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Presented by:

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On the theme:

Study of the performance of Coherent Optical - Orthogonal Frequency Division Multiplexing CO-OFDM systems

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Defended publicly on 18/06/2025 inTiaret in front the jury composed of:

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بسم الله الرحمن الرحيم

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Dedication

This message is dedicated to the Face of God, my Creator, Master, Teacher, and Great Messenger, Muhammad (peace be upon him), who taught us the purpose of life. I dedicate my graduation to my late mother, God willing, she is the one who taught me that love has no age and that giving has no limits The female who shortens all women My dear mother, the candle that burned to light my life path For the soul of my departed mother From our world that remains in my eternal heart in my world to sacred love The pure angel, to whom God made heaven under her feet, to the one who showered me with the flood of her tenderness, to the one who starved to be sated, stayed up to sleep, tried to rest, cried to laugh, and watered me from the source of her tenderness and sincerity, to the one who raised me young and advised me big, the comfort of my eyes and my heart, my dear mother, may God have mercy on you.

I dedicate my graduation to my dear father, who worked hard and made every effort and supported me financially and morally and with all he could, may God prolong his life and grant him health and wellness.

I also dedicate this graduation to all my family, my sisters, my brothers, their wives, their daughters and their children who have been credited with removing many obstacles and difficulties from my path. I love you all.

I also do not forget to give a big thank you to all my friends with whom I have studied over the last years. I should not forget my teachers, who had the greatest role in supporting me and providing me with valuable information, praying to God Almighty to prolong your life and bless you with bounties.

Kacem Mokhtar

Dedication

I dedicate this thesis to:

All my family members. Dad may Allah bless his soul, Mom may Allah grant her health and a long life.

My teachers, colleagues, friends and those who helped me to achieve this work.

Laidi Habib

Summary

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List of Abbreviations

CO-OFDM **:**Coherent Optical-Orthogonal Frequency Division Multiplexing
OFDM **:**Orthogonal Frequency Division Multiplexing
OFDMA **:** Orthogonal Frequency Division Multiple Access
TDM : Time Division Multiplexing
CDM :Code Division Multiplexing
CDMA : Code Division Multiple Access
2G, 3G;4G,5G : Second-Generation ,Third-Generation, Fourth Generation, Fifth Generation
UHF **:**Ultra-High-Frequency
AM **:** Amplitude Modulation
PM **:**Phase Modulation
FM **:** Frequency Modulation
WI-FI :Wireless Fidelity
PSK **:** Phase Shift Keying
QAM **:**Quadrature Amplitude Modulation
QPSK **:** Quadrature Phase-Shift Keying
DPSK **:**Differential Phase Shift Keying
FDMA **:** Frequency Division Multiple Access
OFDMA **:** Orthogonal Frequency Division Multiple Access
OFDM **:** Orthogonal Frequency Division Multiplexing
TDMA **:** Time Division Multiple Access
GSM : Global System for Mobile communications
SNR : Rapport signal sur bruit
DSSS : Direct Sequence Spread Spectrum
FHSS : Frequency Hopping Spread Spectrum
PMD : Polarization Mode Dispersion
SPM : Self-Phase Modulation
XPM : Cross-Phase Modulation
FWM : Four-Wave Mixing
OADM :Optical Add/Drop Multiplexers
EDFA :Erbium Doped Fiber Amplifier
WDM : Wavelength Division Multiplexing
WiMAX : Worldwide Interoperability for Microwave Access
RTO **:**RF-to-optical
OTR :Optical-To-RF
CMOS :Complementary Metal–Oxide Semiconductor
ISI **:**Intersymbol Interference
S=P : Serial-To-Parallel
Gl : Guard Interval Insertion

D=A : Digital-To-Analogue
MZM : Mach-Zehnder modulator
LPF : Lowpass Filter
BPF : Bandpass Filter
(I)DFT : (Inverse) Discrete Fourier Transform
OBPF : Optical Bandpass Filter
PD : Photodiode
LD : Laser Diode
FFT **:** Fast Fourier Transform
IDFT **:**Inverse Discrete Fourier Transform
DSP : Digital Signal Processing
CPE **:**Customer Premises Equipment
MIMO-OFDM : (Multiple Input Multiple Output -OFDM
SISO-OFDM **:** Single-Input Single-Output- OFDM
MISO-OFDM **:** Multiple Input, Single Output- OFDM
SMF :Single-Mode Fiber: Complementary Metal-Oxide-Semiconductor Application-Specific Integrated Circuits
CORDIC :Coordinate-Rotation-Digital-Computer
BER : Bit Error Rate
OSNR : Optical Signal-to-Noise Ratio
DSP **:** Digital Signal Processing
CD **:** Chromatic Dispersion

General Introduction

General introduction

In today’s rapidly evolving world of information and communication technologies, the need for efficient, high-speed, and high-capacity data transmission systems has become more critical than ever. The exponential growth in internet usage, the rise of real-time streaming applications, cloud computing, and the deployment of next-generation mobile networks such as 5G have led to an unprecedented increase in the volume of data exchanged across global networks. These developments have imposed significant technical challenges on traditional communication systems, especially in terms of speed, bandwidth, and reliability.

Optical communication has emerged as the cornerstone of modern telecommunication infrastructure, offering unmatched advantages in terms of data transmission speed, long-distance coverage, and minimal signal attenuation compared to traditional copper-based media. However, as data rates continue to increase and networks grow more complex, optical communication systems face growing limitations. These include chromatic dispersion, polarization mode dispersion (PMD), and nonlinear effects, all of which degrade signal quality and increase the bit error rate (BER), especially in long-haul high-speed transmissions.

To address these challenges, researchers and engineers have proposed Coherent Optical Orthogonal Frequency-Division Multiplexing (CO-OFDM) as a promising solution. CO-OFDM combines two powerful technologies: Orthogonal Frequency-Division Multiplexing (OFDM), which splits the signal into multiple orthogonal subcarriers to enhance spectral efficiency, and coherent detection, which allows precise recovery of both amplitude and phase information using a local oscillator laser. Together, these techniques offer robust resistance to dispersion, improved spectral efficiency, and compatibility with advanced modulation formats such as QPSK and 16-QAM.

In this research, we aim to explore the theoretical and practical performance of CO-OFDM systems. We begin by analyzing the physical structure and characteristics of optical fibers, the principles of digital modulation, and the various multiplexing and access techniques used in optical networks. Then, we focus specifically on the architecture and operating principles of CO-OFDM, highlighting its advantages in long-distance and ultra-high-speed communication.

The ultimate goal of this work is to demonstrate that CO-OFDM systems are a viable and scalable solution for future optical networks, particularly those requiring data rates of 100 Gb/s and beyond. Their adaptability, robustness, and efficiency make them strong candidates for next-generation broadband infrastructures such as 100G/400G Ethernet, backbone networks, and metropolitan optical systems.

CHAPTER I

Fundamentals of Optical and Digital Communications

I.1 Introduction

On this chapter we discover the core principles of optical and digital communications. It begins with the structure and types of optical fibers, including their key characteristics like attenuation and dispersion. Next, it examines digital modulation, multiplexing, and access techniques, highlighting their role in efficient data transmission. The chapter bridges theory and practice, covering components like amplifiers and detectors that enable modern high-speed networks.

I.2 Definition of optical fiber :

An optical fiber is a cylindrical guide composed of two dielectrics called the core and the cladding. The core, with radius (a) and permittivity ($\varepsilon 1$), is surrounded by the cladding with permittivity $\varepsilon 2$, where $\varepsilon 2 < \varepsilon 1$. The dimensions of the dielectrics are invariant along the length of the fiber.

When a light ray enters an optical fiber at one of its ends at an appropriate angle, it undergoes multiple total internal reflections.

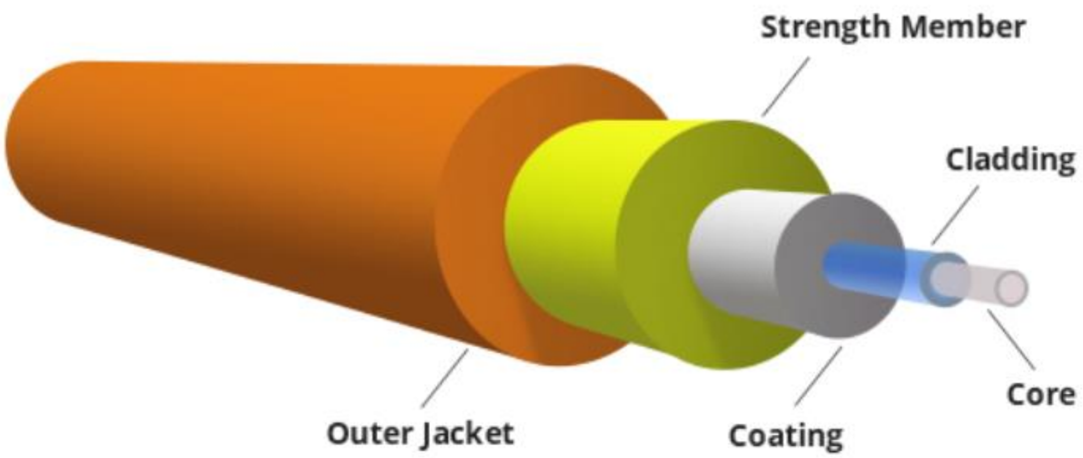


Figure I.1: Optical fiber structure

I.2.1 Types of Optical Fiber :

The types of optical fibers depend on the refractive index, materials used and mode of propagation of light.

The classification based on the refractive index is as follows:

- **Step Index Fibers:** It consists of a core surrounded by the cladding which has a single uniform index of refraction.

