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Simulation Study of High-order Modulation Formats in Optical Communication

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Abstract

The aim of this work is to do a qualitative study by simulation two different advanced high-order modulation schemes: 8PSK and 8QAM in modern optical fiber communication system, and show the effects of the input power and fiber length at three-bit rates level: 15, 30 and 54 Gbps. The performance of the optical fiber link in terms of constellation diagram for the four modulation schemes is compared and discussed.

Dedication

I dedicate this piece of work
To my dear parents
To my brother and sisters
To all my friends

Abo Led

Acknowledgements

We are thankful to Allah, the most gracious and the most merciful for helping us finish this modest work.

We would like to express the deepest appreciation to our supervisor **Pr. Abdelkader Zitouni** for his support and guidance through this project. It has been a privilege to work under his supervision. Moreover, we would like to thank **Abdellah Benmissoum** and **Zakaria ILOUL** for helping us on the simulation. Also, we thank the members of the jury for taking the time to read and analyze this thesis. Last but not least, we would like to thank all the teachers that taught us and shared their precious knowledge and the staff of the INELEC for assisting us with all our study related concerns throughout these five years. Finally, to anybody who attempts to develop the ideas presented here, I hope they can be of use.

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List of Abbreviations

ADC	Analog to Digital Converter
APD	Avalanche Photodiode
ASK	Amplitude Shift Keying
BER	Bit Error Rate
CD	Chromatic Dispersion
CW	Continuous Wave
DSP	Digital Signal Processing
EDFA	Erbium-Doped Fiber Amplifiers
EVM	Error Vector Magnitude
FSK	Frequency Shift Keying
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light Emitting Diode
MMF	Multi Mode Fiber
MZM	Mach-Zhender Modulator
NRZ	Non Return to Zero
PMD	Polarization Model Dispersion
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
ROM	Read Only Memory
SMF	Single Mode Fiber
TIR	Total Internal Reflection
WDM	Wave-length Division Multiplexing

General Introduction

A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Information is often carried by an electromagnetic carrier wave whose frequency can vary from a few megahertz to several hundred terahertz.

Optical fiber communication systems are lightwave systems that employ optical fibers for information transmission. Such systems have been deployed worldwide since 1980 and have indeed revolutionized the technology behind telecommunications. The lightwave technology, together with microelectronics, is believed to be a major factor in the advent of the “information age”.

Optical fiber communication systems have attracted more attention in the recent years, because of the outstanding advantage of optical fibers. The most significant merit of an optical fiber is its enormous bandwidth.

Nowadays, an interest in the signal transmission through optical fibers rapidly increases due to the need for better transmission bandwidths. To increase the performance of the optical transmission system, the analysis of optical fibers is required. Different modulation and coding techniques can be used to achieve optimal performance for transmission systems.

The first step in the design of an optical fiber communication system is to decide how the electrical signal would be converted into an optical bit stream.

Modulation is the process of facilitating the transfer of information over a medium, either a wireless or optical fiber environment. The motivation behind modulation is to enable the transport of data efficiently and without many errors.

With the advent of coherent detection technology and high-speed digital signal processing (DSP), multi-level modulation formats such as multi-level phase-shift keying (M-PSK) and quadrature amplitude modulation (QAM) are recognized as promising approaches to meet the increasing demand for spectral efficiency and system throughout in future optical communication systems.

8-ary modulation formats, for example optical 8-ary phase-shift keying (8PSK) and circular 8-ary quadrature amplitude modulation (8QAM), carry 3 bit per symbol, have similar spectral width, and have comparable implementation complexity.

This work will be presented as follows:

Chapter I: Introduces some basics of optical communications and the components that make up an optical fiber communication system.

Chapter II: Shows four optical modulation schemes and their principle of transmission and detection.

Chapter III: In this chapter, we are going to simulate the four different modulation schemes shown in the second chapter and compare them.

Conclusion: Summarizes the outcome of this work and gives more suggestions about the future work.

Chapter I

Optical Communication System

Chapter I : Optical communication System

A communication system transmits information from one place to another, whether separated by a few kilometers or transoceanic distances. Information is often carried by an electromagnetic carrier wave whose frequency can vary from mega-hertz to several hundreds of tera-hertz .[1]

An optical communication system is similar to any type of communication system. It conveys the data from the information source over the transmission medium to the destination by changing electrical signals into light .[2]

Fiber optic communication is a communication technology that uses light pulses to transfer information from one point to another through an optical fiber. The information transmitted is essentially digital information generated by computers, telephone systems and cable television companies.[3]

Basically an optical fiber communication system comprises three main components as represented in figure 1.1:

- Optical transmitter
- Optical cable
- Optical receiver

There are also some additional elements that are important in this communication system like: connectors, switches, couplers, multiplexing devices, amplifiers and splices.

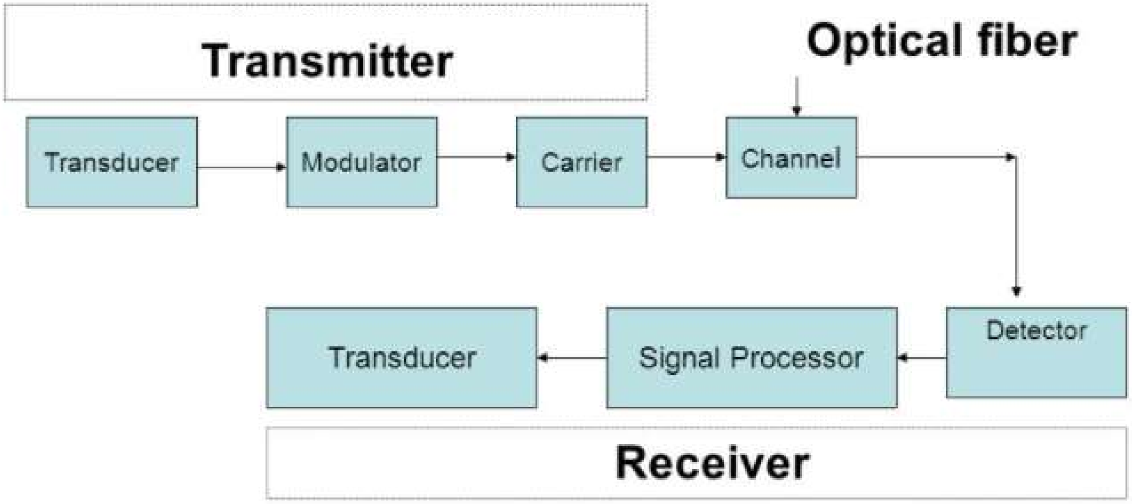


Figure.1.1 *Block Diagram of Optical System [4]*

The Optical Fiber

Optical fiber cable is flexible and transparent, it is made by drawing glass (silica) or plastic. Optical fibers are used most often as means to transmit light between the two ends of the fiber, they permit transmission over longer distances and at higher bandwidths than wire cables. Fibers are used instead of metal wires because signals travel along them with less loss [5].

Optical fiber consists of a very fine cylinder of glass core, through which light propagates. The core is surrounded by another layer of glass, named cladding, which is then wrapped by thin plastic jacket. The core has a slightly higher index of reflection than the cladding glass [6].

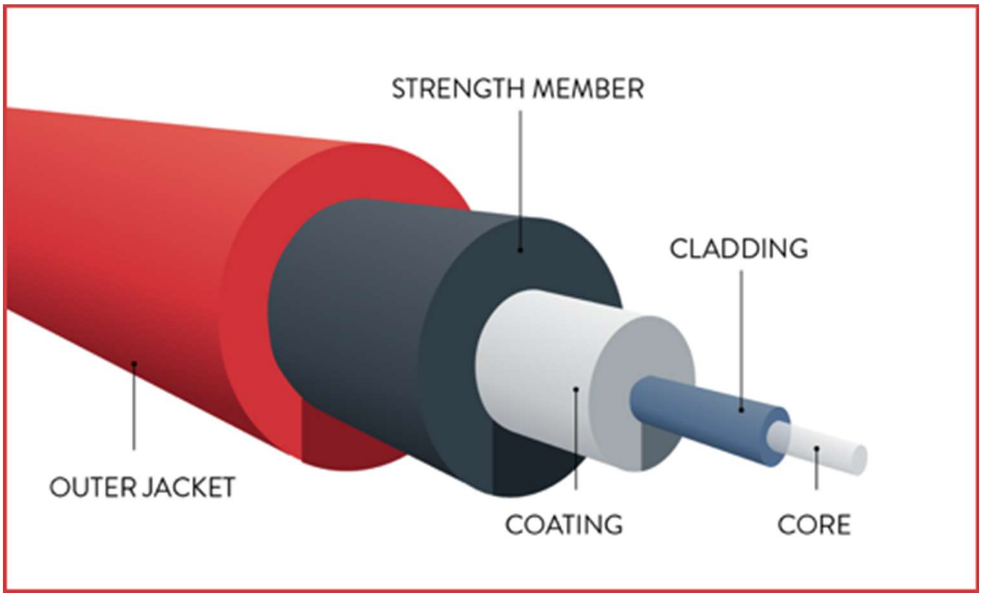


Figure 1.2 *Optical Fiber Structure. [7]*

When a ray of light traverses from one medium to another, it partially gets reflected back into the incident media where it comes from. This principle is known as reflection. The light which is not reflected back into the incident media is refracted into the second media. This phenomenon is known as refraction. The angle of incidence is always equal to the angle of reflection.[8]

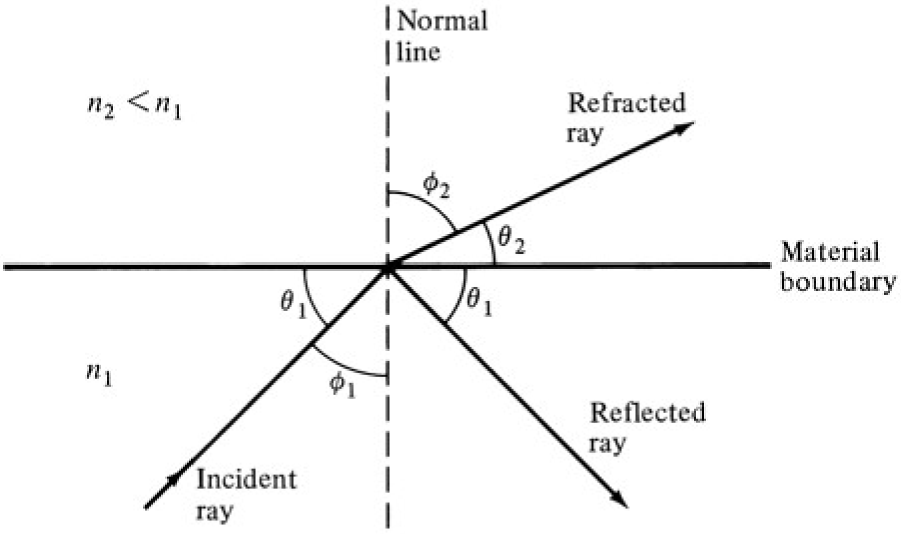


Figure 1.3 Reflected and Refracted rays [9]

What makes fiber optics work is the total internal reflection, when a ray of light goes from the core to the core-cladding boundary at an angle larger than θ_c, the ray is completely reflected back to the core. Thus, light signal can be guided inside optical fibers.[2]

The ratio of refractive indices of core and cladding defines the critical angle θ_c :

$$\sin\theta_c = \frac{n_2}{n_1} \tag{1.1}$$

where n_1 is the refractive index of the core and n_2 is the refractive index of the cladding.

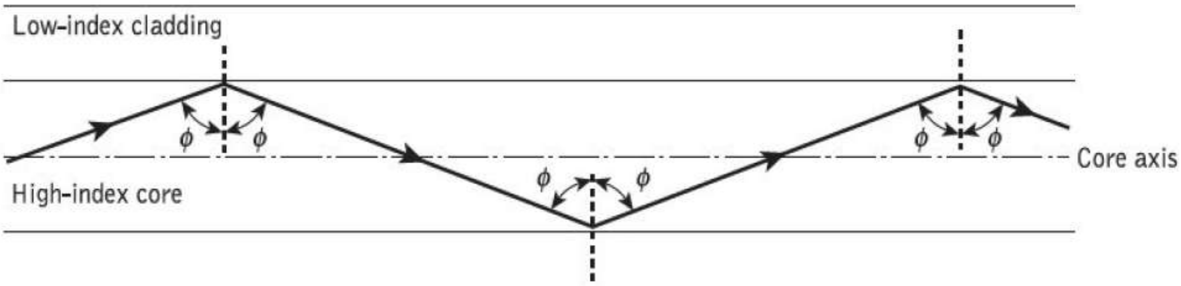


Figure1.4 The transmission of a light ray in a perfect optical fiber.[2]

1.1.1 Single mode fiber (SMF)

A typical single mode optical fiber has a core diameter between 8 and 10.5 µm and a cladding diameter of 125 µm [10].SMFs are used to transmit one mode per fiber. Because of their small size, SMFs have also advantages; it has a large bandwidth-length thanks to its less intermodal dispersion, SMFs are more compatible with integrated-optics technology.

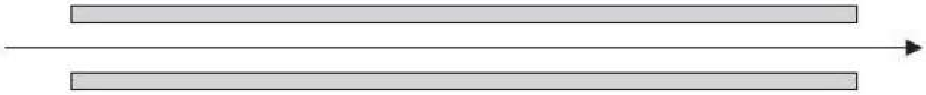


Figure 1.5 *Propagation of light in a single mode fiber.*

1.1.2Multi mode fiber (MMF)

Multimode fiber (MMF) has a larger core diameter than the single mode fiber that allows multiple light modes to propagate through it. This will increase the number of reflections at the core-cladding interface. Hence, the attenuation and losses increase which then cause the quality of the signal to deteriorate over long distances. Therefore, it is better to use it for short distances.

MMFs have several advantages. The core radius is large ($25 - 35\ \mu m$), therefore, it is easier to launch optical power into it and also to splice two MMFs. Furthermore, light can be launched to the fiber from an inexpensive optical source that has a large angular spread such as an LED. In addition to that, its channel capacity is large because, in principle, each mode of a MMF can carry as much information as a single SMF.[11]

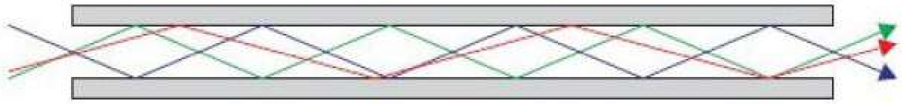


Figure 1. 6 *Propagation of light in a multi mode fiber.*

1.1.3 Advantages of optical fiber

- *Extremely High Bandwidth*: No other cable-based data transmission medium offers the bandwidth that fiber does. The volume of data that fiber optic cables transmit per unit time is far great than copper cables.
- *Longer Distance*: in fiber optic transmission, optical cables are capable of providing low power loss, which enables signals to be transmitted to a longer distance than copper cables.

- *Low Security Risk:* the growth of the fiber optic communication market is mainly driven by increasing awareness about data security. Data or signals are transmitted via light in fiber optic transmission. Therefore there is no way to detect the data being transmitted by "listening in" to the electromagnetic energy "leaking" through the cable, which ensures the absolute security of information.
- *Small Size*: fiber optic cable has a very small diameter, it is smaller than that of coaxial copper cable. Small size saves more space in fiber optic transmission.
- *Lower loss*: Optical fibers have lower attenuation (loss of signal intensity) than copper conductors, allowing longer cable runs and fewer repeaters.
- *Light Weight*: fiber optic cables are made of glass or plastic, and they are thinner than copper cables. These make them lighter and easy to install.

1.1.4 Disadvantages of optical fiber

- *Fragility*: usually optical fiber cables are made of glass, which means they are more fragile than electrical wires. In addition, glass can be affected by various chemicals including hydrogen gas (a problem in underwater cables), making them need more cares when deployed underground.
- *Difficult to Install*: it’s not easy to splice fiber optic cables. And if you bend them too much, they will break. And fiber cable is highly susceptible to becoming cut or damaged during installation or construction activities. All these make it difficult to install.
- *Cost is higher than copper cable*: despite the fact that fiber optic installation costs are dropping by as much as 60% a year, installing fiber optic cabling is still relatively higher than copper cables.

