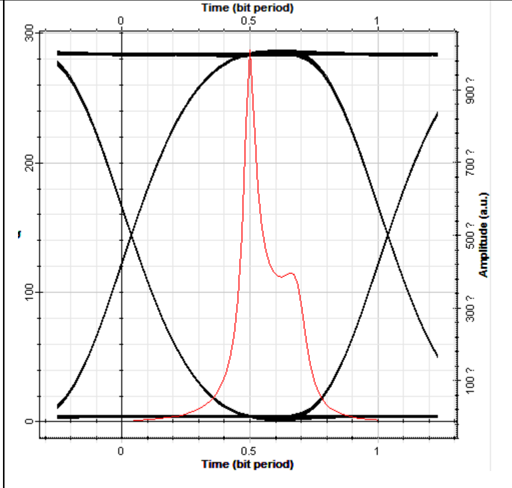
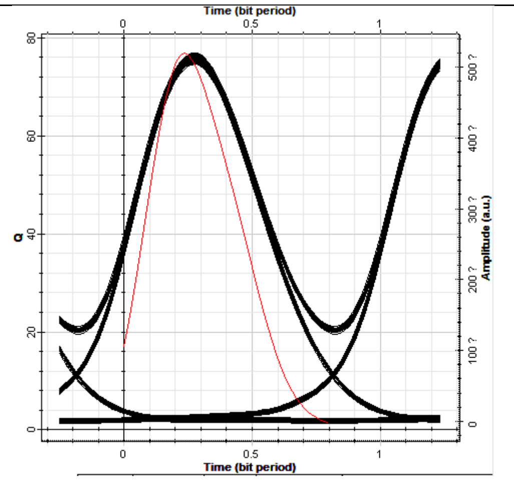
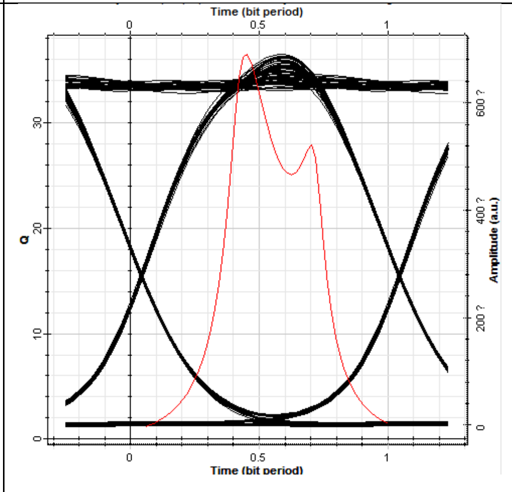
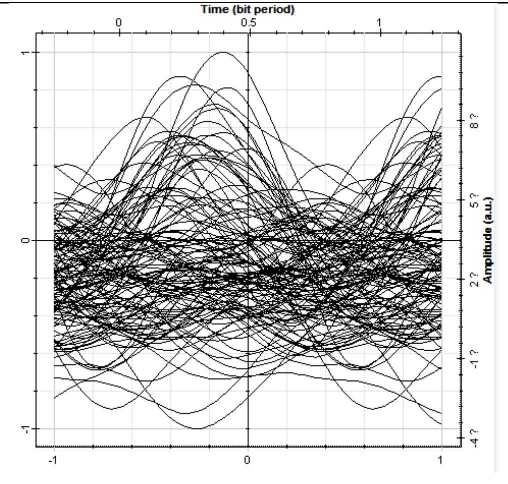
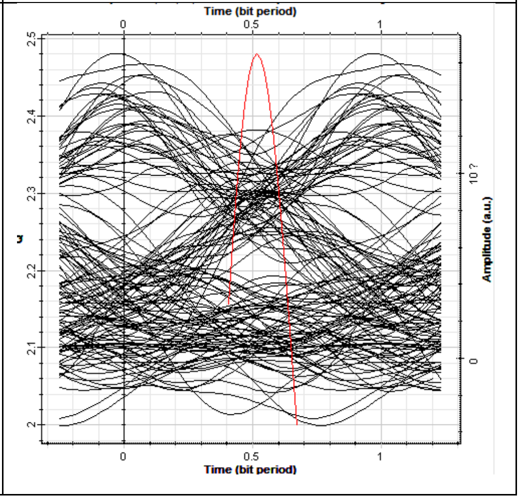


Figure 4-1 BER compare between RZ and NRZ in term of optical fiber length

Table 4-2 Comparison on eye diagram between RZ and NRZ modulation format

Optical Fiber Length	RZ	NRZ
Back to Back		
10km		
100km		

4.2.2 Broadband light source for intensity modulation

Normally during normal IM communication network, broadband light source is not in use due to the CW laser produce a higher power light on the desired frequency; while the broadband light source is producing a same power on the laser bandwidth. For CW laser when the data is modulated on the higher power range, while the noise floor and the dispersion if the optical signal increases; data is still able to be retrieve by just filtering off the lower power noise. Figure 4.2 we can see both differences between white light source and CW laser.

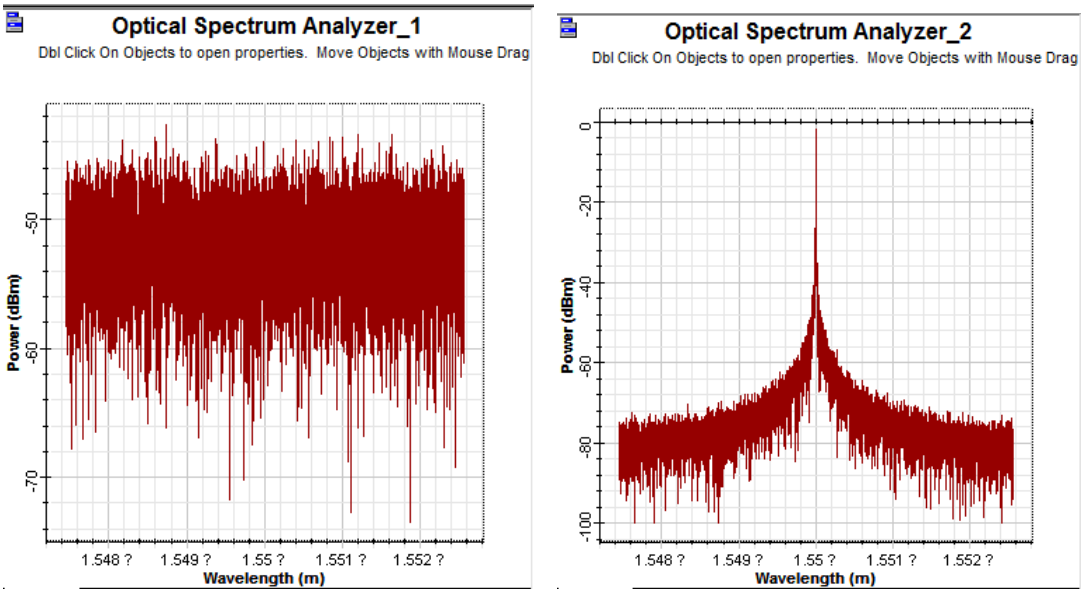


Figure 4-2 Optical Spectrum of White light source (left) Optical Spectrum of CW laser (right)

To show that the statement is true that broadband source is unable to transmit data using IM network, simulation is done by changing the optical source to a broadband light source.

Table 4-3 show the results get from the simulation of intensity modulation with the optical source of white light. For RZ and NRZ modulation format during back to back simulation, there is still a possible to gain an error free communication network; but with the addition of single mode fiber (SMF) with a length of only 2km the communication totally breakdown by giving an BER of 1.

Table 4-3 Intensity modulation using broadband source with RZ and NRZ modulation format

Modulation format	BER
RZ	**1.62E-10**
NRZ	**2.64E-14**
RZ (2km)	**1**
NRZ (2m)	**1**

In the communication of multiple accesses, CW laser will not be able to perform in the communication network. As the data from few users are modulate in to the broadband light source; and encode for long distance transmission. The data will treat as noise during the transmission; while the data is retrieve by decoding the encoded signal. That's why this multiple access transmission is known as a CDMA network. Where else, if OCDMA uses CW laser, only one user data is able to be modulated into the light source say the power of the light source is not constant. This concludes why OCDMA uses broadband light source and not CW laser.

4.3 SAC-OCDMA optical encoding

On Chapter 3, shows that the OCDMA network is simulated based on the conference paper done by Jen Fa Huang. The optical encoding is done by a series of FBGs. When the broadband light sources goes through the FBG with a cut off frequency, a certain part of the broadband light source will be cut off. This is shown on the figure 4.3 that the FBG having a 1550.1 cut off frequency and being pass through by a 1550nm broadband light source. The image is taken from the simulated optical spectrum analyzer. The larger the cut off frequency bandwidth, a wider deep trench will form on the cut off frequency. A better reflectivity; will form a deeper trench on the cut off frequency.

For the SAC-OCDMA, two kinds of optical coding are used for 3 users and 7 user OCDMA simulation. As mention in chapter 3, for 3 users OCDMA network it only uses Walsh Hadamard codes in the simulation, while 7 users OCDMA uses both M- sequence and Walsh Hadamard. Both M sequence and Walsh Hadamard codes are bipolar code, means it only consist of one and zero in the code word.

Therefore the cut off frequency of the FBG coders are designed as a code vector $(\lambda_0, \lambda_k, \dots, \lambda_{k-1})$; k is the number of bit in a code word. When the code word sequence element is equal to logic “1”, the wavelength vector is “present” (remains and not being cut off), where else the code word sequence element is equal to logic “0” , the wavelength vector is “absent” (being cut off).

