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POWER CONTROL IN OPTICAL CDMA

Master's thesis for the degree of Master of Science in Technology submitted for inspection in Vaasa, 12th of May, 2011

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Tayyab Masood Khattak

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ABBREVIATIONS

HD	High Definition
PDA	Personal Digital Assistant
WDM	Wavelength Division Multiplexing
OTDM	Optical Time Division Multiplexing
O-OFDM	Optical Orthogonal Frequency Multiplexing
OCDM	Optical Code Division Multiplexing
MAI	Multiple Access Interference
QoS	Quality of Service
EMI	Electromagnetic Interference
OH	Hydrooxyl
SMF	Single Mode Fiber
MMF	Multimode Fiber
RI	Refractive Index
SBS	Stimulated Brillion Scattering
SRS	Stimulated Raman Scattering
FWM	Four Wave Mixing
OSNR	Optical Signal to Noise Ratio
XPM	Cross Phase Modulation
PMD	Polarization Mode Dispersion

LD	Laser Diodes
WGR	Waveguide Grating Routers
FBG	Fiber Bragg Gratings
DWDM	Dense Wavelegnth Division Multiplexing
CWDM	Coarse Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
ATM	Asynchronous Transfer Mode
SOA	Semiconductor Optical Amplifier
MEMS	Micro Electronic Mirror System
DSF	Dispersion Shifted Fiber
VCSEL	Vertical Cavity Surface Emitting Lasers
CO	Central Office
TFF	Thin Film FIlter
POF	Plastic Optical Fiber
DCO-OFDM	DC-biased optical OFDM
ACO-OFDM	Asymmetrically clipped OFDM
CO-OFDM	Coherent Optical OFDM
DDO-OFDM	Direct Detection Optical OFDM
TDM	Time Division Multiplexing
TL	Transform Limited
LD	Lase Diode

CPM	Colliding-Pulse-Mode-locking
MQW	Multiquantum Well
SC	Super Continuum
SLA	Semi Conductor Laser Amplifier
PLC	Planar lightwave Circuits
NOLM	Non Linear Optical Loop Mirror
PI	Polarization independence
VCO	Volatage controlled Oscillator
SP	Self pulsating
PLL	Phase Locked Loop
OPG	Optical Pulse Generator
EOM	Electro Optic Modulator
OC	Optical Codes
TS	Time Spreading
PD	Photo Detector
SINR	Signal to Interference and Noise Ratio
CIR	Carrier to Interference Ratio

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ABSTRACT

Optical CDMA (OCDMA) is the multiplexing technique over the fiber optics medium to increase the number of users and this is a step towards all optical Passive Optical Networks (PON). Optical OFDM, WDM and Optical TDM have also been studied in this thesis which are also candidates to all optical passive optical networks. One of the main features of Optical CDMA over other multiplexing techniques is that it has smooth capacity. The capacity of OCDMA is constrained by the interference level. Hence, when some users are offline or requesting less data rates, then the capacity will be increased in the network. Same feature could be obtained in other multiplexing techniques, but they will need much more complicated online organizers. However, in OCDMA it is critical to adjust the transmission power to the right value; otherwise, near-far problem may greatly reduce the network capacity and performance. In this thesis Power control concepts are analyzed in optical CDMA star networks. It is applied so that the QoS of the network get enhanced and all users after the power control have their desired signal to interference (SIR) value. Moreover, larger number of users can be accommodated in the network.

Centralized power control algorithm is considered for this thesis. In centralized algorithm noiseless case and noisy case have been studied. In this thesis several simulations have been performed which shows the QoS difference before and after power control. The simulation results are validated also by the theoretical computation.

KEYWORDS: Power Control, Optical CDMA, All Optical PON, Centralized Power Control Algorithm, Next Generation Networks.

1. INTRODUCTION

Telecommunication is one of the fields that is changing tremendously and has seen very big revolutions with in no span of time. With every single day passing more and more entertainment and higher bandwidth consuming products are coming into the market.

Currently we are in the era of digital communication to have fast access of knowledge, sharing of knowledge etc. and now the analog communication seems to be obsolete and because of digital age digital appliances are coming which are spreading like mushrooms. These digital appliances include laptops, digital cameras, High Definition (HD) TV's, Mobile phones, Personal Digital Assistant (PDA's) etc.

Digital communication revolution has formed the world as a global village and the medium for making it possible is Internet. Sharing of high quality data (Pictures, HD videos, simulation files, online gaming (3D), online conferencing, Video on Demand etc.) among several people across the world which is not a dream any more. But the medium which is used for global village has some limits.

As the new standards are developing for videos such as HD videos which takes much more space as compare to other formats of video. Similarly high quality 3D games are produced which also consume a lot of space on internet. So, as the application grows over the internet, the current speed provided for the user is not sufficient and in near future when almost every home will have one to four high definition displays, video phones, still digital cameras, video camera and dozens of internet appliances consuming a lot of bytes per second resulting in the need of huge bandwidth for each user for uplink as well as for downlink.

Research is going on at the moment that how to meet the future demand of internet and how to increase the bandwidth. Researchers are looking for all optical network for the solution of it.

For all optical network a new, next generation design will be needed because of the reason that there will be urge for new higher capacity systems both at the network and user end. Researchers are working on this next generation networks and they come up with the idea that if we enhance multiplexing techniques than we can accommodate large number of users with high data rate. Multiplexing technique which will be used for all optical network to have data rate of 1Terabits/second are as follows:

- Wavelength Division Multiplexing(WDM)
- Optical Time Division Multiplexing(OTDM)
- Optical Frequency Division Multiplexing(O-OFDM)
- Optical Code Division Multiplexing(OCDM)

Each of the multiplexing technique listed above have advantages and disadvantages. I choose OCDM technique for my thesis because of its maturity and number of advantages over other multiplexing techniques listed above.

Disadvantage of OCDM technique is that if we increase the number of users than the Multiple Access Interference (MAI) i.e. interference due to other users causes significant problem to performance of the network and bit error rate degrades significantly. In this thesis power control technique is used in OCDM to mitigate the MAI so that quality of service (QoS) can be improved.

Thesis is divided into six chapters. First chapter consist of introduction, second chapter consist of basic principle regarding optical fiber, third chapter consist of various multiplexing techniques which will be used in all optical networks, and fourth chapter consists of power control in optical CDMA. Fifth chapter is about algorithm analysis and simulation. Sixth chapter discusses conclusion.

2. OPTICAL FIBERS

This chapter explains the optical fibre communication system and also describe how the light propagates through optical fiber. This chapter presents the characteristics of optical fibre as well as various concept and techniques which may be useful in designing optical networks.

2.1. Advantages of optical Fiber Transmission

2.1.1. Distance

We can transmit light signal in optical fibre up to 100 kilometres without the need of any repeater whether it is active or passive repeater. This shows much better performance of an optical fiber medium when compared to copper and metallic based cables where we can transmit electrical signals to only few kilometres without the need of repeaters.

2.1.2. Bandwidth

In optical fiber communication infra red light is used. The bandwidth of installed fibre is very large. In addition to it there is no electromagnetic interference (EMI) in optical fiber.

Optical fiber has three layers and these layers are core, cladding and jacket. Due to these layers optical fibers do not have EMI. Core and cladding have same material but they have different refractive index.

Total internal reflection is a mechanism which is used to guide the light along the fiber.

2.1.3. Electrical Isolation

In electrical system there is always possibility of earth loop (ground loop) which means an unwanted electrical current. Two terminals in an electrical conductor are adjusted to the same potential while the earth or ground is connected to the opposite potential. Consequently when the current flows through the conductor electromagnetic field is induced. As a result EMI occurs in electrical conductor.

On the other hand fiber optics have three layers, light travels in core and cladding and both have different RI profile due to which there is no cross talk or EMI.

2.1.4. Material Cost

The material of fiber optic is made from glass. The glass raw material is sand, which is widely available natural resource. Hence, fiber optics costs significantly less than copper. However, the manufacturing process of fiber may cost more than copper.

2.1.5. Performance

Throughput in fibre optics is very high and losses are very low. Amplifiers and repeaters are used to maintain the power of transmitted signal over channel. Further more signal to noise ratio is very good which indicates that performance of optical transmission system is much better than electrical conductors.

2.2 Coupling of Light

Fiber optics core and cladding is made from same material but they have different refractive index. Due to difference in refractive index the boundary between core and cladding acts as a mirror and light is bound to travel within the core and will not leave the fiber unless it is not tightly bend and this is called as total internal reflection phenomenon. The acceptance cone has acceptance angle that is defined as half the angle of cone. Mathematically, it can be written as $NA = n * sin\theta$ where n is the refractive index of air. NA is numerical aperture which is the measurement of maximum acceptance angle (Dutton 1998).

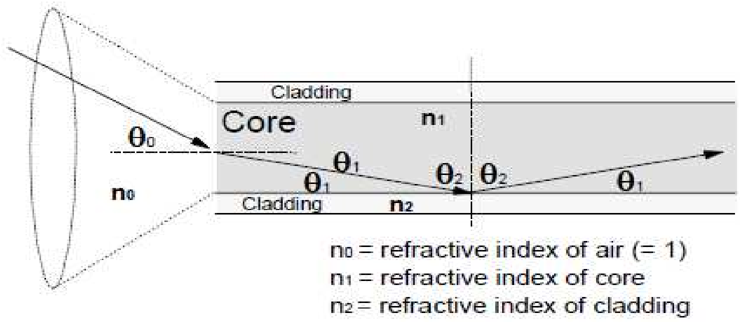


Figure 1.Numerical Aperture and acceptance cone (Dutton 1998).

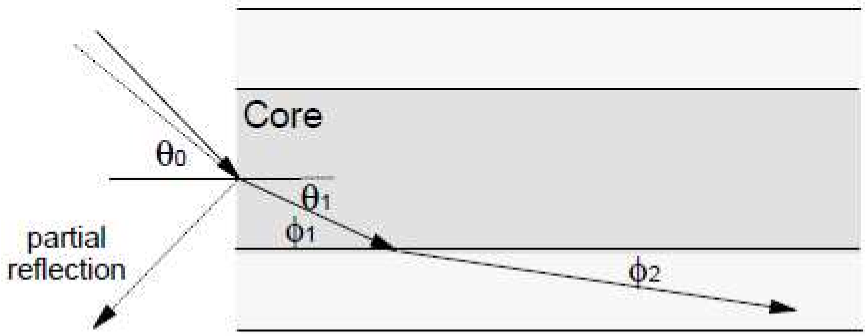


Figure 2. Numerical Aperture and acceptance cone (Dutton 1998).

We observe in Figure 1 that incident light to the core is within the acceptance cone. Therefore it stays within the core but Figure 2 shows that the incident light to the core is out of acceptance cone and the light gets out of the core.

2.3 Light Propagation Modes

There are two light propagation modes in fiber optics.

- Single mode fiber (SMF)
- Multimode fiber (MMF)

Multimode fiber can be classified as multimode step-index and multimode graded-index. Difference between the single mode fiber and multimode fiber is of the core.

Single mode fiber has very narrow core compared to the wavelength of light which is used that light travels only in mono mode or single mode. (Dutton 1998)

Table 1. Frequency Bands in optical communication

Window	Label	Range	Fiber-Type	Applications
1st	-	820-900nm	MMF	Metro,PON
2nd	S	1280-1350nm	SMF	Single λ
3rd	C	1528-1561nm	SMF	DWDM
4th	L	1561-1620nm	DSF	DWDM
5th	-	1350-1450nm	SMF	DWDM
6th	-	1450-1528nm	SMF	DWDM/MAN

2.4. Shortcomings of Optical Fiber Transmission

Glass absorption, impurities and transmission angles are some of the short comings of optical fiber transmission.

Main loss of signal (light) in fiber occurs when the fiber is bent. Light travels out from the cladding and it stays no more in the core.

Some losses are related to the wavelength. There are three windows of wavelength used in optical communication. First window operates from 800-900 nm and in this window 850 nm wavelength has a loss of 4-5 dB/km. Second window operates from 1250-1350 nm and in this window 1310 nm wavelength has a loss of 3dB/km. Third window operates from 1450-1600 nm and in this window the 1550 nm wavelength has a loss of 1 dB/km.

2.5. Characteristics of Optical Fiber

There are two types of characteristics of fiber optics namely linear and non-linear.

2.5.1 Linear characteristics

The main linear characteristics of optical fibers are: attenuation, chromatic dispersion and polarization mode dispersion.

- **Attenuation**

Optical fibre has very low loss and very wide transmission band. Loss is minimum in three windows around 850, 1300 and 1550 nm wavelength. Loss of single mode fibre in the band of 1.5 µm is a few tenths of a dB/km (Frigyes 2006).

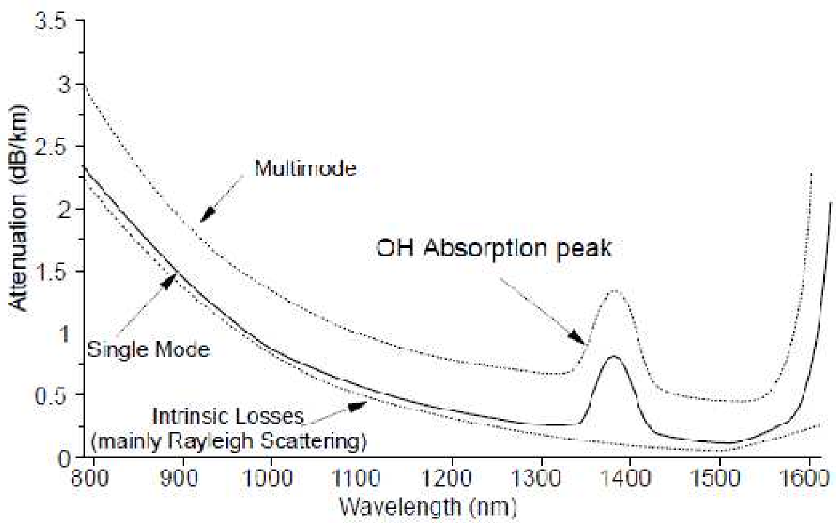


Figure 3. Illustrates attenuation for wavelength from 800-1600 nm (Dutton 1998).

Figure 3 demonstrates about the typical fibre infrared absorption spectrum. We have less attenuation in single mode fibre as compare to the multimode fibre due to less quantity of doping usage. The higher the amount of doping will be used the greater will be the attenuation. We have minimal attenuation from 1260-1620 nm which is 0.5 dB while we have highest attenuation around 800-900 nm because of the presence of Hydrooxyl (OH) atomic bond. The bond is resonant at 1385 nm. The peak at 1385 nm is called as absorption peak.

We have three different windows of transmission for fibre optics, which are known as short wavelength band, medium wavelength band, and long wavelength band.

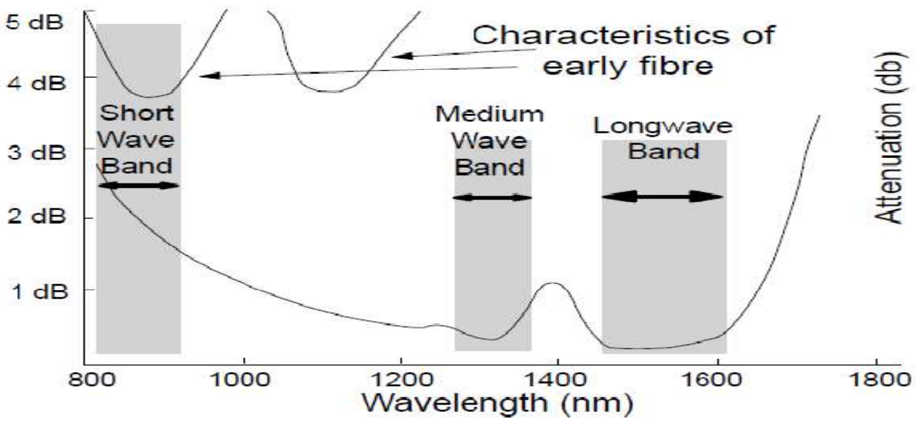


Figure 4. Transmission Window: Three different bands, short wavelength band (first window), medium wavelength band (second window), long wavelength band (third window) (Dutton 1998).