- **Graded Index Fibers:** The refractive index of the optical fiber decreases as the radial distance from the fiber axis increases.

The classification based on the materials used is as follows:

- Plastic Optical Fibers: The polymethylmethacrylate is used as a core material for the transmission of the light.

- Glass Fibers: It consists of extremely fine glass fibers.

The classification based on the mode of propagation of light. The "mode" in fiber optic cable refers to the path in which light travels.

- **Single Mode Fibers:** fiber has a smaller core diameter of 9 microns (8.3 microns to be exact) and only allows a single wavelength and pathway for light to travel, which greatly decreases light reflections and lowers attenuation. Slightly more expensive than its multimode counterparts, single mode fiber optic cable is often used in network connections over long lengths..

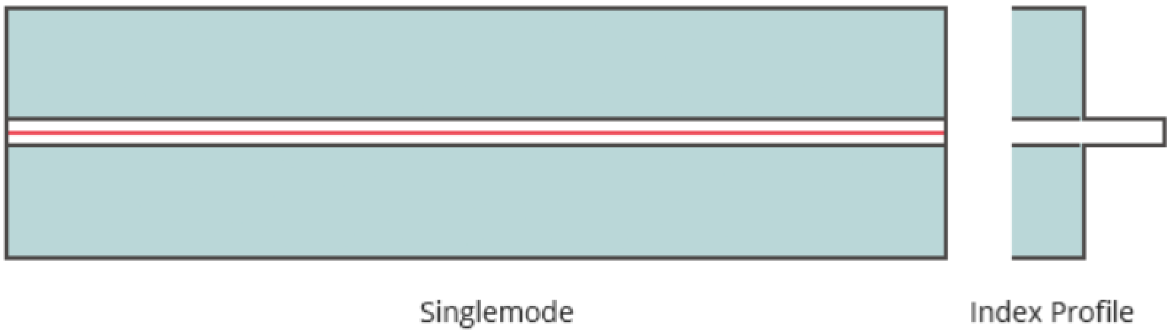


Figure I.2: Single mode fiber

- **Multimode Fibers:** Multimode optical fiber has a larger core diameter than that of single mode fiber optic cable, which allows multiple pathways and several wavelengths of light to be transmitted. Multimode optical fiber is available in two sizes, 50 microns and 62.5 microns. It is commonly used for short distances, including patch cable applications such as fiber to the desktop or patch panel to equipment, data and audio/video applications in LANs. According to the fiber refractive index distribution, multimode fiber can be divided into two types: Step-Index Multimode Fiber vs Graded-Index Multimode Fiber.

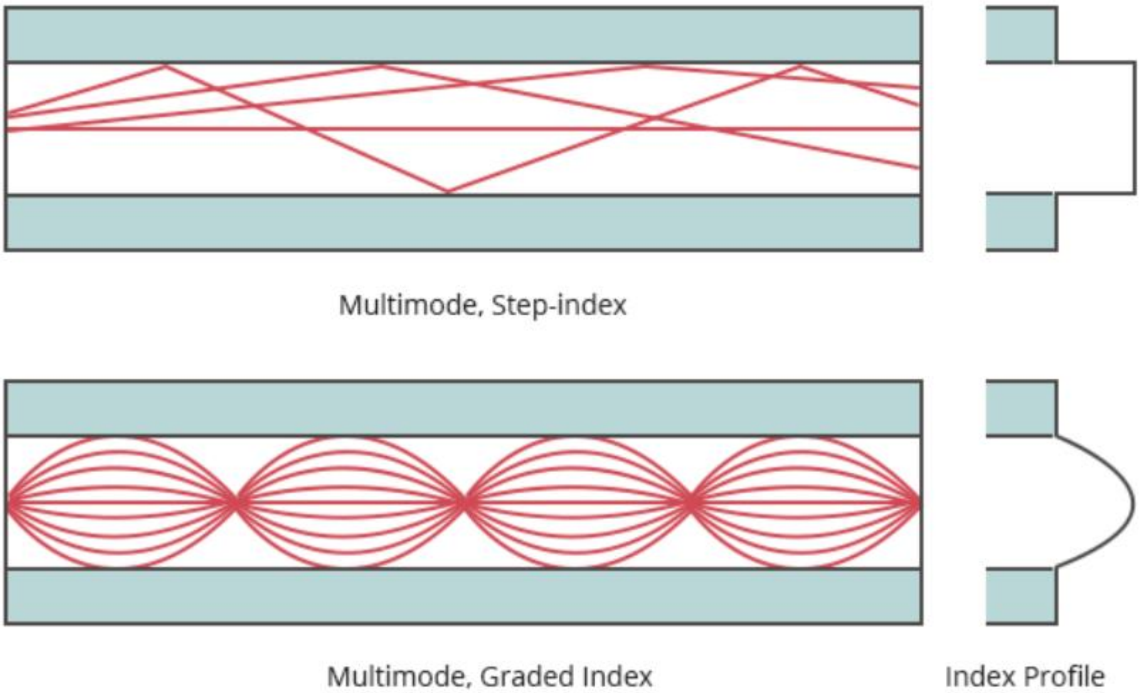


Figure I.3 : Multimode fiber

The mode of propagation and refractive index of the core is used to form four combination types of optic fibers as follows:

- Step index-single mode fibers
- Graded index-Single mode fibers
- Step index-Multimode fibers
- Graded index-Multimode fibers[1].

I.2.3 Characteristics of Optical Fiber

I.2.3.1 Attenuation :

Light power propagating in a fiber decays exponentially with length due to absorption and scattering losses. Attenuation is the single most important factor determining the cost of fiber optic telecommunication systems, as it determines spacing of repeaters needed to maintain acceptable signal levels.

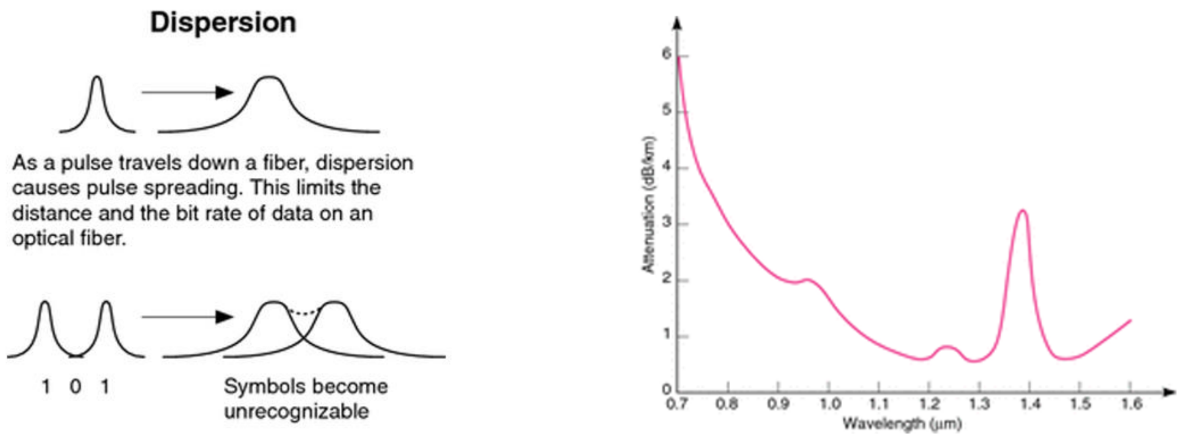
In the near infrared and visible regions, the small absorption losses of pure silica are due to tails of absorption bands in the far infrared and ultraviolet. Impurities — notably water in the form of hydroxylions are much more dominant causes of absorption in commercial fibers. Recent improvements in fiber purity have reduced attenuation losses. State of theart systems can have attenuation on the order of 0.1 dB/km.

Scattering can couple energy from guided to radiation modes, causing loss of energy from the fiber. There are unavoidable Rayleigh scattering losses from smalls cale index fluctuations frozen into the fiber when it solidifies. This produces attenuation proportional to l/λ4. Irregularities in core diameter and geometry or changes in fiber axis direction also cause scattering. Any process that imposes dimensional irregularities — such as microbending — increases scattering and hence attenuation. Typical Spectral [2].

Attenuation is often expressed in decibels per kilometer and is given by the following expression:

$$\alpha = \frac{10}{L} \log\left(\frac{P_{in}}{P_{out}}\right)$$

where P_{in} is the injected power at the input, P_{out} is the measured power at the output, and L is the length of the optical fiber. The maximum distance between the transmitter and the receiver (or between the amplifiers) depends heavily on the constant A and the optical power transmitted by the transmitter.[3]



FigureI.4 :Effect of Dispersion on Optical Fiber Pulse Transmission

Dispersion - t means the expansion of the pulse moving along the optical cable. The dispersion value is determined by the difference of the square of the duration of the pulses coming out of the optical fibers in the optical cable and arriving at the receiver[4]:

$$\Delta\tau_{total} = \sqrt{(\Delta\tau_{mod})^2 + (\Delta\tau_{chrom})^2}$$

$\Delta\tau_{total}$ **:** Total Dispersion (Combined Effects)

$\boldsymbol{\Delta\tau_{mod}}$ **:** Dispersion Modale for multimode fibers

$\boldsymbol{\Delta\tau_{chrom}}$ **:** Chromatic Dispersion (Material + Waveguide Dispersion)

Note :

- For **multimode** fibers, both modal and chromatic dispersion contribute.
- For **single-mode** fibers, chromatic dispersion dominates.

I.2.3.2 Chromatic Dispersion (also called Material Dispersion)

Chromatic dispersion is a phenomenon of signal spreading over time resulting from the different speeds of light rays. The chromatic dispersion is the combination of the material and waveguide dispersion effects.