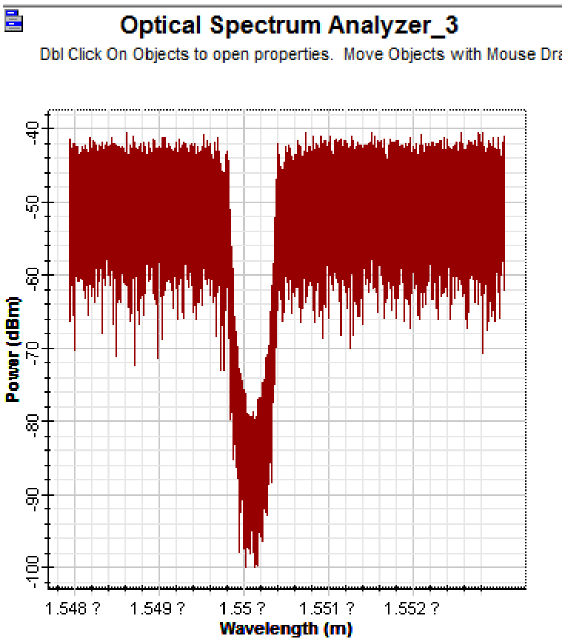


Figure 4-3 Broadband light source filtered by an FBG with a cut off frequency of 1550.1nm

4.3.1 3 Users SAC-OCDMA Optical Encode

According to chapter 3.4.1, for 3 users SAC-OCDMA a Walsh Hadamard Code with a code length of 4 is used. Table 4-4; show the decoded optical signal that is taken from the spectrum analyzer. As mention before, when the code word sequence element is equal to logic “1”, the wavelength vector is “present”, where else the code word sequence element is equal to logic “0”, the wavelength vector is “absent”.

From the Spectrum we can clearly see how the modulated broadband light source is being encoded using the series of 2 FBGs, where all the code word is having 2 logical “0”. For Code “1100” it shows an unclear spectrum, as the two “0”s is able to show a logical “1” in between. But this is not a problem as the decoding part is having the same properties to do match filtering.

Table 4-4 Encoded Optical Signal from Spectrum analyzer

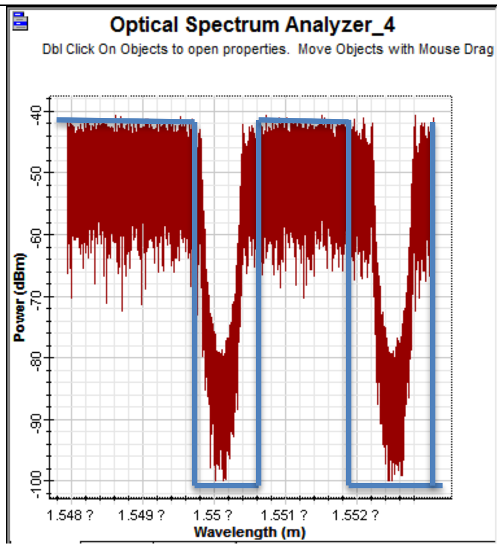
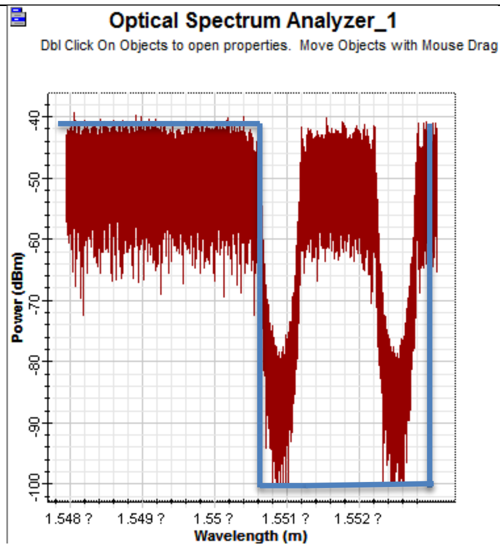
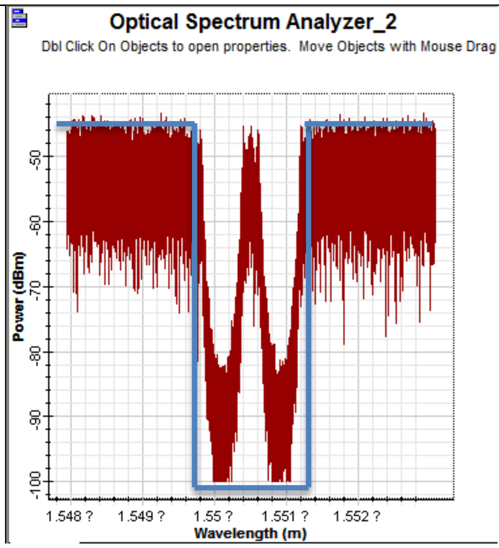
Walsh Hadamard Code	Spectrum Analyzer probe after encoding
1010	
1100	
1001	

Figure 4.4 shows what are the setting is to be done for the optical encoding to be done properly. The FBGs cut off frequency is chosen randomly with in the broadband light source bandwidth. Furthermore, to take in notice on choosing the cut off frequency is not to choose a cut off frequency that is close to another bit and not choosing the cut off frequency that is outside or too near to the upper and lower side of the broadband lights source bandwidth.

The Specification of the Output from the spectrum is stated below:

White Light Specification

White light source Frequency : $1550.5nm$

White light source power : $-115dBm$

Fiber Bragg Grating Specification

FBGs Cut Off Frequency $\lambda_0 = 1548.5nm$, $\lambda_1 = 1550.1nm$, $\lambda_2 = 1550.9nm$, $\lambda_3 = 1552.5nm$

Cut Off Frequency

Bandwidth : $0.6nm$

Reflectivity : 0.9998

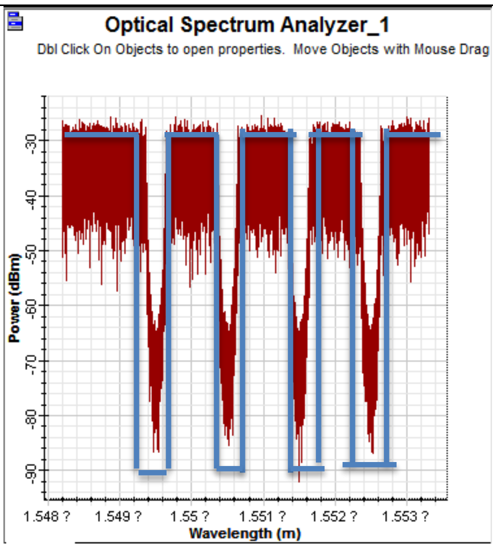
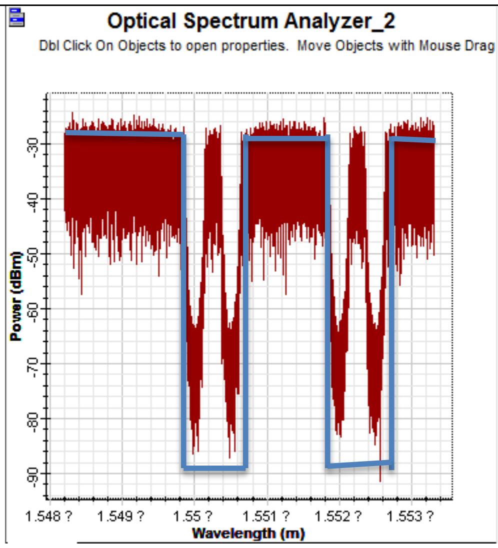
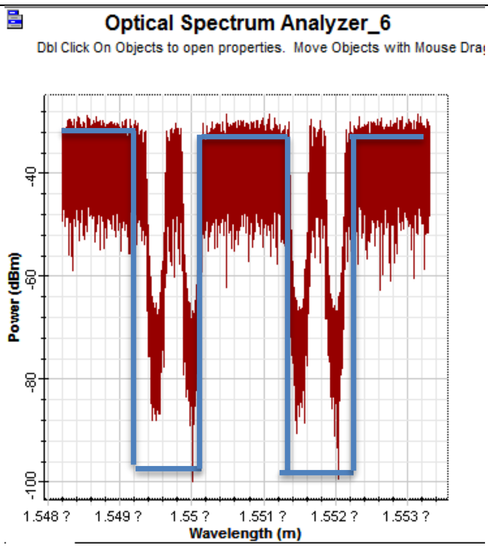
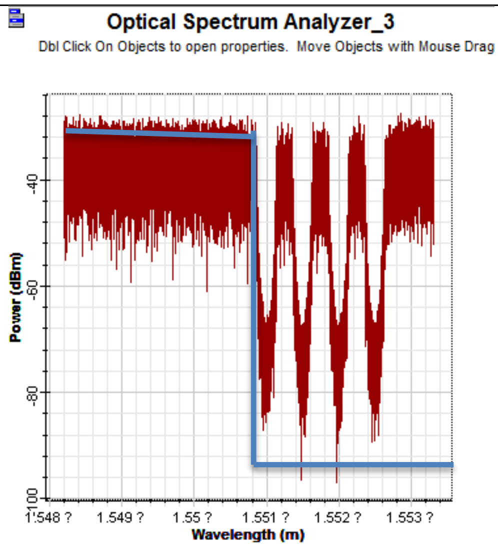
Figure 4-4 White light source and FBGs setting

4.3.2 7 Users SAC-OCDMA Optical Encode

According to chapter 3.4.1, for 7 users SAC-OCDMA a Walsh Hadamard Code with a code length of 8 and a M-sequence with a code length of 7 is used. Table 4-5; show the encoded optical signal that is taken from the spectrum analyzer for Walsh Hadamard code, while table 4-6; shows the encoded optical signal that is taken form the spectrum analyzer. As mention before, when the code word sequence element is equal to logic “1”, the wavelength vector is “present”, where else the code word sequence element is equal to logic “0”, the wavelength vector is “absent”.

Table 3-2 show a group of Walsh Hadamard codes that having a code length of 8. With the Walsh Hadamard that is generated in a group of seven, the code is used for optical encoder with FBGs.