Attenuation is maximum in short wavelength Band and minimum in long wavelength band.

- **Chromatic Dispersion**

Chromatic dispersion plays a vital role in degrading the performance of an optical system. Chromatic dispersion results from a variation in propagation delay (velocity difference) with wavelength and is affected by fiber materials and dimensions resulting in a spreading of pulse. Chromatic dispersion is the sum of material dispersion and waveguide dispersion which can be written as:

$$D_T = D_M + D_{WG} \qquad (1)$$

Where D_T = total chromatic dispersion, D_M=Material dispersion, D_{WG} = Waveguide Dispersion (Binh & Cheung 2005).

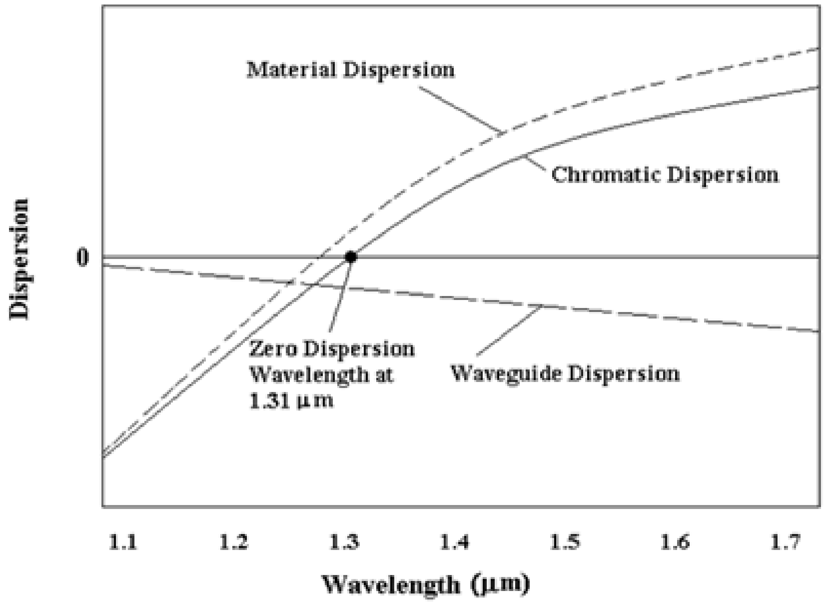


Figure 5. Chromatic Dispersion. (Dispersion in a standard single-mode fiber as a function of wavelength)

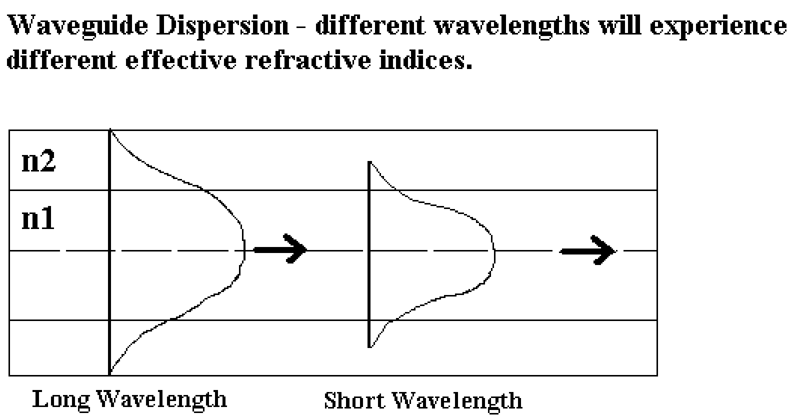


Figure 6. Waveguide Dispersion, n1 refractive index of core, n2 refractive index of cladding.

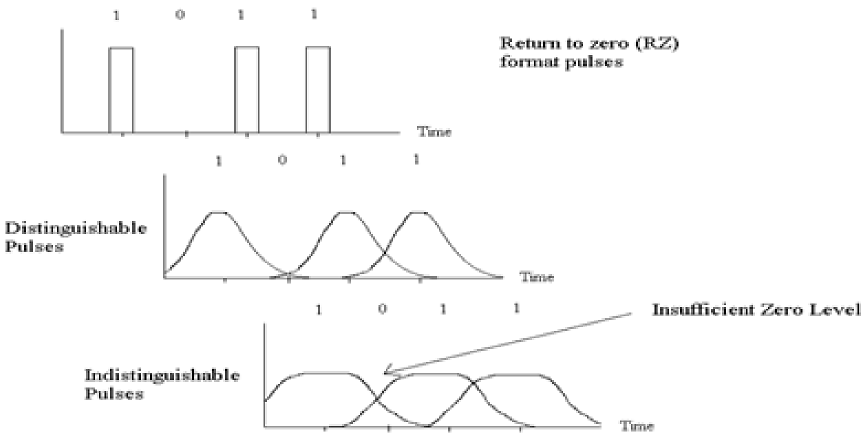


Figure 7. Pulse broadening due to chromatic dispersion.

Due to chromatic dispersion the pulse get spread out or broadened resulting in a loss of data which is clearly reflected from Figure 5. The more chromatic dispersion the greater will be the loss of data.

- **Polarization Mode Dispersion**

Light is considered to have combination of two orthogonal polarizations, vertical and horizontal which is determined by the direction of electric field. In SMF we can send two signals without interference as their polarization is orthogonal but polarization states are not maintained in the SMF because the fiber with circular symmetry cores cannot differentiate between the two polarizations causing the light to shift easily from the two polarization modes. There is slight difference in RI for each polarization and when the light pulse travels along the core the polarizations get circular or elliptical resulting in dispersion (spreading of pulse) but this dispersion is less than 0.5ps/nm/km and is called as polarization mode dispersion (Dutton 1998).

2.5.2 Non-Linear Characteristics

Non-linear effects are those which increase exponentially as the level of optical power is increased. Elastic scattering consist of four-wave mixing while inelastic scattering consist of stimulated brillouin scattering and stimulated raman scattering. Some other non linear characteristics are carrier induced phase modulation (Harris 2008; Dutton 1998).

- **Four wave Mixing:**

This non-linear characteristic is defined as intermodulation products resulting from the interaction of different signals at different frequencies. For example signal at frequency $\omega_1$is mixed with a signal at frequency ω_2 resulting in two new signals at frequency $2\omega_1$-ω_2 and the other at $2\omega_2$-ω_1. This effect increases exponentially as the power increases.

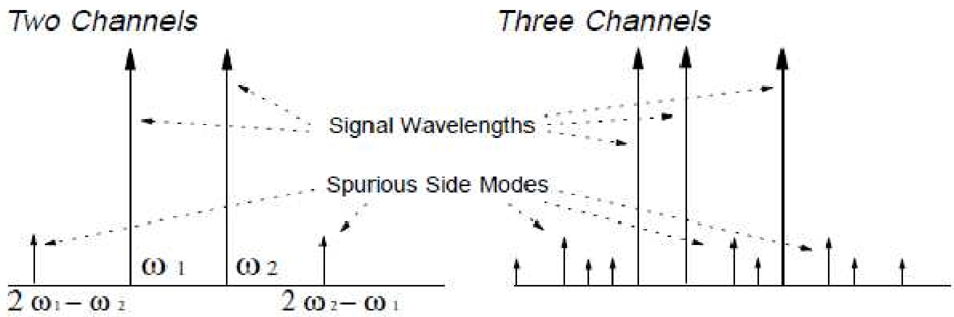


Figure 8. Four Wave Mixing in two channels and three channels system. (Dutton 1998)

- **Stimulated Brillion Scattering and Stimulated Raman Scattering:**

Stimulated Brillion scattering (SBS) is caused by the optical signal. Optical signal has very strong electromagnetic field and this creates mechanical vibrations in fiber optic causing slight changes in refractive index of fiber optic which produces diffraction grating and the light is reflected backward from diffraction grating towards the transmitter causing shift in frequency due to Doppler effect. Signal linewidth has to be less than .1nm for SBS to develop (Dutton 1998).

Stimulated Raman scattering (SRS) is caused by the similar mechanism like SBS but instead of mechanical vibration there is molecular vibration. Scattered light can appear in both directions i.e. forward and reverse. When multiple channels are present, power is transferred from shorter wavelength to higher wavelength and this causes additive noise at the longer wavelengths and subtractive noise at the shorter wavelength (Dutton 1998).

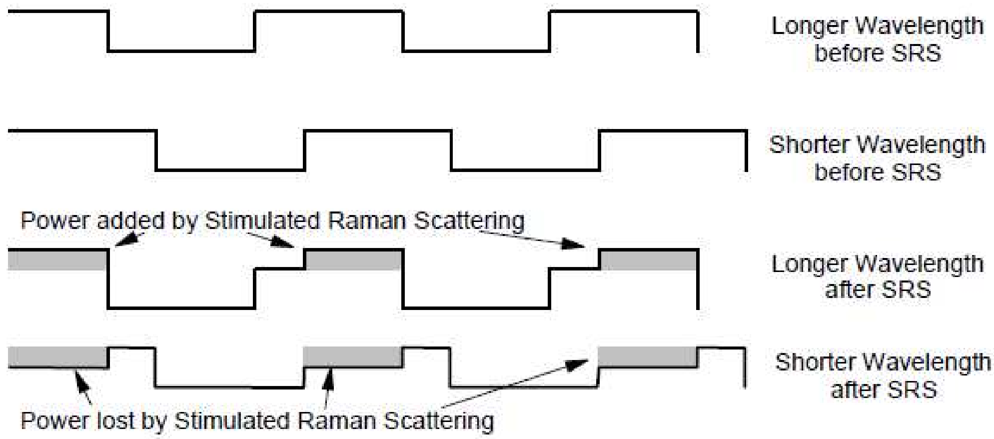


Figure 9. Stimulated Raman Scattering (Dutton 1998).

- **Carrier Induced Phase Modulation:**

The presence of light in fiber optics causes small change in the RI of the material. This is called as Kerr effect. At low power level this effect is linear but at high power level this effect is highly non-linear. At low power level the results of Kerr effect are called as cross phase modulation and self phase modulation.

- **Self phase modulation (SPM):**

The RI of the fiber is different for the different parts of the light pulse (signal). So there is small difference between the RI at the leading edge, middle and trailing edge. This changes the phase of the light waves that make up pulse. Change in phase results the change in frequency so frequency spectrum of the pulse is broadened. This is a serious problem in systems where the phase of the signal is significant e.g. phase shift keyed or coherent systems (Dutton 1998).

- **Cross phase modulation (XPM):**

When multiple signals are present in the fiber at different wavelengths, Kerr effect caused by one signal results in phase modulation of other signals, this is called as cross phase modulation. Without self phase modulation, cross phase modulation cannot happen. Cross phase modulation results in the broadening of the pulse and distortion of pulse (Dutton 1998).

2.6 Intensity Modulation and optical amplification

For optical transport system to be cost effective and efficient, it is necessary to overcome transmission distance limitations due to linear and non-linear optical fiber impairments such as polarization mode dispersion (PMD), self-phase modulation (SPM), cross phase modulation (XPM), four wave mixing (FWM) etc. There is decrease in optical signal to noise ratio (OSNR) due to increase in optical bandwidth which results in the need of increase of signal power but increase in signal power strengthens the fiber optic non-linear effects. To overcome these problems for fiber optic transport system key transmission technologies have been developed. To overcome the effects of dispersion, intensity modulation formats have been developed to achieve higher transmission over the channel. In order to overcome physical limitations of the fiber various technical solutions has been given such as optical signal amplifiers (Haris 2008).

3. MULTIPLEXING TECHNIQUES IN OPTICAL NETWORKS

Multiplexing is a process of combining multiple analog message signals or digital data streams over a shared medium so that bandwidth could be efficiently utilized. In optical networks many multiplexing techniques have been developed so that the cost/kbps can be decreased with increasing data rate and efficient utilization of bandwidth. Multiplexing techniques which are used in optical networks are as follows.

3.1. Wavelength Division Multiplexing (WDM)

WDM is a multiplexing technique for using a fiber to carry many separate and independent optical channels.

3.1.1 WDM Basics

Optical signals are generated by laser diodes (LD) at a series of monochromatic wavelengths $\lambda 1$, $\lambda 2$, $\lambda 3$,…, λN and sent through small fibers to a WDM. WDM combines these input signals into a multiplexed output signal. This multiplexed signal is than launched into optical fiber transmission medium for transporting the signal. At the destination WDM demultiplexer separates the multiplexed signal into different monochromatic wavelengths (Dutton 1998).

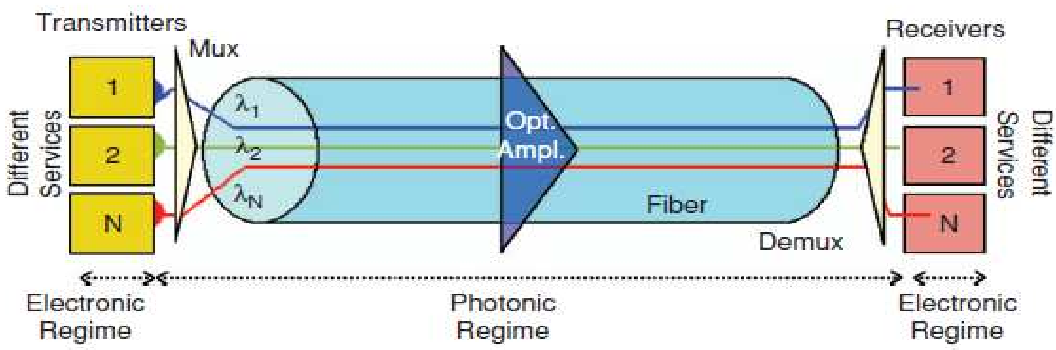


Figure 10. Wavelength Division Multiplexing Block Diagram. (Kartalopoulos 2002)

Multiplexing is done through passive optical components like couplers which do not require any power. Couplers can be used to combine or divide the light. For demultiplexing (dividing the light) couplers are called as splitters. Couplers are used for small number of channels and they have high loss. Some other devices like filters, littrow Gratings and Waveguide grating routers (WGR) are also used for both multiplexing and demultiplexing and can accommodate lot of channels with very less loss (Dutton 1998).

Demultiplexing is basically done through three approaches in WDM.

- Demultiplex the multiplexed light into many mixed output ports than filter each port separately. This approach is applied though 3 db splitter with Fabry –Perot Filters.
- Demultiplex one channel from the multiplexed signal at a time. This is accomplished through circulators with Fiber Bragg Gratings (FBGs).
- Demultiplex the whole signal in one approach. This is done through In-Fiber Bragg gratings with couplers.

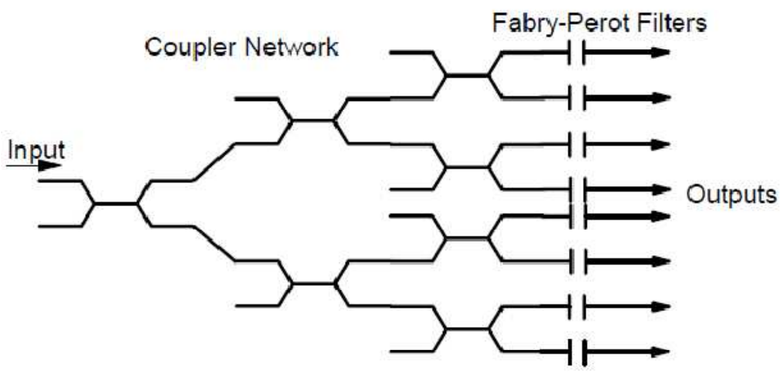


Figure 11. 3-dB splitter array with fabry-Perot filter (Dutton 1998.)