1.2The Optical Transmitter

In order for the data to be transferred through an optical fiber, an optical transmitter is needed. The role of an optical transmitter is to convert the electrical signal into optical form and to launch the resulting optical signal into the optical fiber; this signal is generated by modulating the optical carrier wave.[12]

1.2.1Optical sources

Depending on the application, optical transmitters use either semiconductor LASERs or light emitting diodes (LED) as a source of light:

A. LASER Diode :

It is a semiconductor device, which emits light through stimulated emission. Most fiber-optic communication systems use semiconductor LASERs as an optical source because of their superior performance compared with LEDs, mainly because they are capable of emitting high power (up to 100 mW) and the relatively narrow angular spread of the output beam permits high coupling efficiency (about 50%).[12]

B. Light emitting diode (LED) :

Light emitting diodes are highly efficient devices capable of emitting light of any color by a mechanism known as spontaneous emission [2]. An LED generates only incoherent light; it supports many optical modes within its structure and is therefore used as a multimode source. This device has a number of distinct advantages, which have given it a prominent place in optical fiber communications, mainly: simple fabrication and construction, low cost and reliability.

C. Comparison of LEDs and LASERs:

The advantages of LEDs over LASER include:

- Lower cost due to their simpler fabrication.
- More reliable because they are less sensitive to temperature change.
- They have better linearity since they require simplest circuitry.
- Low power versus laser.
- LEDs relatively wide emission.

The advantages of LASER over LEDs include:

- Compact size and high efficiency.
- Higher wavelength range.
- Small emissive area compatible wave fiber core dimension.
- Higher power output.
- Produce directional and coherent light which is the better option for optical communication.

1.2.2 Optical modulator

For modulation, either an internal or external modulators are used. In an external modulator, the intensity is usually manipulated by manipulating the carrier phase of the light waves guided in one path of an interferometer.

The *Mach–Zehnder* interferometric structure is the most common type used as a modulator, it is used for controlling the amplitude of an optical wave. The input waveguide is split up into two waveguide interferometer arms [13], a voltage V applied to an electrode causes a change in the phase of the optical signal in the arm of the interferometer .

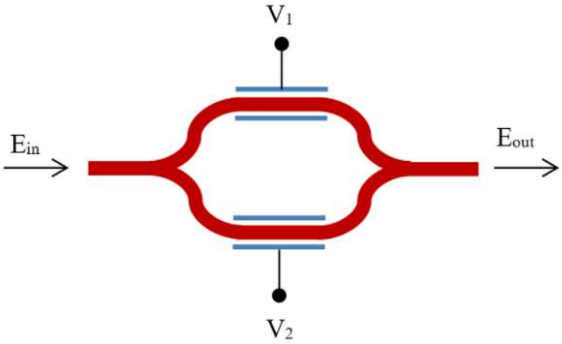


Figure 1. *7 Mach-Zehnder modulator structure.[14]*

There are two types of Mach-Zehnder modulators, Semiconductor and Lithium-Niobate, the latter is the most common used one, and it has two different configurations:

- **Single-drive configuration**: modulating voltage is applied to one arm of the Interferometer causing a phase change of π in the arm.
- **Dual-drive configuration**: modulating voltages are applied to both arms of the interferometer causing a phase changes of ± π/2 in the arms.

1.3 Optical Receiver

An optical receiver converts the optical signal received at the output end of the optical fiber back into the original electrical signal. It consists of a coupler, a photodetector, and a demodulator [12].

The main component of an optical receiver is a photodetector, which converts the optical power into electrical current.

there are several types of photodetectors, the semiconductor-based photodetectors (photodiodes) are used exclusively for optical communication [8]. The most common photodiodes used in optical systems are *PIN photodiode* and *Avalanche Photodiode (APD).*

1.3.1 PIN photodiode

In order to operate at longer wavelengths where the light penetrates more deeply into the semiconductor material, a wider depletion region is necessary. To achieve this, the n-type material is doped so lightly, and to make a low-resistance contact a highly doped n-type (n+) layer is added. This creates a PIN structure.

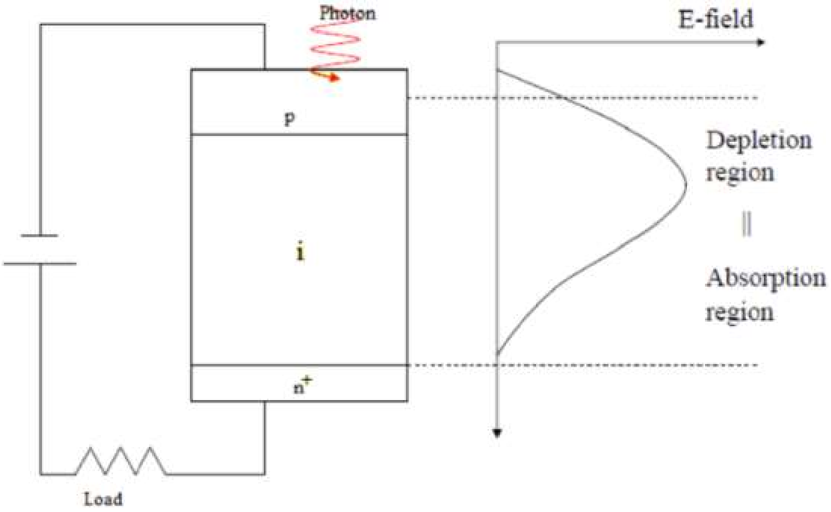


Figure1.8 *PIN photodiode showing combined absorption and depletion..[15]*

1.3.2 Avalanche Photodiode (APD)

The second major type of optical communications detector is the avalanche photodiode (APD). This has a more sophisticated structure than the PIN photodiode in order to create an extremely high electric field region[16], The main difference between the avalanche photodiode and other forms of photodiode is that it operates under a high reverse bias condition. This enables avalanche multiplication of the holes and electrons created by the photon /light impact.

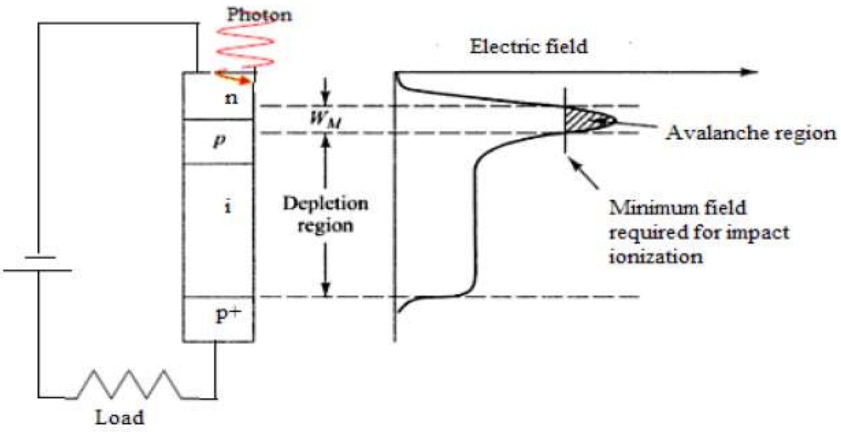


Figure1.9 *Avalanche photodiode showing high electric field region.[16]*

1.4 Optical Amplifier

An optical amplifier amplifies the optical signal directly without requiring its conversion to the electric domain. Most optical amplifiers amplify incident light through stimulated emission.[12]

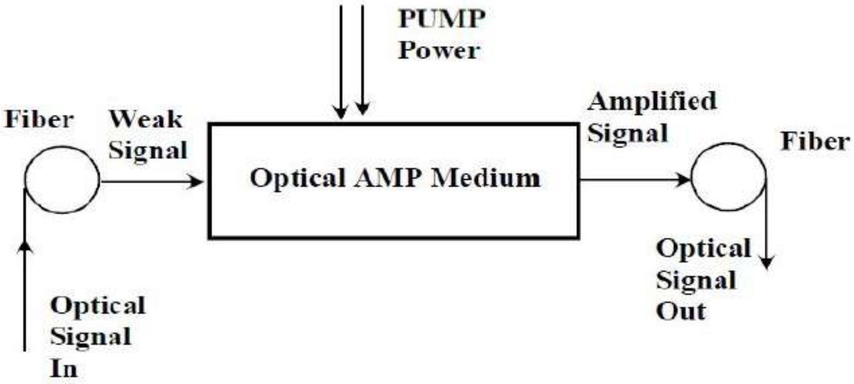


Figure1.10 *The general form of an optical amplifier.[17]*

The most important type of the optical amplifier is the *Erbium-Doped Fiber Amplifier (EDFA).*

1.4.1 Erbium-Doped Fiber Amplifiers (EDFA)

An Erbium-Doped Fiber Amplifier (EDFA) is a device that amplifies an optical fiber signal. A trace impurity in the form of a trivalent erbium ion is inserted into the optical fiber's silica core to alter its optical properties and permit signal amplification.[18]

EDFA optical amplifiers are made of short lengths (a few meters) of optical fiber doped with the element Erbium. A pumping laser excites Erbium ions in the fiber, which can then give their energy to the optical signals passing through. The pump wavelengths are 980 nm and/or 1480 nm.[19]

1.5 Fiber Propagation Effect

During fiber transmission, optical signals are distorted by several linear and nonlinear degradation effects.

In addition of non linear losses, attenuation and pulse dispersion are the most important effects in linear degradation effects and in fiber propagation effects.

1.5.1 Attenuation

Attenuation is defined as the loss of optical power over a set distance. A fiber with a lower attenuation, will allow more power to reach the receiver than a fiber with a higher attenuation. Signal attenuation within optical fibers is usually expressed in decibel per unit length (i.e. dB/km).

If an input power $P1$ results in an output power $P2$, the loss in decibels is given by [20]:

$$\alpha = 10log_{10}\left(\frac{P_1}{P_2}\right) \tag{1.2}$$

There are three basic mechanisms causing signal attenuation in a fiber; they are *Absorption*, *scattering* and *Imperfection Loss* of the optical energy.

A. Absorption loss:

It is related to the material composition and the fiber fabrication process. It results in the dissipation of some of the transmitted optical power as heat in the fiber. Light absorption may be either *intrinsic* or *extrinsic.*

- **Intrinsic Absorption:**

The intrinsic absorption is due to the material nature of absorbing specific wavelength region of light. The intrinsic absorption occurs in both the infrared and ultraviolet ranges. Fortunately, these intrinsic losses are mostly insignificant in the region where fiber systems are operated, but these losses limit the extension of fiber optic communication toward the ultraviolet as well as toward longer wavelength.[21]

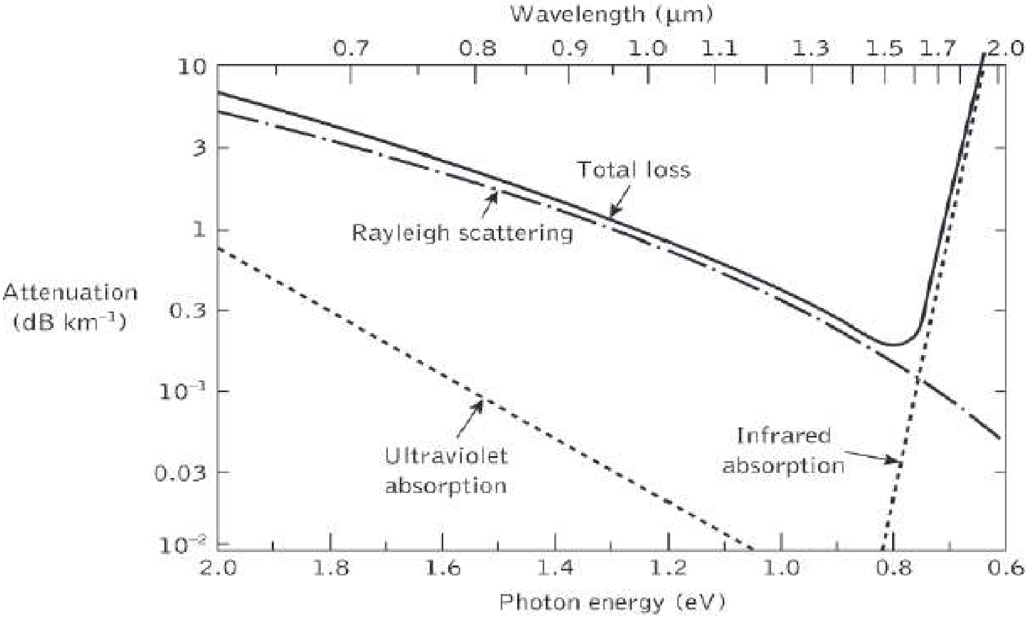


Figure1. 11 *The attenuation spectra for the intrinsic loss mechanism in pure Silicate glass.[2]*

- **Extrinsic Absorption:**

Extrinsic absorption is caused by atomic resonance of impurity particles in the fiber. The most important extrinsic absorption is due to water or hydroxyl ion (OH) bond [22].Because the bond can absorb incident light at its resonant frequency and harmonics, there are absorption peak at wavelength of 2.8/ (n+1) µm.

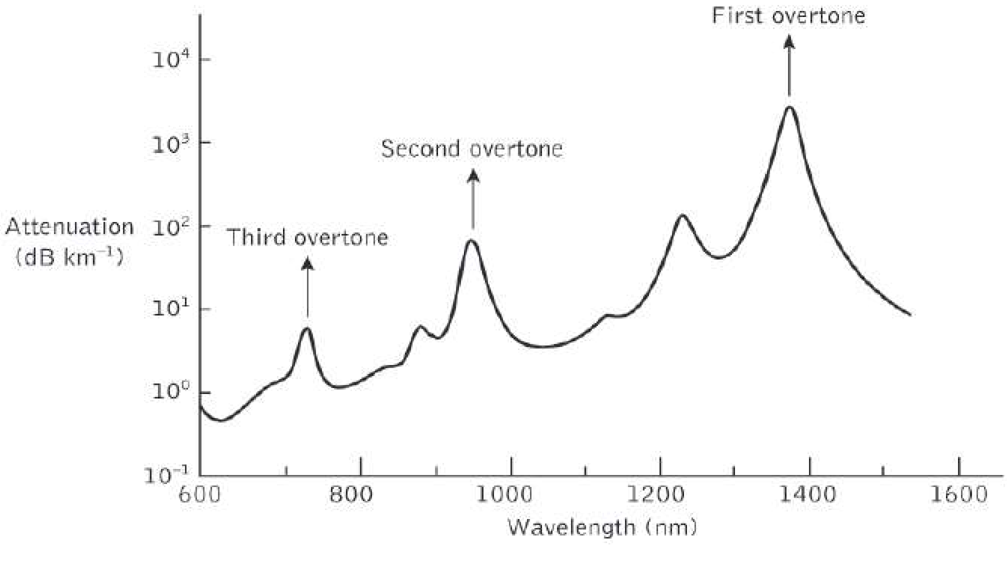


Figure 1.12 *The absorption spectrum for the hydroxyl (OH) group in Silica.[2]*

B. Scattering loss:

Scattering is a process whereby all or some of the optical power in a mode is transferred into another mode. There are four kinds of scattering loss in optical fiber: *Rayleigh*, *Mie*, *Brillouin*, and *Raman* scattering. Rayleigh is the most important scattering loss. During the manufacture process of glass fibers, some localized variation in density may happen due random motion of molecular. These material density variations may be modeled as small scattering objects embedded in an otherwise homogenous material [23].Because these object are much smaller than the operating wavelength, when beam of light passing through these object, some of its energy is scattered and lost.

- **Rayleigh scattering:**

Rayleigh scattering loss is wavelength dependent and is such that shorter wavelengths scatter more than longer wavelengths with the loss proportional to $\lambda{-}4$ where λ is the light wavelength.