Table 4-5 Encoded Optical Signal from Spectrum analyzer for 7 Users OCDMA for Walsh Hadamard Code

Encoded Broadband source in Spectrum Analyzer	Encoded Broadband source in Spectrum Analyzer
 User 1 Code:10101010	 User 2 Code:11001100
 User 3 Code:10011001	 User 4 Code:11110000

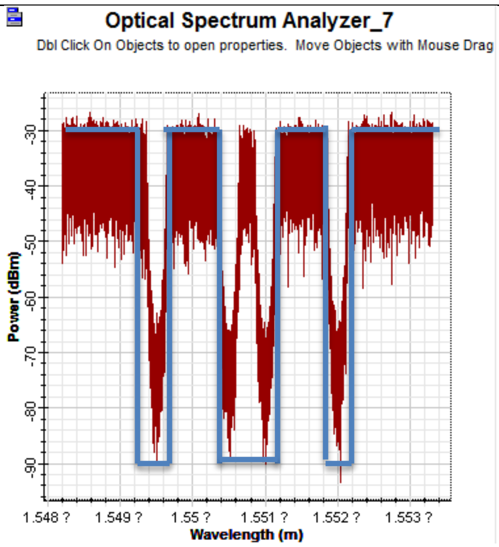
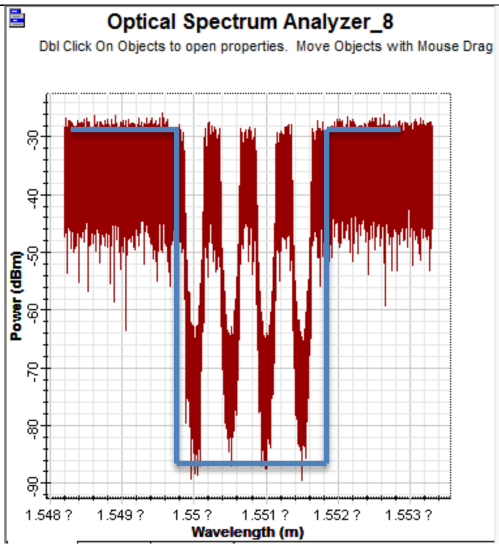
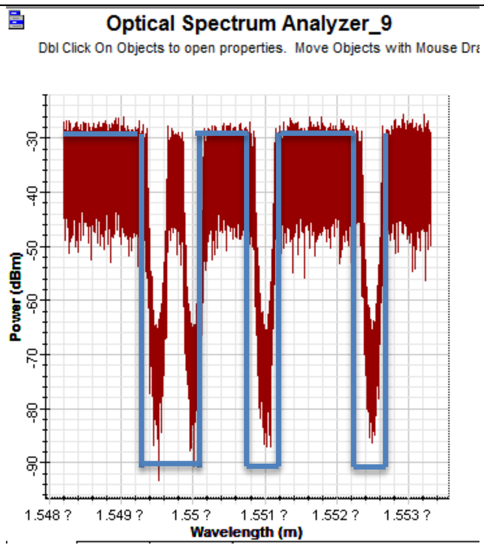
 User 5 Code:10100101	 User 6 Code:11000011
 User 7 Code:10010110	

Table 4-5 show the encoded signal modulated broadband light source, which is encoded by a series of FBGs. The specification of the broadband light source and FBGs, setting is shown on Figure 4.5. Compare to the 3 user OCDMA that uses the same code, the power of the white light source is higher. Additional, the white light frequency is shifted from 1550.5nm to 1550.75nm; due to the cut off frequency that is chosen. Furthermore, the cut off frequency is changed to 0.3 nm, as the cut off frequency of each codes is near to each logical codes as 8 bits have to fit in 1 broadband light source spectrum.

The Specification of the Output from the spectrum is stated below:

White Light Specification

White light source Frequency : $1550.75nm$

White light source power : $-100dBm$

Fiber Bragg Grating Specification

FBGs Cut Off Frequency : $\lambda_0 = 1549.0nm$, $\lambda_1 = 1549.5nm$, $\lambda_2 = 1550.0nm$, $\lambda_3 = 1550.5nm$, $\lambda_4 = 1551.0nm$, $\lambda_5 = 1551.5nm$, $\lambda_6 = 1552.0nm$, $\lambda_7 = 1552.5nm$

Cut Off Frequency

Bandwidth : $0.3nm$

Reflectivity : 0.9998

Figure 4-5 White light source and FBGs for 7 users Walsh Hadamard Codes

For M-sequence code, it is stated on table 3-3 an M- Sequence codes that having a code length of 7 is shown. By cyclic shifting the 7 bits codes it is able to get 7 types of code for 7 users.

Table 4-6 show the encoded signal modulated broadband light source, which is encoded by a series of FBGs. The specification of the broadband light source and FBGs, setting is shown on Figure 4.6. Compare to the 7 users OCDMA using Walsh Hadamard code, the white light source power is change to a lower power. Furthermore are the changes in the cut off frequency sequence of the FBGs.

The Specification of the Output from the spectrum is stated below:

White Light Specification

White light source Frequency : $1550.75nm$

White light source power : $-115dBm$

Fiber Bragg Grating Specification

FBGs Cut Off Frequency : $(\lambda_0 = 1549.0nm\,, \lambda_1 = 1549.6nm\,, \lambda_2 = 1550.2nm\,, \lambda_3 = 1550.8nm\,, \lambda_4 = 1551.4nm\,, \lambda_5 = 1552.0nm\,, \lambda_6 = 1552.6nm\,,)$

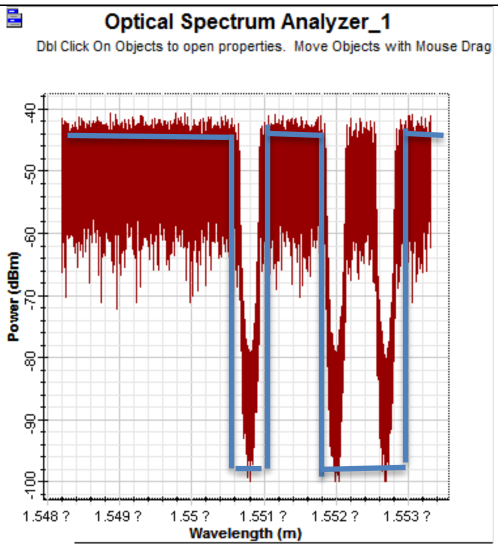
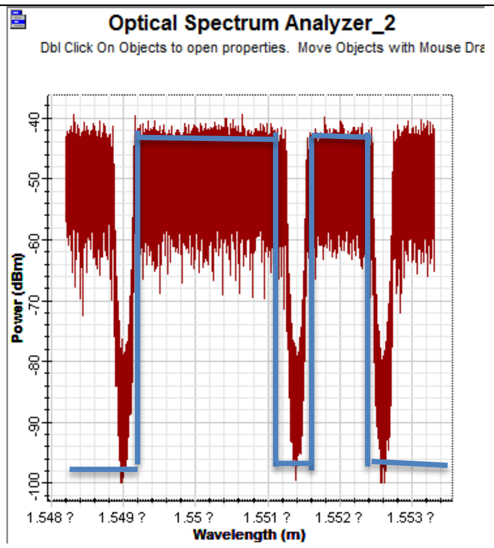
Cut Off Frequency

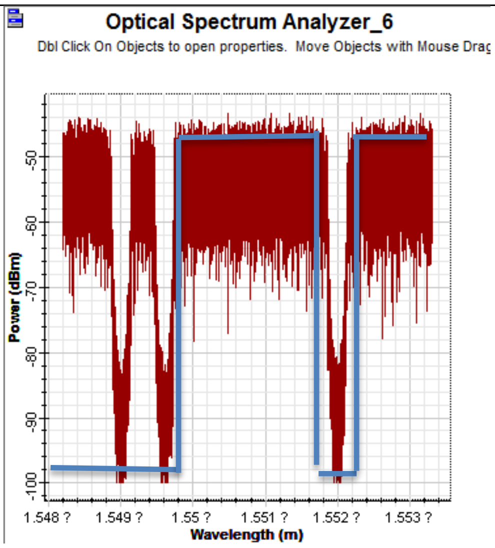
Bandwidth : $0.3nm$

Reflectivity : 0.9998

Figure 4-6 White light source and FBGs for 7 users M-sequence Codes

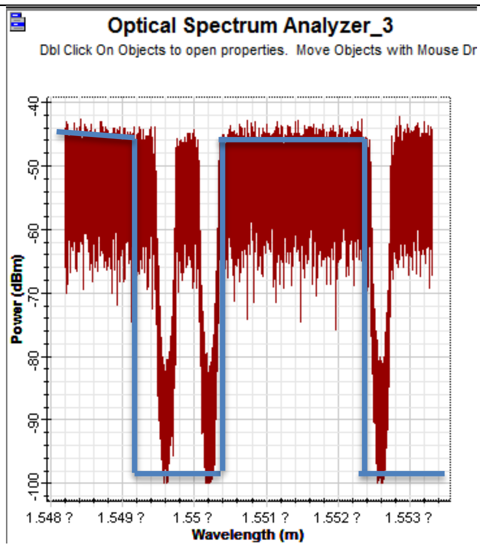
Table 4-6 Encoded Optical Signal from Spectrum analyzer for 7 Users OCDMA for M- Sequence code

Encoded Broadband source in Spectrum Analyzer	Encoded Broadband source in Spectrum Analyzer
	