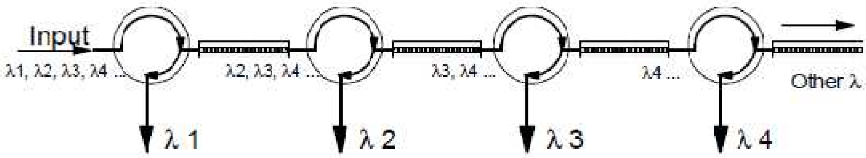


Figure 12. Circulators with FBGs (Dutton 1998.)

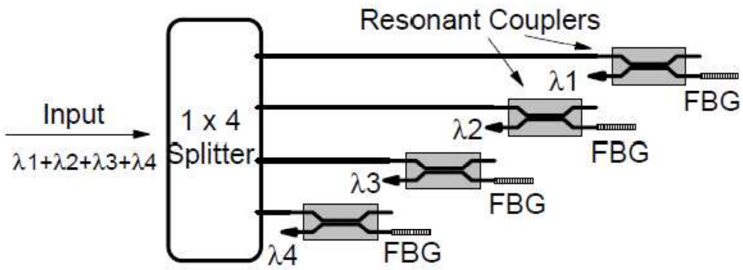


Figure 13. In-Fiber Bragg Gratings with coupler (Dutton 1998)

3.1.2. WDM Application types

WDM comes in two different forms each has its own complexity, specification and cost structure. Dense wavelength division multiplexing (DWDM) and coarse wavelength division multiplexing (CWDM) (Kartalopoulos 2002).

Dense Wavelength Division Multiplexing (DWDM)

DWDM is used for long haul networks which uses hundred's of wavelength in single fiber .In DWDM two approaches are used to send data. One technique uses spectral spacing of 0.4nm or 0.8nm at a higher bit rate of 2.5 or 10Gbits/sec. Other approach uses more spectral spacing with slower bit rate. Both techniques are efficient having peak spectral efficiency around 0.4bit/Hz and capability to transmit data rate of 1.6Tbits/s which can be only used in C band of EDFA amplifier (Roka 2003).

With the advent of new modern photonic devices it is now possible to send up to 1000 wavelengths in the same fiber. Most of these new photonic devices are operating in low loss spectral band of 1.55µm. In DWDM each wavelength carries huge information, for example one wavelength carry internet another SONET or Asynchronous Transfer Mode (ATM). Pure DWDM systems are supposed to be all optical. This can be achieved thorough all-optical devices (Kartalopoulos 2002).

DWDM system components

- **Filters:** Accomplished through Fabry Perot, Bragg Gratings, Mach-Zhender, dielectric, thin-film and acoustic optic filters. Each filter is based on different principles of physics: Fabry-Perot based on interferometry, the Bragg on diffraction and prisms on refractions. Most significant filter is Brag Gratings because they are cost effective, easily manufactured, passive devices and easily integrated with other components. One kind of Fiber Bragg gratings known as chirped Bragg gratings have the ability to compensate for chromatic dispersion.

- **Multiplexers and Demultiplexers:** Wavelength Mux/Demux is accomplished through passive components such as diffraction gratings, thin- films and super prisms.

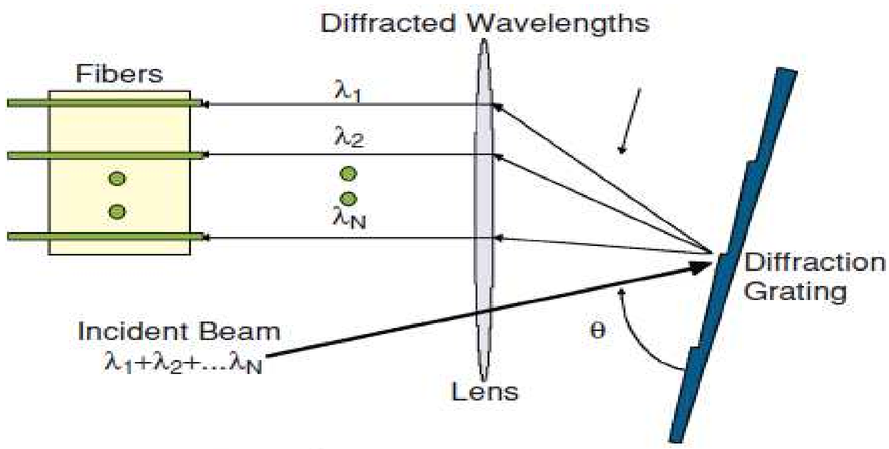


Figure 14. Fibre-Bragg gratings based optical demultiplexer. (Kartalopoulos 2002)

- **Optical Switching:** Optical switching is implemented thorough many different technologies. These are micro electronic mirror system (MEMS), tiny bubbles, liquid crystals, electro-holo-graphic methods, solid state technology called lithium-niobate. Specifications of different optical switches are as follows.

Table 2. Comparative table of Optical Switching Technologies (Kartalopoulos 2002)

			Switching Technologies			
Switch Type	**Switching Speed (appr.)**	**Insertion Loss**	**PDL**	**Crosstalk**	λ Flatness	Typical Size
Fiber-Bragg Grating	~100µs	~2dB	0.5dB/cm	-40dB	NA	Upto 32*32
Acousto Optic	~5 µs	~8dB	~8dB	-25dB	+/-10Db	Upto 1*1024
MEMS	~ 10ms	~0.5dB	~0.5dB	-50dB	~1Db	Upto 1000*1000
Electro-refractive holograms	~ ns	~0.1dB	~40dB	-40dB	~0dB	Upto 16*16 perhaps 64*64
LC	~ 5ms	~0.1dB	~40dB	-40dB	~2Db	Upto 16*16
Bubble jet	~ 10ms	~0.2dB	~50dB	-50dB	NA	Upto 32*32

- **Optical add-drop multiplexing:** This technique makes the bandwidth efficient by adding or dropping one or more channels. It can be accomplished by combination of optical demultiplexers and multiplexers, optical switches, filters, and other components. Add-drop multiplexing can transform any type of network mesh, ring or star into a physical single fiber ring network shown in figure 15.

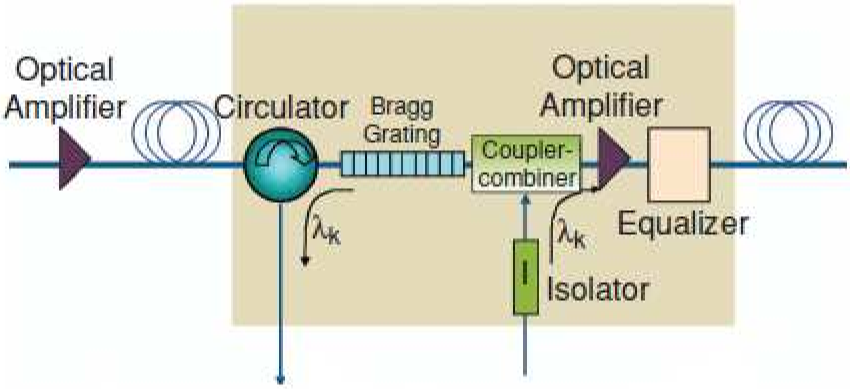


Figure 15. Optical Add/Drop Multiplexing based on Fiber-Bragg Grating (Kartalopoulos 2002)

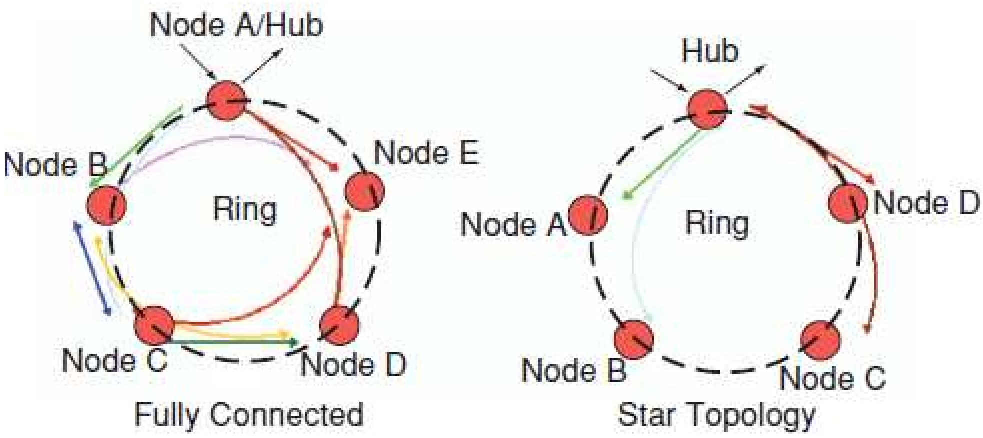


Figure 16. Fully connected and star topology converted into a physical DWDM ring topology. (Kartalopoulos 2002)

- **Optical Amplification :** Optical amplification is accomplished with specialized doped fibers (EDFA's), semiconductor optical amplifier (SOA), and Raman amplification. Each amplifier has its own characteristics and is usable in different spectrum.(Kartalopoulos 2002)

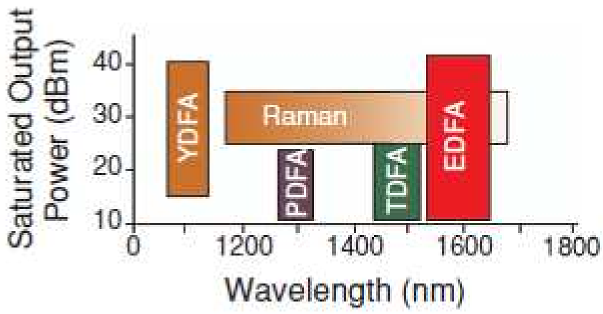


Figure 17. Different kind of amplifiers covers wide spectral range (Kartalopoulos 2002)

Coarse Wavelength Division Multiplexing (CWDM)

CWDM is used for short haul communication i.e. metropolitan area networks. It follows the ITU-T standard G.694.2. In this standard wavelengths have a spacing of 20 nm. Only 18 wavelengths can be put into single fiber ranging from 1270 nm to 1610nm. Zero water peak fiber is used for CDWDM which does not have water peak as conventional fiber G.652 (does not uses E band) have so that the loss of 0.5 db/km (minimum) to 2 db/km (maximum) can be overcome. CWDM can be used over single mode and multimode fiber. (Redfern Broadband networks 2002, IEEE spectrum 2002)

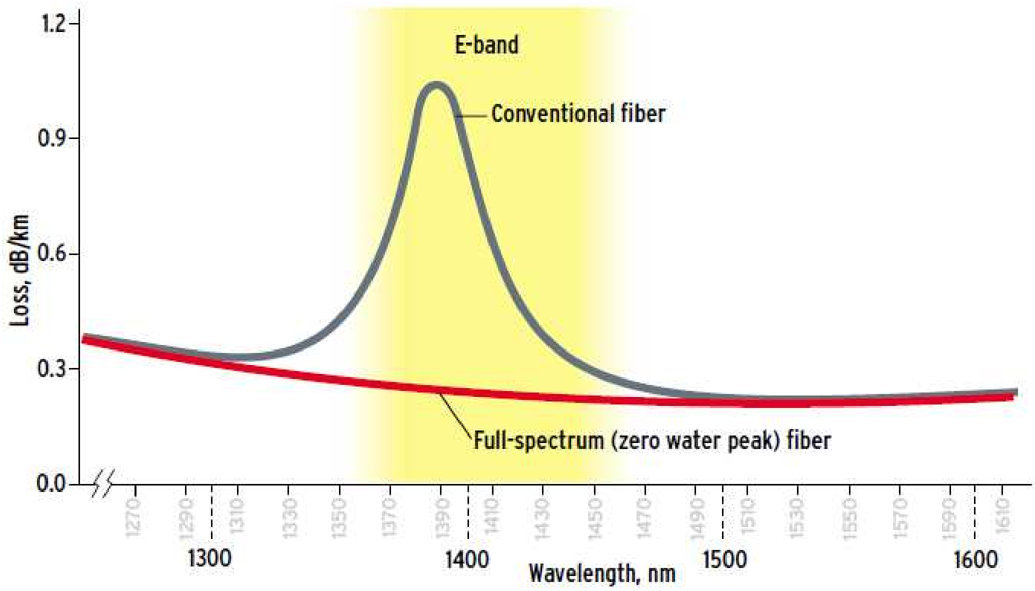


Figure 18. Coarse Wavelength Division Multiplexing (CWDM) systems which operate on 18 wavelengths spaced 20 nm apart between 1270 nm and 1610 nm. (IEEE spectrum 2002)

CWDM System Components

- **Fiber:** Full spectrum (zero fiber peak) fiber is used in CWDM in which water peak at 1383 nm have been eliminated. Dispersion shifted Fiber (DSF) which cannot be used with DWDM in the C-band due to 4 wave mixing can be used with CWDM.
- **Lasers:** Two lasers can work as transmitter at a time for CWDM applications which are direct modulated CWDM lasers and Vertical Cavity Surface Emitting Lasers (VCSELs). Direct modulated lasers are low cost with bit rate up to 2.5 Gbits/s over 80 km. 4*10Gbits/s O-Band CWDM lasers that can be used for VSR LANs and central Office (CO) interconnect. These lasers are cheap as compare to DWDM because lasers linewidth can be allowed to drift as in CWDM the channel spacing are 20nm apart.
- **Filters:** CWDM filters implemented through using thin film filter (TFF) technology. CWDM filters are less expensive to make than DWDM filters due to fewer number of layers in filter design. Overall CWDM are 40 percent less expensive than DWDM systems if same number of channels are used (IEEE spectrum 2002, Redfern Broadband Networks 2002).

Comparison between WDM, CWDM and DWDM

Table 3. Comparison between WDM, CWDM and DWDM

	Coarse WDM	WDM	DWDM
Channels Spacing	Large , from 1.6nm to 25nm	1310nm, 1550nm	Small, 200GHZ and less
Number of bands used	O,E,S,C and L	O and C	C and L
Cost per channel	Low	Low	High
Number of channels delivered	17-18 at most	2	Hundreds of channel
Best Application	Short-haul, Metro	PON	Long-haul

3.2 Optical Orthogonal Frequency Division Multiplexing (O-OFDM)

Orthogonal frequency division multiplexing is a technique which is used in many broadband wired and wireless communication systems. It is an effective solution for inter symbol interference caused by dispersive channel. Despite of its many advantages, recently many researchers have described different solution that how OFDM can be used in optical communication system including single mode fiber (SMF), multimode fiber (MMF), plastic optical fiber (POF) and optical wireless systems

Before understanding optical OFDM it is necessary to know the fundamental difference between the typical optical systems and conventional OFDM systems which is summarized in Table4.

Table 4. Comparison of Typical OFDM systems and Typical Optical Systems

Typical OFDM System	Bipolar	Information carried on electrical field	Local Oscillator at receiver	Coherent Reception
Typical Optical System	Unipolar	Information carried on optical intensity	No Local Oscillator (laser) at receiver	Direct Detection

For an OFDM system to operate successfully the system must be linear between the transmitter IFFT input and the receiver FFT output. Different optical OFDM solutions have been proposed for different application. These optical OFDM solutions can be divided into two groups. First group comprises techniques for systems where many optical modes are received and are represented by intensity of the optical signal. The second group includes technique for single mode fiber and are represented by optical field (Armstrong 2009).

3.2.1. Optical OFDM using intensity modulation

In optical wireless system and other system where many modes are received, the OFDM signal must be represented as optical intensity. This means that modulating signal must be both real and positive and this makes a difference with the electrical OFDM system where the modulating signal is bipolar and complex as shown in Table 4. To make an OFDM signal unipolar two forms have been given through which OFDM signal can become unipolar.