Since Rayleigh scattering loss decreases with increases in wavelength, optical fibers operating at higher wavelengths are expected to have lower losses if all other loss mechanisms are eliminated.

the Rayleigh loss is given by:

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F \tag{1.3}$$

Where γ is the Rayleigh scattering, λ is the optical wavelength, n is the refractive index of the medium, p is the average photo elastic coefficient, βc is the isothermal compressibility at a fictive temperature TF and K is the Boltzmann’s constant.[2]

- **Mie scattering:**

It may occur at inhomogeneities which are comparable in size (> λ /10) to the guided wavelength. This results from the non-perfect cylindrical structure of the waveguide. The scattered light is unequal in energy to the incident light (inelastic scattering) and it is angle dependent where the energy is most intense towards the direction of the incident light.[2]

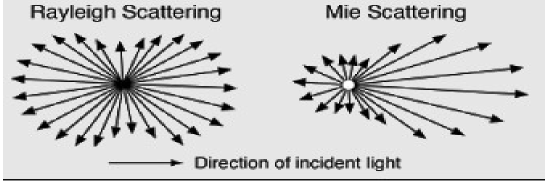


Figure1.13 *Difference between Rayleigh and Mie scattering.[24]*

C. Imperfection Loss:

Imperfection loss includes: *bending* and *splicing* losses.

- **Bending loss:**

It is a phenomenon that occurs when the optical fiber is bent tightly above the critical bend radius. Reasons for these bend losses are poor cable design, microscopic fiber deformation and improper handling of the optical fiber.[25]

There are two types of bending *Macro* and *Micro* bending. If the fiber is sharply bent so that the light traveling down the fiber cannot make the turn and gets lost then it is *Macro-Bending*. When small bends in the fiber created by crushing, construction cause the loss then it is called *Micro-Bending*. Generally, bending loss is not significant and can be neglected, unless the bending curvature is too large.[2]

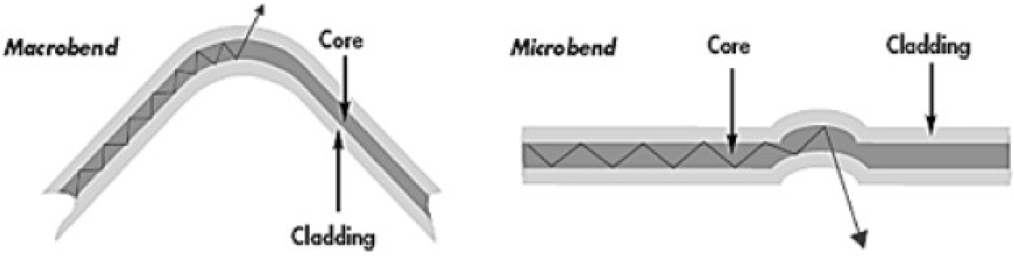


Figure1.14 *Macro- and Micro-bending in fibers.*

- **Splicing loss:**

Splicing loss refers to the part of the optical power that is not transmitted through the junction of two connected fibers and is radiated out of the fiber. The total loss in decibels at the fusion splice is given by the following equation:

$$\alpha_{Splice} = 10log_{10}\frac{P_{in}}{P_{trans}} \tag{1.4}$$

Where P_{in} is the total power incident on the fusion splice and P_{trans} is the portion of the optical power transmitted across the fusion splice.

1.5.2 Dispersion:

Dispersion is the major cause of signal distortion. It is the spreading of light pulse as its travels down the length of an optical fiber. Dispersion limits the bandwidth or information carrying capacity of a fiber. The bitrates must be low enough to ensure that pulses are farther apart and therefore the greater dispersion can be tolerated .[26]

The types of dispersion that affect the optical fiber are: *modal dispersion*, *material dispersion*, *waveguide dispersion*, *chromatic dispersion* and *polarization-mode dispersion.*[20]

A. Material dispersion:

It is the result of different wavelengths of light traveling at different velocities in the fiber. The slower wavelengths begin to lag behind as the light travels down the fiber core, causing the light to spread. If the light must travel a great distance, the lag in the slower wavelengths can cause them to overlap the faster wavelengths of the bits following them. These overlaps can degrade and ultimately destroy the signal.

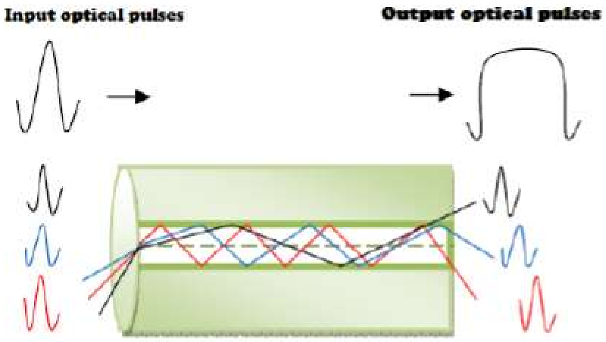


Figure 1.15 *Effects of material dispersion.*

B. Waveguide Dispersion :

Waveguide dispersion is most significant in a single-mode fiber, it occurs because optical energy travels in both core and cladding which have slightly different refractive indices. Altering the internal structures of the fiber, allows waveguide dispersion to be substantially changed, thus changing the specified overall dispersion of the fiber.[26]

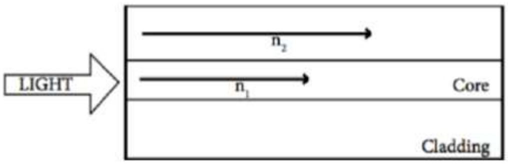


Figure 1. 16 *Effect of waveguide dispersion.*

C. Modal Dispersion:

It results from light taking different paths, or modes as it passes through the fiber. The number of modes the light can take is determined by the diameter of the fiber core, the refractive indices of the fiber core and cladding and the wavelength of the light. Depending on the mode, some parts of the light will pass through the fiber more quickly than others. The difference in travel time can cause parts of the light pulses to overlap each other, or in extreme cases to arrive in a different order from the order they were transmitted. The signal is then no longer usable.

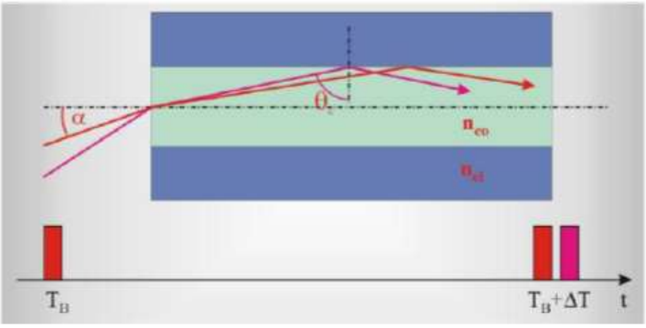


Figure1. 17 *Modal dispersion in multimode fiber.*

D. Chromatic Dispersion:

It refers to the different spectral components of light pulse traveling at different velocities with a propagation delay, this delay results from the combination of effects of material dispersion and waveguide dispersion.

E. Polarization modal dispersion:

Polarization modal dispersion (PMD) is a dispersion phenomenon usually associated with single mode fibers, where two polarized modes travel at different speed due to the variation in the cylindrical geometry of the fiber that results from the mechanical stress exerted upon it as well as the imperfections during the manufacturing process.

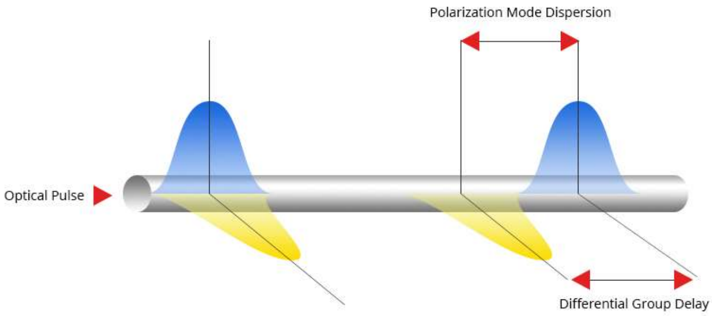


Figure1. 18 *Polarization mode dispersion in single mode fibers.*

1.5.3 Non linear effects

There exist two categories of non linear effects. The first arises due to the inelastic scattering where the light waves interact with phonons (molecular vibrations) in the silica medium. The second set of nonlinear effects is due to the dependence of the refractive index on the intensity of the applied electric field [27].

A. First category:

This category includes the two effects of Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS). Both of them can be understood as scattering of a photon to a lower energy photon such that the energy difference appears in the form of a phonon. The main difference between the two is that optical phonons participate in Raman scattering, whereas acoustic phonons participate in Brillouin scattering. Both scattering processes result in a loss of power at the incident frequency.

Even though SRS and SBS are quite similar in their origin, different dispersion relations for acoustic and optical phonons lead to the following differences: SBS occurs only in the backward direction whereas SRS can occur in both directions, the scattered light is shifted in frequency by about 10 GHz for SBS but by 13 THz for SRS, the Brillouin gain spectrum is extremely narrow compared to the Raman gain spectrum [1].

B. Second category:

The most important nonlinear effects in this category are Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four-Wave Mixing (FWM).

1.6 Wavelength Division Multiplexing (WDM)

In fiber optic communications, Wavelength Division Multiplexing (WDM) is a technology where a fiber is used to carry many separate and independent optical channels. The number of multiplexed channels is increased by reducing the channel spacing. The reduction in channel spacing increases the crosstalk and hence the performance of the system degrades considerably. WDM is an efficient mean for enabling bi-directional communication and increasing the transport capacity, or usable bandwidth particularly for optical single mode fibers.

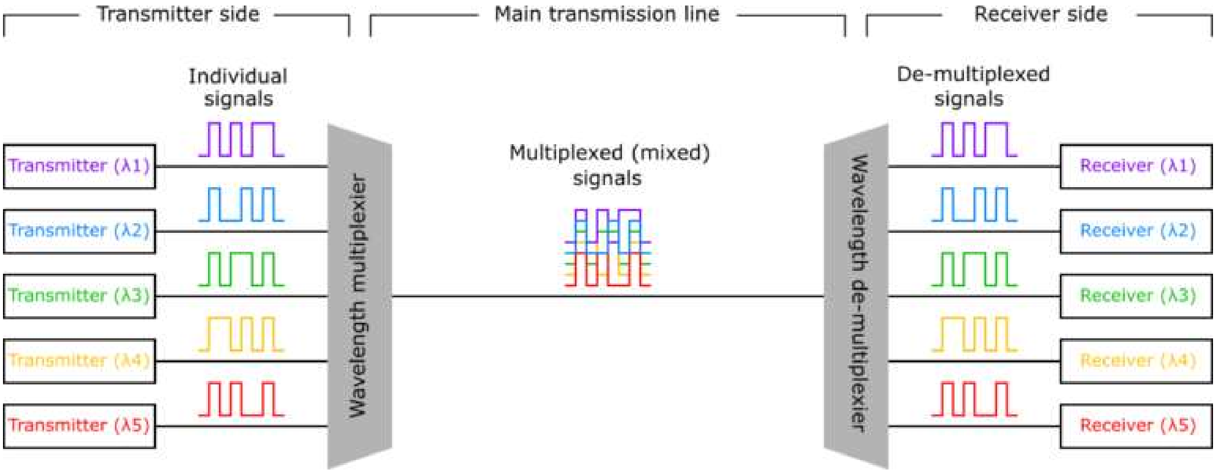


Figure 1.19 *Wavelength Division Multiplexing (WDM).[28]*

One primary advantage of using WDM technology is in reducing the number of fibers used in the main transmission line. The distance of an optical transmission line sometimes exceeds 1,000 km, and the cost of fiber cable manufacturing/deployment would become a serious issue if we need to install a high-fiber-count cable over a very long distance. Using WDM technology, the number of fibers in an optical cable is reduced, and the number of wavelength multiplexer/de-multiplexer basically remains the same no matter how long the transmission distance is. For that reason, WDM generally becomes advantageous as the transmission distance becomes longer.[28]

Chapter II

Optical Modulation Scheme

Chapter II : Optical Modulation Scheme

Modulation is the process of facilitating the transfer of information over a medium. In optical communications, the process of converting information so that it can be successfully sent through the optical fiber is called optical modulation. This can be performed by the optical transmitter that tends to modulate the carrier, being the optical signal, by *amplitude*, *frequency,* or *phase*.

2.1 Digital Modulation

In digital modulation techniques, an analogue carrier signal is usually modulated by a binary message code, and this process can be achieved by varying the physical characteristics of the carrier, such as amplitude, frequency, or phase, or a combination of them.[29]

Therefore, when the carrier amplitude varies, the modulation is named amplitude shift keying (ASK). When the carrier frequency changes on the basis of the message signal, the modulation is called frequency shift keying (FSK). When the carrier phase varies in accordance with the signal, the modulation is called phase shift keying (PSK). In addition, QAM is a combination of PSK and ASK.[29]

Then, three digital modulation formats can be defined: ASK, FSK, and PSK. Those digital modulation schemes form the basis of modulation formats in advanced optical fiber communication systems.

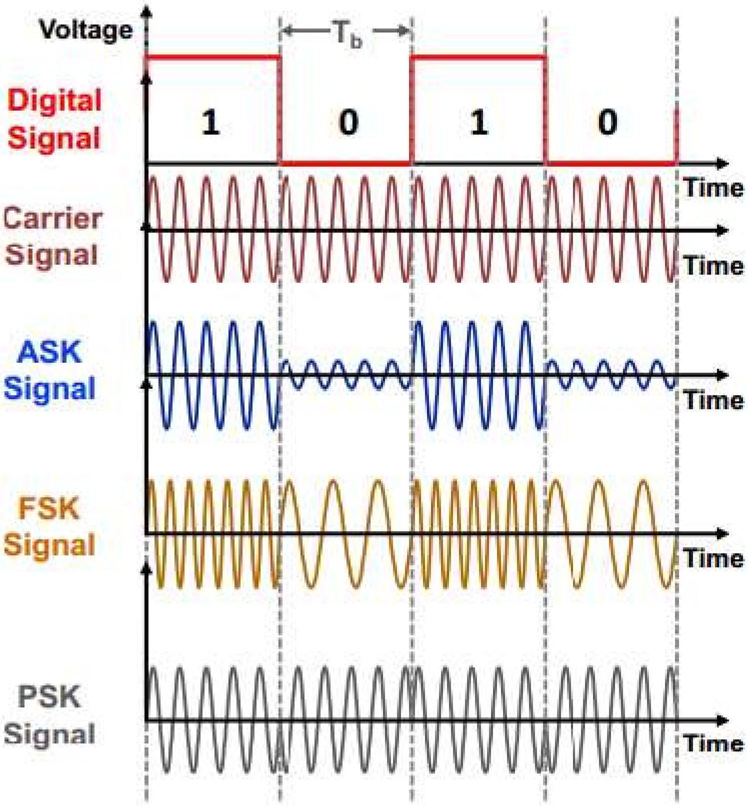


Figure 2. 1 *Illustration of ASK, FSK, and PSK with the symbol and the variation of the optical carrier: amplitude, frequency and phase.*

The optical signal field has the ideal form during the duration of 1-bit period given As[30]:

$$E_S(t) = E_p(t)a(t)\cos[\omega(t)t + \theta(t)] \quad 0 \le t \le T \qquad (2.1)$$

Where:

$E(t)$: is the optical signal field.

$E(t)$: is the polarized field coefficient as a function of time.

$a\ (t)$: is the amplitude variation.

$\omega(t)$: is the optical frequency change with respect to time.

$\theta(t)$: is the phase variation with respect to time.

In ASK, the amplitude of the lightwave carrier, normally generated by a narrow-linewidth laser source, is changed in response to the digital data, keeping everything else fixed. That is, bit 1 is transmitted by the lightwave carrier of a particular amplitude. To transmit 0, the amplitude is changed keeping the frequency unchanged.[31]

In FSK, the frequency of the carrier represents the digital information. One particular frequency is assigned to 1, and another frequency is assigned to 0.[31]

In PSK, the phase of the lightwave carrier is changed to represent the information. The phase in this context is the shift of the angle at the phasor vector initial position at which the sinusoidal carrier starts. To transmit a 0, the phase would be shifted by π and a 1 with no change of phase.[31]

2.2 M-ary Modulation

With the advent of coherent detection technology and high-speed digital signal processing (DSP), multi-level modulation formats such as multi-level phase-shift keying (M-PSK) and quadrature amplitude modulation (QAM) are recognized as promising approaches to meet the increasing demand for spectral efficiency and system throughout in future optical communication systems[32].

An M-ary modulation is a type of digital modulation where instead of transmitting one bit at a time, two or more bits are transmitted simultaneously. This type of transmission results in reduced channel bandwidth. However, sometimes, two or more quadrature carriers are used for modulation.

The word *binary* represents two bits. M represents a digit that corresponds to the number of conditions, levels, or combinations possible for a given number of binary variables.