Material dispersion is caused by the wavelength dependence of the refractive index on the fiber core material. Waveguide dispersion occurs due to dependence of the mode propagation constant on the fiber parameters (core radius, and difference between refractive indexes in fiber core and fiber cladding) and signal wavelength. At some particular frequency, these two effects can cancel each other out giving a wavelength with approximately 0 chromatic dispersion.

What's more, chromatic dispersion isn't always a bad thing. Light travels at various speeds at different wavelengths or materials. These varying speeds cause pulses to either spread out or compress as they travel down the fiber, making it possible to customize the index of refraction profile to produce fibers for different applications. For example, the G.652 fibers are designed in this way.

Expression for the chromatic dispersion coefficient of a sample fiber [5]:

$$\boldsymbol{D(\lambda) \approx -\frac{c}{L}\left[\frac{\phi_2}{\lambda^2} + \frac{c.\phi_3}{\lambda^3}\right]}$$

Where :

$\boldsymbol{D(\lambda)}$: Chromatic dispersion at wavelength λ (units: PS/(nm·km))

$\boldsymbol{c}$ **:** Speed of light in vacuum (≈3×108 m/s≈3×108m/s)

$\boldsymbol{L}$ **:** Length of the fiber (units: km)

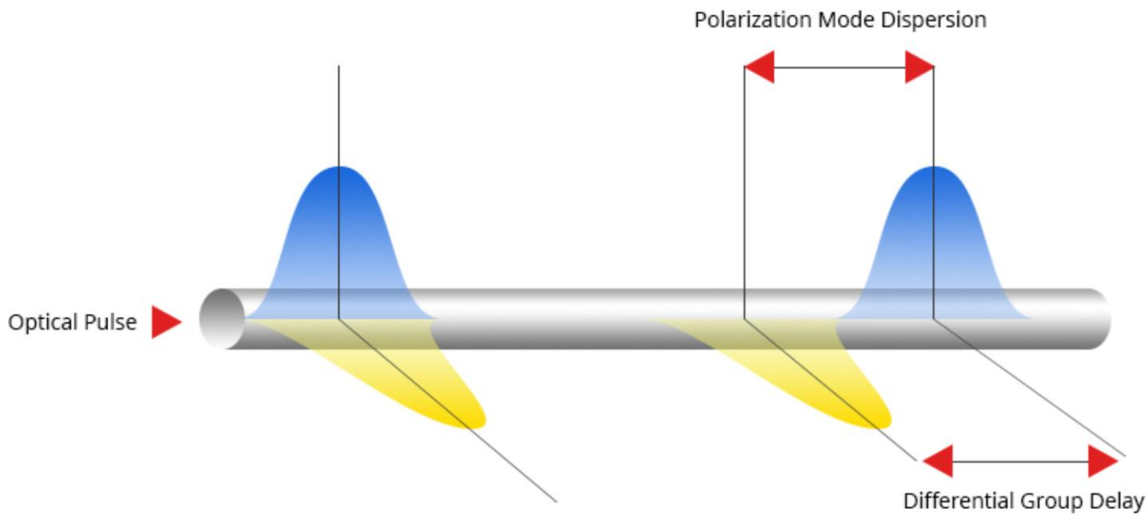
$\boldsymbol{\phi_2}$**:** Second-order phase term (Group Velocity Dispersion, GVD)

$\boldsymbol{\phi_3}$ **:** Third-order phase term (Dispersion Slope)

$\boldsymbol{\lambda}$ **:** Wavelength of light (units: nm or µm)

I.2.3.3 Polarization Mode Dispersion

Polarization mode dispersion (PMD) represents the polarization dependence of the propagation characteristics of light waves in optical fibers. In optical fibers, there is usually some slight difference in the propagation characteristics of light waves with different polarization states. When the light is defined as an energy wave or energy region, it possesses 2 mutually perpendicular axes, namely the electromotive force and magnetomotive force. The moment the energy inside these two axes transfers at different speeds in a fiber, PMD occurs.



FigureI.5 :Polarization Mode Dispersion (PMD) in Optical Fibers

The Formula for Pulse Broadening due to PMD[6]:

$$\Delta\tau = D_{PDM} \times \sqrt{L}$$

Where:

$\Delta\tau$: The **average pulse broadening** or mean **Differential Group Delay (DGD)** due to PMD (**in picoseconds, ps**). This represents the average time separation between the arrival of the fastest and slowest polarization components of the pulse.

D_{PDM} : The **PMD Coefficient** of the fiber (in $Ps\sqrt{km}$). This is usually specified by the fiber manufacturer or measured.

L : The **length of the fiber** (in **kilometers, km**).

PMD has small effects for networks whose link speeds are lower than 2.5 Gbps even if the transmission distance is longer than 1000 km. However, as speeds increase, it becomes a more important parameter especially when the speeds are over 10 Gbps. In addition to the major inherent PMD caused by the glass manufacturing process, the PMD can be affected or caused by the fiber cabling, installation and the operating environment of the cable as well.

I.2.3.3 Bandwidth

Bandwidth of an optical fiber determines the data rate. The mechanism that limits a fiber's bandwidth is known as dispersion. Dispersion is the spreading of the optical pulses as they travel down the fiber. The result is that pulses then begin to spread into one another and the symbols become indistinguishable. There are two main categories of dispersion, intermodal and intramodal.

LP_{01} Mode Distribution *LP_{11} Mode Distribution*

FigureI.6 :LP_{01} and LP_{11} Modes in Optical Fibers

- **Intermodal Dispersion:** As its name implies, intermodal dispersion is a phenomenon between different modes in an optical fiber. Therefore, this category of dispersion only applies to multimode fiber. Since all the different propagating modes have different group velocities, the time it takes each mode to travel a fixed distance is also different. Therefore, as an optical pulse travel down a multimode fiber, the pulses begin to spread, until they eventually spread into one another. This effect limits both the bandwidth of multimode fiber as well as the distance it can transport data.

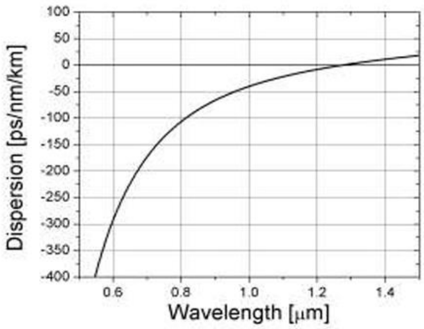


Figure 1.7: Dispersion Coefficient as a Function of Wavelength in Standard Single-Mode Fiber

Dispersion is expressed in units of ps/nmkm. Notice to minimize dispersion, operating around ~1.3um (zero dispersion wavelength) will significantly reduce dispersion.

- **Intramodal Dispersion**: Intramodal Dispersion, sometimes called material dispersion, is a result of material properties of optical fiber and applies to both single mode and multimode fibers. There are two distinct types of intramodal dispersion: **chromatic dispersion** and **polarization-mode dispersion**

The index of refraction varies depending upon wavelength. Therefore, different wavelengths will travel down an optical fiber at different velocities. This is known as **Chromatic Dispersion.**

This principle implies that a pulse with a wider FWHM will spread more than a pulse with a narrower FWHM. Dispersion limits both the bandwidth and the distance that information can be supported. This is why for long communications links it is desirable to use a laser with a very narrow line width. Distributed Feedback (DFB) lasers are popular for communications because they have a single longitudinal mode with a very narrow line width.

Nonlinear effects (Kerr effects) :

The variation in the optical fiber refractive index due to the intensity of the pulse propagating in the optical fiber is called the optical Kerr effect. Mathematical description of this phenomenon can be given as :

$$\boldsymbol{n} = \boldsymbol{n_0} + \boldsymbol{n_2 I} = \boldsymbol{n_0} + \boldsymbol{n_2}\left(\frac{\boldsymbol{P}}{\boldsymbol{A_{eff}}}\right)$$

where n represents refractive index of the optical fiber occurring due to optical Kerr effect, $\boldsymbol{n_0}$ is linear refractive index of the optical fiber, $\boldsymbol{n_2}$ describes nonlinear refractive index of the optical fiber, $\boldsymbol{I}$ denotes intensity of the light pulse propagating in the optical fiber, $\boldsymbol{P}$ is the power of the light pulse and $\boldsymbol{A_{eff}}$represents effective area of the optical fiber.Nonlinear impairments occurring as a result of the optical Kerr effect are SPM, XPM and FWM[7].

- **Self-Phase Modulation (SPM) :**Self-phase modulation refers to the self-induced phase shift induced by the optical field during its propagation in optical fibers. Higher intensity portions of optical pulse encounter a higher refractive index of the fiber compared with the lower intensity portions while it travels through the fiber. The leading edge experiences positive refractive index gradient (dn/dt) and trailing edge experiences negative refractive index gradient (-dn/dt). This temporally varying index change results in temporally varying phase change. Different parts of the pulse undergo different phase shifts due to the dependency of phase fluctuations in intensity. This results in frequency chirping. Hence, SPM results in broadening the spectrum of the pulse keeping the temporal shape unaltered Self-phase modulation plays the role in soli-tongeneration, optical switching, pulse compression.

- **Cross-Phase Modulation (XPM) :**The cross-phase modulation occurs because the nonlinear refractive index seen by an optical beam depends on the intensity of that beam and the intensity of the other copropagating beams. In fact, XPM converts power fluctuations in a particular wavelength channel to phase fluctuations in other copropagating channels. The results of XPM may be asymmetric spectral broadening and distortion of the pulse shape. For increased wave-length spacing, pulse overlaps for such a short time that XPM effects are virtually negligible. Optical switching, pulse compression, pulse retiming can be done through the XPM phenome-non.