User 1 Code:1110100	User 2 Code:0111010



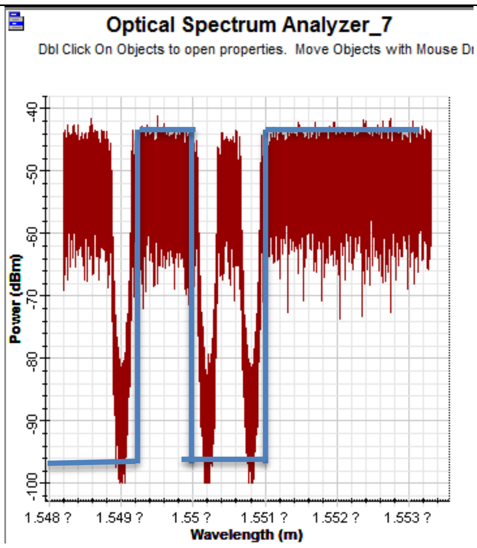
User 3

Code:0011101



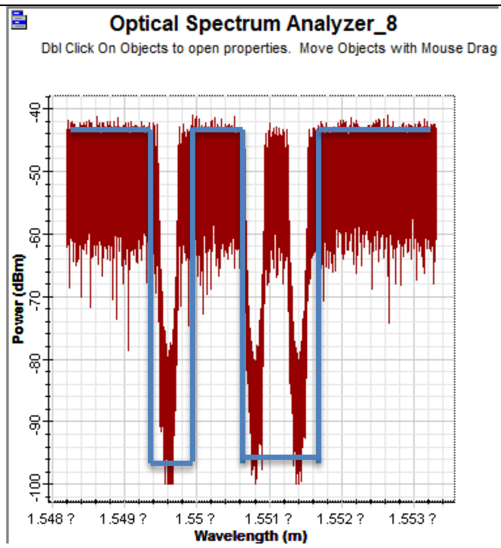
User 4

Code:1001110



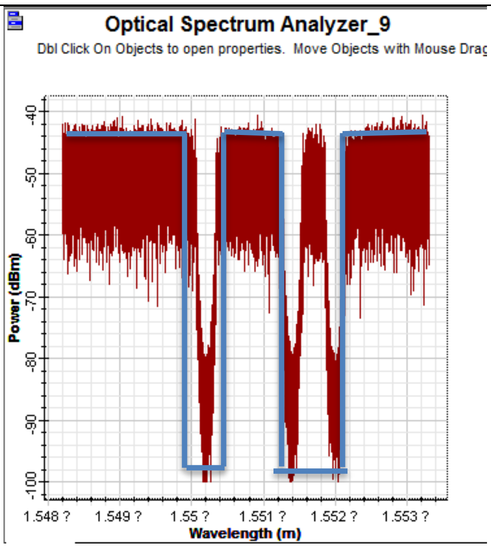
User 5

Code:0100111



User 6

Code:1010011



User 7

Code:1101001

4.4 Full characteristic simulation on 3 Users SAC OCDMA

The setup of the 3 users SAC OCDMA network is introduced on chapter 3.3 and chapter 4.3.1. Few simulations are done and discussed on research of the characteristic of the communication network. All of the simulations are done in the environment of Optisystem. Simulations done are:

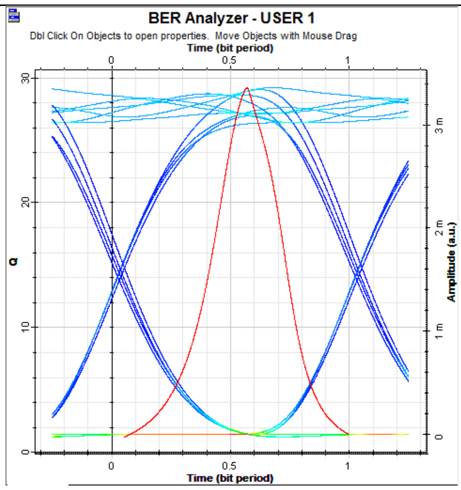
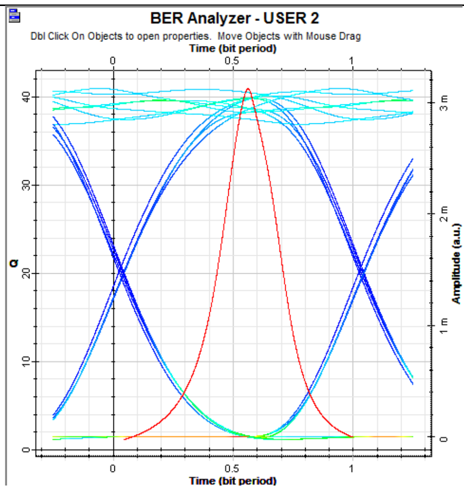
- One user network with different coding implement
- Simulation on number of users in the network
- The effects of the FBG cut off frequency bandwidth to the network
- The effects of the changes of room temperature to the network
- The effects of deflects FBGs to the network

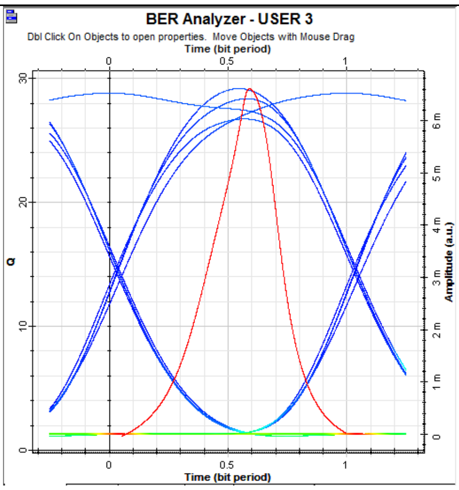
4.4.1 One User network with different coding implement

In the beginning of this chapter, we discuss on the IM simulation and also implement the white light source in to the IM simulation. The results come out that it shows, the communication totally break down during long distances transmission or it's to be said that white light source totally cannot function in IM transmission. But in an OCDMA network, the white light is modulated and encode; the results shows a zero error transmission with fiber length of 10km. Table 4-7 shows the BER and eye diagram that is gain from the simulation on the one user transmission with different coding.

On table 4-7, the BER for each coding is nearly to zero, the eye diagram gain from the BERT during simulation show the eye widely open. This proves that when a broadband source is encoded and decoded with optical codes, it shows better results than normal CW laser IM transmission. This is due to the broadband source is able to modulate more data’s than the CW laser, with the condition of before match filtering; the broadband light source is encoded and decoded properly.

Table 4-7 The BER and Eye diagram of one to one transmission with different coding applied

User 1 (1010) BER: **4.89E-188**	
User 2 (1100) BER: **0**	

User 3 (1001) BER: **5.60E-188**	

4.4.2 Simulation on number of users in the OCDMA network

With the increase of numbers of users in the network, it also increases the ISI to the communication network. This is due to there will be crosstalk among the encoded white light signals, when all the encoded white light signal is combined together with a Nx1 power combiner for going through the SMF. Table4-8 shows the result gain from the simulation.

According to table 4-8 we can see that, when the number of users decreases, the BER also decreases. This means the lesser the number of users the better the transmission.

Table 4-8 BER gain by changing the numbers of Users in the network

No. of Users	User 1	User 2	User 3
1 user	7.154E-242	0.000E+00	2.443E-246
2 users	3.127E-19	2.392E-25	N/A
2 users	1.902E-91	N/A	1.693E-22
2 users	N/A	4.131E-137	3.862E-33
3 users	9.832E-20	1.310E-26	4.587E-14

4.4.3 Effects of FBGs cut off frequency bandwidth to the network

The FBGs cut off frequency bandwidth shows an important role to the network. With a smaller cut off frequency bandwidth the OCDMA system is able to use a longer code length code; longer code means more users in the network. But smaller cut off frequency bandwidth will cause the dispersion of signal during the transmission through SMF; and cause the increase of BER. This means larger cut off frequency bandwidth will have a smaller BER; but there still a limit on widening the cut off frequency bandwidth, for avoiding crosstalk causing ISI to the network. Table 4-9 shows the results gain from the simulation.

Table 4-9, shows the BER of each user by changing the cut off frequency bandwidth for each FBG in the network. It shows that the BER is affected by the changing of cut off frequency bandwidth from a range of 0.1nm to 0.8nm. The best results gain from the simulation is with a cut off frequency bandwidth of 0.6nm; where the BER start to increase when the cut off frequency bandwidth is more widen. This match with the statement above where there is a limit on increasing the cut off frequency bandwidth of the FBG in the network. A significant result from table 4-9 proved the statement. This is also shown on figure 4.7 for a clearer view on the effects of FBG cut off frequency bandwidth on the BER.

Table 4-9 BER gain by changing the cut off frequency bandwidth

Cut Off Frequency bandwidth (nm)	BER		
	User 1	User 2	User 3
0.1	1.4959E-10	2.8756E-09	1.2899E-04
0.2	1.6052E-13	6.5145E-15	1.1210E-12
0.3	1.4554E-18	2.7435E-16	5.8001E-14
0.4	1.1552E-17	7.3115E-25	1.4911E-10
0.5	1.4304E-23	1.7414E-18	8.8888E-18
0.6	8.6812E-34	7.4491E-34	1.5489E-25
0.7	6.3010E-23	4.1260E-22	5.4499E-18
0.8	9.8324E-20	1.3104E-26	4.5873E-14

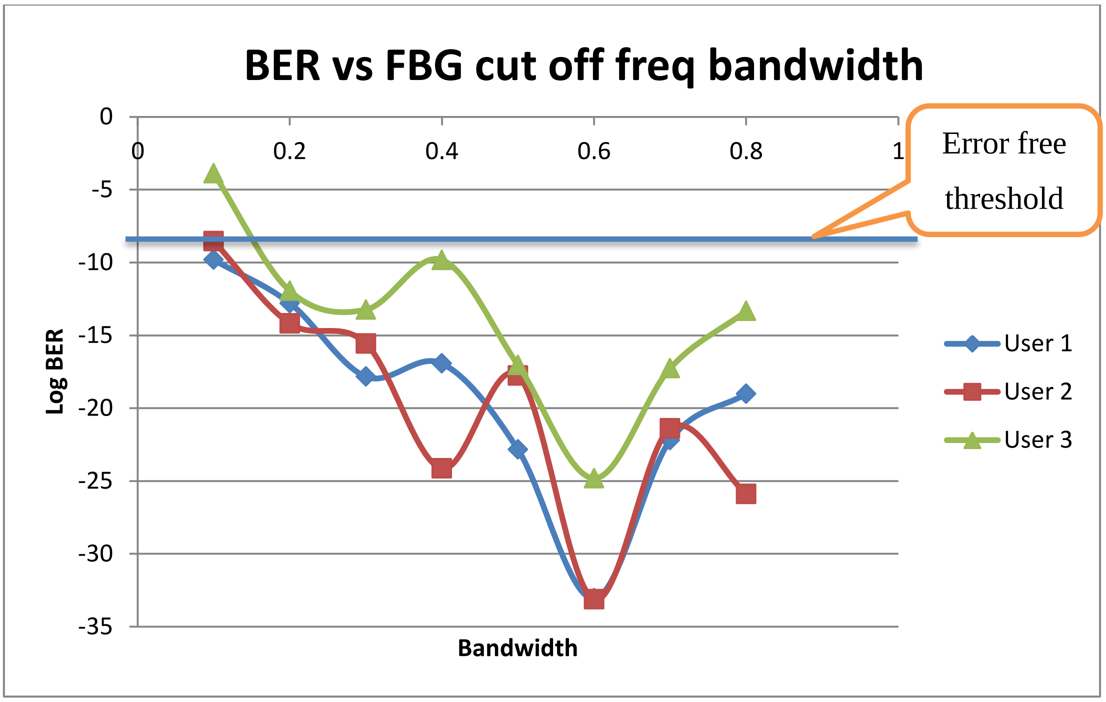


Figure 4-7 A graph of BER versus FBG cut off frequency bandwidth

4.4.4 The effect of the changes of Room temperature to the network

Fiber Bragg Grating (FBG) is a periodic or aperiodic perturbation of the effective refractive index in the core of an optical fiber. This cause the FBG to reflects certain wavelength while light passing through.