- DC-biased optical OFDM(DCO-OFDM)
- Asymmetrically clipped OFDM(ACO-OFDM)

DC-Biased optical OFDM (DCO-OFDM): In this technique, DC bias is added to the original OFDM signal to make the signal unipolar but due to large peak–to- average power ratio of OFDM some negative peaks will be clipped resulting in terms of noise to the signal and due to DC-biasing the average optical power will become high (Armstrong 2009, Armstrong & Lowery 2006).

Asymmetrically clipped OFDM (ACO-OFDM): In this technique, there is no DC-biasing and all the negative values are clipped to zero thus reducing the mean optical power. But this clipping adds noise, if only the odd frequency OFDM subcarriers are non-zero at the input of IFFT, all of the clipping noise will fall on the even sub carriers and data carrying odd frequency components are not impaired (Armstrong 2009, Armstrong & Lowery 2006).

3.2.2 Optical OFDM using Linear field Modulation

There are two techniques through which optical OFDM can be implemented in the single mode fiber. Coherent optical OFDM (CO-OFDM) and direct detection optical OFDM (DD-OFDM). Both techniques have some advantages and disadvantages.

Coherent Optical OFDM (CO-OFDM): Coherent Optical OFDM is simply a conventional OFDM which is applied on optical carrier instead of radio frequency (RF) carrier. The function of OFDM transmitter is to map the data bits into each OFDM signal, than complexed value time domain waveform is generated by inverse fast fourier transform (IFFT) afterwards guard interval is given and then it is modulated onto an RF carrier than this OFDM spectrum is linearly shifted from the RF domain to the optical domain through the optical up converter. This up conversion takes place through Mach-Zehnder Modulator (linear modulator). This makes a linear relationship between an optical field of transmitted signal and the OFDM baseband signal (Shieh & Athaudage 2006; Lowery & Armstrong 2006; Armstrong 2009).

At the receiver the optical OFDM signal is demultiplexed with the locally generated carrier by laser and it is converted to electrical form through photodiode (Shieh & Athaudage 2006) and this process is called as coherent detection with local oscillator (Jasen, Morita, Schenk, Borne, Tanaka 2008).

Than this demultiplexed OFDM signal goes to OFDM receiver where same signal processing is applied which is similar to conventional OFDM receiver.

Direct Detection optical OFDM (DDO-OFDM): Direct detection optical OFDM is divided into two categories with respect to signal generation. Linearly mapped LM-DDO-OFDM and non-linearly mapped NLM-DDO-OFDM.

Linearly mapped DDO-OFDM: In this technique we get the linear copy of RF OFDM spectrum with an addition of an optical carrier at the output of O-OFDM transmitter. (Shieh, Djordjevic 2010). DDO-OFDM requires more transmitted optical power as some power is required for the transmitted carrier (Armstrong 2009). This type of DDO-OFDM is described as

$$S(t) = e^{j2\pi f0t} + \alpha e^{j2\pi(f0+\Delta f)t}.sB(t) \qquad (2)$$

Where s (t) is the optical OFDM signal, $f0$ is the main optical carrier frequency, Δf is the guard band between the main optical carrier and the OFDM band and α is the scaling coefficient that describes the OFDM band strength related to main carrier and $s_B(t)$ is the baseband OFDM signal.

The receiver consists of a single photodiode to convert the optical field back to electrical domain. (Jansen, Morita, Schenk, Borne, Tanaka 2008). When the signal is received at the photodetector some nonlinearities also add up to the transmitted signal which has to be removed. There are four approaches which are used to remove nonlinearities (Shieh & Djordjevic 2010).

- Offset SSB-OFDM
- Baseband optical SSB-OFDM
- Subcarrier interleaving
- Iterated distortion reduction

These four approaches have some advantages and disadvantages (Shieh & Djordjevic 2010).

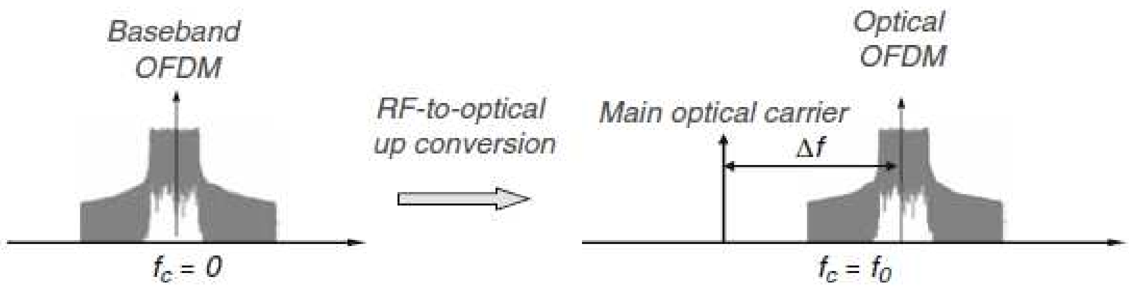


Figure 19. This figure illustrates the linear mapping of base band OFDM to optical OFDM (Shieh & Djordjevic 2010)

Non-linearly mapped DDO-OFDM: The NLM-DDO-OFDM is generated by direct modulation of a laser. NLM-DDO-OFDM has multiple OFDM bands with significant spectral distortion which means that there is no linear mapping between the baseband OFDM and the optical OFDM. When there will be any type of dispersion in the link like chromatic, polarization, modal than this dispersion will become a cause for the nonlinearity of the NLM-DDO-OFDM systems, therefore, there will be no more linear mapping between baseband OFDM and the optical OFDM and the linear baseband OFDM will not be recovered hence, NLM-DDO-OFDM is fit for only short-haul applications (Shieh & Djordjevic 2010).

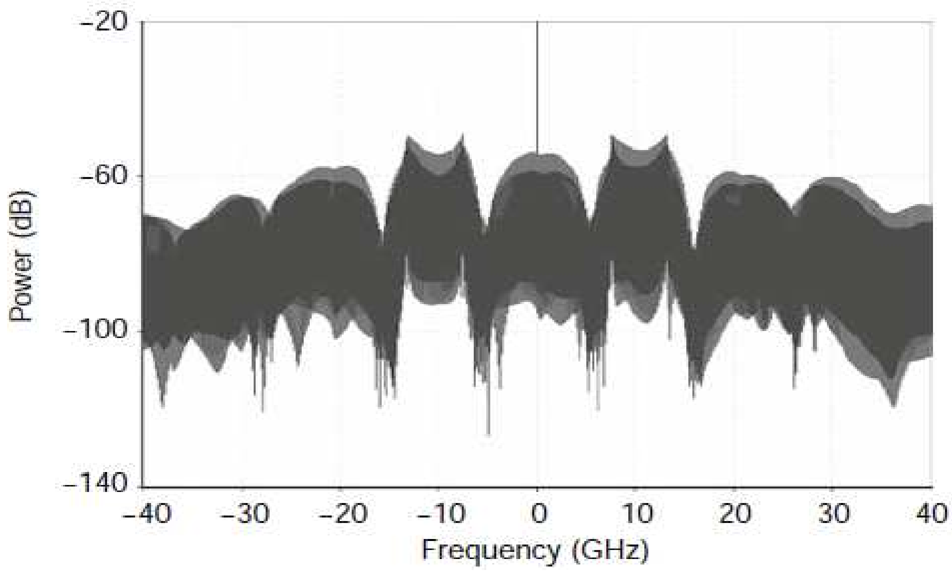


Figure 20. NLM-DDO-OFDM spectra with multiple OFDM bands (Shieh & Djordjevic 2010)

3.3 Optical Time Division Multiplexing (OTDM)

In present Time Division Multiplexing (TDM) systems lower multiple sub-channel signals are multiplexed into a high speed signal in the time domain using high speed electrical circuits (electrical TDM). The speed of the electrical TDM is mainly limited by the speed of electronics. To overcome speed problem of electrical TDM, optical TDM was proposed (Kawanishi 2002).

Key building blocks for high bit rate optical time division multiplexing (OTDM) systems are optical short pulse generation, time division multiplexing/demultiplexing and synchronization or timing extraction (Kawanishi 2002).

3.3.1. Ultra short Optical pulse generation

To achieve high speed OTDM transmission systems, it is essential for optical sources to generate picoseconds transform-limited (TL) chirp less pulses at repetition rate ranging from 10 to 40 GHz. Optical short pulses can be generated by several methods which are as follows:

Gain switching of distributed-feedback laser diodes (DFB-LDs): Gain switching of DFB-LDs can generate 5-7pico second (ps) nearly transform limited (TL) optical short pulses by applying a down-chirp compensation technique at arbitrary repetition frequencies between 1-20 GHz. (Saruwatari 2000)

Gating of continuous wave (CW) light with an electro absorption (EA) modulator: This is based on nonlinear transmittance of InGaAsP-EA modulators with respect to applied voltage. Nearly transform limited (TL) 20-ps soliton pulses have been obtained at 10Gb/s but this technique cannot be applied to high speed TDM systems (100 Gb/s) because of its large pulsewidth(>10ps).(Saruwatari 2000)

Mode-Locking of laser diodes (LDs): Ultra-high-speed purely transform limited (TL) pulses with less than 1ps at 40 and 350 GHz repetitive frequency are generated by colliding-pulse-mode-locking(CPM). In order to mode lock at moderate speed, a long cavity LD integrated with a passive waveguide and a Bragg reflector was developed. This was used for 8 GB/s 4000-km soliton-transmission experiments.

There are various kinds of mode-locking LDs with improved operation characteristics. Active mode-locked monolithic multiquantum well (MQW) LDs integrated with MQW-EA modulators can generate subpicosecond pulses with tunable pulse width. Micromechanically-tunable LDs or active mode-locking of external cavity LDs generates repetition-rate tunable lasers. Active mode locked LDs are used to generate very high speed or femtosecond optical pulse generation (Saruwatari 2000).

Harmonic mode locking of EDF laser: It can generate a purely TL-pulse train in the 10 GHz region without any pulse compression or chirp compression. 3.0-3.5 ps TL pulses have been generated by this laser upto 20 GHz (Saruwatari 2000).

SuperContinuum (SC) in Fiber: it is a spectral superbroadening phenomenon 200nm which is caused when optical pulse transits a low-dispersion silica fiber. Less than 1 ps TL pulses have been generated with dispersion shifted fiber (Saruwatari 2000; kawanishi 2002).

Semiconductor Optical Amplifier (SOA) based ring laser: This method consist of ring cavity a DFB laser and an EDFA. Ring cavity consists of SOA, a tunable filter for wavelength selection an isolator to ensure unidirectional oscillation and a fiber coupler to insert/extract the external gain modulating and the mode-locked signal. Gain modulation is obtained by injecting an external low –repetition-rate signal into the cavity. The principle of operation relies on fast gain saturation of the SOA by the external optical signal resulting in a formation of mode locked pulse, 7 ps pulses were generated by this method (Saruwatari 2000).

Table 5. Comparison of various optical pulse generation techniques (Saruwatari 2000)

Method	Repetition Frequency[limitation]	Δτ(ps)	Δτ. Δv	Comment
Gain switching of DFB-LD	Arbitrary (RC constant)	~20 (6) (0.8)	>TL (~TL) (~TL)	Down-chirping (with chirp compensation:CC) (with CC + adiabatic soliton compression)
CW+EA-modulator	Arbitrary (modulator)	~15 (2.5)	~TL (~TL)	Relatively large pulse width (with adiabatic soliton compression)
Mode-locking of LD	fixed	~10 (<1)	>TL (~TL)	Conventional type (CPM type or EA modelocker)
Harmonic mode locking of EDF laser	Tunable (mode locker)	~3	TL	Wavelength –tunable, ~20nm
SC generation in DSF	Tunable (pump frequency)	<1	~TL	Wavelength-tunable >200nm
SOA based ring laser	Tunable(rational harmonic mode locking)	7	~TL	

3.3.2. Optical time division multiplexing/demultiplexing

In optical time division multiplexing (OTDM), a high bit-rate data stream is constructed directly by time-multiplexing several lower bit-rate optical streams. Similarly at the receiver end of the system, the very high bit-rate optical signal is demultiplexed to several lower bit-rate optical signals before detection and conversion to the electrical domain. (Tucker, Eisenstein, Korotky 1988)

All-Optical Multiplexer (MUX): all optical modulation combined with an ultra high speed optical clock can be used to realise an all-optical transmitter at >100Gbits/s. (Kawanishi, Okamoto, Ishii, Kamatani, Takara, Uchiyama 1997). Optical multiplexer can be implemented through different approaches which are as follows.

OTDM MUX using four wave mixing: In this approach 100GHz, 1.547μm optical pulse source is modulated by two 6.3 Gbits/s, 1.537 μm optical modulation signals at different time slots to generate a 1.557 μm TDM signal at the FWM output.

Two MUX are used which consist of WDM coupler and optical nonlinear medium (in this case 3 km FWM fiber). A 100 GHz optical pulse train is multiplexed with 6.3 GHz, 1.537 μm optical signal in the first multiplexer through WDM coupler and then passed to FWM fiber. There are three optical signals at the output of first MUX, 1.547 μm optical pulse train, 1.537 μm optical modulation signal and at 1.557 μm new optical signal due to FWM.

1.537 μm optical signal is removed through WDM coupler at the input of MUX2 and the 100GHz optical pulse and FWM signal were amplified and injected into MUX2 along with second 6.3Gbits/s optical signal having a delay of 10ps with respect to first modulating signal. At the output of MUX2, same signals appeared but the second 6.3Gbit/s optical signal appeared with 10 ps delay to the first 6.3Gbits/s optical signal at (Time Slot)TS2 (Kawanishi & Kamatani 1994).