- **Four-Wave Mixing (FWM) :**FWM process arises due to the nonlinear response of bound elec-trons of a material to an applied optical field. The polarization induced in the medium contains linear and the nonlinear terms. The magnitudes of these terms are determined by the nonlinear susceptibilities of different orders. The FWM process occurs due to third order nonlinear sus-ceptibility. **Figure 9** shows a simple example of mixing of two waves at frequencies (or wave-lengths) $\omega 1$ and $\omega 2$. When these waves get mixed up, they generate sidebands at ($2\omega1 - \omega2$) and ($2\omega2 - \omega1$). These sidebands pass along with original waves and reduce signal strength. In general, for N wavelengths launched into fiber, the number of generated mixed products M is [8] :

$$\boldsymbol{M = \frac{N^2}{2}(N-1)}$$

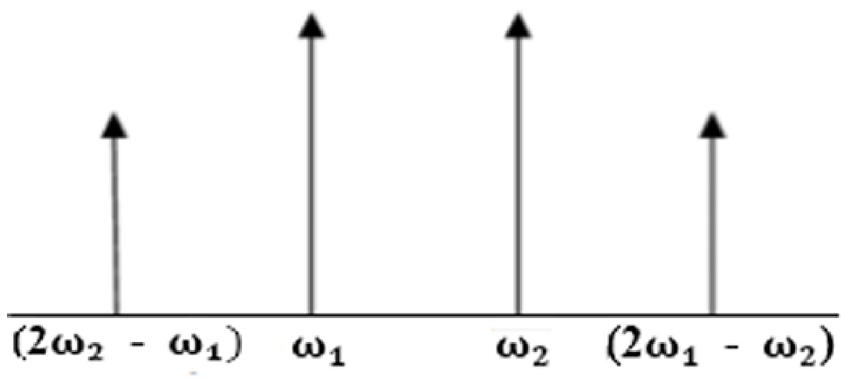


Figure I.8 :Mixing of two waves

I.2.4 Advantages and Disadvantages of Optical Fiber

Though optical fiber has speed and bandwidth advantages over copper cable, it also contains some drawbacks. Here are the advantages and disadvantages of optical fiber cable.

I.2.4.1 Advantages of Optical Fiber :

- **Greater bandwidth & faster speed :** Optical fiber cable supports extremely high band-width and speed. The large amount of information that can be transmitted per unit of optical fiber cable is its most significant advantage.
- **Cheap:** Long, continuous miles of optical fiber cable can be made cheaper than equiv-alent lengths of copper wire. With numerous vendors swarm to compete for the market share, optical cable price would sure to drop.
- **Thinner and light-weighted:** Optical fiber is thinner, and can be drawn to smaller di-ameters than copper wire. They are of smaller size and light weight than a comparable copper wire cable, offering a better fit for places where space is a concern.
- **Higher carrying capacity:** Because optical fibers are much thinner than copper wires, more fibers can be bundled into a given-diameter cable. This allows more phone lines to go over the same cable or more channels to come through the cable into your cable TV box
- **Less signal degradation:** The loss of signal in optical fiber is less than that in copper wire.
- **Light signals:** Unlike electrical signals transmitted in copper wires, light signals from one fiber do not interfere with those of other fibers in the same fiber cable. This means clearer phone conversations or TV reception.
- **Long lifespan:** Optical fibers usually have a longer life cycle for over 100 years.

I.2.4.2 Disadvantages of Optical Fiber

- **Low power:** Light emitting sources are limited to low power. Although high power emitters are available to improve power supply, it would add extra cost.
- **Fragility:** Optical fiber is rather fragile and more vulnerable to damage compared to copper wires. You’d better not to twist or bend fiber optic cables too tightly.

- **Distance:** The distance between the transmitter and receiver should keep short or repeaters are needed to boost the signal.

I.2.5Application of Optical Fiber

Optical fiber is used by many telecommunications companies to transmit telephone signals, Internet communication, and cable television signals. Due to much lower attenuation and interference. Optical fiber has large advantages over existing copper wire in long-distance and high-demand applications. However, infrastructure development within cities was relatively difficult and time consuming, and fiber-optic systems were complex and expensive to install and operate.

Due to these difficulties, fiber-optic communication systems have primarily been installed in long-distance applications, where they can be used to their full transmission capacity, offsetting the increased cost. Since 2000, the prices for fiber-optic communications have dropped considerably.

These price for rolling out fiber to the home has currently become more cost-effective than that of rolling out a copper based network.

- **Telecommunication:** Telecommunication applications are widespread, ranging from global networks to desktop computers. These involve the transmission of voice, data, or video over distances of less than a meter to hundreds of kilometers, using one of a few standard fiber design in one of several cable designs.

- **Network:** Carriers use optical fiber to carry plain old telephone service (POTS)across their nationwide networks. Local exchange carriers(LECS) use fiber to carry this same service between central office switches at locals levels, and sometimes as far as the neighborhood or individual home.

- **Transmission:** Optical fiber is also used effectively for transmission of data. Multinational firms need secure, reliable systems to transfer data and financial information between buildings to the desktop terminals or computer and to transfer data around the world. Cable television companies also use fiber for delivery of digital video and data services. The high bandwidth provided by fiber makes it perfect choice for transmitting broadband signals, such as high-definition television (HDTV) telecasts.

Intelligent transport systems, such as smart highways with intelligent traffic lights, automated tollbooths, and changeable message signs, also use fiber-optic-based telemetry systems[9].

I.3 Main elements of the optical transmission chain :

I.3.1 Modulation :

Optical Modulation is the process by which a light wave is modulated (modified) according to a high-frequency electrical signal that contains information. These modified light waves are then transmitted either by a transparent medium or through an optical fiber cable.

More specifically, we can say that it is the process by which an electrical signal that contains message is converted into a light signal.

Basically, there exist two different methods of modulating the optical signal. These two methods are classified as:

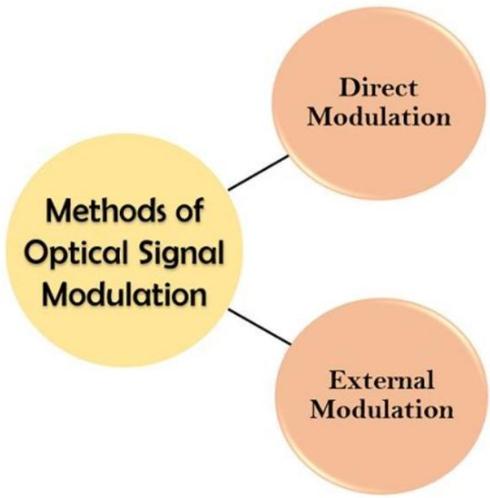


Figure I.9 :Two Primary Methods of Optical Signal Modulation

I.3.1.1 Direct Modulation

As the name itself is indicating that it is a modulation technique in which the information that has to be transmitted is directly placed over a light stream emitted by the source.

In this method, simply the driving current of the light source i.e., the laser is changed directly with the electrical information signal in order to generate a changing optical power signal. So, it does not require individual optical modulators for the modulation of the optical signal.

In this modulation technique, the major drawback is associated with the carrier lifetimes of spontaneous and stimulated emission along with photon lifetime of the source.

While performing direct modulation with the laser transmitter, the laser turns on and off according to the electrical signal or the driving current. But, in this case, the laser linewidth somehow gets widened. This widening of laser linewidth is known as chirp. Due to this reason, direct modulation technique becomes unsuitable for data rates above 2.5 Gbps.

I.3.1.1 External Modulation

In external modulation, separate optical modulators are used that performs the modification of optical signals in order to change the signal characteristics.

It is basically used to modulate the signals having data rates of more than 10 Gbps. However, there is no any compulsion to use this method only for high data rate signals.

The figure below shows the operational technique of external modulator:

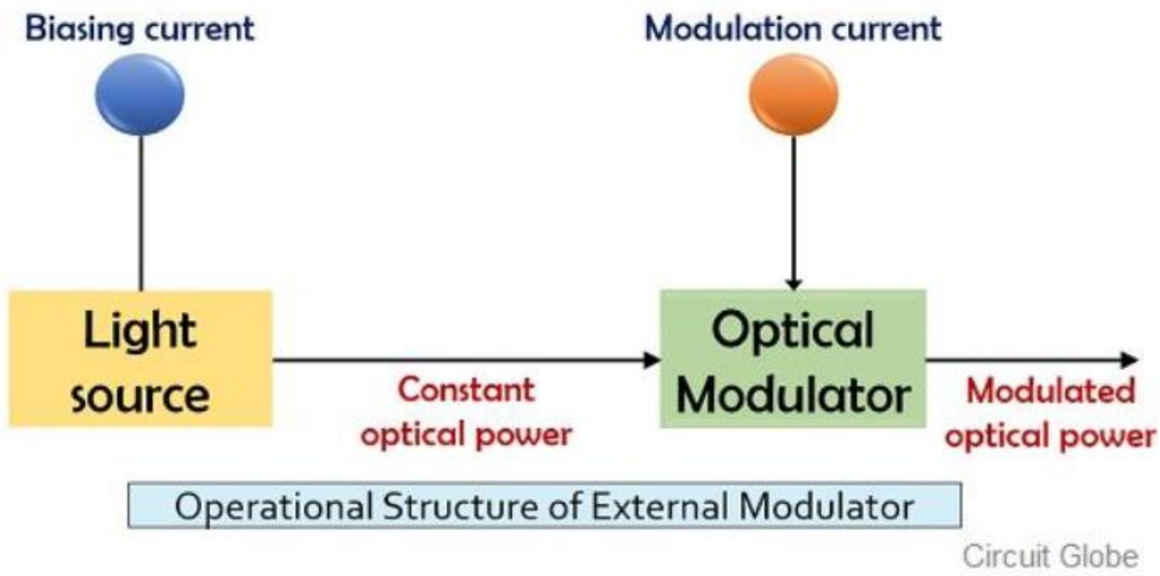


Figure I.10 :Optical Structure of external modulator

Here, the first block represents the light source which is basically a laser diode. After the diode, an optical modulator circuit is present that modulates the light wave emitted by the source according to the electrical signal[10].