Multi-level M−ary modulation techniques are used in digital communications as the digital inputs with more than two modulation levels are allowed on the transmitter’s input. Hence, these techniques are bandwidth efficient.

There are many M-ary modulation techniques. Some of these techniques, modulate one parameter of the carrier signal, such as *amplitude*, *phase*, and *frequency*.

- **M-ary ASK** : M-ary Amplitude Shift Keying M-ASK or M-ary Pulse Amplitude Modulation PAM. The *amplitude* of the carrier signal, takes on M different levels.

$$S_m(t) = A_m \cos(2\pi f_c t) ; \quad m = 1,2, \dots \dots M \text{ and } 0 \leq t \leq T_s \tag{2.2}$$

- **M-ary FSK** : M-ary Frequency Shift Keying M−aryFSK. The *frequency* of the carrier signal, takes on M different levels.

$$S_i(t) = \sqrt{\frac{2E_s}{T_s}} \cos\left(\frac{\pi}{T_s}(n_c + i)t\right) ; \quad i = 1,2, \dots \dots M \text{ and } 0 \leq t \leq T_s \tag{2.3}$$

- **M-ary PSK** : M-ary Phase Shift Keying M−aryPSK. The *phase* of the carrier signal, takes on M different levels.

$$S_i(t) = \sqrt{\frac{2E}{T}} \cos(\omega_0 t + \phi_i t) ; \quad i = 1,2, \dots \dots M \text{ and } 0 \leq t \leq T \tag{2.4}$$

Where the phase term, $\phi_i(t) = \frac{2\pi i}{M}$.

Advanced M-ary modulation formats have received considerable attention in the area of Optical communication. In this work, we examine four techniques, namely: **M-PSK(8-PSK)** , **M-QAM(8-QAM)**.

8-ary modulation formats, for example optical 8-ary phase-shift keying (8PSK) and circular 8-ary quadrature amplitude modulation (8QAM), carry 3 bit per symbol, have similar spectral width, and have comparable implementation complexity.

2.3 M-PSK(Q/8-PSK) Modulation

Phase-shift keying (PSK) is a digital modulation process which conveys data by changing (modulating) the phase of a constant frequency reference signal (the carrier wave). The modulation is accomplished by varying the *sine* and *cosine* inputs at a precise time.

Any digital modulation scheme uses a finite number of distinct signals to represent digital data. PSK uses a finite number of phases, each assigned a unique pattern of binary digits. Usually, each phase encodes an equal number of bits. Each pattern of bits forms the symbol that is represented by the particular phase.

The M-PSK modulator transmits a series of information symbols drawn from the set

$\boldsymbol{m} \in \{\boldsymbol{1}, \boldsymbol{2}, \dots, \boldsymbol{M}\}$.

Each transmitted symbol holds $\boldsymbol{k}$ bits of information ($\boldsymbol{k} = \boldsymbol{log2}(\boldsymbol{M})$). The information symbols are modulated using M-PSK mapping.

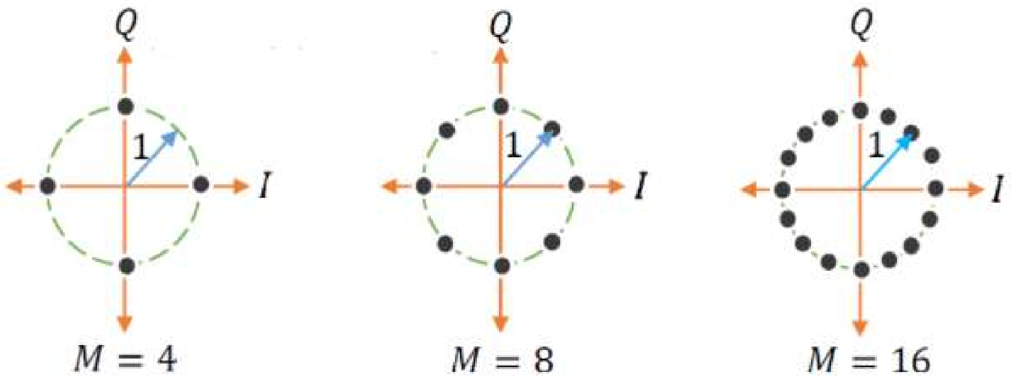


Figure 2. 2 *Signal space constellations for various MPSK modulations.[5]*

For PSK, all of the symbols have the same carrier frequency and amplitude; only their phase is different. For that reason, on a PSK constellation diagram, all of the symbols appear on a circle about the origin.

The general expression for a M-PSK signal set is given by :

$$S_m(t) = A\cos\left[2\pi f_c t - \frac{(m-1)2\pi}{M}\right]; \quad m \in \{1,2,\dots,M\}. \tag{2.5}$$

M denotes the modulation order and it defines the number of constellation points in the reference constellation. The value of ***M*** depends on the parameter ***k*** – the number of bits we wish to squeeze in a single MPSK symbol.

2.3.1 Transmitter

The transmitter uses the equation 2.5 to construct the output signal of M-PSK modulator, such that:

$$S_m(t) = A\cos[2\pi f_c t - \varphi_m]; \quad m \in \{1,2,\dots,M\}. \tag{2.6}$$

$$\varphi_m = -\frac{(m-1)2\pi}{M}$$

$$S_m(t) = A[\cos(2\pi f_c t)\cos(\varphi_m) - \sin(2\pi f_c t)\sin(\varphi_m)]$$

$$S_m(t) = A\left[\sqrt{\frac{2}{T}}\cos(2\pi f_c t)\sqrt{\frac{T}{2}}\cos(\varphi_m) - \sqrt{\frac{2}{T}}\sin(2\pi f_c t)\sqrt{\frac{T}{2}}\sin(\varphi_m)\right]$$

$$S_m(t) = A\sqrt{\frac{T}{2}}\cos(\varphi_m)\sqrt{\frac{2}{T}}\cos(2\pi f_c t) - A\sqrt{\frac{T}{2}}\sin(\varphi_m)\sqrt{\frac{2}{T}}\sin(2\pi f_c t)$$

$$S_m\,(t) = \sqrt{E}\ \cos(\varphi_m)\ \theta_1\,(t) + \sqrt{E}\ \sin(\varphi_m)\ \theta_2\,(t) \qquad (2.7)$$

E is the signal's energy, φ_m is the phase that represents each symbol, $\theta_1(t)$ and $\theta_2(t)$ are called the basis of the signal such that $\theta_1(t) = \sqrt{\frac{2}{T}}\cos(2\pi f_c t)$ and $\theta_2(t) = \sqrt{\frac{2}{T}}\sin(2\pi f_c t)$, from Equation (2.7) the transmitter is no more than two multiplications and one addition

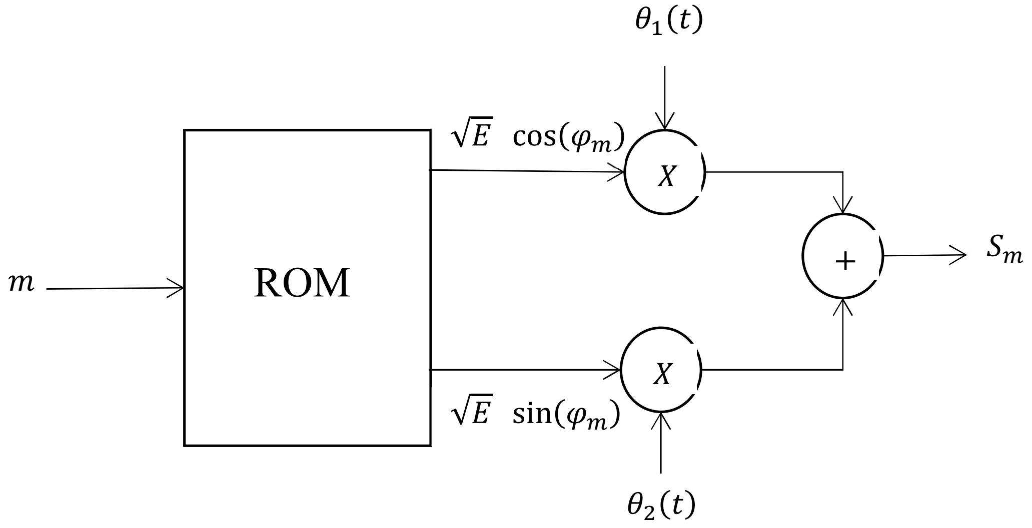


Figure 2. 3 *M-PSK Transmitter*

2.3.2 Receiver

As the signal S_m travels through the channel a noise $n(t)$ is added to it, this makes the design of the receiver more complicate, the noise is assumed random signal with This signal is added to a white Gaussian noise, the signal at the receiver $R_m$can be written as:

$$R_m(t) = S_m(t) + n(t)$$

Figure 2.6 shows the structure of M-PSK receiver, the received signal passes through two correlators each correlator defined by is basis function ($\theta_1(t)$ and$\theta_2(t)$) the correlators are used in order to minimize the probability of error of the receive, the output of the correlators passes through decision device to decide which symbol was sent.

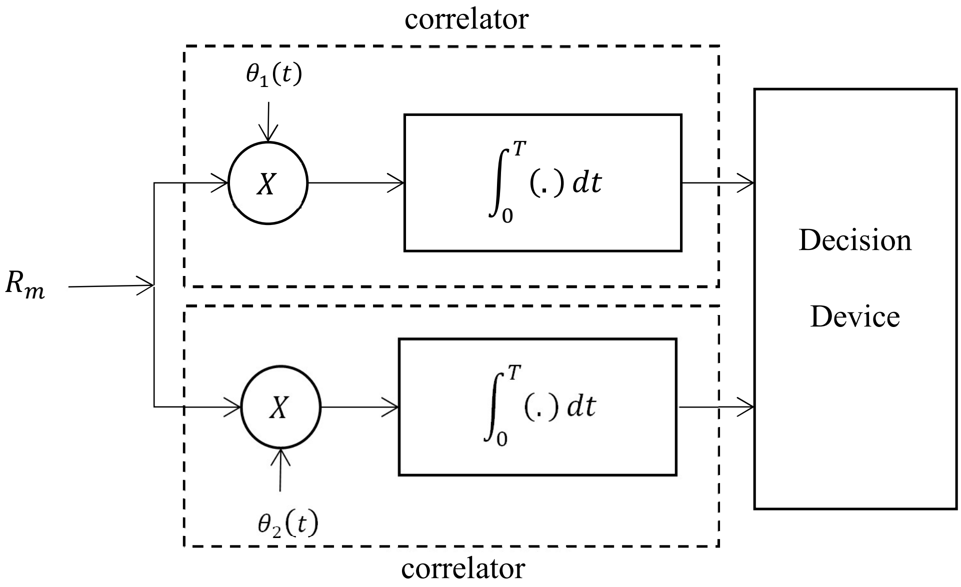


Figure 2. 4 *M-PSK receiver*

2.4 M-QAM(4/8-QAM) Modulation

By combining amplitude (PAM) (by varying the amplitudeA_m) and phase modulation (PSK) (by varying the phase φ_m) we can obtain the signal waveform for QAM.

$$S_m(t) = A_m \cos(2\pi f_c t - \varphi_m)$$

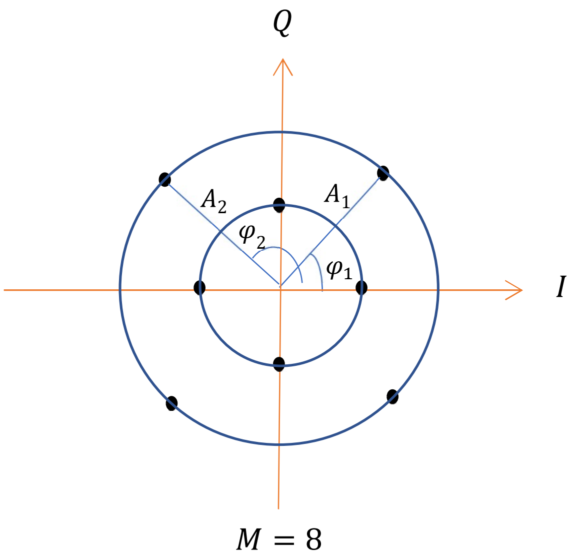


Figure 2. 5 *Signal space constellations for 8-QAM modulation.*

2.4.1 Transmitter

Like M-PSK, the signal of M-QAM modulator is two numbers (they represent the message m) each one multiplied by a basis functions The Basis $\theta_1(t) = \sqrt{\frac{2}{T}}\cos(2\pi f_c t)$ and $\theta_2(t) = \sqrt{\frac{2}{T}}\sin(2\pi f_c t)$.

$$S_m(t) = A[\cos(2\pi f_c t)\cos(\varphi_m) - \sin(2\pi f_c t)\sin(\varphi_m)]$$

$$S_m(t) = A_m\left[\sqrt{\frac{2}{T}}\cos(2\pi f_c t)\sqrt{\frac{T}{2}}\cos(\varphi_m) - \sqrt{\frac{2}{T}}\sin(2\pi f_c t)\sqrt{\frac{T}{2}}\sin(\varphi_m)\right]$$

$$S_m(t) = A_m\sqrt{\frac{T}{2}}\cos(\varphi_m)\sqrt{\frac{2}{T}}\cos(2\pi f_c t) - A_m\sqrt{\frac{T}{2}}\sin(\varphi_m)\sqrt{\frac{2}{T}}\sin(2\pi f_c t)$$

$$S_m(t) = \sqrt{E_m}\ \cos(\varphi_m)\ \theta_1(t) + \sqrt{E_m}\ \sin(\varphi_m)\ \theta_2(t)$$

E_m is the signal's energy of the symbol m, φ_m is the phase that represents the symbol m, $\theta_1(t)$ and $\theta_2(t)$ are the basis of the signal such that $\theta_1(t) = \sqrt{\frac{2}{T}}\cos(2\pi f_c t)$ and $\theta_2(t) = \sqrt{\frac{2}{T}}\sin(2\pi f_c t)$, the numbers $I = \sqrt{E_m}\ \cos(\varphi_m)$ and $Q = \sqrt{E_m}\ \sin(\varphi_m)$, Each symbol can be represented by a Binary code Figure 2.7, in this way we can convert $I = \sqrt{E_m}\ \cos(\varphi_m)$

and $Q = \sqrt{E_m}\ \sin(\varphi_m)$ using two level converter (in this case DAC), M-QAM transmitter is shown in Figure 2.8.

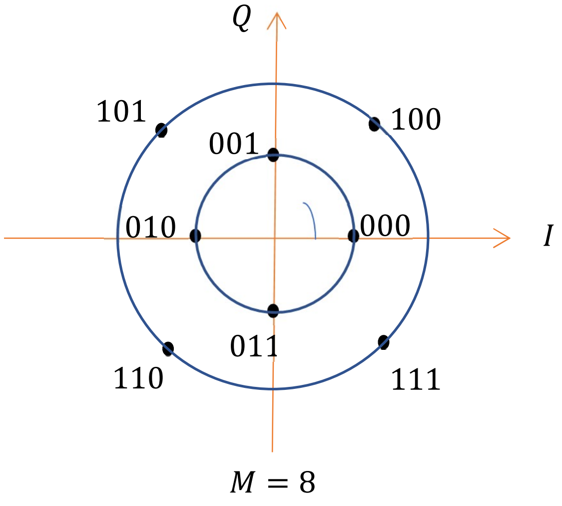


Figure 2.6 *Binary Representation of 8-QAM Symbols.*

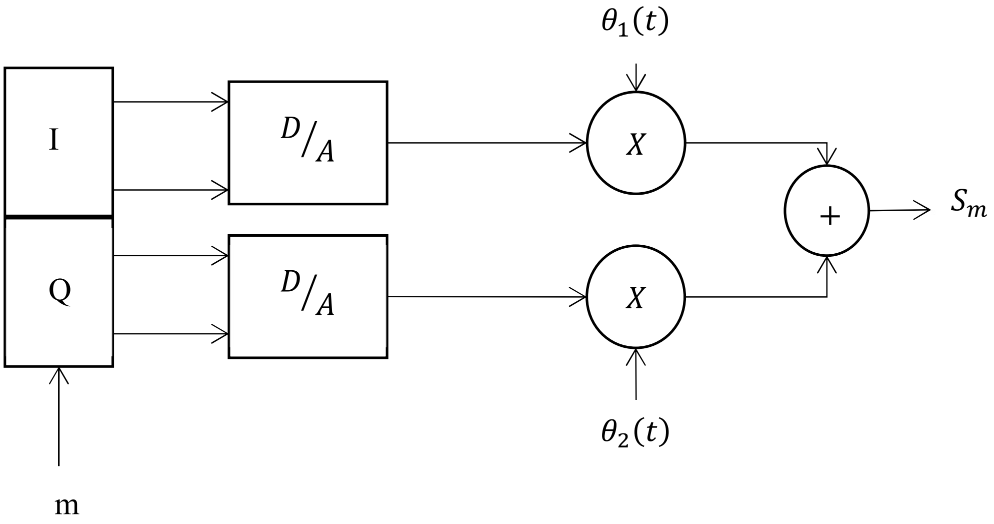


Figure2.7 *Basic architecture of M-QAM transmitter*

2.4.2 Receiver

The receiver of M-QAM has the same structure as M-PSK, two correlators, two level converters (Analog to Digital Converter) and parallel to serial converter (PSC).