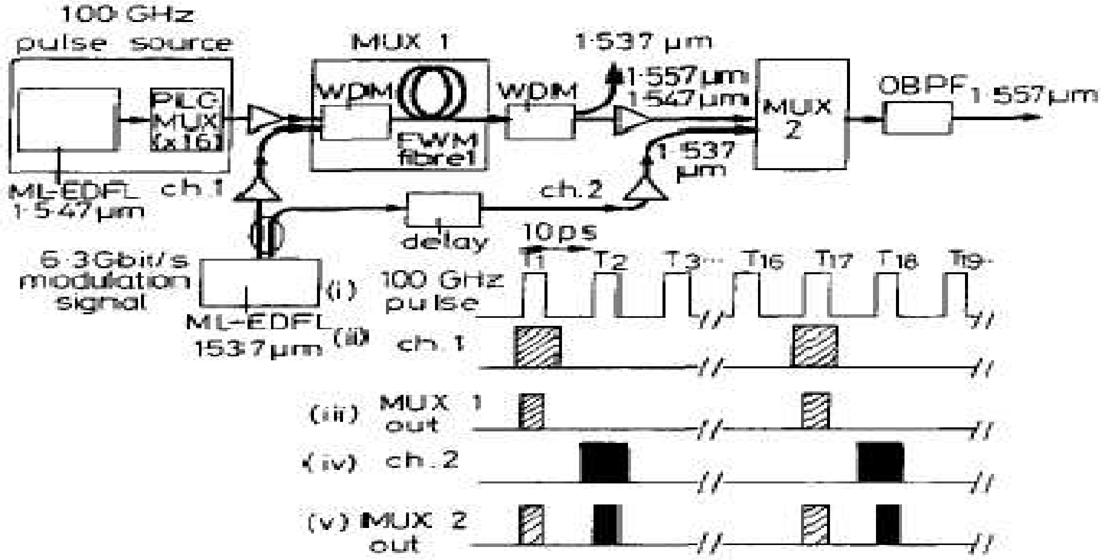


Figure 21. Schematic configuration and optical time division multiplexing using four wave mixing. (Kawanishi & Kamatani 1994)

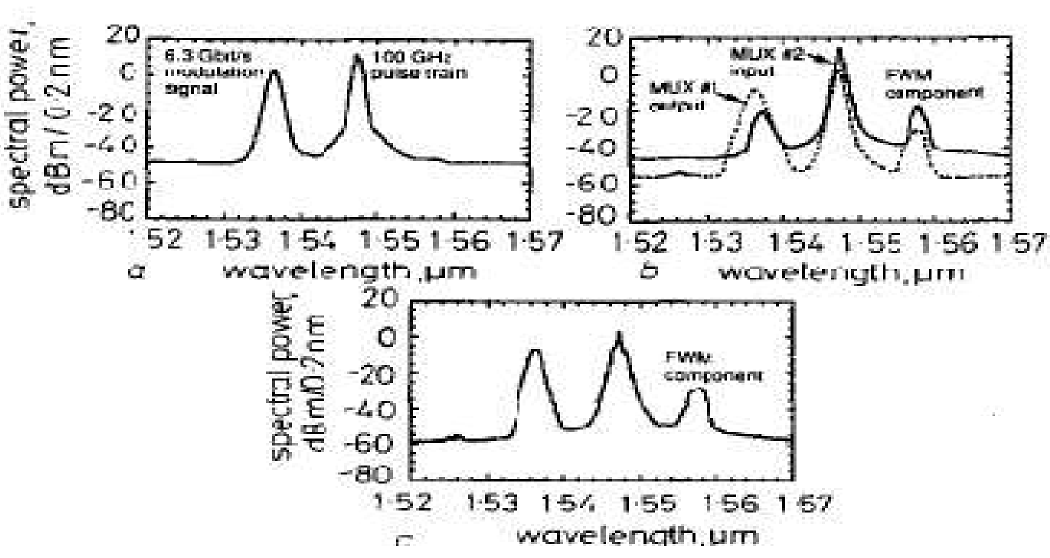


Figure 22. Optical spectra at (a). Entrance of FWM fiber, (b). Input of MUX2 superimposed on output of MUX1, (c) Output of MUX2. (Kawanishi & Kamatani 1994)

OTDM MUX using FWM in Semiconductor Laser Amplifier (SLA): This approach is similar to which is discussed by Kawanishi and Kamatani. The major difference is that instead of Fiber optic as a non-linear medium, SLA is being used for FWM. (Kawanishi et al 1997)

Planar LightWave Circuit (PLC) MUX: PLC based MUX consist of 2*2 couplers and optical delay line waveguides. Input signal is divided into two branches which are fed into coupler, where it is time division multiplexed and by using delay lines OTDM signal is generated. Another kind of PLC MUX consists of delay lines and couple of multimode waveguides as branching or combining devices.

All Optical Demultiplexer (DEMUX): Demultiplexer is the most critical element of OTDM system. It comprises of clock recovery and a fast optical switch. Following requirements should be met before implementing OTDM DEMUX to transmission system.

- Stable bit error free operation
- Low control power capable of LD or EDF laser pumping
- Polarization independence(PI)
- Multiple output operation (full DEMUX)

There are various techniques for all-optical DEMUX like optical Kerr switch, four wave mixing using a fiber or an SOA, cross-phase modulation (XPM) bases switching, and fiber loop based switches called non-linear optical loop mirror (NOLM), semiconductor laser amplifier in a loop mirror configuration (SLALOM), Terahertz optical asymmetric demultiplexer (TOAD). Important techniques are discussed as follows:

Optical Kerr Switch: Polarization of optical signals is switched by 90 degrees by means of optical control pulses The polarization direction is rotated by 90 degrees when the phase difference between the x and y components of the signal is changed from 0 to π. Phase difference is changed by the optical intensity in the Kerr medium which changes the refractive index of the material. Refractive index will be different for x and y components of material (Shimada, Nakagawa, Saruwatari, Matsumoto 1993). This refractive index difference between x and y components of material causes phase difference between the x and y components of the signal. (Dutton 1998)

Only the signal polarization superimposed by intense control pulses can be switched by 90 degrees because polarizations beam splitter discriminate orthogonal polarization light. In this way, the desired TDM channel signal is demultiplexed from an ultrafast optical signal stream. (Shimada et al 1993)

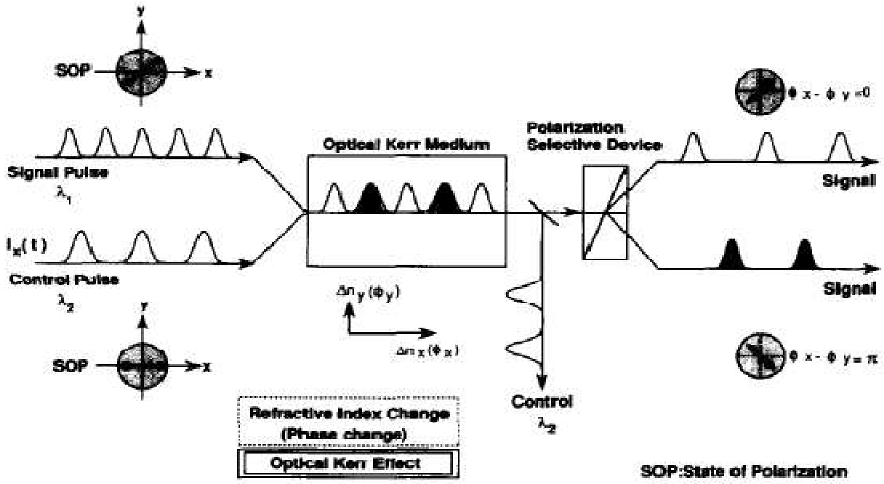


Figure 23. Principal of all optical Kerr switch DEMUX (Shimada et al 1993)

FWM switch: FWM switch uses the FWM process that occurs in silica fiber or SOAs. From 16 GB/s to 500 GB/s demultiplexer testing based on FWM have been conducted. First error-free-all-optical DEMUX driven by LD sources together with EDFAs uses 14 km dispersion shifted fibers as FWM device for demultiplexing. FWM based multiple output 100 GB/s demultiplexing was achieved using linearly chirped square-pump pulse. With this technique 4 channel, 10-Gb/s signals were demultiplexed from a 100-Gb/s TDM signal. By using 300-m-long DSF PANDA fiber as non linear media, 10-Gb/s signal pulses have been successfully demultiplexed from 500-Gb/s (Saruwatari 2000).

Demultiplexing using four wave mixing in SOA was done at 20-Gb/s, 100-Gb/s and 200-Gb/s (Saruwatari 2000).

XPM Switch: It is an optical switch based on induced frequency shifts**.** There are several approaches which uses XPM switch for demodulation process. One approach that uses polarization mirror configuration to do XPM-induced frequency shift, after chirping polarization-independent four multiple channel output DEMUX is used which is based on wavelength selective device for demultiplexing.

Another approach of XPM switch is based on down-chirping as the XPM-induced frequency shift exhibits up-chirping. The down-chirped clock pulse is locally compensated in the time domain, resulting in increase in frequency components, according to temporal position of the signal pulses. Simultaneous TDM to WDM signal conversion can be achieved in one operation. 100-6.3 Gb/s demultiplexing has been successfully demonstrated (Saruwatari 2000).

Non-linear Optical Loop Mirror (NOLM) Switch: This DEMUX configuration uses induced phase in NOLM based on sagnac interferometer (Saruwatari 2000). Control signal and data signal are sent into the loop. Data signal is divided into two equal beams through coupler such that both beams travel in opposite direction. Control signal is coupled into the loop through polarization beam splitter and propagate along the clockwise direction (Zhang 1997).Since it utilizes the interference between two counter propagating lights transiting the same fiber loop, only those signal pulse coinciding with the control pulse is reflected (Saruwatari 2000). The NOLM uses cross-phase modulation between control and signal pulses to switch the signal pulse from one output arm to the other (Zhang 1997).

3.3.3. Optical Timing Extraction

Timing extraction which extracts the timed clock from the received optical signals is an important issue in designing ultra-high speed OTDMA systems. Requirements for optical timing extraction include ultra-fast operation, low-phase noise, high sensitivity and Polarization independence (PI). In particular ultra low phase noise yielding <1-ps rms jitter is required for 100 Gb/s. Many approaches have been studied to increase the operating speed and are classified into three categories.

- Optical tank circuit using a Febry-Perot resonator or Brillouin gain in fiber

- Injection-locking of LDs or EDF lasers
- Phase Lock Loop circuits using electrical voltage controlled oscillators (VCOs)

Optical Tank circuit: The optical signal created by the return to zero (RZ) intensity modulation consists of optical carrier frequency f_c and line components f_c +/- f_0 . All optical timing extraction can be obtained by extracting the carrier spectral components f_c and line spectral components f_c +/- f_0 . By using a Febry-Perot optical tank circuit, an optical clock has been extracted from 2-Gb/s pseudo random optical data (Saruwatari 2000).

The injection locking: injection locking utilizes self pulsating (SP) LDs such as multielectrode LDs or optical inverters which alternate between TE and TM modes, whose output repetition frequency is locked to that of an injected pulse train. Using these techniques a wavelength and PI clock recovery module based on SP DFB-LD was developed and tested in 10 Gb/s , 105-km transmission experiment but its performance including timing rms jitter and relative phase error is not good enough for speed over 50 Gb/s.

All-optical signal generator, which used all optical clock recovery scheme based on mode-locked Er fiber laser and a NOLM regenerator has been demonstrated. It restored the pulse timing and removed noise and intensity fluctuations (Saruwatari 2000).

Phase locked loop (PLL) circuits: PLL has no phase error and complete retiming is possible. Optical PLL circuits have been developed based on cross-correlation technique. First optical phase correlator was based on TW-SOA. The SOA gain is instantaneously modulated by the intense optical clock, the cross-correlated (Δf) signal which contains the phase difference between the optical signal and optical clock is compared with the reference signal in a conventional low-speed electrical phase comparator, and the output of which is returned to the VCO to close the PLL.

With this PLL configuration, a 6.3-GHz retimed signal has been recovered using a residual 6.3- GHz component in a 100-Gb/s optical TDM signal. In order to extract retimed clock from completely multiplexed TDM signal using SOA phase detector, we have to apply PLC multiplier which generates an N-times multiplied optical clock frequency to the above PLL (Saruwatari 2000).

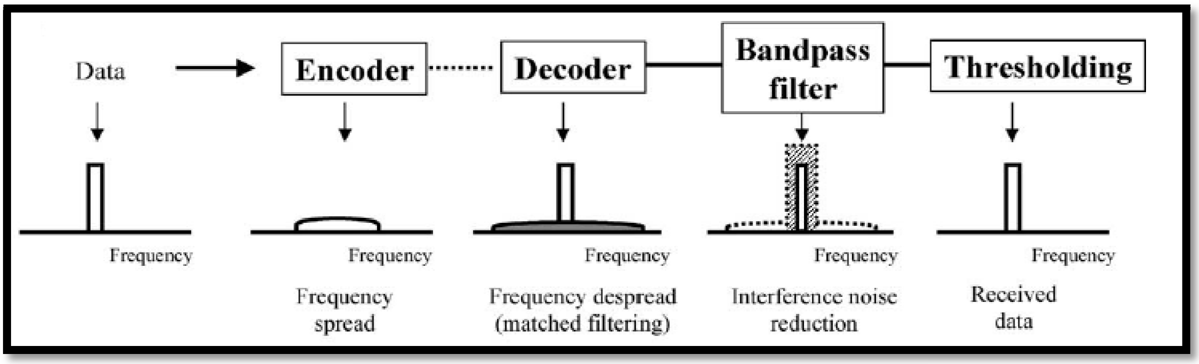
3.4. Optical Code Division Multiplexing (OCDM)

Optical Code Division Multiplexing is another technique applied to make best use of the available bandwidth. OCDM is a multiplexing technique in which each communication channel is distinguished by a code rather wavelength or time slot. Transmitter performs the encoding operation which encodes each channel with special codes and the receiver decodes the corresponding code of the transmitter through correlation of local code (Fouli & Maier 2007).

3.4.1. Principle

In an optical CDMA system, an optical short pulse is spread over bit duration T by the encoding process (Kitayama, Sotobayashi, Wada 1999). Each bit is divided up into n time periods, called chips, by sending a short optical pulse during some chip intervals but not others, a codeword can be generated. The total number of illuminated chips in the address codeword is called the weight w. Each user has unique codeword. The encoder of each transmitter represents each 1 bit by sending the codeword; however, a binary 0 bit is not encoded and is represented using an all zero sequence. The encoded signal is sent to the star coupler where it is broadcasted to all nodes (Stok, Sargent 2000).

In decoding process the time despreading of the encoded signal is performed by reconstructing the original short pulse only if the codes between the transmitter and the receiver match. Unmatched codes remain despreaded over T after decoding (Kitayama, et.al 1999).



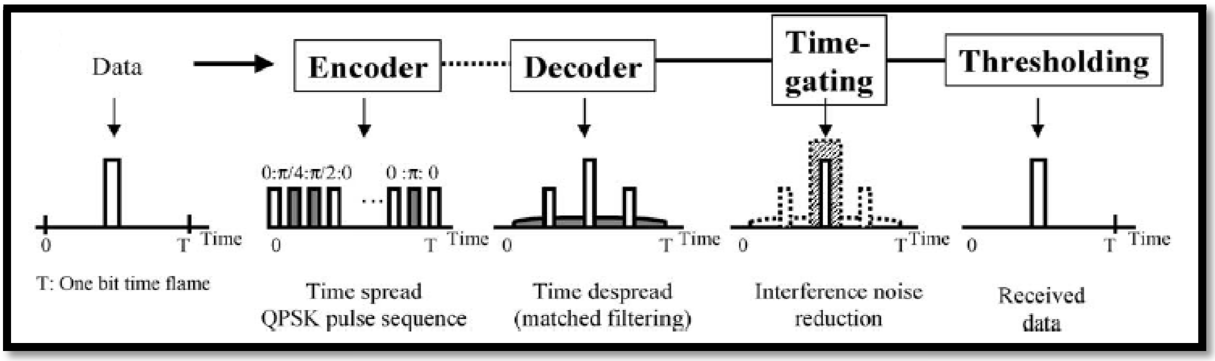


Figure 24. Principle of code-division multiplexing system based on frequency spread/despread and time spread/despread respectively (Sotobayashi, Chujo, Kitayama 2004)

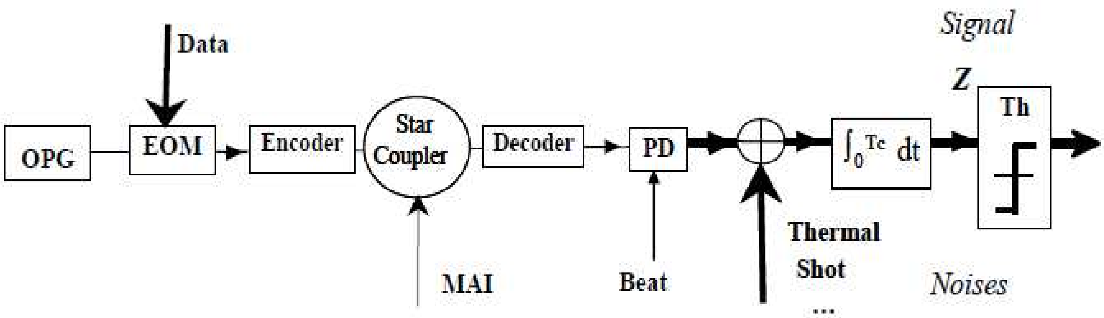


Figure 25. System model of OCDMA network (Wang & Kitayama 2004)

3.4.2. Transmitter

In the transmitter, the optical pulse stream generated from the optical pulse generator (OPG) is modulated by the electro optic modulator (EOM) with the payload data and each bit '1' is encoded into pseudorandom pulse train by the encoder and is forwarded to the transmission medium through coupler. (Wang 2004)

Encoding: OCDMA schemes are classified by two criteria. The first is by working principle OCDMA is divided into coherent and incoherent. In incoherent OCDMA, the coding is performed on optical power basis, therefore, the optical codes (OCs) are handled in unipolar (0, 1) manner. In coherent OCDMA, the coding is performed on amplitude, so OCs are handled in the bipolar (-1, +1) manner. Another is by coding dimensions, the coding can be 1-dimensional (1-D) to be performed either in time domain or frequency domain, or be 2- dimensional (2-D) to be performed in frequency and time domains simultaneously. (Wang 2004)

In time domain encoding the bit is split into smaller time components called chips. Time domain encoding is done in two ways i.e. positive or bipolar. Positive encoding manipulates the power of the optical signal while bipolar coding is applied on the phase of the optical signal as shown in Figure 28.