FBG cut off frequency is very sensitive to the temperature. As FBG act as an important role in our OCDMA network; therefore, the situation of FBG being affected to room temperature is also take in to the account of full characterization of SAC OCDMA system.

In chapter 3, it is mention that the cut off wavelength of the FBG to form optical coding is chosen randomly by fitting the sequence of $(\lambda_0, \lambda_1, \lambda_2, \cdots, \lambda_{k-1})$ within the broadband light source bandwidth (k is the code length). This means when the FBG cut off frequency in the whole system shift left or right that's within the light source bandwidth it will not cause a problem to the network. Table 4-10 shows the result taken from the simulation.

Table 4-10 BER of FBG changes on room temperature

		FBG cut off frequency			
		right shift 0.2 nm	right shift 0.4 nm	left shift 0.2nm	left shift 0.4 nm
BER	user 1	2.00028E-25	1.59760E-10	2.48815E-39	3.93668E-08
	user 2	4.43354E-27	7.55003E-10	1.32784E-40	2.48854E-10
	user 3	6.86133E-46	6.94498E-25	1.10271E-38	6.65098E-08

According to figure 4.8, we can see that during the FBG cut off frequency right and left shift till 0.4nm, the BER increases till a non – error free communication network. For FBG cut off frequency right or left shift of 0.2nm, the BER show it still at an acceptance level, which is lower than the error free threshold. This is due to during the FBG cut off frequency right or left shift of 0.2nm, the shifting still inside the broadband light source bandwidth; as for FBG cut off frequency right or left shift of 0.4, the FBG cut off frequency with a bandwidth of 0.6nm is out of the broadband light source bandwidth. Figure 4.9 show an example that what happens when the deep trench of the FBG cut off frequency is move out of the broadband light source bandwidth. This is observed by probe the encoder (that consists of a series of FBG) output with the optical spectrum analyzer (OSA) during simulation.

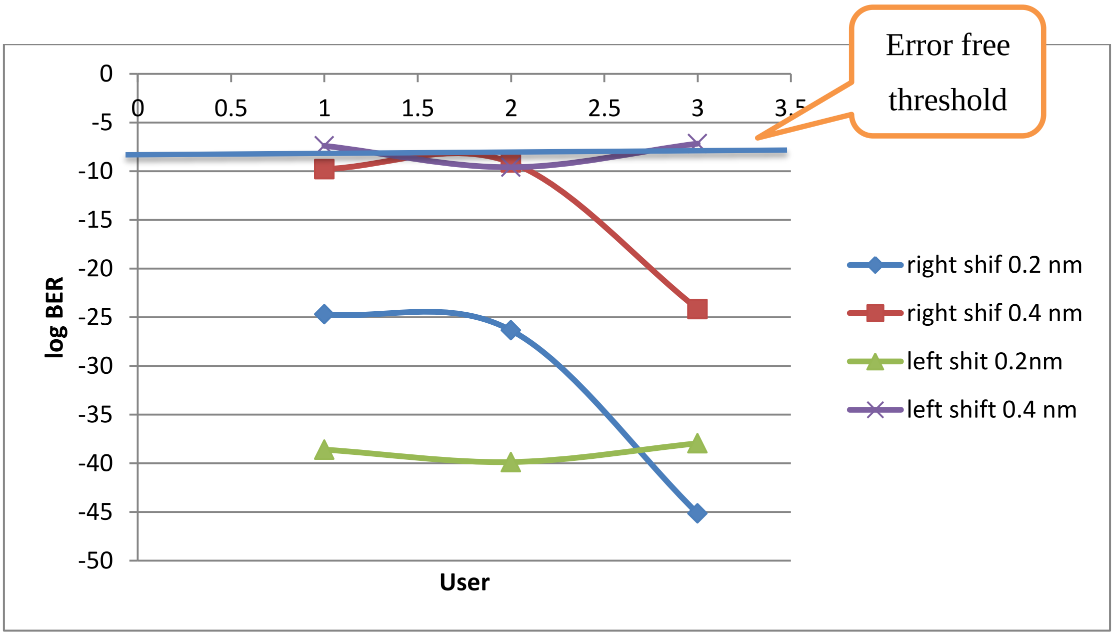


Figure 4-8 A graph the BER effected by temperature

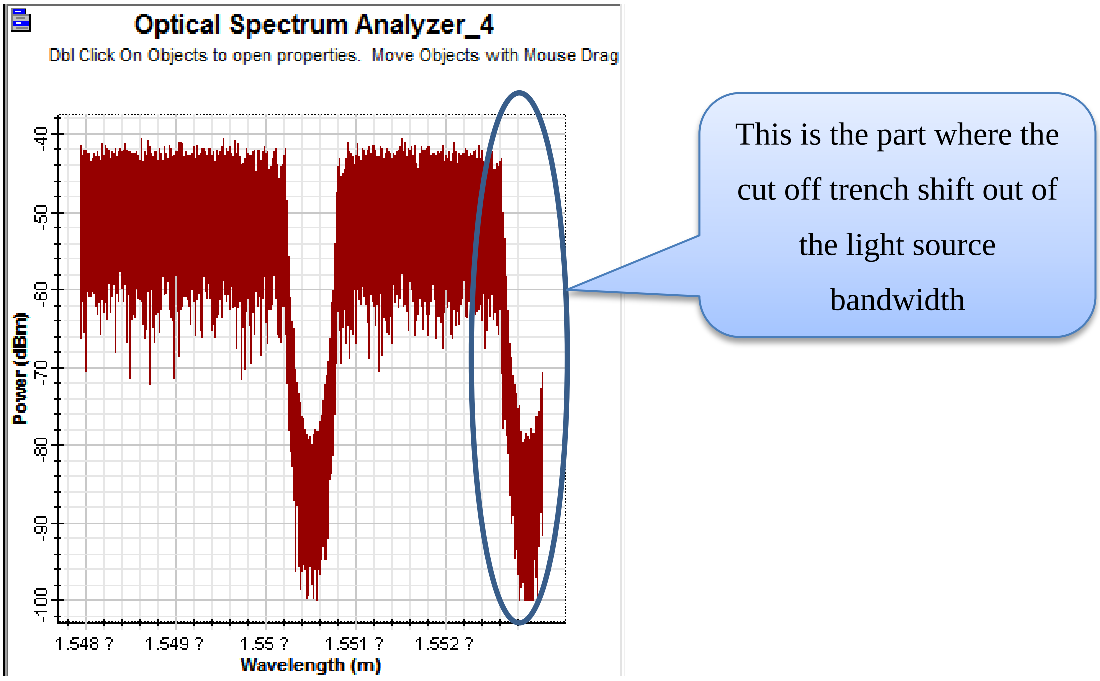


Figure 4-9 FBG cut off frequency shift out of the broadband light source frequency

4.4.5 Effect of deflects FBG to the OCDMA network

To form a FBG is to print different reflective index on the fiber core. For the OCDMA network, the cut off frequency should be very precise with less than 1% of marginal error is allowed in the network. A deflects FBG is a FBG that is having an inaccurate cut off frequency. For this situation it is take account in to the simulation on characterizing the SAC-OCDMA network.

Few situation is take account in the simulation network, the results is shown on table 4-11, 12 and 13. All three tables show the simulated results on few situation of FBG deflect on the OCDMA system. All three table shows that when there is only 1 FBG deflects in the system, the communication network still an error free network. But if more than 1 deflects in the system, the BER will increases dramatically. Figure 4.10 show a combination of all three tables.

There are few situation when the deflect FBG only occurs on one particular user, this is shown on the table 4-12 and table 4-13 with the BER result in red font. During this situation happens, the simulation shows that the user with the deflect FBG; it will not cause problems to other users, as the BER increases only on that particular user with deflect FBG. Besides, with the BER increases on one user, the other users in the system will have a decreased BER.

Table 4-11 Deflects FBGs on the encoder part

Deflects FBGs on the encoder part		
No. of FBG deflects in the system	Users	BER
1	User 1	1.68529E-30
	User 2	3.61505E-23
	User 3	1.16080E-17
2	User 1	1.24562E-12
	User 2	4.65162E-15
	User 3	1.77671E-10
3	User 1	2.09327E-09
	User 2	1.95838E-10
	User 3	8.61583E-12

Table 4-12 Deflects FBGs on the decoder part

Deflects FBGs on the decoder part		
No. of FBG deflects in the system	Users	BER
1	User 1	3.30246E-39
	User 2	9.13967E-42
	User 3	7.63175E-17
2	User 1	8.68122E-34
	User 2	7.44913E-34
	User 3	7.77489E-04
3	User 1	1.07218E-08
	User 2	7.25744E-11
	User 3	1.54892E-25

Table 4-13 Deflects FBGs on the encoder and decoder part

Deflects FBGs on the encoder and decoder part		
No. of FBG deflects in the system	Users	BER
1	User 1	1.05125E-28
	User 2	1.32784E-40
	User 3	1.10270E-38
2	User 1	1.00000E+00
	User 2	3.14638E-24
	User 3	2.29049E-03
3	User 1	3.11442E-03
	User 2	4.14992E-02
	User 3	1.91094E-04