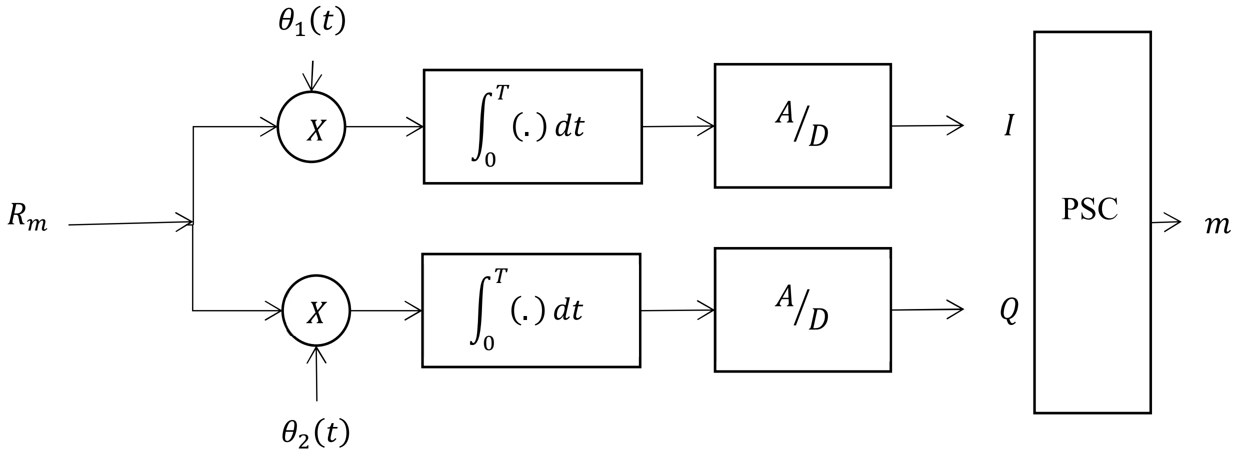


Figure 2. 6 *M-QAM receiver*

2.5 Coherent Communication

Intensive modulation of direct detection (IM/DD) is a method where a simple and cost-effective light-wave transmission scheme in which the light intensity of the optical source is modulated linearly with respect to the input electrical signal voltage. This scheme pays no attention to the frequency or phase of optical carrier, since a photodetector at the receiving end only responds to the changes in the power level (intensity) that falls directly in it. The photodetector then transforms the optical power level variations back to the original electrical signal format. Although methods adopt IM/DD offer simplicity and relatively low cost, their sensitivities are limited by noise generated in the photodetector and receiver preamplifier. These noises degrade the receiver sensitivities of square-law IM/DD transmission systems by 10 to 20 dB from the fundamental quantum noise limit.

Coherent optical transmission is a technique that uses modulation of the amplitude and phase of the light, as well as transmission across two polarizations, to enable the transport of considerably more information through a fiber optic cable.

Coherent detection solves this problem that network providers are facing. It takes the typical ones and zeroes in a digital signal (the blinking on and off of the light in the fiber) and uses sophisticated technology to modulate the amplitude and phase of that light and send the signal across each of two polarizations. This, in turn, imparts considerably more information onto the light speeding through a fiber optic cable. The reason is that the digital coherent receiver enables us to employ a variety of spectrally efficient modulation formats such as M-ary phase-shift keying (PSK) and quadrature-amplitude modulation (QAM), relying upon stable carrier-phase estimation in the digital domain. In addition, because the phase information is preserved after detection, we can equalize linear transmission impairments such as group-velocity dispersion (GVD) and polarization-mode dispersion (PMD) of transmission fibers via digital signal processing (DSP).

Also, motivation is to develop methods for meeting the ever-increasing bandwidth demand with multi-level modulation formats based on coherent technologies[33]. The first step in the revival of coherent optical communications research was triggered by the QPSK modulation/demodulation experiment featuring optical IQ modulation (IQM) and optical delay detection [34]. The next stage emerged with high-speed DSP. In the field of optical communications, digital techniques have been widely applied to transmitters and receivers.

A receiver, in which the signal is interfered with a local oscillator (LO) so as to extract the phase information of the signal, is called a coherent receiver. In the case of coherent receivers, we can restore full information on optical carriers, namely, in-phase and quadrature (IQ) components (or amplitude and phase) of the complex amplitude of the optical electric field . In order to gain such a significant advantage, coherent receivers are highly sensitive to random variations in the phase and SOP of the incoming signal.[35]

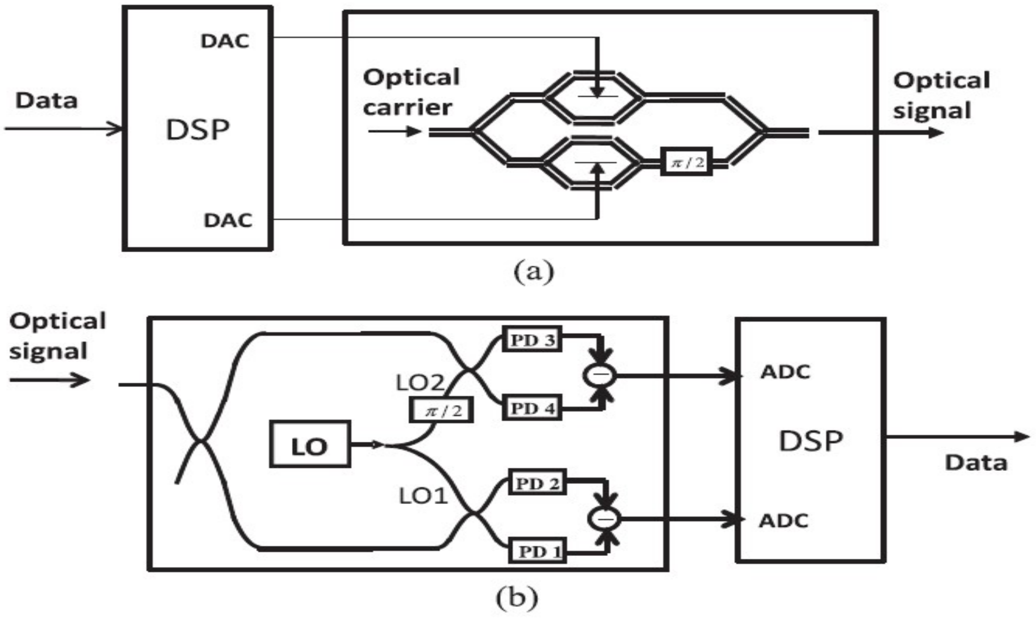


***Figure 2.** 7 Coherent communication (a)transmitter (b)receiver.[8]*

Figure (2.9) illustrates the fundamental concept of coherent light-wave systems. The main idea in the coherent detection technique is to amplify the incoming signal by coupling it to a local generated continuous wave (CW) optical field. In communication systems, coupling means that if we have two signals with frequencies $\omega 1$ and $\omega 2$, the output will be other waves with frequencies equal to $2\omega 1$, $2\omega 2$, and $\omega 1 \pm \omega 2$. All these frequencies are filtered at the receiver except $\omega 1 - \omega 2$ in coherent light-wave systems. CW signal is created by a device called local oscillator (LO). Result of this coupling process is a dominant receiver noise. Then the LO noise that can be subtracted to get the original signal i.e. limited sensitivity at receiver.

To simplify this concept and to find out how receiver sensitivity performance will be improved, let us consider the electric field of transmitted signal having the form:

$$E_s = A_s \cos[\omega_s t + \varphi_s(t)] \tag{2.12}$$

where, As is the amplitude of the optical signal field, ωs is the optical signal carrier frequency, and $\varphi_s(t)$ is the phase of the optical signal. So, amplitude, frequency or phase of the optical signal can be modulated to send information. Following are the modulation techniques that can be used:

- Phase shift keying (PSK). In this method, data is transmitted by varying the phase with sine wave $\varphi s(t) = \beta \sin \omega_m t$, where β is the modulation index and ω_m is the modulation frequency.
- Quadrature amplitude modulation (QAM).In this method, data is transmitted by varying two parameters, the phase with sine wave $\varphi_s(t) = \beta \sin \omega_m t$,and the amplitude which will carry 0 or 1 bit during each bit-period depending on which is transmitted.

And If local oscillator (LO) has the form:

$$E_{LO} = A_{LO} \cos[\omega_{LO} t + \varphi_{LO}(t)] \tag{2.13}$$

where, A_{LO} is the amplitude of the LO signal field, ωLO is the optical LO carrier frequency, and $\varphi_{LO}(t)$ is the phase of the optical LO. Then the detected current $I_{coh}(t)$ will be proportional to the square of the total electric field of the signal falling on the photodetector. Here, we have to mention that LO wave will be coupled with received signal before (on the surface) the photodetector, This info gives:

$$I_{coh}(t) = (E_s + E_{LO})^2 \tag{2.14}$$

$$= \frac{1}{2}A_s^2 + \frac{1}{2}A_{LO}^2 + A_s A_{LO} \cos[(\omega_s - \omega_{LO})t + \varphi_s(t) - \varphi_{LO}(t)] \cos\theta(t)$$

Where,

$$\cos\theta(t) = \frac{E_s E_{LO}}{|E_s||E_{LO}|} \qquad (2.15)$$

Represents the polarization misalignment between the signal wave and LO wave. Since the optical power is proportional to the intensity at the photo detector, we then have

$$P(t) = P_s + P_{LO} + 2\sqrt{P_s P_{LO}} \cos[(\omega_s - \omega_{LO})t + \varphi_s(t) - \varphi_{LO}(t)] \cos\theta(t) \qquad (2.16)$$

where, P_s and P_{LO} are the signal and LO optical powers, respectively, with $P_{LO} \gg P_s$. Thus, we see the angular frequency difference $\omega_{IF} = \omega_s - \omega_{LO}$ is an intermediate frequency, and the phase angle $\varphi(t) = \varphi_s(t) - \varphi_{LO}(t)$ is the time-varying phase difference between the signal and LO levels. Normally, ωIF is in radio frequency range of tens or hundreds of megahertz.

Chapter III

Simulation and Results

The purpose of this simulation is to examine two different optical modulation formats (*M-PSK* and *M-QAM*) at different modulation order (*M=4* & *M=8*).

Different bit rate levels of 15Gbps, 30Gbps and 56Gbps will be used, and each level will be tested under different input power and different optical fiber lengths.

The performance of the tested communication systems will be analyzed by comparing the resulting bit errors and the constellation diagrams at the coherent receiver of the systems.

The simulations will be performed using the *Optisystem* as simulator.

3.1 Optisystem Software

OptiSystem is an optical communication system simulation package for the design, testing, and optimization of virtually any type of optical link in the physical layer of a broad spectrum of optical networks, from analog video broadcasting systems to intercontinental backbones. A system level simulator based on the realistic modeling of fiber-optic communication systems, OptiSystem possesses a powerful simulation environment and a truly hierarchical definition of components and systems.

3.2 Constellation Diagram

A constellation diagram is a representation of a signal modulated by a digital modulation scheme such as quadrature amplitude modulation or phase-shift keying.[36] It displays the signal as a two-dimensional XY-plane scatter diagram in the complex plane at symbol sampling instants. The angle of a point, measured counterclockwise from the horizontal axis, represents the phase shift of the carrier wave from a reference phase. The distance of a point from the origin represents a measure of the amplitude or power of the signal.

The carrier representing each symbol can be created by adding together different amounts of a cosine wave representing the "I" or in-phase carrier, and a sine wave, shifted by 90° from the I carrier called the "Q" or quadrature carrier. Thus each symbol can be represented by a complex number, and the constellation diagram can be regarded as a complex plane, with the horizontal real axis representing the I component and the vertical imaginary axis representing the Q component. A coherent detector is able to independently demodulate these carriers. This principle of using two independently modulated carriers is the foundation of quadrature modulation. In pure phase modulation, the phase of the modulating symbol is the phase of the carrier itself and this is the best representation of the modulated signal.

Most digital modulation schemes involve a discrete number of symbols which are used to convey information. These symbols are mapped to a discrete set of magnitude and phase values on the I/Q plane, which are referred to as constellation points.[37]

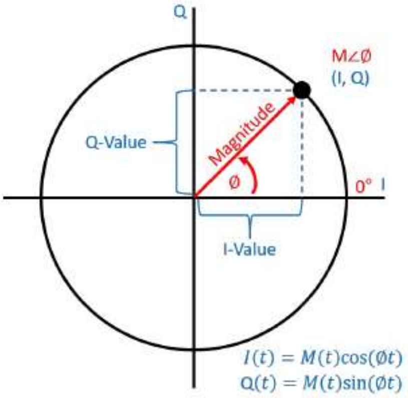


Figure 3. 1 *I/Q diagram superimposed on polar diagram.[2]*

constellation diagrams are useful for graphically visualizing signal data to quickly identify problems, it is also useful to quantify the disparity between measured and ideal signals.

Magnitude error is the difference in magnitude between the actual and ideal signals, while phase error is the angle between the measured and ideal phasors.

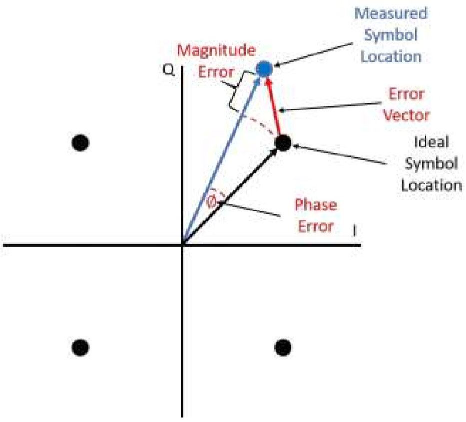


Figure 3. 2 *Error vector for constellation diagram.[2]*

EVM is the scalar distance between the end points of the measured and ideal phasors, and is a measure of how well a digital communications system is performing. EVM can be defined in both percentage and dB .

3.3 Simulation

In our simulation, we are going to study the effect of modulation on the fiber communication system.to do so, two modulation format (M-PSK, M-QAM) are chosen, these modulations are tested under three parameter variables (length, input power and bit rate).

These parameters valued in the following table:

Table 3. 1 *System parameters*

Parameters	**Value**
Bit rate	15 Gbps, 30 Gbps, 56 Gbps
Wavelength	1550 nm
Order of modulation	8 (3 bits/symbol)
Dispersion coefficient of fiber	16 ps/nm/km
Attenuation of fiber	0.2 dB
Laser linewidth	10e-04 MHz
Laser input power	5 dBm, 10dBm, 15dBm
Fiber length	0 – 200 km

3.3.1 Transmitter models

A. M-PSK transmitter model

The optical coherent 8-PSK transmitter is shown in the figure (3.3). The 8-PSK signal is generated by using Mach-Zehnder (MZ) modulators to encode the 8-PSK symbols onto an optical carrier. Each modulator branch modulates the in-phase (I) and quadrature component (Q) of a carrier.

First, the PSK sequence generator generates two parallel 8-ary symbol sequences from binary signals using phase shift keying modulation (PSK). These symbol sequences are transformed into multilevel pulses, and the pulses are encoded into an optical signal by two MZ modulators, one in each branch with a phase difference of π/2 between them. Finally, we combine the two parallel conjugate outputs using a 3dB cross coupler.