In wavelength domain coding, transmitted bits consist of unique subset of wavelengths forming the code.

In 2D-coding combination of both wavelength selection and time spreading occurs. A data bit is encoded as consecutive chips of different wavelengths, the unique wavelength constituting the code (Fouli & Maier 2007). Various classifications of encoding techniques are indicated in Table 6.

Table 6. Various classifications of encoding techniques (Fouli & Maier 2007)

Coding Domain	Encoding Device	Chip Modulation	Source	Medium
Time	Fiber delay lines	Power, phase	Coherent, Incoherent	In-fiber, PLC
	Mach-Zhender Interferometer	Phase	Coherent	External
	External Phase Modulator	Phase	Coherent	External
	Phase Modulator and local oscillator	Phase	Coherent	External
	PLC w/delay and phase modulator	Phase	Coherent	PLC
	Segmented fiber grating	Phase	Coherent	In-fiber
	Uniform Bragg grating	Phase	Coherent	In-fiber
	Liquid Crystal Modulator	Phase, power	Coherent	External
	Broadband source	Power	Incoherent	In-fiber
Wavelength	AWG and phase-plates	Phase	Coherent	PLC
	Superstructured Bragg grating	Phase	Coherent	In-fiber
	AWG and holograms	Phase	Coherent	External
2D	Fiber Bragg grating	Power	Incoherent	In-fiber
	Integrated Laser source	Phase, Power	Incoherent	PLC

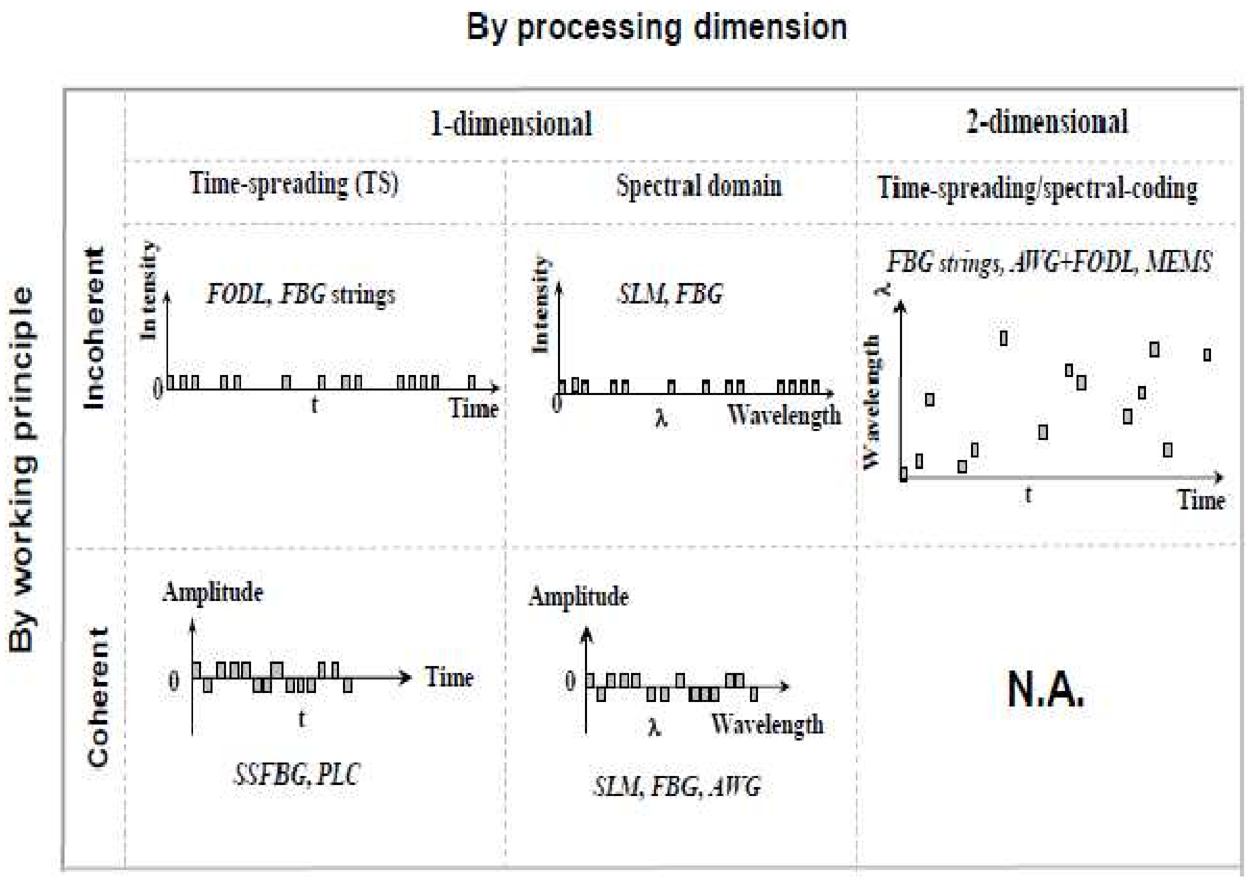


Figure 26. Classifications of different OCDMA schemes (Wang 2004)

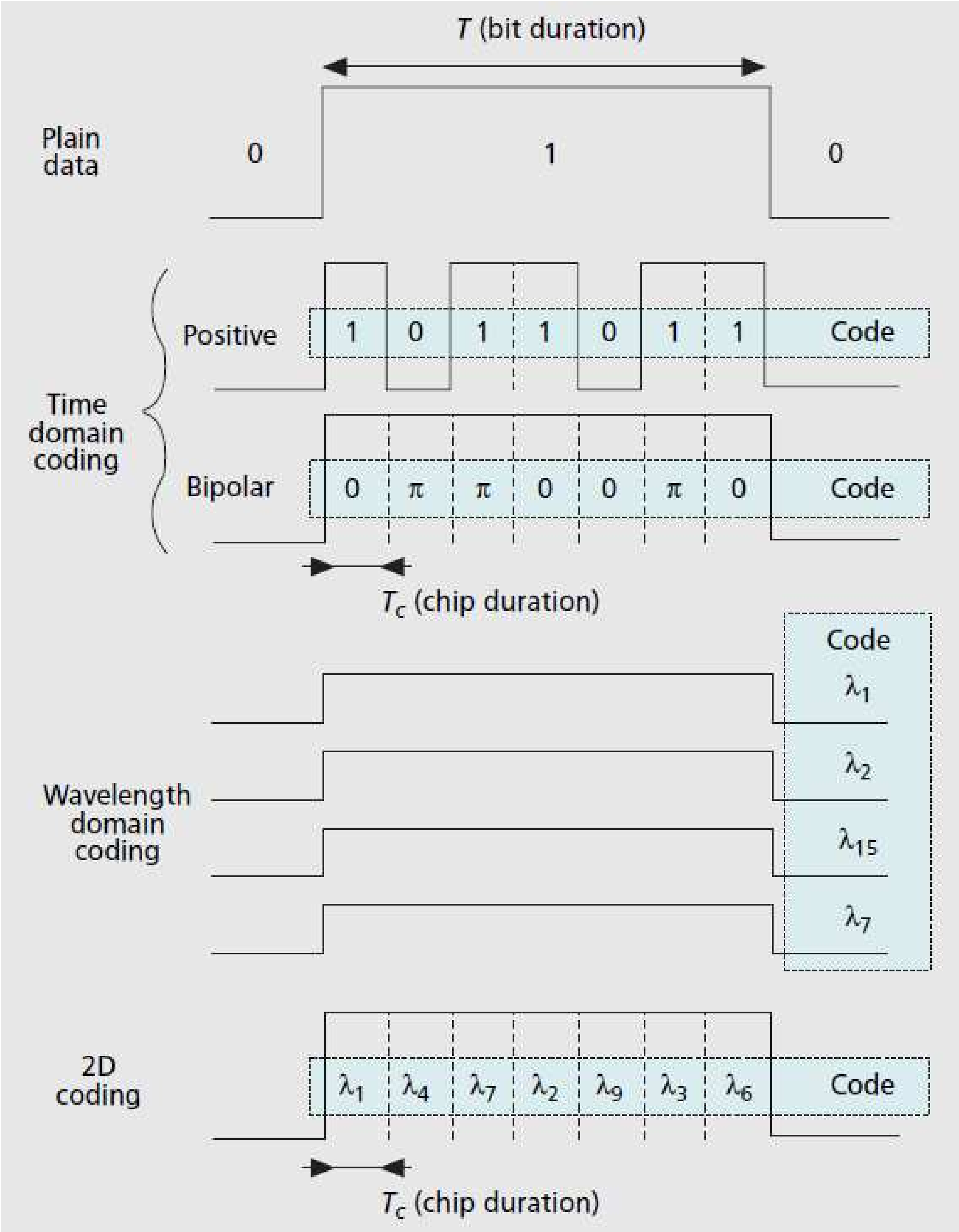


Figure 27. Optical Coding Dimensions (Fouli & Maier 2007)

Optical Sources: Optical sources differ with different OCDMA schemes. For incoherent time spreading (TS) the source should be high speed (chip rate) and high power as the code is very sparse of ‘1’s. For 2-D scheme, the source should be with broad bandwidth or multiwavelength. For incoherent spectral coding the source should be broadband incoherent light source with high spectral power density. In coherent schemes, the sources should be coherent that the generated optical pulses are transform limited. (Wang 2004)

For TS scheme, short pulse source (<10ps) is preferred, while in spectral coding scheme, ultra short (<1ps) light sources is needed.

Light sources with different OCDMA schemes are given in table 7.

Table 7. Light sources for different OCDMA schemes (Wang 2004).

	Scheme	Requirements	Sources		Data rate	Chip	Remarks
Incoherent	TS	High speed (chip-rate); High power; Incoherent	GS-DFB-LD, GS-FP-LD		~1 Gbps	<100 ps	Coherent noise with DFB LD
	Spectral coding	Broadband; Incoherent	LED,SLD, ASE		155 Mbps		Low data rate, high intensity noise
	2-D	High speed (chip-rate), Broadband, Incoherent	LED,SLD,ASE + high speed modulator		2.5 Gbps	<100 ps	High intensity noise, two modulator needed
			Multiwavlegth DFB LD array + EAM		10 Gbps	<100 ps	Coherent noise
			SC source		2.5 Gbps	<10ps	
			GS-FP-LR	Free running	250 Mbps	<100 ps	Mode partition noise
				Self-seeding	1 Gbps	<100 ps	
Coherent	TS	High speed (chip-rate), Coherent (transform limited)	MLLD		2.5 Gbps	<10 ps	
	Spectral coding	Ultra-high speed, (<1ps), coherent (transform limited)	MLLD + pulsewidth compressor		2.5 Gbps	<1ps	

3.4.3. Receiver

After transmission through the network, the encoded signals arrive at the decoders of user receivers, which perform match filtering to decode the received signal. For a target user the decoder recovers the original optical pulse, while for other users, output will be pseudorandom noise called multiple access interference (MAI). The decoded optical signal will be detected by the photo detector (PD) (Wang 2004).

Decoding: Decoding a signal encoded by the same code represents a logical auto-correlation of a single code, other wise the operation represents a cross-correlation between two different codes (Fouli & Maier 2007).

- Matched Filtering:

Matched filtering in the optical domain is the basis of the despreading. The impulse response of the matched filter h (t) along with its Fourier spectrum H (w) are as follows:

$$H_d(\omega) = H_e(\omega) * e^{-j\omega t_0} \quad (3)$$

$$H_d(t) = h_e(t_0 - t) \quad (4)$$

Where $h_e(t)$ is the impulse response of the optical encoder, $H_e(\omega)$ is its Fourier spectrum. Output of the matched filter is expressed by the convolution of the impulse responses of the encoder and the matched filter.

$$\text{Output} = \int_{-\infty}^{\infty} \text{He}(\omega)\text{Hd}(\omega)e^{j\omega t}\, df$$

$$= \int_{-\infty}^{\infty} |\text{He}(\omega)|^2\, e^{j\omega(t-t_0)}\, df$$

$$= \int_{-\infty}^{\infty} h_e(t^/)h_e(t^/ - t + t_0)df$$

$$= \psi\,(t-t_0) \quad (5)$$

Where ψ (t) represents the autocorrelation function of the input optical code $h_e(t)$. When the optical codes between the encoder and the decoder match, the decoded time-despread signal reconstructs the original short pulse as an autocorrelation, where as unmatched codes remain spread over one bit time frame of T after the decoding as a cross-correlation waveform.(Sotobayashi, Chujo, Kitayama 2004)

Optical Time Gate: Time gate opens the time window g (t) for the duration of $\Delta\tau$ at the bit rate $1/T$ at the moment when the autocorrelation main lobe passes. It samples only the data-bearing fraction of each bit, rejecting the side lobes of auto-correlation and the interference code that fall outside the gate interval (Kitayama, Sotobayashi, Wada 1999).

Optical Thresholding: Time gating technique could improve the BER performance by eliminating the multiple access interference (MAI) noises outside the gating window, however, strict synchronization (chip level) is needed that makes it not suitable in asynchronous OCDMA. Therefore, optical thresholder is a device which performs chip rate MAI noise elimination without synchronization. Details of different optical thresholding techniques are given in (Wang 2004).

3.4.4. Optical Encoder/Decoder

There are various kind of encoders and decoders that implements the encoding and decoding technique. Each encoder/decoder has its own advantages and disadvantages. Overall the SLM, PLC, FBG and MEMS are best suited OCDMA encoder and decoder. Important optical Encoder/Decoders are indicated in Table 8.

Table 8. Comparison of en/decoders (Wang 2004)

En/decoders	FODL	AWG	PLC	SLM	FBG	MEMS
Application	Incoherent & Coherent TS	Incoherent TS, 2-D coherent spectral coding	Coherent TS	Incoherent & Coherent Spectral Coding	Incoherent & Coherent TS and spectral coding, 2-D	2-D
Ability of generating long code	Low	Medium	Medium	High	High	Medium
Reconfigurable ability	Difficult	Available	Easy	Easy	Available	Easy
Insertion loss	Medium	High	High	Medium	Low	Medium
Integration	Low	Medium	Medium	Medium	High	Medium
Reliability	Low	Medium	Medium	High	High	High
Complexity	Medium	High	Medium	Medium	Low	High
Cost	Low	High	Medium	Medium	Low	Medium

3.4.5. Noise sources in OCDMA

There are three major sources of noise in optical CDMA which are classified as multiple access interference (MAI), beat noise and receiver noise as shown in Figure 26 (Wang & Kityama 2004).

Multiple Access Interference (MAI): MAI is the effect of other users on the user of interest. At the receiver there is false positive detection due to cross correlation interference. Thus transmitted 0 can be falsely detected as 1 due to MAI (Willner, Saghari, Arbab 2007). MAI noise arising source is network (star coupler). MAI noise is dominant in incoherent system (Wang & Kitayama 2004)

Beat noise: Beat noise is dominant in coherent systems (Wang & kitayama 2004). This noise is generated optically between pulses with close wavelength (Fouli and Maier 2007). Optical signals have both wave and particle properties. Since all users occupy the same wavelength space simultaneously, they will interfere with each other in a random manner give rise to an optical beat noise which is proportional to the optical power falling on the photodetector (Lam 2000).