The laser diode produces an optical signal of constant amplitude. So, in this case, the electrical signal instead of changing the amplitude of the optical signal varies the power level of the optical signal. Hence, at the output of the modulator, a time-varying optical signal is generated. It is to be noted here that the circuitry of the external modulator can be integrated combinely with the optical source or it can be considered as an individual device.

I.3.2 Sources Laser

Most systems use a "transceiver" which includes both transmission and receiver in a single module. The transmitter takes an electrical input and converts it to an optical output from a laser diode or LED. The light from the transmitter is coupled into the fiber with a connector and is transmitted through the fiber optic cable plant. The light from the end of the fiber is coupled to a receiver where a detector converts the light into an electrical signal which is then conditioned properly for use by the receiving equipment.

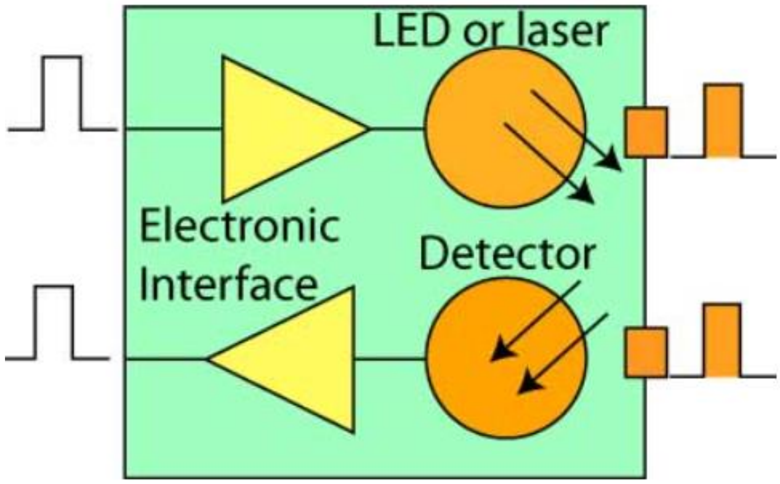


Figure I.11 :Optoelectronic Signal Chain: Transmitter-Channel-Receiver

Typical Fiber Optic Source Specifications[11] :

Device Type	Wavelength (nm)	Power intoFiber (dBm)	Bandwidth	Fiber types
LED	850 , 1300	-30 to -10	<250 MHz	MM
Fabry-Perot Laser	850, 1310 (1280-1330) 1550 (1480-1650)	0 to +10	>10 GHz	MM , SM
DFB Lazer	1550 (1480-1650)	0 to +25	>10 GHz	SM
VCSEL	850	-10 to 0	>10 GHz	MM

Table I.1 : Typical Fiber Optic Source Specifications

I.3.3 Fiber Amplifiers

While the low loss of optical fiber allows signals to travel hundreds of kilometers, extremely long haul lines and submarine cables require regenerators or repeaters to amplify the signal periodically. In the beginning, repeaters basically consisted of a receiver followed by a transmitter. The incoming signal was converted from a light signal to an electrical signal by a receiver, cleaned up to remove as much noise as possible, then was retransmitted by another laser transmitter.

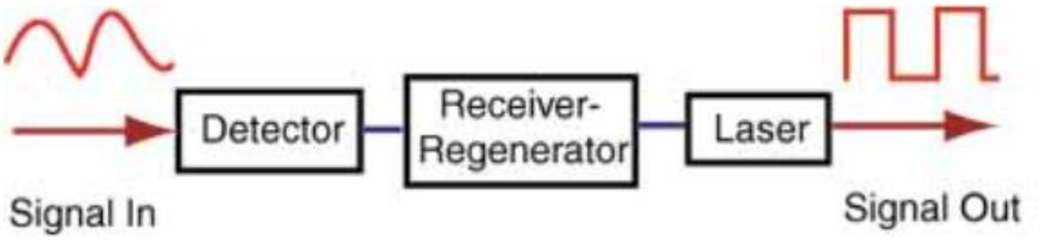


Figure I.12 : Electronic Repeater

These repeaters added noise to the signal, consumed much power and were complicated, which means they were a source of failure. They also had to be made for the specific bit rate of transmission and upgrading required replacing all the repeaters, a really difficult task in an undersea cable!

Since the 1960s, researchers knew how to make fiber lasers. Proper doping of the fiber (introducing small amounts of active elements into the glass fiber) allowed it to be pumped with external light sources until stimulated emission occurred. While making fiber amplifiers was hypothesized early in the stages of fiber optic development, it was not until 1987 that working models were realized. Major contributors to the development included Bell Labs and NTT.

The typical fiber amplifier works in the 1550 nm band and consists of a length of fiber doped with Erbium pumped with a laser at 980. The pump laser supplies the energy for the amplifier, while the incoming signal stimulates emission as the pulse passes through the doped fiber.

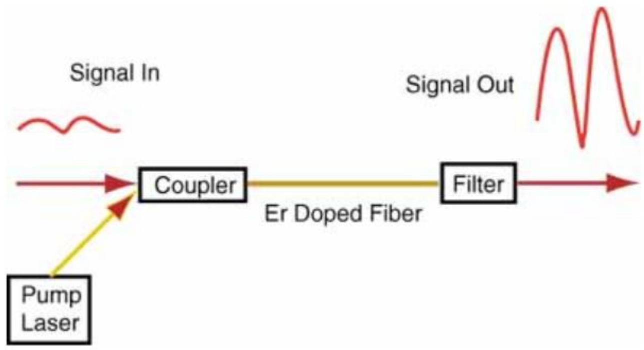


Figure I.13 :How Optical Signals Are Amplified in Fiber Networks

The stimulated emission stimulates more emission, so there is a rapid, exponential growth of photons in the doped fiber. Gains of >40 dB (10,000X) are possible with power outputs >+20 dBm (100 MW).

To date, the most efficient fiber amplifiers have been Erbium-Doped Fiber Amplifiers (EDFAs) operating in the 1550 nm range. Since most systems still work at 1310 nm, considerable research has been done to find materials that would work in this range. Praseodymium-doped fluoride fiber amplifiers (PDFFAs) using fibers made from zirconium fluoride or hafnium fluoride have shown some promise, but have not developed the performance needed for widespread applications.

The basic structure of an EDFA is very simple. The amplifier itself emits light energy in a signal wavelength (usually about 1540nm) using energy supplied to it by photons in a pump wavelength (usually 980nm) when stimulated by incoming photons in the signal - the signal which needs amplification. Just like in a laser, the emitted photons then stimulate other emissions, so there is an exponential growth of photons. Supporting the amplifier is a pump laser, which supplies the amplifier's energy, a coupler, which combines the pump laser beams and the signal laser beam and puts them on a single fiber, and an optical filter, which removes the remaining traces of the pump beam so that it doesn't interfere with reception of the signal.

I.3.4 Photodiodes

Photodiode is a semiconductor device that detects light and converts it into an electrical current. It works by absorbing photons, which create electron-hole pairs in the semiconductor material, generating a measurable current proportional to the light intensity. This deviceare designed to operate primarily in reverse bias mode, which enhances their speed and sensitivity, making them ideal for applications requiring fast response times. They are widely used in fiber-optic communication systems to receive optical signals, as well as in various light detection applications like medical sensors, industrial automation, and consumer electronics. Different materials, such as silicon, germanium, or Ingas, allow photodiodes to detect specific wavelengths of light, from ultraviolet to infrared. Their ability to provide precise, linear light detection with quick response makes them essential components in many modern optoelectronic systems.

Photodiodes are essential components in optical fiber communication systems, serving as the primary optical-to-electrical converters at the receiver end. Their performance directly impacts signal detection, data rates, and overall system efficiency. The most commonly used types are PIN photodiodes and avalanche photodiodes (APDs). PIN photodiodes, with their simple P-Intrinsic-N structure, offer fast response times and low noise, making them ideal for short to medium-range applications like local area networks (LANs) and fiber-to-the-home (FTTH) systems. However, they lack internal gain, limiting their sensitivity for weak signals. In contrast, APDs provide signal amplification through avalanche multiplication, enhancing their effectiveness in long-haul and high-speed communication, such as telecom backbone networks. However, this gain comes at the cost of increased noise and higher operational complexity.

The choice between PIN and APD photodiodes depends on factors like wavelength compatibility, responsivity, bandwidth, and noise performance. For instance, silicon-based PIN diodes work well with 850 nm multimode fibers, while indium gallium arsenide (InGaAs) variants are better suited for 1310 nm and 1550 nm single-mode fibers. APDs, though more sensitive, require precise bias control and are typically used where signal strength is critically low. Noise considerations also play a role—PIN diodes are preferred in low-noise, high-linearity applications like analog fiber systems, whereas APDs are reserved for scenarios where signal amplification outweighs noise concerns.

Ultimately, photodiodes shape the reliability and efficiency of fiber optic systems. Selecting the right type involves balancing sensitivity, speed, cost, and environmental factors to ensure optimal performance for the intended application. Whether in high-speed data centers or undersea cables, the photodiode's characteristics determine how effectively optical signals are recovered and processed, making them a cornerstone of modern optical communication[12].