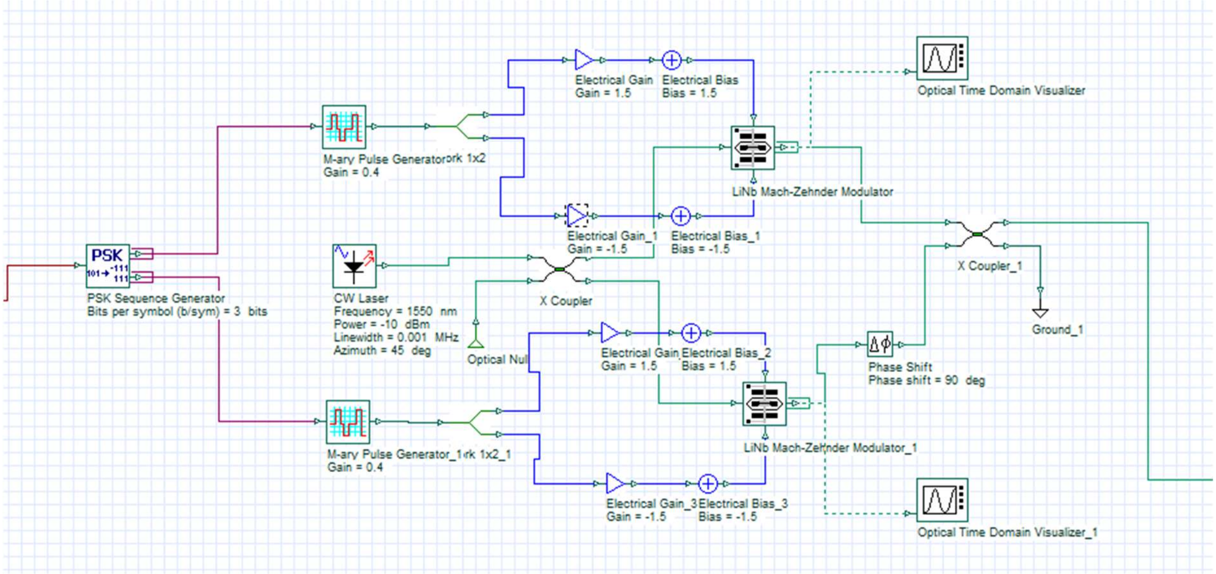


Figure 3. 3 *8-PSK transmitter model.*

B. M-QAM transmitter model

The same optical modulation as the previous one, the differences are in the 8-QAM transmitter (sequence generator).

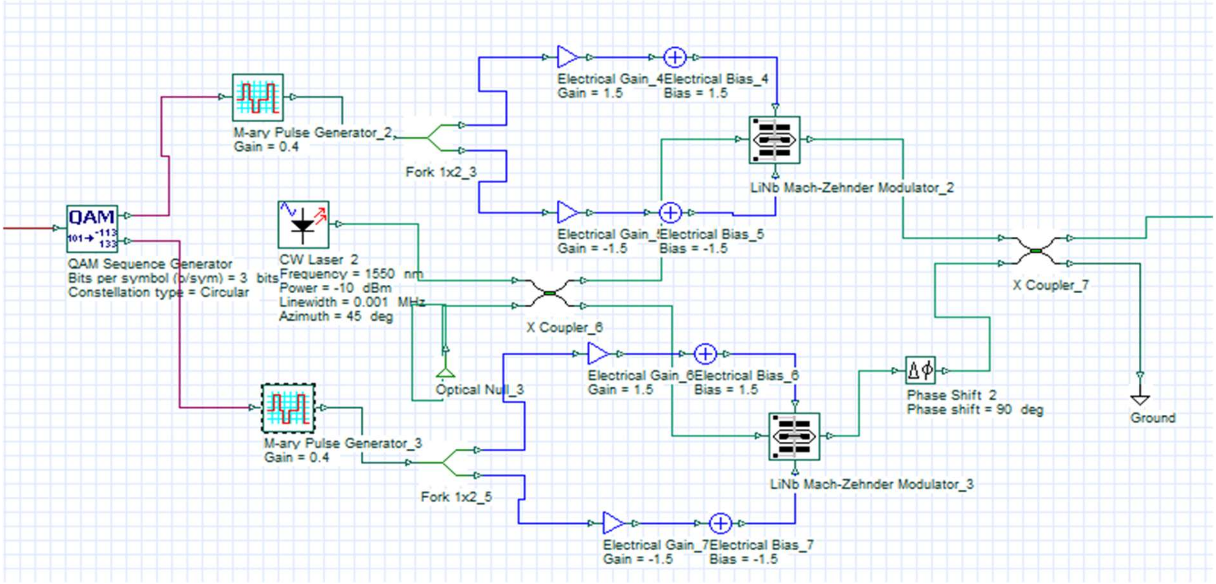


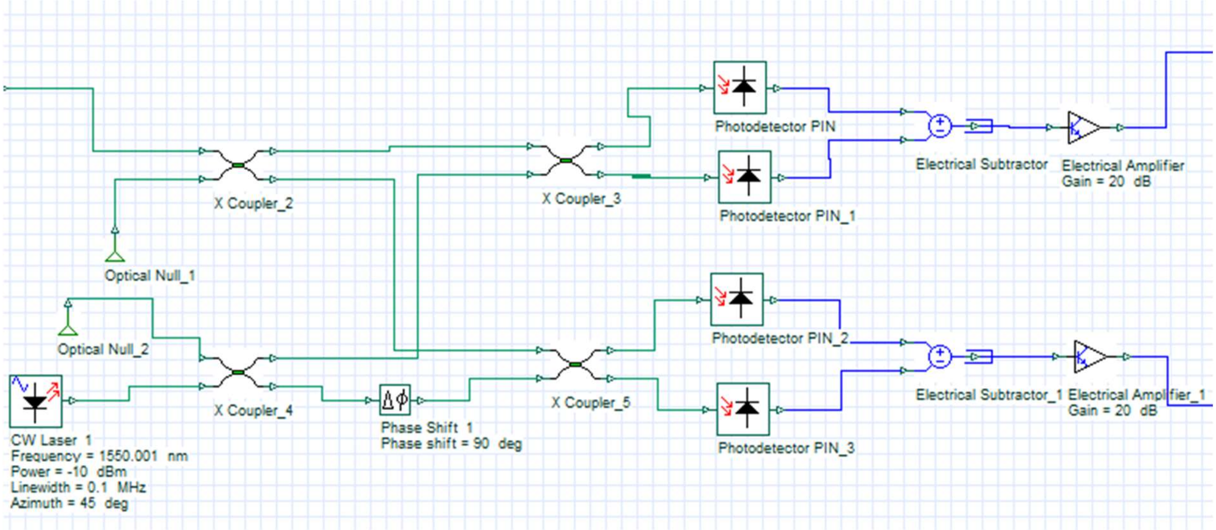
Figure 3. 4 *8-QAM transmitter model.*

3.3.2 Receiver Models

A. M-PSK receiver model

The receiver model consists of a coherent detector and digital signal processing (DSP) modules. The coherent detector is formed by a set of 3 dB fiber couplers, an LO laser, and a balanced detection. Figure (3.5) shows the layout representing the receiver.

The DSP modules perform several important functions to aid in recovering the incoming transmission channel(s) after coherent detection.



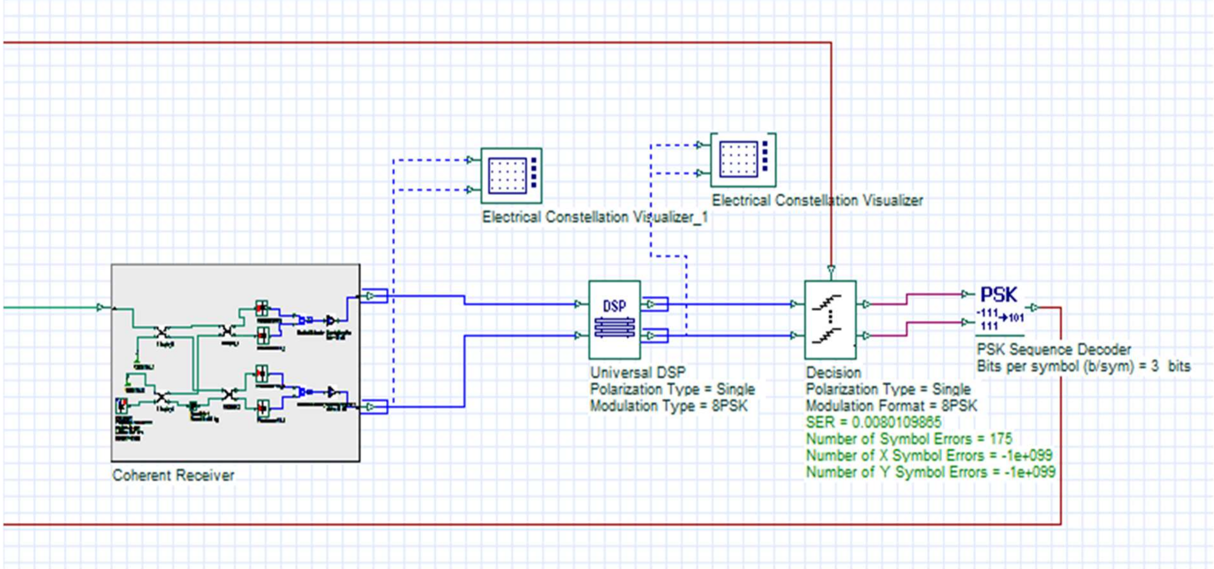
Electrical Amplifier
Gain = 20 dB

Electrical Amplifier_1
Gain = 20 dB

CW Laser 1
Frequency = 1550.001 nm
Power = -10 dBm
Linewidth = 0.1 MHz
Azimuth = 45 deg

Phase Shift 1
Phase shift = 90 deg

Figure 3. 5 Coherent detector.



Universal DSP
Polarization Type = Single
Modulation Type = 8PSK

Decision
Polarization Type = Single
Modulation Format = 8PSK
SER = 0.0080109865
Number of Symbol Errors = 175
Number of X Symbol Errors = -1e+099
Number of Y Symbol Errors = -1e+099

PSK Sequence Decoder
Bits per symbol (b/sym) = 3 bits

Figure 3. 6 8-PSK receiver.

B. M-QAM receiver model

The same optical coherent detector as the previous one, the differences are in the 8-QAM DSP module which uses different algorithms in recovering this type of modulation.

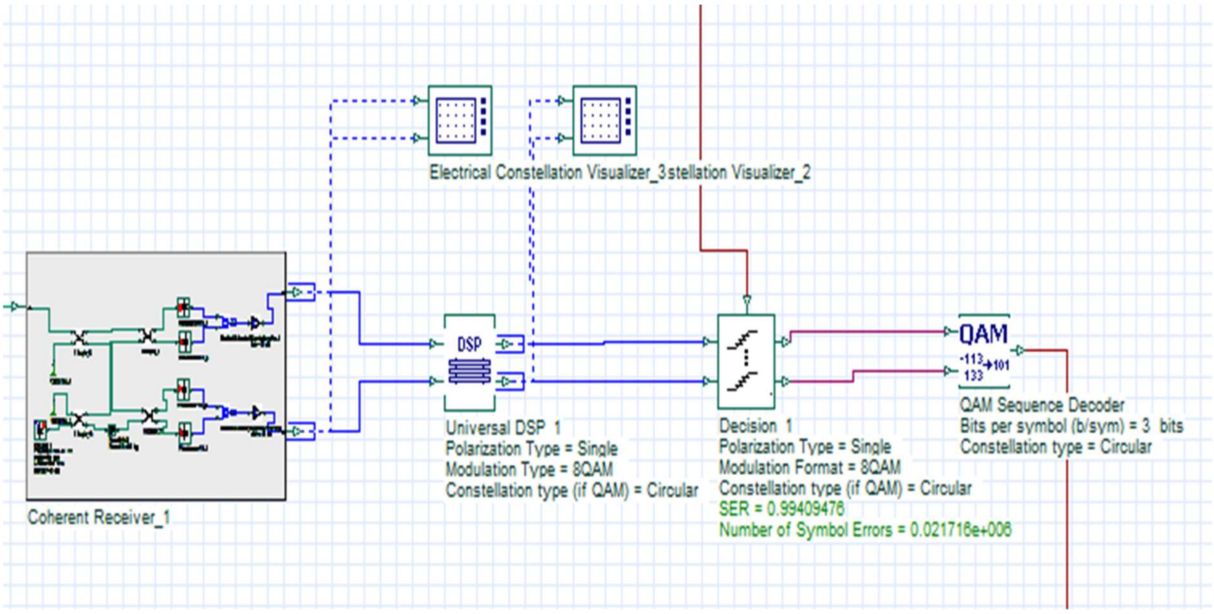


Figure 3. *7 8-QAM receiver.*

3.4 Simulation Result & discussion

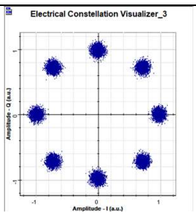
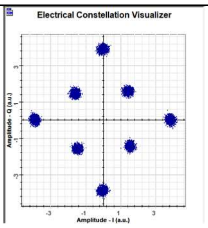
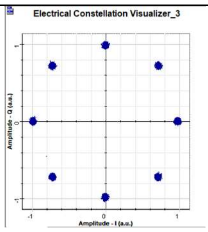
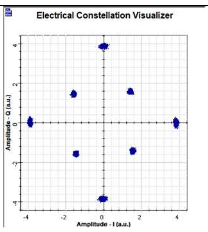
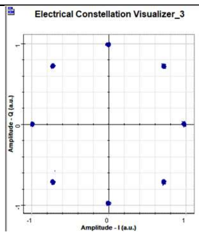
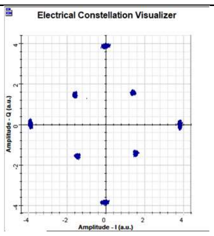
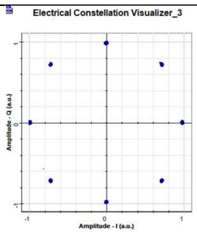
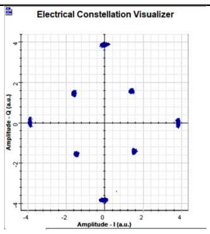
Using the specification in the table 3.1 with three-bit rate levels 15Gbps, 30Gbps and 54Gbps for the two-modulation format (M-PSK&M-QAM), the tests done by varying the input power and the fiber length.

3.4.1 Bit rate 15Gbps

A. Input power sweeps:

The simulation sweeps the power range [-10dBm to 15dBm] in a back-to-back system for the two modulation formats.

Table 3. 2 Constellation diagrams of 8-PSK/QAM for different power levels at 15 Gbps.