Receiver Noise: In receiver, different kind of noises are generated which are thermal and shot noise but shot noise is more dominant. Shot noise builds as the square root of the received optical power, proportional to the active users in the system, thus limiting the scalability of the system. (Lam 2000)

3.4.6. Advantages and Disadvantages of OCDMA

Advantages: advantages of OCDMA are as follows:

- **All optical signal processing**: Coding operations are performed all optically in OCDMA.
- **Fully asynchronous transmission:** The OCDMA network can work with fully asynchronous transmission without requiring expensive electronic equipment and protocol.
- **Low-delay access:** OCDMA enables a low access delay as the coding operation is performed all optically and passively.
- **Soft capacity on demand:** Easy to add or delete users from the system according to the requirement.
- **Potential Security:** OCDMA has inherent security due to long pseudorandom codes for transmission. (Wang & Kitayama 2004)
- **Simple Protocol:** OCDMA does not require complicated protocol. It uses simple protocol like tell and go access protocol (Sotobayashi et al. 2004).

Disadvantages: Disadvantages of OCDMA are as follows:

- **Crosstalk (MAI) elimination:** In OCDM a single code cannot be completely separated from the others by using filters. Optical threshold detector is needed at the receiver which is not used in other multiplexing techniques to eliminate the crosstalk.

- **Electrical noise:** Electrical noise which originates from the optical channel interference limits the active number of users to small values.
- **Optical Power Budget:** There is fundamental lack of a real code filter which prevents from power efficient decoding and detection. So optical power budget of an OCDM network scales inversely with the square of the number of channels.(Pfeiffer 2002)

4. POWER CONTROL IN OCDMA

Power control aim is to achieve certain quality of service (QoS). These QoS parameters depend on number of parameters. One of the important parameter of QoS is the ratio of the average power of the desired signal to the average power of the interference and noise signals commonly known as signal to interference and noise ratio (SINR), alternative names for SINR are signal to noise ratio (SNR) where noise is dominant part, signal to interference ratio (SIR) where the interference is dominant and carrier to interference ration (CIR) which is used at band pass signal (koivo & Elmusarati 2009).

Factors that degrade the network performance in optical CDMA are shot noise and thermal noise at receiver but the noise created due to MAI is more dominant than shot noise and thermal noise in short range networks. Due to MAI, OCDMA networks suffer from near- far problem and optical power control is applied to enhance the performance of the network like RF-CDMA networks.

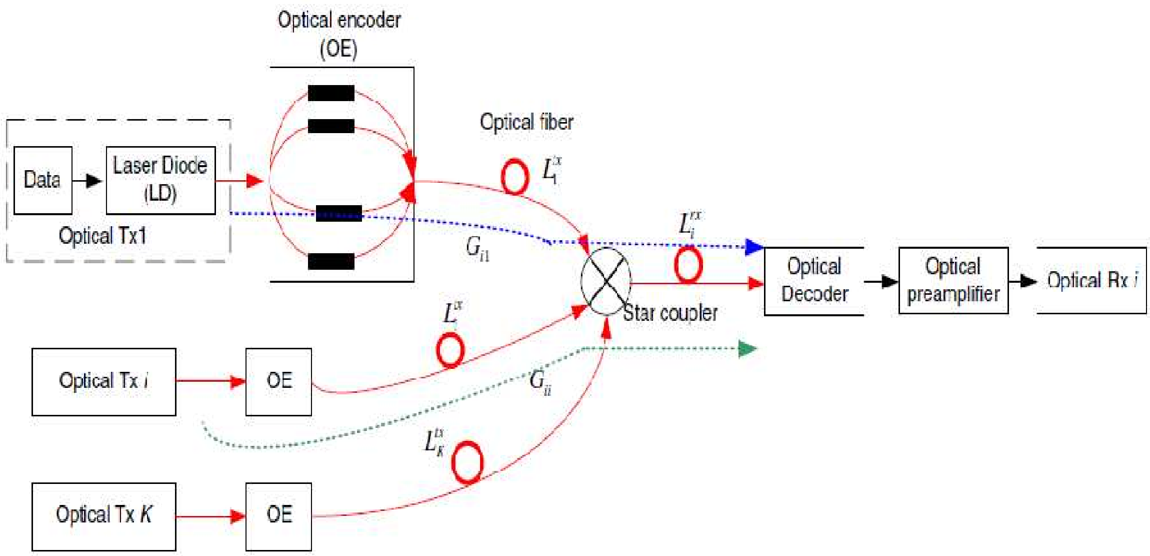


Figure 28. An Optical CDMA star network (Tarhuni, Korhonen,ELmusrati 2005)

4.1. System Description

A star coupled fiber optic CDMA is shown in Figure 29 where the nodes are connected by a passive K*K star coupler. Two fiber links are used by each user, one is for transmission and other is for reception. If the node distance from the star coupler is quite different, then some kind of power control is required.

In Figure 29 transmitter and receiver are denoted by Tx i and Rx i respectively. At transmitter, laser diode is used to convert signal from electrical to optical. Encoder is used to encode signal optically by optical tapped delay line to produce temporal OCDMA signal.

Optical powers of the laser are denoted by P_i for i = 1,2…k. Optical signals gets attenuated for two times, first by fiber connecting the node to star coupler and than by star coupler. Fiber attenuation is taken into consideration while fiber dispersion and nonlinearity coefficients are not taken into consideration.

Star coupler multiplexes all the transmitting signals and than send the multiplexed signal over the fiber optic channel to each receiver. Every receiver has optical decoder which uses optical match filter technique to despread desired signal from other interfering signals.

Mathematically, the above figure can be modelled as follows.

$$\alpha L = 10\log\left(\frac{P_t}{P_r}\right) + 10\log\left(a_{star}\right) \qquad (6)$$

Taking antilog of eq. (6), we get

$$e^{\alpha L} = \frac{P_t}{P_r} * a_{star} \qquad (7)$$

Rearranging eq. (7)

$$P_r = e^{-\alpha L} P_t a_{star} \qquad (8)$$

$$G = \frac{P_r}{P_t} = e^{-\alpha L} a_{star} \qquad (9)$$

Where P_r is the received power, P_t is the transmitted power, and $\alpha = \frac{a}{10\log(e)}$ [km^{-1}], a is the attenuation coefficient of the fiber in [db/km]. a_{star} is the attenuation of the star coupler which is common to all user and it is given in dB by

$$a_{star} = 10log_{10}K - (log_2 K)10log_{10}\gamma \qquad (10)$$

Where γ is the excess loss ratio. In Figure 29, the network nodes having radius of $L_{min} \leq r \leq L_{max}$ are distributed around star coupler. The length of the fiber connecting the *i*-th receiving node to the *j*-th transmitting node through the star coupler can be represented by

$$L_{ij} = L_j^{tx} + L_i^{rx}; for\ i, j = 1,2, \dots, k \qquad (11)$$

Where L_j^{tx} and L_i^{rx} are the *j*-th and *i*-th fiber length from the transmitting node and the receiving node to the coupler respectively. Fiber attenuation matrix connecting all the transceiver pairs by **G** which can be evaluated by substituting (11) in (9),

With perfect power control, the signal to interference ratio (SIR) is given by,

$$SIR = \gamma = \frac{q^2}{\sigma^2(k-1)} \qquad (12)$$

Where q^2 is length of prime code sequences, σ^2 is the variance for prime codes and *k* is the number of users.

The probability of error can be approximated by

$$P_E = Q(\frac{\sqrt{\gamma}}{2}) \qquad (13)$$

4.2. Power control types

There are two types of power control implementation techniques. One is centralized power control and other is distributed power control. The main task of power control algorithms is to keep the transmitter value of the transmitter at the minimum power required to achieve the target quality of service (QoS) in the communication link (Koivo & Elmusarati 2009).

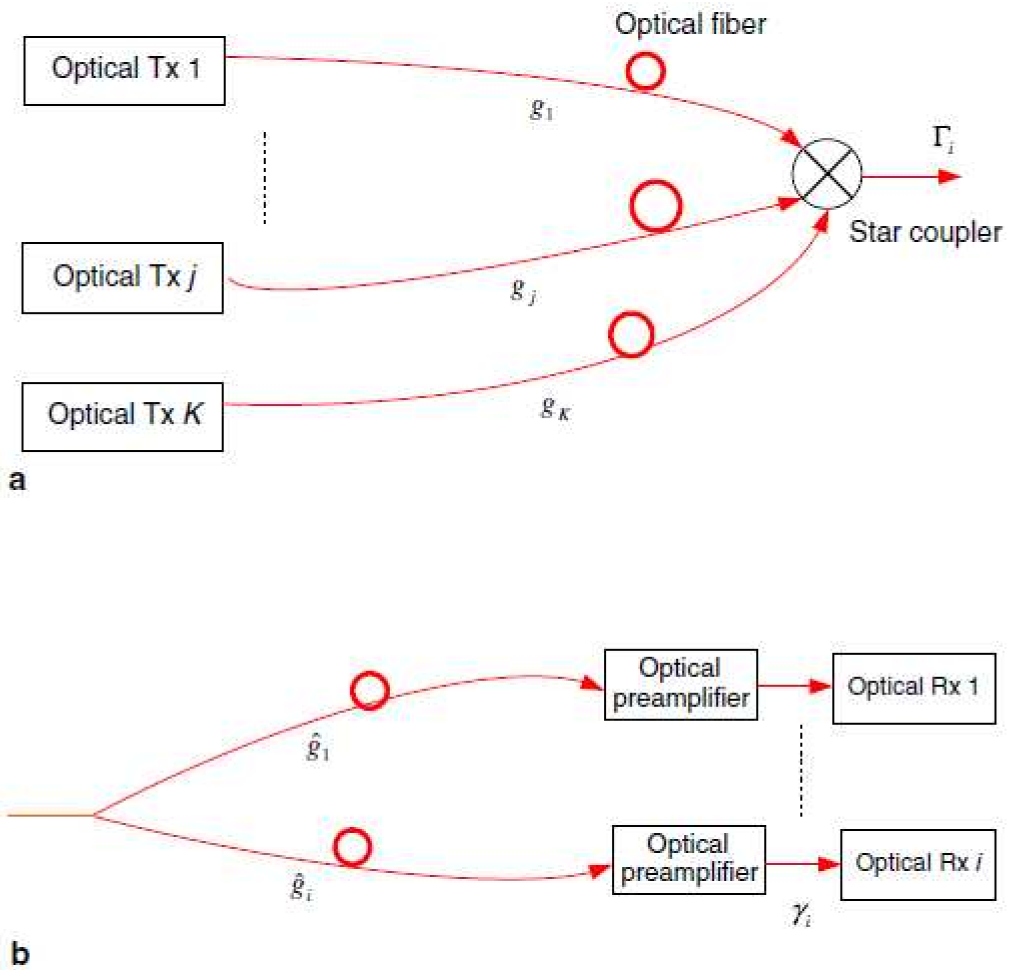


Figure 29. Partitioning the star topology into (a) Access Part (b) Broadcast part (Tarhuni, Korhonen, Elmusrati 2005)

4.2.1. Centralized Optical Power Control algorithm

The target carrier to interference power ratio (CIR) required to get certain QoS as measured by BER for user i is denoted by Γi, and the corresponding SIR is denoted by γi. Let the transmitted optical power vector be denoted by k-dimensional column vector

$$\mathbf{P} = [P_1, P_2, \ldots, P_K]^T \quad (14)$$

Then optical power control can be considered as an optimization problem by finding the vector P minimizing the cost function.

$$J(P) = 1^{T}P = \sum_{i=1}^{k} Pi \qquad (15)$$

Subject to constraint,

$$\Gamma_i = \frac{Pi\ Gii}{\sum_{j=1;j\neq i}^{k} PjGij} \geq \Gamma_{min} \qquad (16)$$

And $0 \leq Pi \leq Pmax; \forall i = 1, \ldots, k$

Where

$1^{T} = [1,\ldots, 1]$

K= number of active users in the network

Gij = attenuation between transmitting node j and receiving node i including fibers, star coupler and encoders splitting losses.

Γmin= minimum target to carrier to interference power ratio

Pmax = maximum transmit optical power

- $\boldsymbol{MAI\ dominant\ and\ nosie\ free\ case}$

In (16) the CIR is at the input of OCDMA decoder. Optical noises sources are neglected and MAI is considered in this case. Rearranging terms in (16) we get

$$P_i \geq \Gamma_{min} \sum_{j=1;j\neq i}^{k} P_j \frac{G_{ii}}{G_{ij}} \qquad (17)$$

Let **P**= $[P_i]$ and

$$\mathbf{H} = \begin{cases} 0 & when\ i = j \\ \frac{Gij}{Gii} & when\ i \neq j \end{cases}$$

then eq. (17) in matrix form can be written as

P ≥ Γ_{min} **PH**

Or **P**- Γ_{min} **PH** $= 0$

P [**I**-Γ_{min} **H**] =0 (18)

Where I is the identity matrix and H is a non negative matrix and called interference matrix.

Expanding equation (18) we get,

$$P[\frac{I}{\Gamma_{min}} - H] = 0$$

Or we can write as

$$\text{P } [H - \frac{I}{\Gamma_{min}}] = 0 \quad (19)$$

$$P(A - \lambda I) = 0 \quad (20)$$

By comparing (19) with (20), we get

$$\lambda = \frac{1}{\Gamma_{min}}$$

where $\frac{1}{\Gamma_{min}}$ is the eigenvalue of H.

One solution to (19) is that we switch off all users and that is not feasible solution. Other solution exist only when $1/\Gamma_{min}$ is an eigenvalue of H and its corresponding positive eigenvector P* will be the optimum power. According to Perron-Frobenius theorem there exists a positive vector associated to maximum eigenvalue of the nonnegative and irreducible k*k matrix H. So the solution of power control for (8) is the eigenvector **P*** corresponding to the largest absolute eigenvalue |λmax| or the spectral radius ρ(H) of the interference matrix **H.** Hence the maximum achievable CIR (target CIR satisfied by all nodes at the same time) is $\Gamma_{\max} = 1/|\lambda_{max}|$. (Tarhuni,Korhonen,Elmusrati & Mutafungwa 2005)

When perfect power control is assumed than maximum achievable CIR in optical star network is,

$$\Gamma_{\max} = {}^{1}/_{k} - 1 \tag{21}$$

Therefore, from (21) and $\Gamma_{\max} = {}^{1}/_{|\lambda_{max}|}$, the maximum eigenvalue of the k*k matrix **H** is k-1.

- **ASE noise non-negligible**

When optical amplifier noise is non-negligible than the SIR constraint will be used to evaluate the optimum power as follows. The SIR before the photodetector is given by,

$$\gamma_i = \frac{G_{amp}\, q^2 P_i G_{ii}}{\sigma^2 G_{amp}\, \sum_{j=1;j\neq i}^{k} P_j G_{ij} + 2\, N_{sp}} \geq \gamma min \tag{22}$$

where the factor 2 that multiplies the noise term Nsp accounts for the two optical polarization modes and σ^2 is the average variance of cross correlation magnitude.

$$N_{sp} = n_{sp}\, h\, fc(G_{amp} - 1)B_o \tag{23}$$

where n_{sp} is the spontaneous emission factor around 2-5, Gamp is the amplifier gain, Bo is the optical bandwidth, h is the Planck's constant and fc is the carrier frequency.