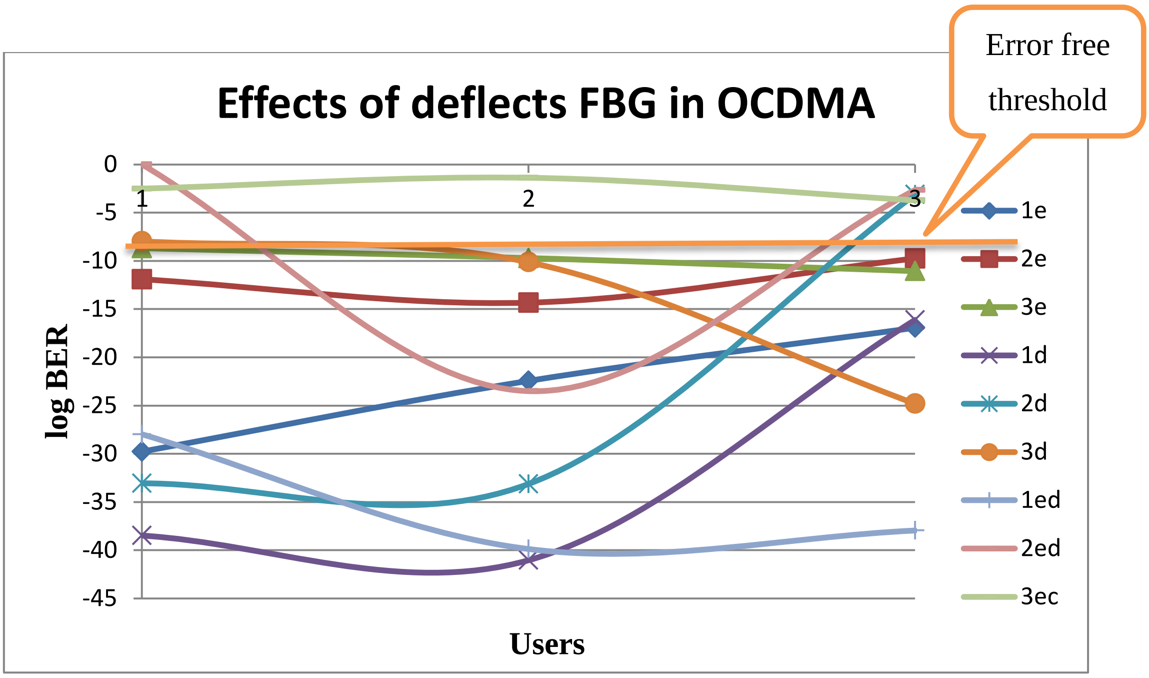


Figure 4-10 Deflects FBG in OCDMA system

4.5 Full characteristic simulation on 7 Users SAC-OCDMA with Walsh Hadamard coding method

The setup of the 7 users SAC OCDMA network is introduced on chapter 3.3 and chapter 4.3.2. Few simulations are done and discussed on research of the characteristic of the communication network. All of the simulations are done in the environment of Optisystem. Simulations done are:

- One user network with different Walsh Hadamard coding implement
- Simulation on number of users in the network
- The effects of the FBG cut off frequency bandwidth to the network
- Effect of FBG reflectivity to the SAC OCDMA system

4.5.1 One user network with different Walsh Hadamard coding implement

On chapter 4.4.1, the simulation on one user is the network is done on the 3 users SAC OCDMA network on Walsh Hadamard code. For the 7 users of SAC- OCDMA network, the Walsh Hadamard code comes with a different code length. The setup of this simulation is stated on chapter 3 and the beginning part of chapter 4.

Table 4-14 BER gain on the specific Walsh Hadamard code

Users	Walsh Hadamard Code	BER on one by one
User 1	10101010	2.2157E-272
User 2	11001100	0.0000E+00
User 3	10011001	0.0000E+00
User 4	11110000	0.0000E+00
User 5	10100101	1.1132E-216
User 7	11000011	3.6900E-230
User 6	10010110	0.0000E+00

Table 4-14, show the BER from the specific Walsh Hadamard code, that used by each users. The SMF in this network is 10km. Again it shows results of zero error transmission. As mention before the FBG cut off frequency bandwidth act as a very important role in the SAC-OCDMA network, this simulation is done on the bandwidth of 0.4nm. Later the bandwidth will be discussed on why it is chosen.

4.5.2 Simulation of number of Users in the network

On the 3 users SAC-OCDMA simulation on the number of users in a SAC- OCDMA network, the simulation didn't shows a clearer results as the number of user in 3 users SAC OCDMA is very limited. It is better to explain the simulation of number of user in a 7 users SAC-OCDMA network. Whereby, the Walsh Hadamard code for 7 users uses a code length of 8 bits, it show more complicated and ISI rate is higher than a code length of 4 bits for 3 users OCDMA. In chapter 4, we conclude that the lesser the users in a network, the lower the BER. Table 4-15 shows the result gain from the simulation.

According to table 4-15, when the system is with 7 users, it is unable to get a full system of error free OCDMA network. With the reduction of 1 user, in the network, all the 6 users in the network is able to get an error free transmission. This is due to the increases of code length in the network; it also increases the crosstalk within all the users. That's why with the reduction of users in SAC-OCDMA network the BER is lesser.

Table 4-15 Effect of number of users in the SAC-OCDMA network to the BER

No. of Users	BER						
	User 1	User 2	User 3	User 4	User 5	User 6	User 7
1	9.32E-188						
2	3.19E-28	1.22E-89					
3	2.62E-23	1.90E-57	6.18E-24				
4	1.48E-22	1.61E-36	3.74E-23	3.89E-15			
5	6.07E-14	9.51E-23	3.91E-22	6.35E-17	1.78E-18		
6	1.22E-10	2.99E-17	8.80E-14	3.21E-09	4.73E-11	7.37E-10	
7	3.87E-08	7.00E-16	1.26E-12	3.03E-08	1.82E-12	1.25E-10	1.55E-09

4.5.3 The effects of FBG cut off frequency bandwidth to the network

As mention in chapter 4.4.3, the characteristic of the FBG act as an important role in the network, especially the FBG cut off frequency bandwidth. Same as the assumption given in chapter 4.4.3, every system have its ideal FBG cut off frequency bandwidth to get the best results. Table 4-16; shows the BER gain from simulation on changing the FBG cut off frequency bandwidth for encoder and decoder from 0.1nm to 0.5nm.

Table 4-16 Effects of FBG cut off frequency bandwidth on the BER

FBG Cut Off frequency bandwidth(nm)	BER						
	User 1	**User 2**	**User 3**	**User 4**	**User 5**	**User 6**	**User 7**
0.1	3.882E-04	6.229E-06	2.650E-04	9.171E-03	3.244E-06	1.204E-04	6.518E-05
0.2	9.286E-08	3.575E-08	3.741E-08	9.011E-06	4.426E-11	7.753E-07	1.685E-12
0.3	3.867E-08	6.999E-16	1.257E-12	3.026E-08	1.820E-12	1.249E-10	1.553E-09
0.4	4.478E-13	3.683E-14	8.750E-12	2.223E-13	2.923E-12	1.123E-05	1.259E-07
0.5	1.113E-09	4.311E-08	1.820E-05	1.025E-08	3.305E-05	2.620E-03	3.443E-06

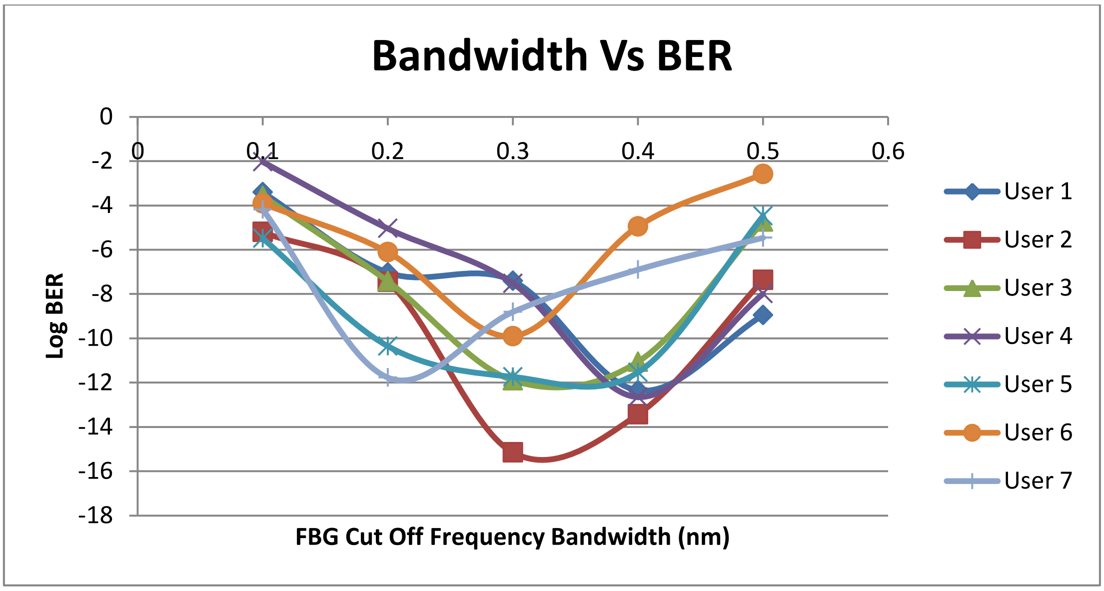
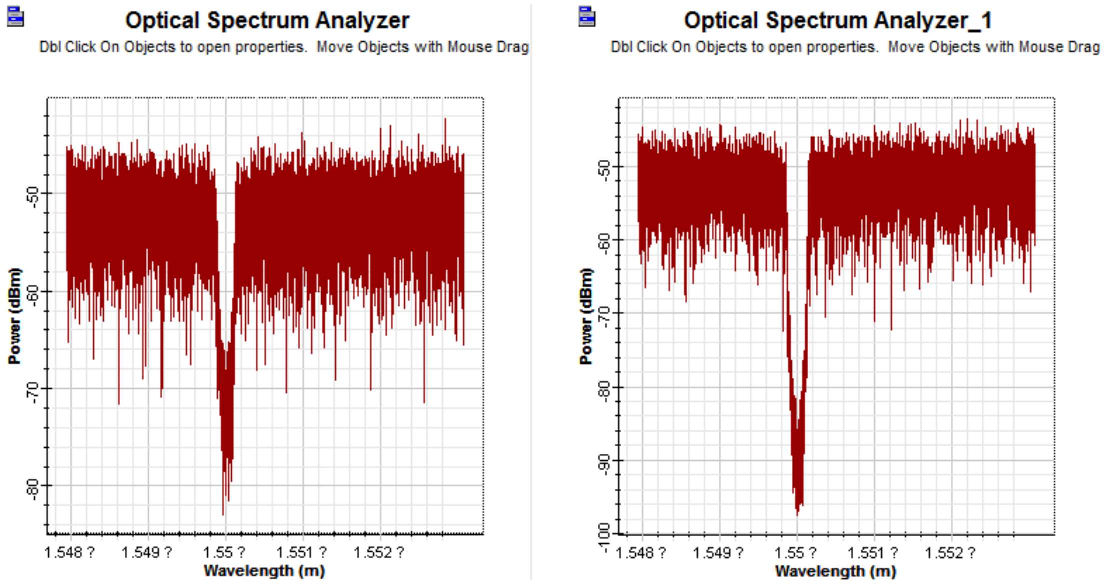


Figure 4-11 Effects of FBG cut off frequency bandwidth on the BER

4.5.4 The effects of FBG reflectivity to SAC-OCDMA network

A small brief introduction on FBG is given on chapter two, as FBGs is made up by a SMF with different refractive index printed on the SMF core. So that the FBG reflects a particular wavelengths of light and transmits all others. The FBG reflectivity is the percentage of the power reflect back and also means the cut off frequency power. Figure 4.12 (a) shows the output of a FBG with a reflectivity of 99% that is taken from an OSA. Figure 4.12 (b) shows the output of a FBG with a reflectivity of 99.98% that is taken from an OSA.