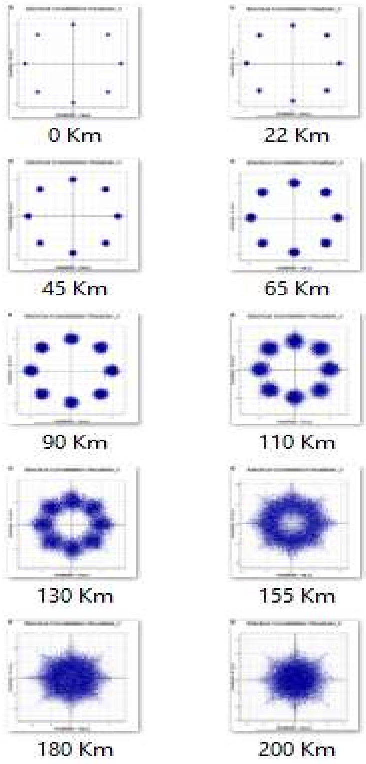
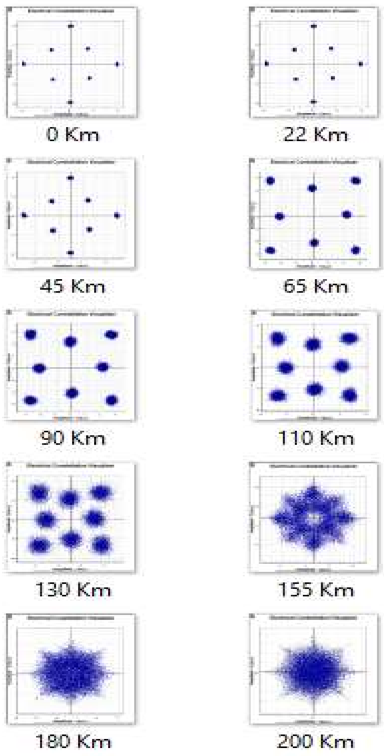
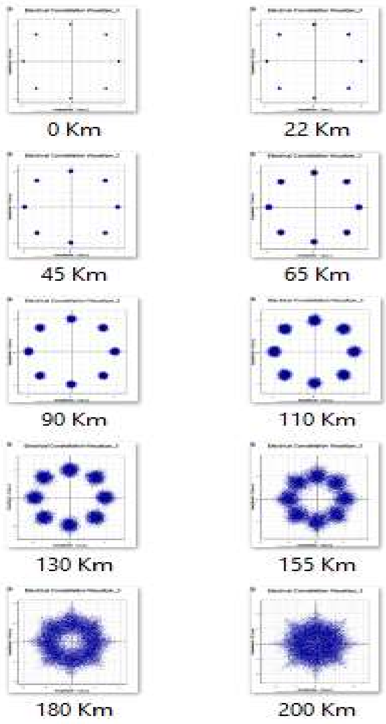
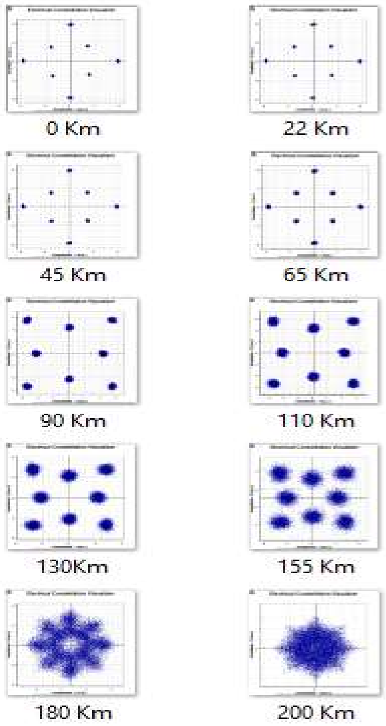
	8-PSK	8-QAM
-10 dBm		
0 dBm		
10 dBm		
15 dBm		

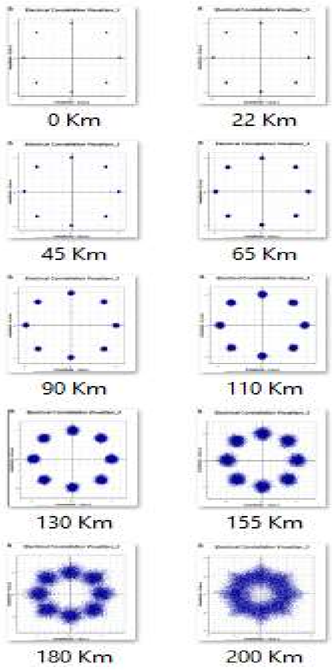
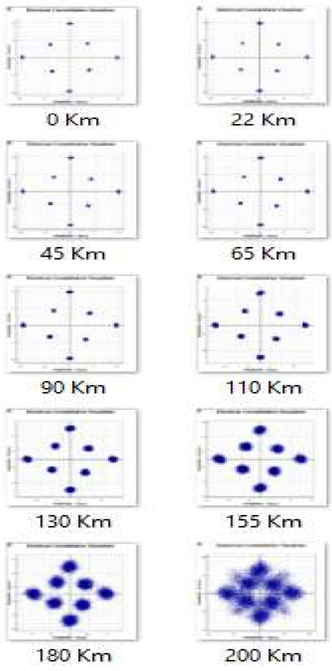
We can see that when increasing power injected into the continuous wave (CW) laser at the transmitters of both modulation formats, the quality of received signals has improved, as seen in table 3.2 with the constellation diagrams.

B. **Fiber length sweeps:**

The simulation sweeps the optical fiber length [0km – 200km] at three input power levels 5dBm, 10 dBm, 15 dBm.

Table 3. 3 *Constellation diagrams of 8-PSK/QAM for different fiber lengths & powers at 15 Gbps.*

	8- PSK	8-QAM
5 dBm	 0 Km 22 Km 45 Km 65 Km 90 Km 110 Km 130 Km 155 Km 180 Km 200 Km	 0 Km 22 Km 45 Km 65 Km 90 Km 110 Km 130 Km 155 Km 180 Km 200 Km
10 dBm	 0 Km 22 Km 45 Km 65 Km 90 Km 110 Km 130 Km 155 Km 180 Km 200 Km	 0 Km 22 Km 45 Km 65 Km 90 Km 110 Km 130Km 155 Km 180 Km 200 Km

15 dBm		

We see from the three input power levels, as expected, that the quality of the receiving signal is decreasing as the fiber length increases. On the other hand, the minimum accepted length for signals in which the constellation points can be differentiated is increasing as the input power level increases.

For 5 dBm power, 8-PSK max accepted length is at 110 Km. In case of 8-QAM there is a phase rotation (phase ambiguity) by $\pi/4$ at fiber length of 65 Km and the max accepted length is at 130 Km.

For 10 dBm input power, 8-PSK the min accepted threshold is increased compared to 5 dBm and it's at 130 Km. In case of 8-QAM phase rotation is also increased at 90 Km and the max length is at 150 Km.

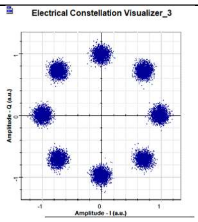
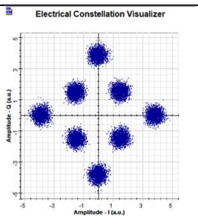
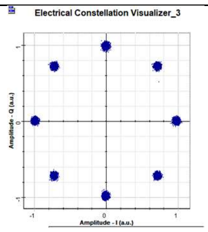
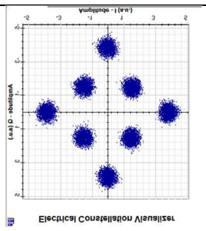
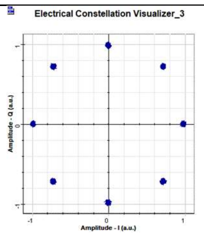
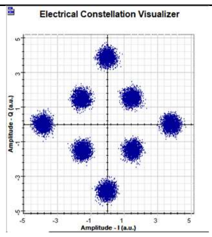
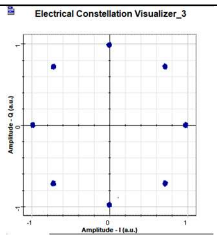
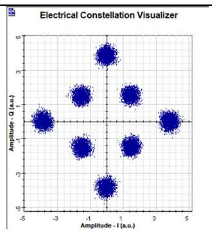
For 15 dBm input power, 8-PSK max length is increased as expected and it is at 150 Km. In case of 8-QAM there is no phase ambiguity and the max length is at 180 Km.

3.4.2 Bit rate 30 Gbps

A. Input power sweeps:

The simulation sweeps the power range [-10dBm to 15dBm] in a back-to-back system for the two modulation formats.

***Table 3. 4** Constellation diagrams of 8-PSK/QAM for different power levels at 30 Gbps.*

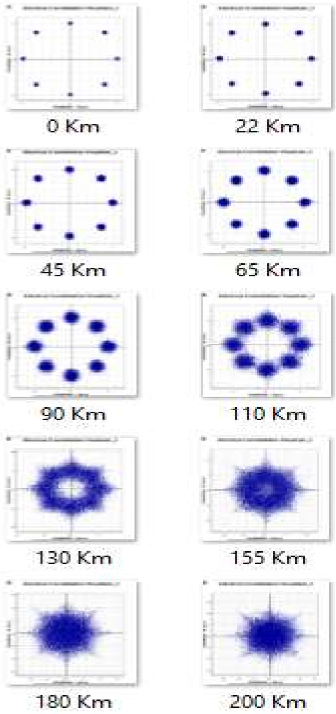
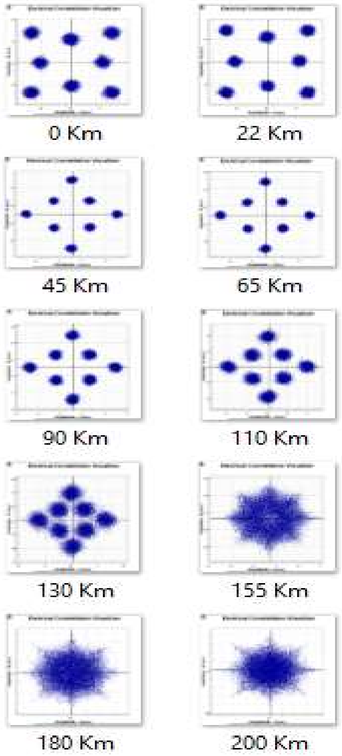
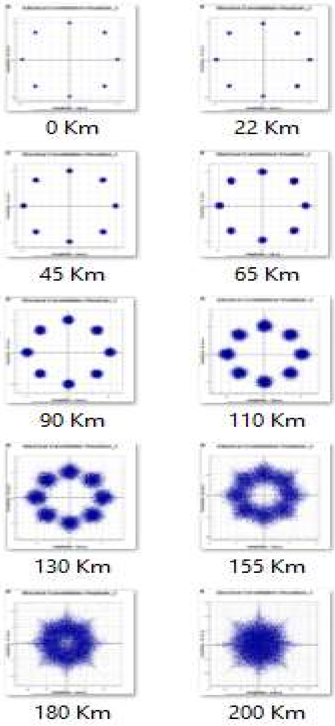
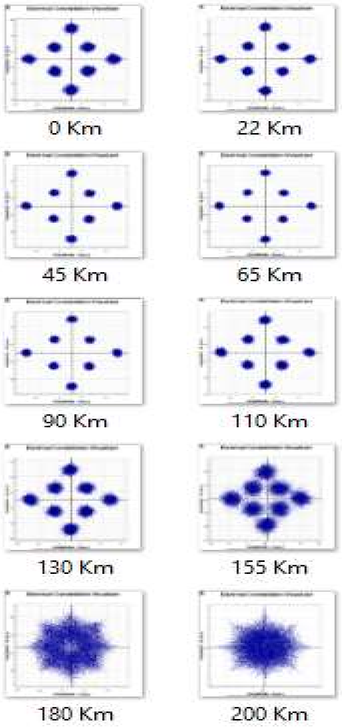
	8-PSK	8-QAM
-10 dBm		
0 dBm		
10 dBm		
15 dBm		

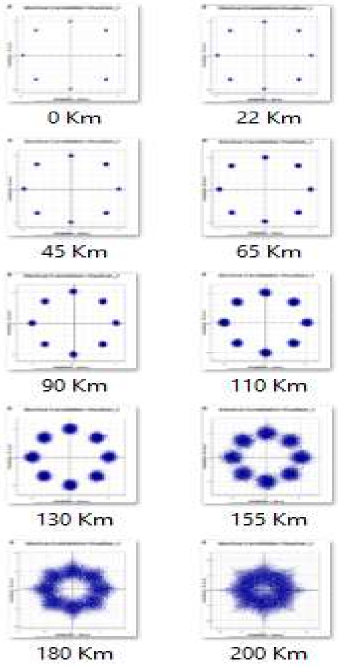
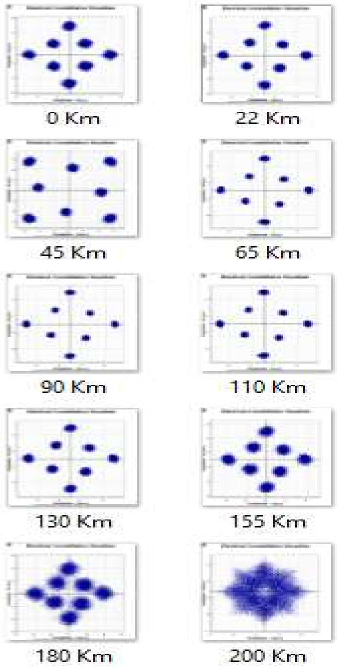
In table 3.4 differences, we can see that increasing the power injected into the continuous wave (CW) laser at the transmitters improves the quality of received signals for 8-PSK modulation, but there is no improvement in the quality of the signal for 8-QAM modulation as the power increases. The quality of 8-PSK signals is higher than that of 8-QAM signals at this bit rate level.

B. Fiber length sweeps:

The simulation sweeps the optical fiber length [0km – 200km] at three input power levels: 5dBm, 10 dBm, 15 dBm, at a 30 Gbps bit rate.

Table 3. 5 *Constellation diagrams of 8-PSK/QAM for different fiber lengths & powers at 30 Gbps.*

	8- PSK	8-QAM
5 dBm	 0 Km 22 Km 45 Km 65 Km 90 Km 110 Km 130 Km 155 Km 180 Km 200 Km	 0 Km 22 Km 45 Km 65 Km 90 Km 110 Km 130 Km 155 Km 180 Km 200 Km
10 dBm	 0 Km 22 Km 45 Km 65 Km 90 Km 110 Km 130 Km 155 Km 180 Km 200 Km	 0 Km 22 Km 45 Km 65 Km 90 Km 110 Km 130 Km 155 Km 180 Km 200 Km

15 dBm	 0 Km 22 Km 45 Km 65 Km 90 Km 110 Km 130 Km 155 Km 180 Km 200 Km	 0 Km 22 Km 45 Km 65 Km 90 Km 110 Km 130 Km 155 Km 180 Km 200 Km

We can see from the three input power levels that the quality of the receiving signal decreases as the fiber length increases for 8-PSK modulation, but for 8-QAM, there is a fluctuation in the quality of the received signal, phase ambiguity at first, an improvement after that, and a deterioration.

On the other hand, the minimum accepted threshold for signals in which the constellation points can be differentiated is increased as the input power level increases.

For 5 dBm power, 8-PSK min accepted threshold is at 90 Km. In case of 8-QAM there is a phase ambiguity by π/4 at range [0 Km to approx 30 Km], after which the phases return to their original position and the signal quality improves. The min accepted threshold is at 110 Km.

For 10 dBm input power, 8-PSK the min accepted threshold is increased compared to 5 dBm and it’s at 110 Km. In case of 8-QAM there is no phase rotation as the previous power level. The min accepted threshold is at 130 Km.

For 15 dBm input power, 8-PSK max accepted length is increased as expected and it is at 130 Km. In case of 8-QAM there is a phase rotation(ambiguity) by π/4 at range [25 Km to approx 50 Km] and the max accepted length is at 155 Km.

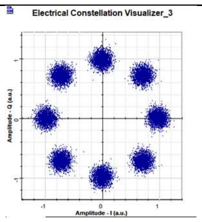
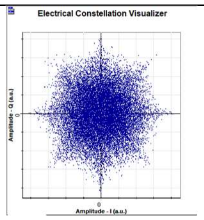
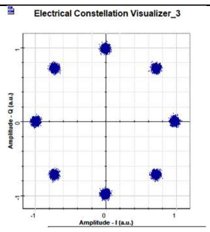
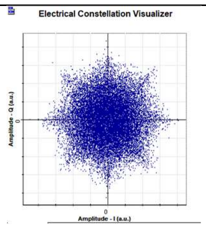
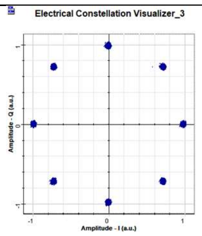
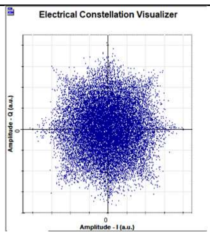
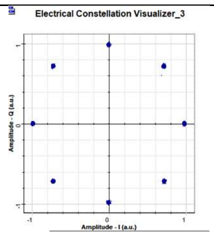
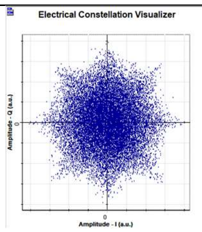
In general, the quality of 8-PSK modulation signals is much better than the signals of 8-QAM modulation. At this bit rate level.

3.4.3 Bit rate 54 Gbps

A. Input power sweeps:

The simulation sweeps the power range [-10dBm to 15dBm] in a back-to-back system for the two modulation formats.