Rearranging terms in (22), we get transmitted optical power for *i*-th user

$$\boldsymbol{P_i} = \frac{\gamma_i \sigma^2}{q^2} \sum_{j=1;j\neq i}^{k} P_j \frac{G_{ii}}{G_{ij}} + \frac{2\gamma_i N_{sp}}{q^2 G_{amp} G_{ii}} \tag{24}$$

Equation (24) in compact form by defining scaled SIR and noise power as,

$$\boldsymbol{\Lambda_i} = \frac{\gamma_{i\sigma^2}}{q^2} \tag{25}$$

And

$$\boldsymbol{u_i} = \frac{2\, \gamma_i\, N_{sp}}{q^2\, Gamp\, Gii} \tag{26}$$

$$\boldsymbol{H} = \begin{cases} 0 \; when \; i = j \\ \frac{Gij}{Gii} \; when \; i \neq j \end{cases} \quad (27)$$

Equation (24) becomes in matrix form as follows

$$\boldsymbol{P} \;\; = \boldsymbol{\Lambda} \;\; \boldsymbol{PH} + \boldsymbol{u} \quad (28)$$

Similiarly, we can write as

$\boldsymbol{P} - \boldsymbol{\Lambda PH} \geq \boldsymbol{u}$, or

$$\boldsymbol{P}[\boldsymbol{I} - \boldsymbol{\Lambda H}] \geq \boldsymbol{u} \quad (29)$$

Where the matrix **Λ** is a diagonal matrix with (25) as its elements and reduces to single element if target SIR of all nodes is same.

Equation (29) can be written as follows to give the optimum transmitted power required by all users.

$\boldsymbol{P}^* = \frac{\boldsymbol{1}}{[\boldsymbol{I} - \boldsymbol{\Lambda H}]} \boldsymbol{u}$, or

$$\boldsymbol{P}^* = [\boldsymbol{I} - \boldsymbol{\Lambda_{max} H}]^{-\boldsymbol{1}} \boldsymbol{u} \quad (30)$$

The resulting optical power in (30) is the optimum power required to achieve the target CIR. When target SIR for all nodes is equal and the perfect power balancing is assumed then it can be shown that the maximum achievable SIR (MAI limited noise free) from (14) is given as

$$SIR_{max} = \gamma_{max} = \frac{q^2}{\sigma^2 (k-1)} \quad (31)$$

- **Partitioned optical power control**

The evaluation of the optimum power can be simplified by partitioned the star network into two parts: The access network and broadcasting network. The transmitting node fiber attenuation plus star coupler loss and the receiving node fiber attenuation denoted by

$g_j = a_{star} \exp(-\alpha L_i^{tx})$

And

$\hat{g_i} = \exp(-\alpha L_i^{rx})$

Respectively using $G_{ij} = g_j \hat{g_i}$in (22) the SIR at the i-th receiver is given by,

$$\gamma_i = \frac{G_{amp}\ q^2 P_i}{\sigma^2 G_{amp}\ \sum_{j=1;j\neq i}^{k} Pj \frac{g_j}{g_i} + 2\frac{N_{sp}}{g_i \hat{g_i}}} \geq \gamma_{min} \tag{32}$$

Interference matrix for above case can be written as,

$$H_{ij} = \begin{cases} 0 \ \rightarrow i = j \\ \frac{g_j \hat{g_i}}{g_i \hat{g_i}} \rightarrow i \neq j \end{cases} = \begin{cases} 0 \rightarrow i = j \\ \frac{g_j}{g_i} \rightarrow i \neq j \end{cases} \tag{33}$$

At the output of the star coupler CIR Γ_i can be written as,

$$\Gamma_i = \frac{P_i g_i}{\sum_{j=1}^{k} P_j g_j} \tag{34}$$

If the background noise is assumed to be zero than from (32) and (34),

$$\Gamma_i = \gamma_i \ if \ \frac{N_{sp}}{\hat{g_i}} \ll \sum_{j=1}^{k} P_j \frac{g_j}{g_i} \tag{35}$$

From above results Tarhuni et al. stated theorem which states that when noise is very small compared to MAI in star coupled network than the maximum achievable SIR at the receiving nodes equals the maximum achievable CIR at the star coupler output times a processing gain factor of $\frac{q^2}{\sigma^2}$, i.e. the fibre lengths after the star coupler play no role in optimum power evaluation. In this case the solution of the balanced power control problem is the eigen vector corresponding to the largest absolute eigen value of H.

5. ALGORITHM ANALYSIS AND SIMULATION

In this chapter Centralized algorithm have been implemented and noiseless and noise case have been discussed. The simulation environment is discussed as follows:

Table 9. Simulation Parameters

Parameters	Value
Number of Users	31
Network nodes distance from star coupler(Ltx)	2≤r≤50
Star coupler coefficient	0.2 Db
Fiber attenuation coefficient	0.2dB/km
Operating wavelength	1550nm
Bit Rate	2.5Gb/s
Reciever Noise Power for each reciever	5*(10^-13) A^2
Maximum Laser Power assumed	20dBm
Code length (q)	31
σ^2	0.29

SIMULATAIONS FOR CENTRALIZED POWER CONTROL ALGORITHM

For simulation case I considered a network of 31 nodes that are uniformaly distributed over an area with a radius of $2 \leq r \leq 50$ [km] and the star coupler is at the area center. A star coupler loss of 0.2 dB, and the fiber attenuation coefficient of 0.2 dB/km at the operating wavelength of 1550nm. Bit rate of 2.5 Gbps and a maximum allowable transmit laser power 20 dbm for all nodes is assumed before power control. I have neglected the effect of dispersion by assuming the use of dispersion shifted fiber links. Fiber non-linearity is also neglected because of the relatively short fibers, low data rates and low optimum power levels encountered. By using network partitioning optimum power have been calculated and due to those reason lengths from the star coupler to receivers have not taken into consideration.

CASE1: Noiseless Case for 31 users

For noiseless case our CIR is given as:

CIR= $\frac{1}{k-1} = \frac{1}{31-1} = \frac{1}{30}$ = 0.0333= 15.2 dBm

Before power control nodes near to the star coupler will be able to achieve target CIR but users which are far away from the star coupler will not be able to achieve target CIR. Thus after optimum power vector near and far effect will be overcome and every user will be able to achieve desired CIR.

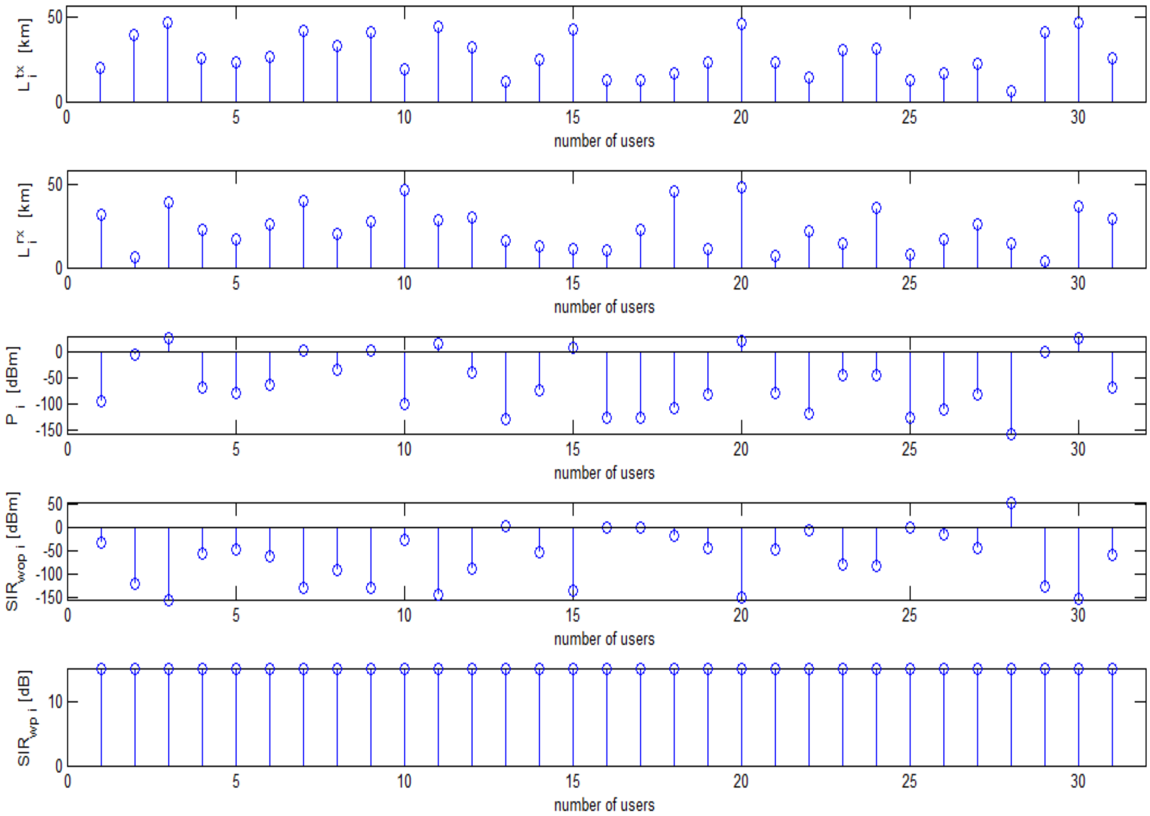


Figure 30. (a) Fiber lengths from transmitter to star coupler. (b) Fiber lengths from star coupler to receiver (c) Optimum power (d) CIR before power control (e) CIR after power control

CASE2: Noisy Case for 31 users

In noisy case we have included noise and it is given in the Table 5. SIR for the noisy case is given by using eq. 31. It is given as follows.

$$\mathrm{SIR}_{\max} = \gamma_{\max} = \frac{q^2}{\sigma^2(k-1)}$$

$$\mathrm{SIR} = \frac{31^2}{0.29*(31-1)} = 110.45 = 50.4\ dBm$$

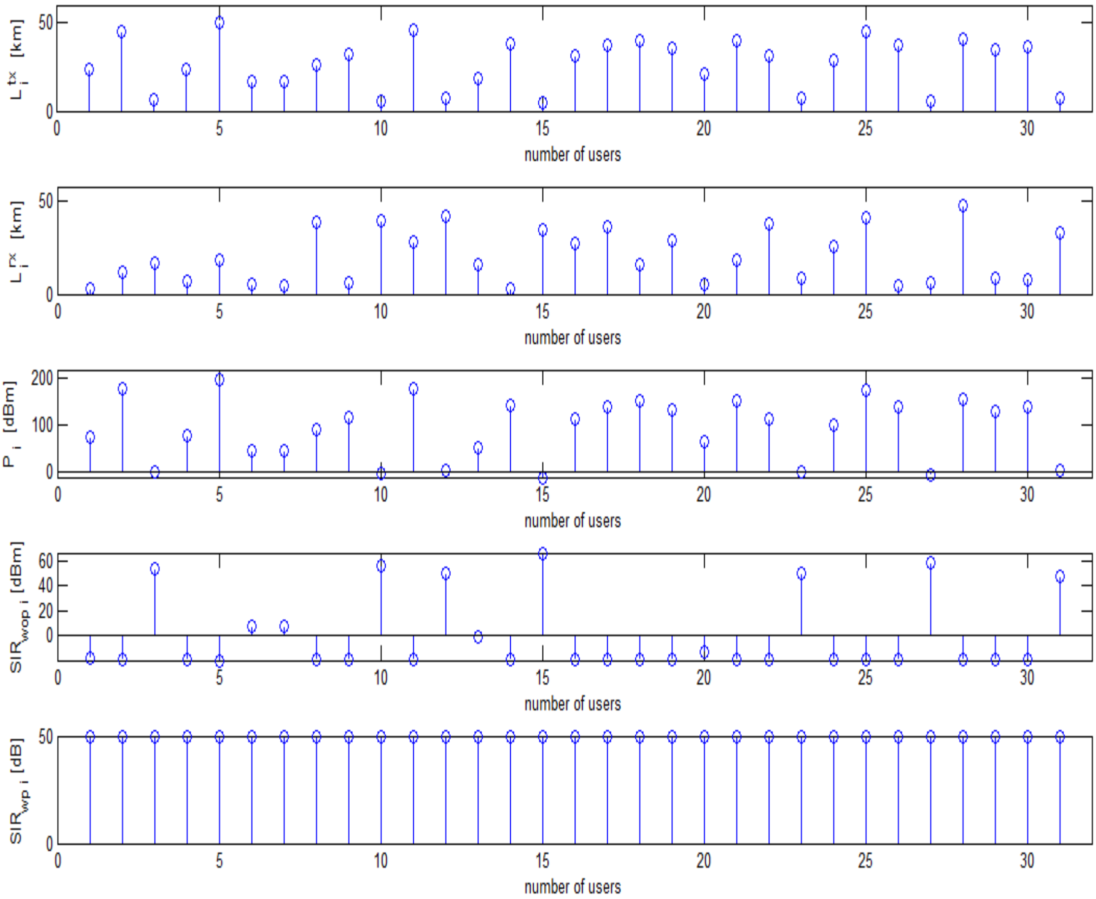


Figure 31. (a) Fiber lengths from transmit nodes to coupler. (b) Fiber lengths from star coupler to receiver. (c) Optimum laser powers (d) SIR before power control (e) SIR after power control

It is clear from Figure 31(d) that only 6 users are accommodated without power control for target SIR of 50.4dBm while all 31 users are accommodated after power control for the same target SIR of 50.4 dBm which is shown in Figure 31(d) which is clear indication of improved QoS.

6. CONCLUSION AND FUTURE WORK

In this thesis brief overview about fiber optics has been given, afterwards four multiplexing techniques WDM, OTDM, O-OFDM and OCDMA for all optical passive optical networks has been discussed. Optical CDMA is considered as a best candidate for all optical passive optical networks. Power control concept is studied and implemented for optical CDMA as this increases the QoS of the system.

We considered a star coupled network with uniformly distributed user nodes around the star coupler. Fiber attenuation, star coupler splitting loss are taken into account. Amplified spontaneous emission noise is considered is the main noise along with multiple access interference. Furthermore, it is also shown that by using optimum optical transmit powers, the capacity of the network in terms of the number of supported users could be enhanced significantly, and then, it is shown that the fibers after the star coupler are irrelevant to the optimum power evaluation. It is also demonstrated that by partitioning the network to access and broadcast parts of SIR at the receiving nodes and the CIR at the star coupler output are related by a gain factor that is in turn related to the code correlation properties.

In simulation part of the thesis Centralized power control algorithm has been discussed, furthermore noisy and noiseless case have been implemented which shows that CIR or SIR after power control accommodates large number of users as compare to CIR or SIR before power control. In a nutshell every user has same CIR or SIR after power control which is an indicator of improved Qos.

Future Work: As we have been progressing in this topic as many new doors of questions and problems have been opening. However, since the time duration to perform this thesis was rather limited, we have decided to continue working in this research topic in future. Some of the research points are:

- Comparison of different Distributed Power Control Algorithms with respect to power control implementation.
- Performance analysis with respect to power control in Optical CDMA, Optical TDMA, WDM and Optical OFDM.

Due to number of advantages of OCDMA it has been proposed to support number of applications in future. Some of them are mentioned briefly here.

OCDMA has been proposed for metro level optical virtual private network (VPN). VPN primary goal is to provide secure data link over an insecure platform. OCDMA signals that are multiplexed and demultiplexed at the end points in VPN network providing enhanced security and can be decoded only at the corresponding end point.

It has also been proposed for Image transmission where there is no need for serial to parallel conversion and vice versa, in contrast to TDM. Pixels streams are transmitted simultaneously over user specific code-channels.

OCDMA has also been proposed for Radio-over-fiber. Radio over fiber enables fiber access networks to connect wireless base station. Due to the OCDMA large channel count, the mapping of individual radio channel to the OCDMA channels for multiplexing and transport to the core network becomes easy when compare to other multiplexing techniques.

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