I.4 Multiplexing techniques

I.4.1Frequency Division Multiplexing (FDM)

Frequency Division Multiplexing (FDM) is a method used to transmit multiple signals simultaneously over a single communication channel. By dividing the available bandwidth into distinct frequency bands, FDM allows each signal to occupy a unique portion of the spectrum, thus preventing interference among them. This technique is pivotal in various applications, including radio broadcasting and telecommunications, where efficient use of bandwidth is crucial. In this practical guide, we will delve into the mechanics of FDM, explore its benefits and limitations, and provide real-world examples to help you understand what is frequency division multiplexing and how it impacts everyday technology.

Frequency Division Multiplexing (FDM) is a technique that enables multiple signals to be transmitted over a single communication medium. By assigning each signal a distinct frequency band within the available spectrum, FDM ensures that signals do not interfere with one another. This separation allows for simultaneous data transmission, making the process efficient and effective. FDM is widely used in various fields, such as radio and television broadcasting, where it supports the transmission of different channels over the same network. In telecommunications, FDM enables multiple calls to occur concurrently over a single cable. This method maximizes the use of available bandwidth, which is a critical resource in communication systems. Understanding what is frequency division multiplexing is essential for grasping how modern communication networks operate without interference, delivering clear and reliable signals to users[13].

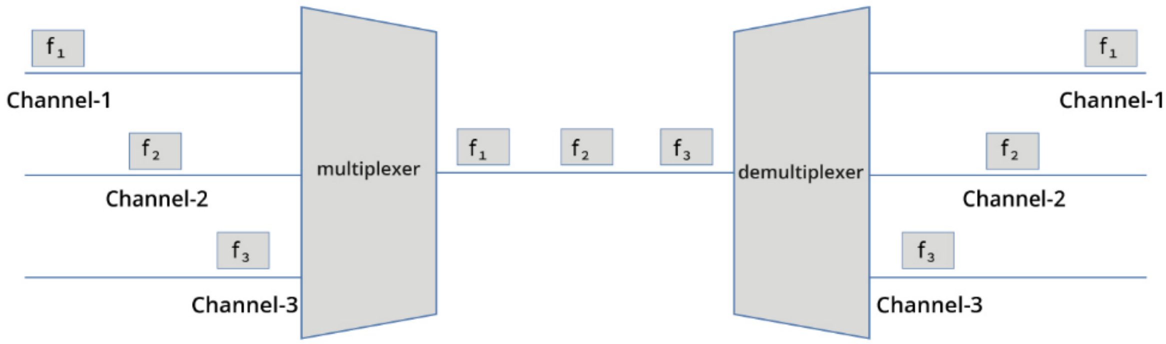


Figure I.14: FDM Working Principle

I.4.1.1 Advantages and Disadvantages of FDM

1- Advantages :

There are some advantages of frequency division multiplexing (FDM) which are given below,

- Signals continuously send data
- Full duplex information flow
- Works for analog and digital
- Noise reduction on analog
- It does not need synchronization between its transmitter and receiver.
- Frequency division multiplexing (FDM) is simpler and easy demodulation.
- Due to slow narrow band fading only one channel gets affected.
- A large number of signals (channels) can be transmitted simultaneously.

2- Disadvantages :

- Each communication line requires its own frequency
- Optimization issues: one channel may be busy while another is idle

- Communication issues on one channel can affect others[14]

I.4.1.2Applications of Frequency Division Multiplexing

- **Telecommunications and Broadcasting :** Frequency Division Multiplexing is integral to both telecommunications and broadcasting industries. In telecommunications, FDM enables the concurrent transmission of multiple phone calls or data streams over the same physical medium, such as a wire or fiber optic cable. This ability to handle multiple conversations simultaneously is essential for efficient network operation and cost-effective infrastructure use. Meanwhile, in the broadcasting sector, FDM allows multiple radio and television channels to be transmitted over a single frequency spectrum. Each station is assigned a specific frequency band, ensuring that signals do not interfere with one another. This allocation maximizes the use of available spectrum, providing diverse content to audiences without collision. Understanding what is frequency division multiplexing and its application in these fields highlights its role in delivering seamless, multi-channel communication and entertainment, supporting the modern demand for connectivity and content variety.

- **Internet and Data Transmission: Frequency** Division Multiplexing also plays a significant role in internet and data transmission. It facilitates the simultaneous transfer of multiple data streams over the same broadband connection. This capability is especially crucial for DSL (Digital Subscriber Line) internet services, which use existing telephone lines to deliver high-speed internet access. FDM divides the available bandwidth into separate channels for internet data and voice communication, allowing users to browse the web and make phone calls simultaneously without interference. In data centers and network infrastructures, FDM supports efficient data transmission by enabling multiple data streams to coexist on a single fiber optic cable, maximizing throughput and reducing latency. Understanding what is frequency division multiplexing and its application in internet and data transmission underscores its importance in maintaining fast, reliable connectivity in an increasingly digital world. As data demands grow, FDM's role in optimizing bandwidth usage becomes even more vital.

- **Other applications:**

- The applications of frequency division multiplexing include the following.

- Earlier, FDM is used in the cellular telephone system and harmonic telegraphy communication system.
- Frequency division multiplexing is mainly used in radio broadcasting.
- FDM is also used in TV broadcasting.
- This type of multiplexing is applicable in the telephone system to help in transmitting several phone calls over a single link or single transmission line.
- FDM is used in a satellite communication system for transmitting various data channels.
- It is used in FM transmission systems or stereo frequency modulation.
- It is used in AM radio transmission systems/Amplitude Modulation.
- It is used for public telephones and cable TV systems.
- It is used in broadcasting.
- It is used in AM and FM broadcasting.
- It is used in wireless networks, cellular networks, etc.
- FDM is used in broadband connection systems and also in DSL (Digital Subscriber Line) modems.[15]
- FDM system is mainly used for multimedia data like audio, video & image transmission.

I.4.2Time Division Multiplexing (TDM)

Time division multiplexing (TDM) is a technique used to transmit multiple signals simultaneously over a single communication channel. In TDM, the channel is divided into several time slots, and each signal is transmitted during its allocated time slot. As a result, several signals share the channel without interfering with each other.

TDM is commonly used in telecommunications, broadcasting, and computer networking to increase data transmission efficiency.

TDM’s workflow is represented as:

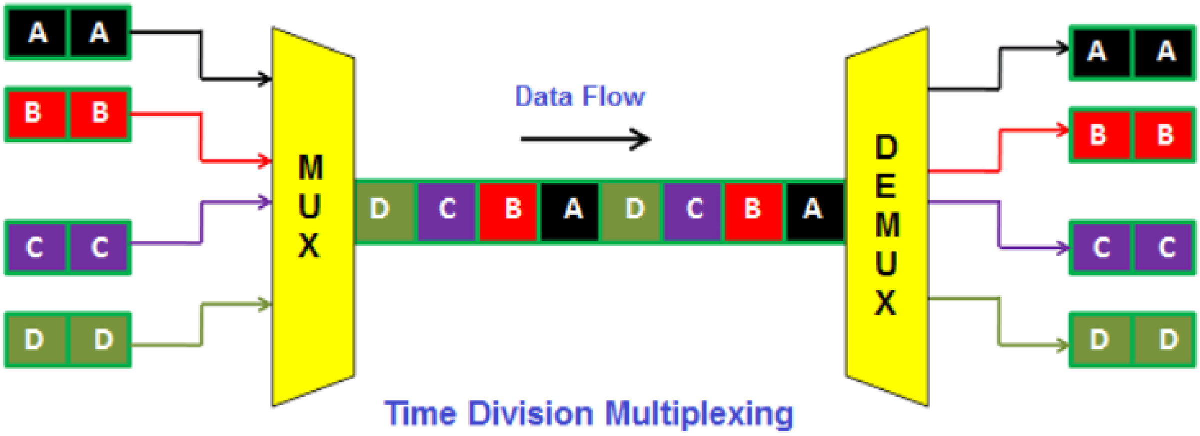


Figure I.15 :Time Division Multiplexing

I.4.2.1Synchronous TDM

The input is synchronous time division multiplexing is simply connected to a frame. In TDM, if there are 'n' connections, then the frame can be separated into 'n' time slots. So, each slot is simply allocated to every input line. In this method, the sampling rate is familiar to all signals, and thus similar clock input is given. The mux assigns the same slot to every device at all times.

The advantages of synchronous TDM mainly include; order being maintained and no addressing data is necessary. The disadvantages of synchronous TDM mainly include; it needs a high bit rate and if there is no input signal at a single channel since a fixed time slot is allocated to every channel, then the time slot for that specific channel does not hold any data & there is bandwidth wastage.

I.4.2.2Asynchronous TDM

Asynchronous TDM is also known as Statistical TDM which is a type of TDM where the o/p frame gathers information from the input frame till it is filled but not leaving an unfilled slot like in Synchronous TDM. In this type of multiplexing, we have to include the address of particular data within the slot that is being transmitted to the output frame. This type of TDM is very efficient because the capacity of the channel is completely used & improves the efficiency of bandwidth.

The advantages of asynchronous TDM mainly include; its circuitry is not complex, low capacity communication link is used, there is no severe crosstalk problem, no intermediation distortion and for each channel, the complete channel bandwidth is used. The disadvantages of asynchronous TDM mainly include; it needs a buffer, frame sizes are different and address data is required.[16]

I.4.2.3 Advantages and Disadvantages of TDM

1-Advantages:

The advantages of time division multiplexing include the following :

- The circuit design of TDM is simple.
- TDM uses the total bandwidth of the channel for signal transmission.
- In TDM, the intermediation distortion issue is not there.
- TDM systems are very flexible compared to FDM.
- For every channel, the complete available channel bandwidth is used.
- Sometimes, pulse overlapping can cause crosstalk however it can be decreased using guard time.
- In this multiplexing, unwanted signal transmission between communication channels takes place rarely.