In the SAC-OCDMA network, the FBG reflectivity also a crucial aspect to for having an error free SAC-OCDMA network. With a higher reflectivity, the optical coding is able to have a higher contrast. This means the higher the reflectivity the lower the BER of the network. The simulation is done on changing the reflectivity of the FBGs on the SAC-OCDMA network and also done on different cutoff frequency bandwidth. Table 4-17 show the results gain from the simulation.



(a) (b)

Figure 4-12 (a) FBG with a reflectivity of 99% (b) FBG with a reflectivity of 99.98%

Table 4-17 The BER for different FBG reflectivity and cut off frequency bandwidth

FBG cut off frequency bandwidth	FBG reflectivity	BER						
		User 1	User 2	User 3	User 4	User 5	User 6	User 7
0.3	0.99	2.075E-09	7.310E-14	1.959E-11	2.441E-13	3.278E-15	8.026E-07	9.314E-07
0.5	0.99	2.017E-11	3.873E-10	3.493E-10	3.485E-17	9.429E-10	2.232E-04	7.308E-08
0.3	0.9998	1.265E-07	1.177E-15	7.248E-13	4.461E-08	2.773E-13	1.387E-10	9.662E-10
0.5	0.9998	1.532E-09	4.624E-08	1.577E-05	1.185E-08	2.648E-05	2.550E-03	3.045E-06

Table 4-17 shows the BER for every user in the seven users SAC-OCDMA with Walsh Hadamard codes network. From the table, the BER has taken from the simulation of FBG with a reflectivity of 0.9998 shows a better result than the FBG with a reflectivity of 0.99. But, when the FBG cut off frequency changes to a higher bandwidth, the BER difference between two kinds of FBG reflectivity shows a little difference. This is due to when the FBG cut off frequency bandwidth is broaden it means that the incident wave is completely reflected before reaching the end of the grating. That’s why with a different reflectivity it makes no different in the results.

4.6 Full characteristic simulation on 7 users SAC-OCDMA using M-sequence code.

The setup of the 7 users SAC OCDMA network is introduced on chapter 3.3 and chapter 4.3.2. Few simulations are done and discussed on research of the characteristic of the communication network. All of the simulations are done in the environment of Optisystem. Simulations done are:

- One user network with different M-sequence coding implement
- The effects of the FBG cut off frequency bandwidth to the network
- Effect of FBG reflectivity to the SAC OCDMA system

4.6.1 One User network with different M-sequence coding implement

On chapter 4.4.1, the simulation on one user is the network is done on the 3 users SAC OCDMA network on Walsh Hadamard code. For the 7 users of SAC- OCDMA network, the Walsh Hadamard code comes with a different code length. At chapter 4.5.1, 7 users SAC-OCDMA show a very good result on having one user on the network and implement each code available. As for the 7 users SAC-OCDMA M-sequence coding method, same simulation is done on this method.

Table 4-18 BER gain on the specific M- sequence code

Users	M-Sequence	BER
user 1	1110100	0
user 2	0111010	0
user 3	0011101	0
user 4	1001110	1.101891e-319
user 5	0100111	0
user 6	1010011	0
user 7	1101001	0

Table 4-18, show the BER from the specific M-sequence code, that used by each users. The SMF in this network is 10km. Again it shows results of zero error transmission. As mention before the FBG cut off frequency bandwidth act as a very important role in the SAC-OCDMA network, this simulation is done on the bandwidth of0.3nm.

4.6.2 The effects of FBG cut off frequency bandwidth to the SAC-OCDMA network

As mention in chapter 4.4.3, the characteristic of the FBG act as an important role in the network, especially the FBG cut off frequency bandwidth. Same as the assumption given in chapter 4.4.3, every system have its ideal FBG cut off frequency bandwidth to get the best results. Table 4-19; shows the BER gain from simulation on changing the FBG cut off frequency bandwidth for encoder and decoder from 0.1nm to 0.6nm.

Table 4-19 Effects of FBG cut off frequency bandwidth on the BER

FBG cut off frequency bandwidth	BER						
	User 1	User 2	User 3	User 4	User 5	User 6	User 7
0.1nm	1.70E-03	5.92E-03	1.03E-02	1.03E-03	1.10E-02	1.80E-02	1.14E-02
0.2nm	9.07E-10	1.74E-05	5.79E-05	3.11E-09	4.47E-04	7.78E-04	4.08E-05
0.3nm	1.78E-09	8.06E-18	3.69E-05	4.02E-16	2.54E-08	1.80E-04	1.20E-07
0.4nm	1.52E-10	2.79E-20	2.39E-08	2.79E-22	3.26E-07	8.51E-05	1.08E-09
0.5nm	2.34E-05	1.89E-13	6.83E-06	5.58E-55	5.89E-08	3.51E-04	2.21E-06
0.6nm	1.99E-04	9.49E-07	1.17E-07	4.03E-23	4.12E-06	2.98E-03	4.50E-04

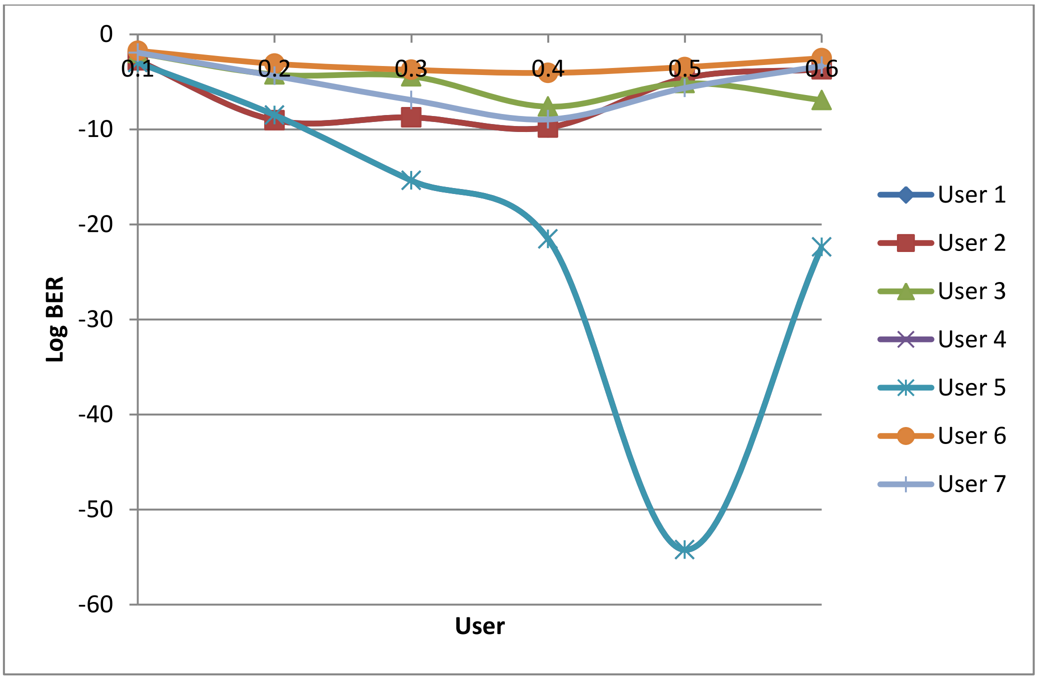


Figure 4-13 Effects of FBG cut off frequency bandwidth on the BER

4.6.3 The effects of FBG reflectivity to SAC-OCDMA with M-sequence code network

In the SAC-OCDMA network, the FBG reflectivity also a crucial aspect to for having an error free SAC-OCDMA network. With a higher reflectivity, the optical coding is able to have a higher contrast. This means the higher the reflectivity the lower the BER of the network. The simulation is done on changing the reflectivity of the FBGs on the SAC-OCDMA network and also done on different cutoff frequency bandwidth. Table 4-20 show the results gain from the simulation.