Table 3. 6 *Constellation diagrams of 8-PSK/QAM for different power levels at 54 Gbps.*

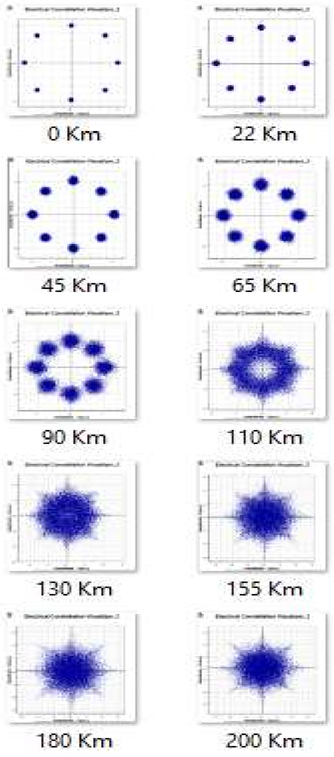
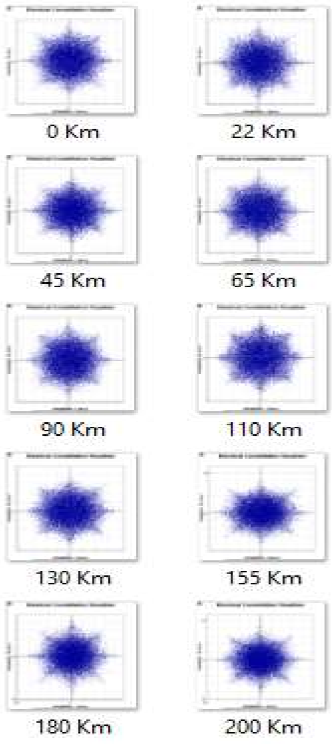
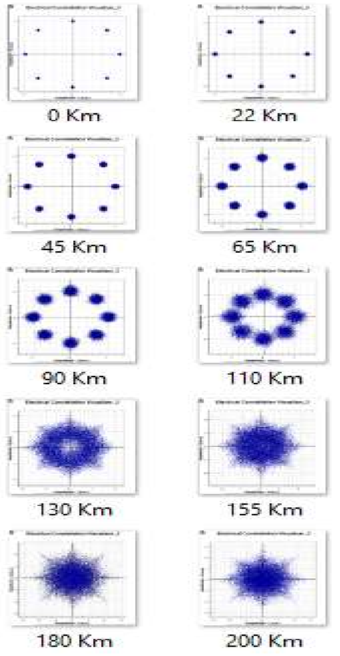
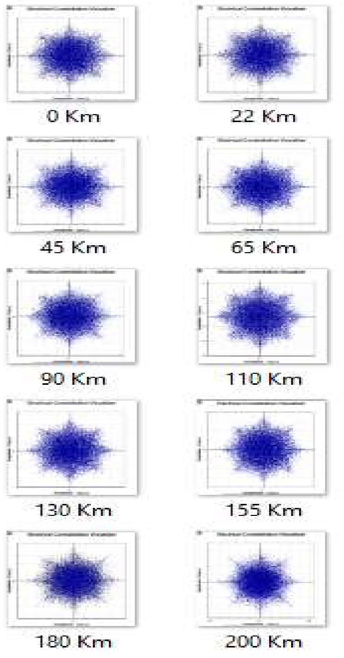
	8-PSK	8-QAM
-10 dBm		
0 dBm		
10 dBm		
15 dBm		

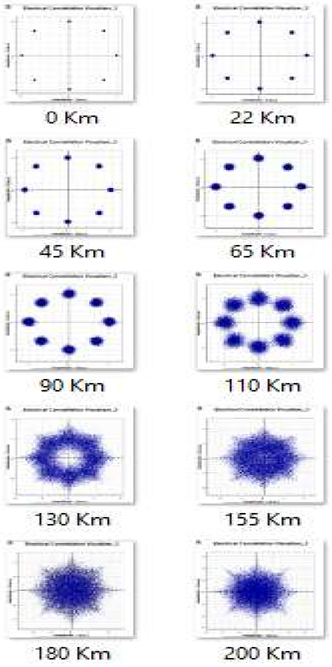
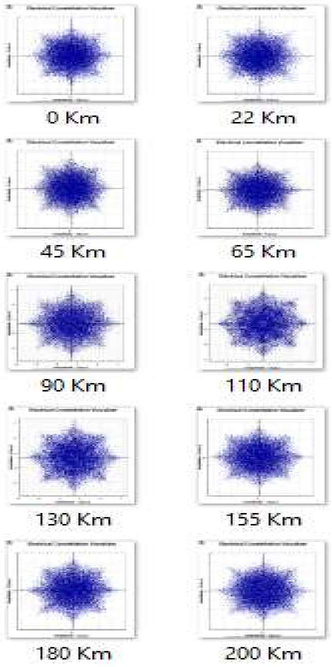
In table 3.6 differences, we can see that increasing the power injected into the continuous wave (CW) laser at the transmitters of both modulation formats improves the quality of received signals for 8-PSK modulation, but in the case of 8-QAM, the signal is completely lost at this bit rate level, whatever the injected power is.

B. Fiber length sweeps:

The simulation sweeps the optical fiber length [0km – 200km] at three input power levels: 5dBm, 10 dBm, 15 dBm, at a 54 Gbps bit rate.

Table 3. *7 Constellation diagrams of 8-PSK/QAM for different fiber lengths & powers at 54 Gbps.*

	8- PSK	8-QAM
5 dBm		
10 dBm		

15 dBm		

We can see from the three input power levels that the quality of the receiving signal decreases as the fiber length increases for 8-PSK modulation.

For 5 dBm power, the 8-PSK max accepted length is at 65 Km, and for 10 dBm input power, the 8-PSK max accepted length is increased compared to 5 dBm and it’s at 90 Km, 15 dBm input power, 8-PSK max accepted length value still the same at 90 Km.

In case of 8-QAM modulation the signal is completely distorted and lost at this bit rate level.

3.5 Discussion

The results show that at this order of modulation (M=8), M-PSK gives better results than M-QAM. The quality of the received signal was much better, especially at higher bit rate levels.

Also, we’ve noticed that increasing the input power increases the received power quality, especially for 8-PSK modulation.

8-QAM shows phase ambiguity with lower input power & small fiber lengths. In addition, it cannot support high bit rate levels (above 36Gbps) at this order of modulation.

Because of phase ambiguity at small fiber distances at bit rate levels (~30 Gbps) for the 8-QAM, the max length Lmax is insufficient, and we must use the min length threshold Lmin to ensure that the fiber length does not fall below.

General Conclusion

There are many advanced modulation schemes which have proved to be more efficient than the conventional formats used in optical communication systems.

In this report, we presented a simulation study of two advanced modulation formats, namely: 8 order phase shift keying (8-PSK) and 8 order quadrature amplitude modulation (8-QAM) using coherent detection techniques, and studying the effect of power and fiber length at different bit rate levels: 15, 30 and 54 Gbps.

We see that these types of modulations can deal with higher bit rate levels in a better way compared to conventional modulations and transmission techniques (RZ, NRZ, IM-DD, ...). Also, they can support longer optical fiber distances without any optical amplification or noise filtering. This is due especially to the coherent receiver and the DSP techniques that play a major role in overcoming phase ambiguities, which are a common issue with high order modulations, and also in the compensation of linear impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD), which are particularly crucial in high bit rate transmission systems.

It has been found, also, that increasing input power levels gives better results, especially for 8-PSK, and for 8-QAM at lower bit rates. This result matches what has been said in [38] and [39] that there are significant performance advantages to operating externally modulated fiber-optic links with high average optical power, but in practice, the improvements are limited by a variety of deleterious effects such as light ionizing iron impurities and nonlinear attenuation (stimulated Brillouin scattering SBS).

We also saw that 8-QAM is very sensitive to phase noise at this order level, especially with higher bit rates. This noise ambiguity effect is an important constraint in coherent systems and it is induced by the signal laser (CW) & the free running local oscillator (LO) laser. Phase noise can be compensated for by using digital carrier phase estimation (CPE) algorithms, as said in [40].

Finally, at this order, PSK gives better performance than QAM, but for higher order modulation, QAM is better and the most used, because the PSK becomes too sensitive to noise. Thus, it is recommended to use PSK at a lower order ($M \leq 8$) and QAM for a higher order ($M \geq 16$).

Conclusion

In future work, we propose using dual polarization techniques to test the system performance of the aforementioned modulation schemes.

Appendix

Technical Background of OptiSystem elements

1. Universal DSP :

The Universal DSP component performs several important functions to aid in recovering the incoming transmission channel(s) after coherent detection. It can be used with coherent system designs that utilize m-QAM or m-PSK modulation with single polarization (X channel) or dual polarization (X and Y channel) multiplexing. Block diagram of the universal DSP is illustrated in Figure (A1.1).

The Universal DSP component includes 12 functions and algorithms starting with a preprocessing stage (3 functions) followed by the signal recovery stage (8 functions and algorithms):

Preprocessing stage:

- Add Noise to Signal (Samples/Symbol = (4 or 8) x Samples per bit)
- DC Blocking (Samples/Symbol = (4 or 8) x Samples per bit)
- Normalization (Samples/Symbol = (4 or 8) x Samples per bit)

Main algorithms stage:

- Bessel Filter (Samples/Symbol = (4 or 8) x Samples per bit)
- Resampling (Samples/Symbol = 2)
- Quadrature Imbalance (QI) Compensation (Samples/Symbol = 2)
- Chromatic Dispersion (CD) Compensation (Samples/Symbol = 2)
- Nonlinear (NL) Compensation (Samples/Symbol = 2)
- Timing Recovery (Samples/Symbol = 2)
- Adaptive Equalizer - AE (Samples/Symbol = 2)
- Down-sampling (Samples/Symbol = 1)

Appendix

- Frequency Offset Estimation - FOE (Samples/Symbol = 1)

- Carrier Phase Estimation - CPE (Samples/Symbol = 1)

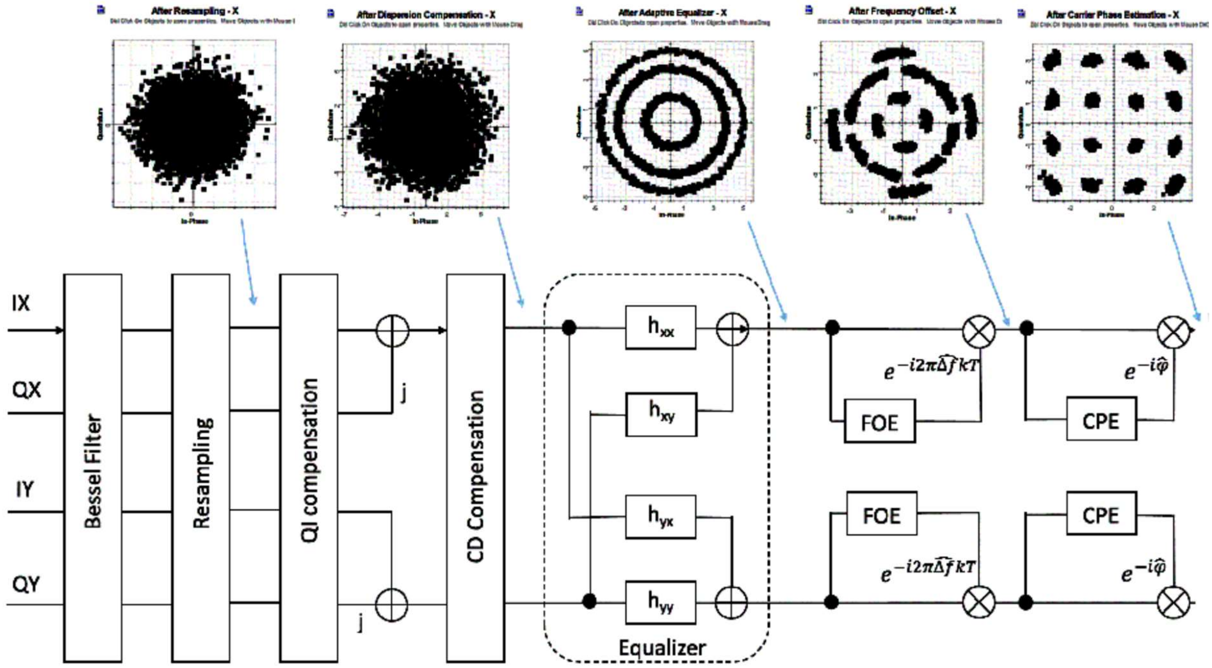


Figure A1.1 *Universal DSP High Level Algorithm Design.*

2. Decision:

The Decision component processes the I and Q electrical signal channels received from the DSP stage, normalizes the electrical amplitudes of each I and Q channel to the respective m-PSK or m-QAM grid and performs a decision on each received symbol based on normalized threshold settings. It supports the following modulation formats:

- BPSK, QPSK, 8PSK, 16PSK

- 8QAM, 16QAM, 32QAM, 64QAM, 128QAM, 256QAM

In addition, for QAM modulation formats; square, star, and circular constellation formats are supported. The Decision component supports single or dual polarization (SP/DP) multiplexing schemes Prior to processing the input data, the electrical signals are first re-sampled to 2 Samples per symbol (1st and N/2+1 sampled signal are used for the re-sampling (where N = Samples per symbol). The second data point (N/2+1) is then selected - to bring the sampling rate to 1 Sample/symbol. The Decision component performs the following functions (in order):

- DC blocking

Appendix

- Normalization
- Error Vector Magnitude (EVM) calculation
- Decision
- Calculate Symbol Error Rate (SER)

The decision algorithm performs a soft decision on all the received symbols based on the threshold boundaries. For example, for QPSK the boundaries (x = 0; y = 0) are used. Similarly, for 16-QAM the boundaries (x = -1, 0, 2; y = -2, 0, +2) are used. See Figure (A1.2).

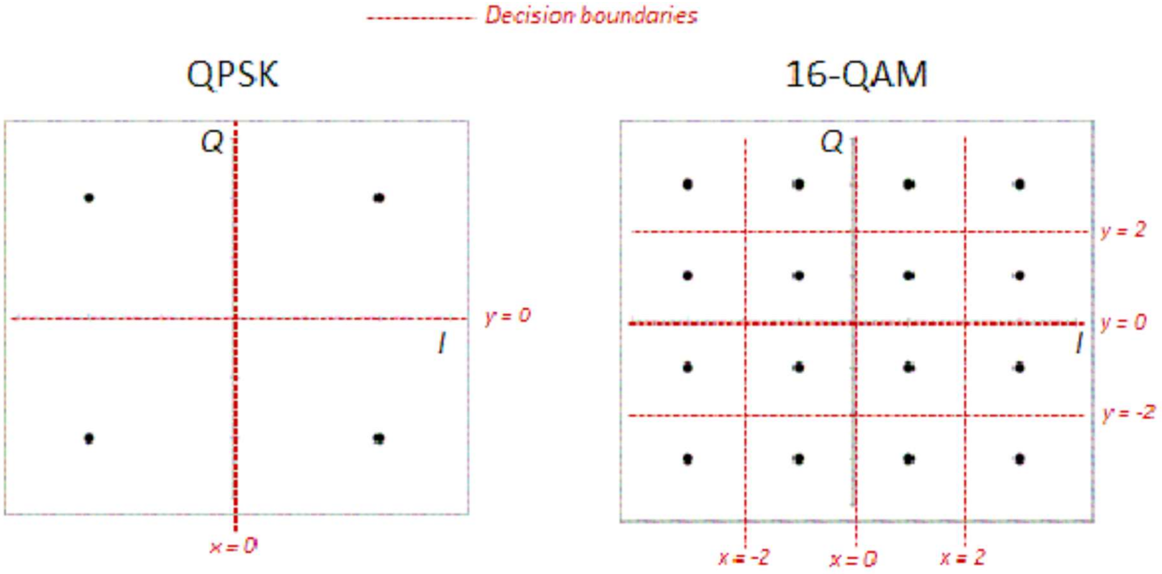


Figure A1.2 *Examples decision boundaries for QPSK and 16-QAM*

When “Optimize decision” is selected, three additional procedures are performed tocorrect any residual mis-alignment or rotations in the constellation prior to applying the soft decisions.

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