1-Disadvantages:

- Both the transmitting & receiving sections should be synchronized properly to have right signal transmission & reception.
- TDM is complex to implement.
- As compared to FDM, this multiplexing has lower latency.
- TDM systems require addressing the data & the buffer.
- The channels of this multiplexing may get exhausted because of slow narrowband fad-ing.
- In TDM, synchronization is very significant.
- In a TDM, a buffer & address information are necessary.

I.4.2.4Applicationsof TDM

- The applications of time division multiplexing are discussed below.

- TDM is utilized in Integrated Services Digital Network telephone lines.
- This multiplexing is applicable in public switched telephone networks (PSTN) and SONET (Synchronous Optical Networking).
- TDM is applicable in telephone systems.
- TDM is utilized in wireline telephone lines.
- Earlier, this multiplexing technique is used in the telegraph.
- TDM is used in cellular radios, satellite access systems, and digital audio mixing systems.
- TDM is the most common technique used in fiber optic communication/optical data transmission systems.
- TDM is used for analog & digital signals where a number of channels with less speed are simply multiplexed into high-speed channels are utilized for transmission.
- It is used in cellular radio, digital communication & satellite communication system[[17]].

I.4.3 Code Division Multiplexing (CDM)

The term CDM stands for "Code division multiplexing" and it is a multiplexing technique where various data signals are merged for instantaneous transmission above a common frequency band. Once this multiplexing technique is utilized for allowing several users to transmit a single communications channel, then this technique is known as CDMA or code division multiple accesses.

Code division multiplexing works by assigning a series of bits known as spreading code to every signal to differentiate one signal from another. This spreading code is merged with the original signal to generate a new flow of encoded data, after which it is transmitted over a shared medium. After that, a demux that knows the code can retrieve the original signals by simply subtracting out the spreading code which is called dispreading

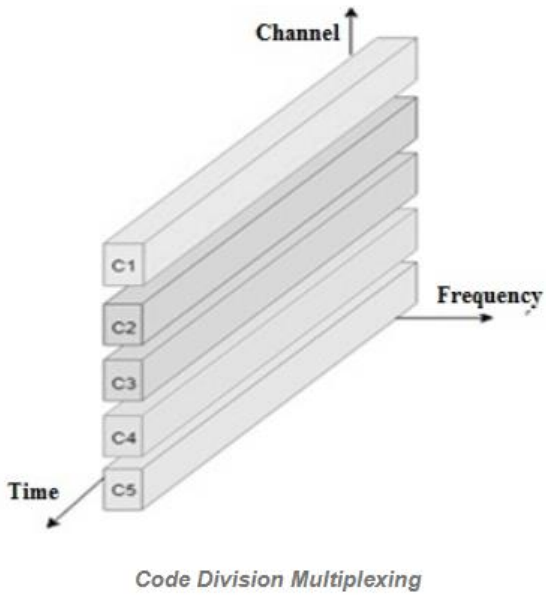


Figure I.16 : Code Division Multiplexing

I.4.3.1 Advantages and Disadvantages of CDM

1-Advantages:

The advantages of code division multiplexing include the following.

- The signal quality is better.
- It protects from interference & tapping because the sender & the receiver only knows the spreading code.
- It is much protected from hackers.
- The addition of users is simple & with no boundary for the number of users.
- Large signal bandwidth decreases the multipath fading.
- Efficient use of particular frequency spectrum.
- Resources distribution is flexible.
- It is efficient highly.
- It does not need any synchronization.
- In this multiplexing, a number of users can split the same bandwidth.

- CDM is scalable.
- It is compatible with other types of cellular technologies.
- It uses a fixed frequency spectrum efficiently.
- Interference is decreased due to different code words assigned to each user.
- The improved security, resistance to interference and jamming, and efficient use of bandwidth. CDMA's spread spectrum technique makes it more difficult for an eavesdropper to intercept the signal, and the unique spreading codes make it resistant to interference and jamming.

1-Disadvantages:

The disadvantages of code division multiplexing include the following.

- When the number of users increases then the overall service quality will be decreased.
- The problem of near-far occurs.
- It needs time synchronization.
- In CDM, the transmitted bandwidth of each user is enlarged than the digital data speed of the source.
- The rate of data transmission is low.
- CDM is complex.

I.4.3.2Applicationsof CDM

The applications of code division multiplexing include the following.

- CDM is widely used in so-called second-generation (2G) and third-generation 3G wireless communications. The technology is used in ultra-high-frequency (UHF) cellular telephone systems in the 800-MHz and 1.9-GHz bands. This is a combination of analog-to-digital conversion and spread spectrum technology.
- CDM networking technique is used to combine several data signals for simultaneous transmission above a common frequency band.
- This multiplexing is extensively used in second-generation & third-generation wireless communications.

- It is used in UHF (ultra-high-frequency) cellular telephone systems within the 800-MHz & 1.9-GHz bands. So this is a combination of both analog-to-digital conversion & spread spectrum technology.[18]

I.5 Basics of Digital Communication:

I.5.1 Digital Transmission Chain

I.5.1.1 Definition

Digital Transmission refers to the process of converting analog signals into digital form for transmission over networks, enabling noise-free signal transmission using square waves and digital repeaters instead of analog amplifiers.

I.5.1.2 Baseband Digital Transmission Block Diagram

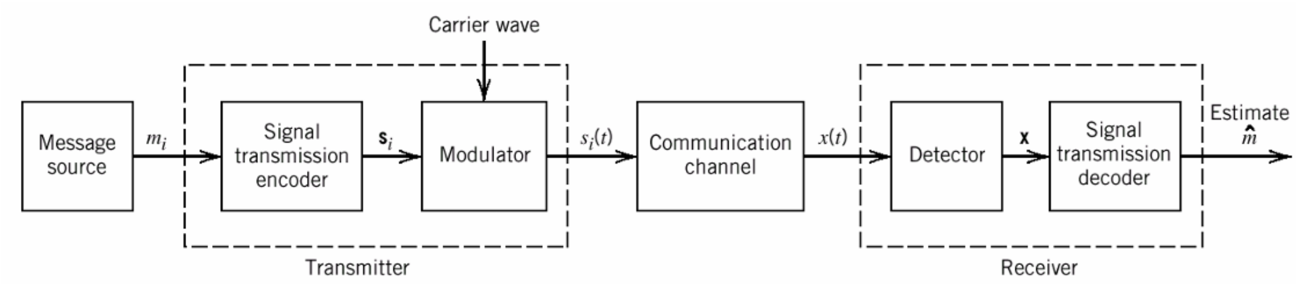


Figure I.17 : Baseband Digital Transmission Block Diagram

This block diagram illustrates the basic components of a digital communication system, divided into Transmitter and Receiver sections.

- **Transmitter Section: The** process begins at the **message source**, where the input data (e.g., voice, text, or video) is converted into a digital format. This raw data, denoted as m_i, is then passed to the **signal transmission encoder**, which prepares it for reliable transmission. The encoder performs multiple functions, including **source coding** (compressing data to remove redundancy) and **channel coding** (adding error-correcting bits to protect against noise). The encoded signal S_i is then fed into the **modulator**, where it is converted into an analog waveform $S_i\ (t)$ by modifying a **carrier wave**'s amplitude, frequency, or phase. This modulated signal is finally transmitted through the **communication channel**, which could be a wired or wireless medium.

- **Communication Channel** : The communication channel is the physical medium (e.g., optical fiber, radio waves, or copper cables) that carries the signal from the transmitter to the receiver. However, during transmission, the signal $S_i(t)$may be altered by noise, interference, or attenuation, resulting in a modified signal $x(t)$ at the receiver's end.

- **Receiver Section:** The receiver's first component is the **detector**, which captures the incoming signal $x(t)$ and converts it back into a digital form. This involves **demodulation**, where the carrier wave is stripped away, and **symbol detection**, where the received signal is sampled and compared to predefined thresholds to estimate the transmitted symbols. The detected symbols are then passed to the **signal transmission decoder**, which reverses the encoding process applied at the transmitter. The decoder performs **error correction** (fixing corrupted bits using redundancy) and **source decoding** (decompressing the data if necessary). The final output is an estimated message $\hat{m}$, which should ideally match the original message m_i as closely as possible.[19]

I.5.1.3 Digital modulation

a) Definition

For better quality and efficient communication, the digital modulation technique is employed. The main advantages of digital modulation over analog modulation include permissible power, available bandwidth, and high noise immunity. In digital modulation, a message signal is converted from analog to digital message and then modulated by using a carrier wave.
The carrier wave is keyed or switched on and off to create pulses such that the signal is modulated. Similar to the analog, here the parameters like amplitude, frequency, and phase variation of the carrier wave decides the type of digital modulation.

- **Phase modulation:** The phase of a carrier wave is varied in response to the vibrations of the sound source in phase modulation (PM). This form of modulation is often considered a variation of FM. The two processes are closely related, because phase cannot be changed without also varying frequency and vice versa. Also, the rate at which the phase of a carrier changes is directly proportional to the frequency of the audio signal.

  Like FM, PM minimizes various types of interference to broadcast reception at frequencies below 30 MHz. The two techniques are commonly used together. FM cannot be applied during the amplification of a sound signal in broadcasting, and so PM is used instead. PM is also used in some microwave radio relays and in some Wi-Fi and satellite television systems

Phase-shift keying: When phase is the parameter altered by the information signal, the method is called phase-shift keying (PSK). In the simplest form of PSK, a single radio frequency carrier is sent with a fixed phase to represent a 0 and with a 180° phase shift—that is, with the opposite polarity—to represent a 1.