Table 4-20 the effects of the FBG reflectivity to the SAC-OCDMA with m-sequence code

FBG reflectivity	FBG cut off frequency bandwidth	BER						
		User 1	User 2	User 3	User 4	User 5	User 6	User 7
0.9998	0.1nm	1.697E-03	5.923E-03	1.032E-02	1.026E-03	1.101E-02	1.799E-02	1.137E-02
0.9998	0.2nm	9.071E-10	1.741E-05	5.787E-05	3.107E-09	4.471E-04	7.780E-04	4.077E-05
0.9998	0.3nm	1.777E-09	8.059E-18	3.693E-05	4.017E-16	2.543E-08	1.801E-04	1.204E-07
0.9998	0.4nm	1.524E-10	2.794E-20	2.395E-08	2.789E-22	3.261E-07	8.508E-05	1.083E-09
0.9998	0.5nm	2.343E-05	1.894E-13	6.835E-06	5.583E-55	5.891E-08	3.508E-04	2.212E-06
0.9998	0.6nm	1.993E-04	9.487E-07	1.174E-07	4.025E-23	4.122E-06	2.982E-03	4.503E-04
0.99	0.1nm	2.316E-04	6.279E-03	8.327E-03	1.652E-03	7.656E-03	2.644E-02	6.875E-03
0.99	0.2nm	3.017E-12	9.604E-05	5.742E-06	5.014E-09	4.350E-05	3.026E-03	2.104E-04
0.99	0.3nm	2.655E-08	3.354E-14	1.945E-09	4.506E-08	5.427E-09	5.194E-04	4.041E-05
0.99	0.4nm	9.220E-06	3.724E-13	6.572E-12	1.073E-10	3.969E-10	6.200E-06	1.983E-06
0.99	0.5nm	3.052E-08	1.218E-10	1.377E-07	1.469E-14	9.390E-10	7.105E-05	2.239E-05
0.99	0.6nm	5.072E-06	7.535E-14	1.265E-06	1.540E-21	6.548E-07	1.936E-03	1.941E-04

Table 4-20 shows the BER for every user in the seven users SAC-OCDMA with M sequence code network. From the table, the BER have taken from the simulation of FBG with a reflectivity of 0.9998 shows a better result than the FBG with a reflectivity of 0.99. But, when the FBG cut off frequency changes to a higher bandwidth, the BER difference between two kinds of FBG reflectivity shows a little difference. This is due to when the FBG cut off frequency bandwidth is broaden it means that the incident wave is completely reflected before reaching the end of the

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Throughout the simulation conducted in Optisystem, the basic idea about optical communication is understand, throughout the simulation of Intensity Modulation network, with the combination of different modulation format on (Return to Zero) RZ and (Non-Return to Zero) NRZ. Besides that, the construction a Spectral Amplitude Coding (SAC) – OCDMA or Frequency Encoded (FE) – OCDMA simulation increases the understanding of OCDMA system. Furthermore, the increase number of users to the SAC-OCDMA network by integrating different coding methods is studied and simulated.

A SAC-OCDMA uses broadband light source for intensity modulation, for the sake of the data from different users is able to undergo modulation and transmission over a SMF. For a normal one user to one user intensity modulation network, broadband light source is not suitable for the network as; the dispersion rate of the broadband light source is very high. That is why the results show a difference between normal IM and OCDMA network.

Moreover, SAC-OCDMA integrates Optical coding methods to increase the number of subscribers and the security levels of the network. In this report two kinds of optical coding methods is studied and simulated with the SAC-OCDMA network. Both optical coding methods are Walsh Hadamard code and M-sequence code. Both codes are characterized based on simulations of different scenarios, and both off the coding methods provide a very good results in the SAC-OCDMA system.

Furthermore, the Fiber Bragg Gratings act as a very important role on the SAC-OCDMA network. If the Fiber Bragg Gratings are not well fabricated, the whole SAC-OCDMA network will sure breakdown. That's why the basic knowledge and characteristics are studied. Based on the few characteristic of a FBG, for example the cutoff frequency bandwidth and the reflectivity; that will cause some changes to the network, simulations are done.

Finally, based on all the simulation is done. A full characterization of both 3 users and 7 users SAC-OCDMA system are discussed. From all the simulations done, the characteristics of SAC-OCDMA are well noticeable and understand.

5.2 Recommendations

With the simulation environment in Optisystem, the basic idea to construct the SAC-OCDMA network is achieved. All the parameters can be altered to be suit the reality environment, but it is best if we were given a chance to do hand on experiment. With the real experiment equipment on hand, the skill of troubleshoot the complexity of running on an optical experiment can be an extra advantage. The skill of splicing technique, utilizing a real Optical Spectrum Analyzer (OSA) and Bit Error Rate Tester (BERT), fabricating Fiber Bragg Grating filters that can be incorporate in to the SAC-OCDMA network. With these skills, it prepared us to face the real industry world of Optical Communication. The parameter given, are treated as a guideline and the SAC-OCDMA network are capable for fine tuning. Furthermore, the simulated results are able to compare with the real experiment, to prove that how well is the SAC-OCDMA actually performed.

5.3 Future Work

Ever since completing this thesis report, optical communication design is learned. The basic and yet crucial technique is to simulate an OCDMA network for multiple access. In future, if a chance, a proper time and opportunity is given, I am willing to explore deeper in different kinds of OCDMA methods. Besides that, for the investigation it will be on 2D coding methods for increasing the numbers of subscribers, data rate and transmission length; and the different kinds of OCDMA network that is more complex and required lots of research and experiment are both take in to account.

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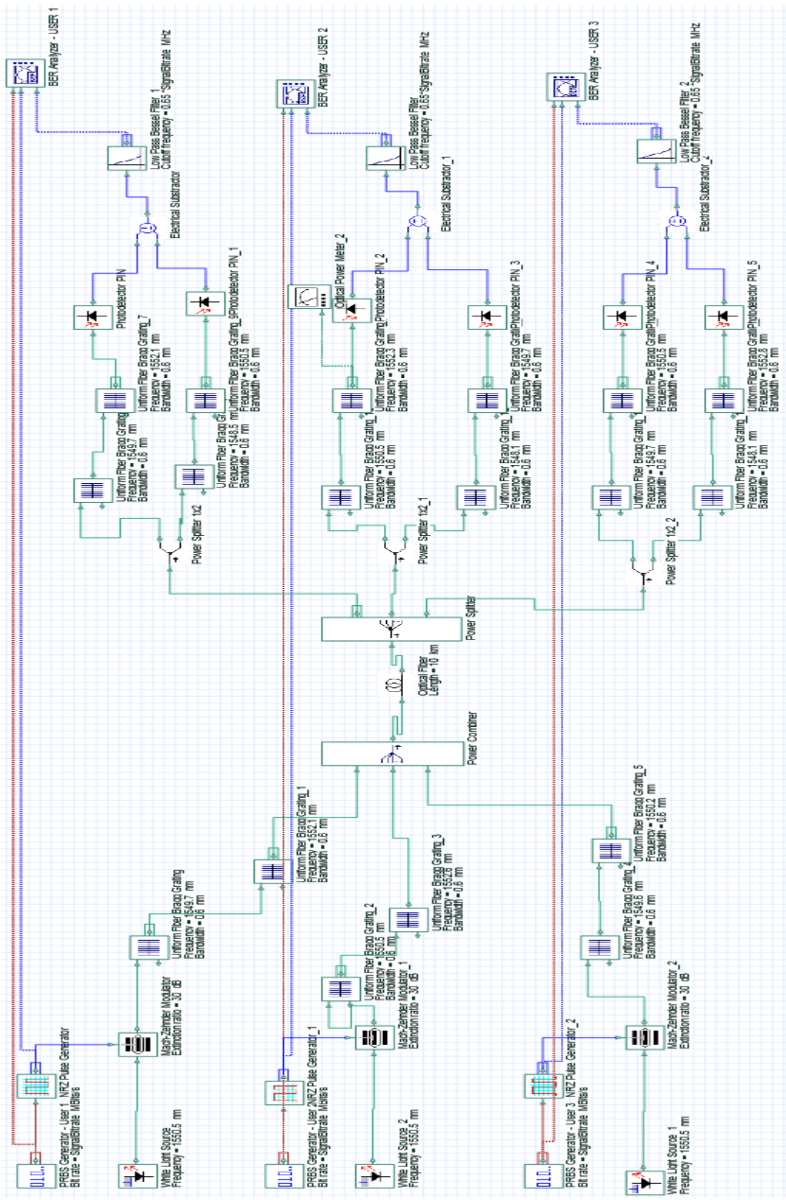
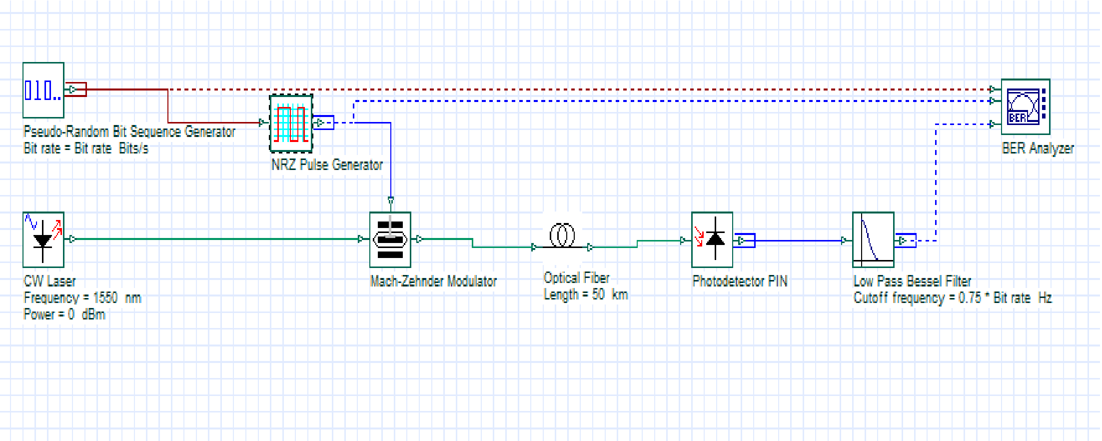
APPENDICES

APPENDIX A: Simulation Environments

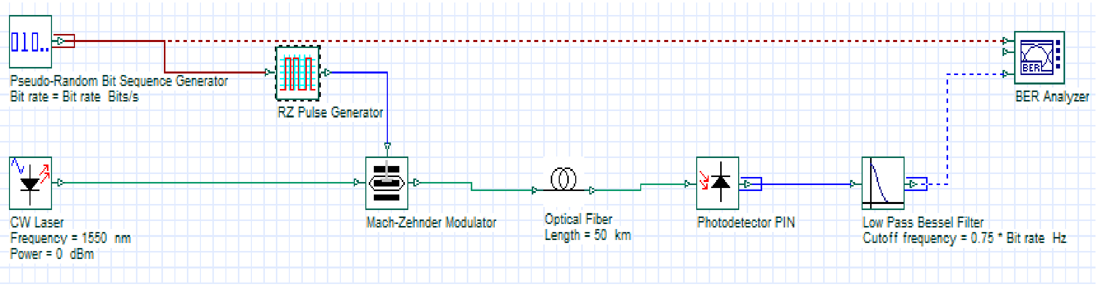
3-user SAC-OCDMA with Walsh Hadamard code



Intensity Modulation with NRZ modulation format



Intensity Modulation with RZ modulation format



7 User SAC OCDMA