- **Frequency modulation :**In frequency modulation (FM), unlike AM, the amplitude of the carrier is kept constant, but its frequency is altered in accordance with variations in the audio signal being sent. This form of modulation was developed by the American electrical engineer Edwin H. Armstrong during the early 1930s in an effort to overcome interference and noise that affect AM radio reception. FM is less susceptible than AM to certain kinds of interference, such as that caused by thunderstorms and by random electrical currents from machinery and other related sources. These noise-producing signals affect the amplitude of a radio wave but not its frequency, and so an FM signal remains virtually unchanged.

  FM is better adapted than AM to the transmission of stereophonic sound, audio signals for television programs, and long-distance telephone calls by microwave radio relay. Commercial FM broadcasting stations are assigned higher frequencies than are AM stations. The assigned frequencies, spaced 200 kHz apart, range from 88 to 108 MHz

  Frequency-shift keying : If frequency is the parameter chosen to be a function of the information signal, the modulation method is called frequency-shift keying (FSK). In the simplest form of FSK signaling, digital data is transmitted using one of two frequencies, whereby one frequency is used to transmit a 1 and the other frequency to transmit a 0[20].

- **Quadrature Amplitude Modulation (QAM): is** a signal where two carriers, shifted by 90 degrees in phase (sine and cosine), are modulated and combined. These two signals are known as the In-phase ("I") and Quadrature ("Q") signals. Due to their 90° phase difference, QAM combines both amplitude and phase variations in a single signal, effectively blending amplitude and phase modulation [21].

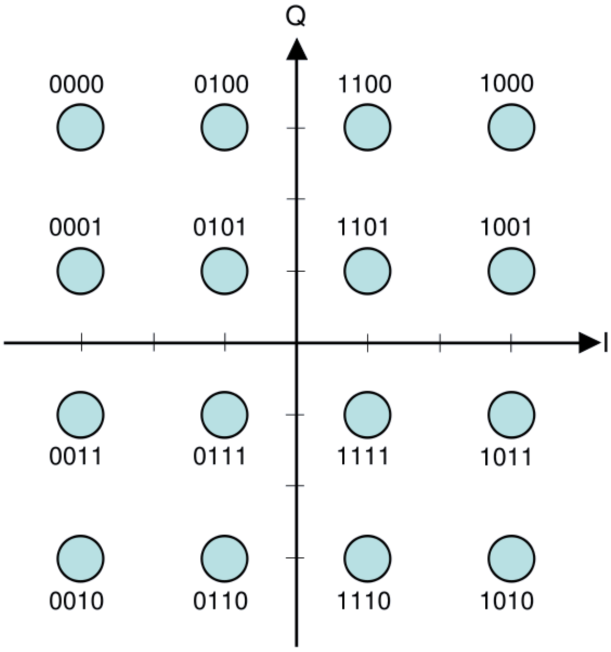
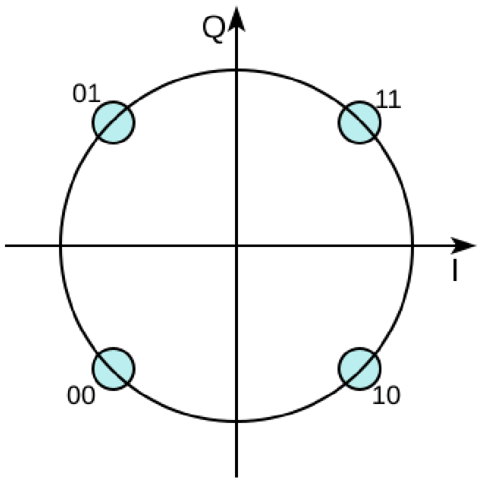


Figure I.18 : Constellation diagram showing the 16 possible states for 16-QAM

- **Quadrature Phase-Shift Keying (QPSK): Quadrature** Phase Shift Keying is a digital modulation method. In this method, the phase of the carrier waveform is changed according to the digital baseband signal. The phase of the carrier remains the same when the input logic is the 1 but goes a phase shift when the logic is 0. In Quadrature Phase Shift Keying, two information bits are modulated at once, unlike Binary Phase Shift Keying where only one bit is passed per symbol. Here, there are four carrier phase offsets with a phase difference of ±90° for four possible combinations of two bits(00, 01, 10, 11). Symbol duration in this modulation is twice the bit duration [22].



FigureI.19 :Constellation diagram for QPSK with Gray coding

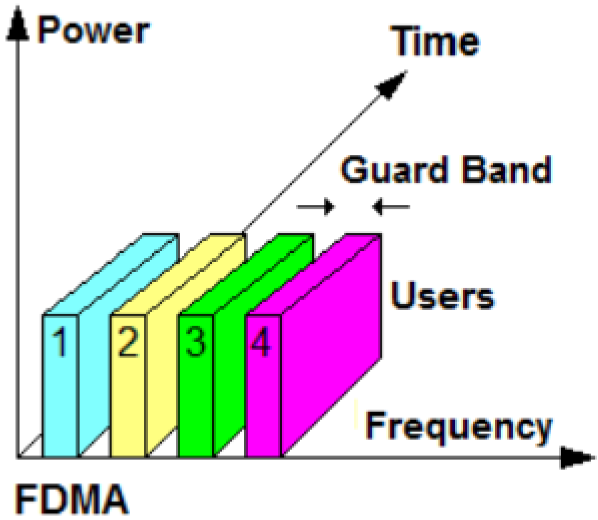
I.5.2 Access technics

I.5.2.1 Frequency Division Multiple Access (FDMA)

Frequency Division Multiple Access (FDMA) is a channel access method in which the available frequency spectrum is divided into smaller frequency channels, each assigned to a specific user or group of users. It is commonly used in wireless communication systems, such as cellular networks and satellite communications, to allow simultaneous data transmissions from multiple users.

Key Features of FDMA:

- **Frequency Division:** The total frequency spectrum is split into several narrow channels, each allocated to a particular user for exclusive use.
- **Channel Allocation:** Users are assigned distinct frequency channels during their transmission period, reducing interference with other signals.
- **Simultaneous Transmission:** FDMA enables multiple users to communicate at the same time by utilizing different frequency channels, allowing parallel data transmissions.
- **Low Interference:** By assigning separate frequencies to users, FDMA minimizes the risk of interference between different signals [23].



FigureI.20 :Diagram of Frequency Division Multiplexing (FDMA)

I.5.2.2 Orthogonal Frequency Division Multiple Access (OFDMA)

OFDMA is a multi-user version of the OFDM digital-modulation technology. In Wi-Fi 6 (802.11ax), OFDMA is one of the critical feature to improve network performance [24].

Both OFDM and OFDMA split transmitted data into several small packets, to move small bits of information in a simple way. Furthermore, OFDMA subdivides a channel into smaller frequency allocations called subcarriers. By subdividing the channel, small packets can be parallel transmitted to multiple devices simultaneously. Arrived packets proceed to transmit and don't have to wait for other packets. In downlink OFDMA, router can use different sub-carrier groups to send packets to different clients and latency can be managed. This flexible and decentralized method of communication increases network speed and efficiency[25].

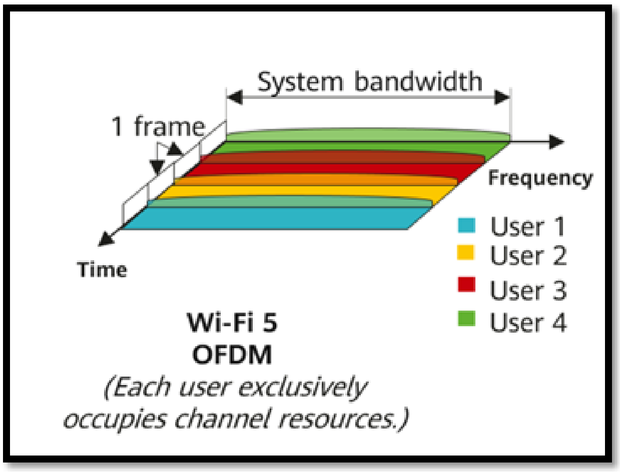


Figure I.21: OFDM working mode

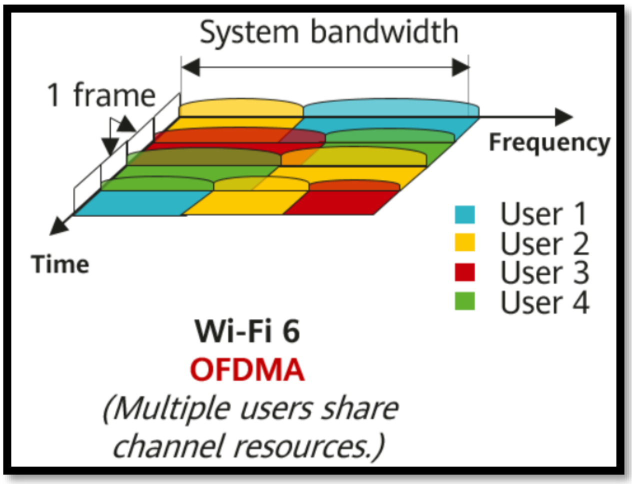


Figure I.22: OFDMA working mode

I.5.2.3 Time Division Multiple Access (TDMA):

Time Division Multiple Access (TDMA) is a channel access method for shared-medium networks, including cellular and satellite communication systems, which enables multiple users to access a single radio frequency channel without interference. By dividing the signal into different time slots and assigning each slot to a different user, TDMA allows multiple parties to share the same frequency band, effectively increasing the efficiency of the available bandwidth. This article explores the concept, benefits, uses, and features of TDMA, along with addressing frequently asked questions related to this pivotal technology in the telecommunications field.

TDMA works by allocating time slots in a cyclic pattern over a single frequency band. Each user is given a unique time slot during which they can transmit or receive data. This method ensures that users do not interfere with each other despite sharing the same frequency channel. TDMA is widely used in digital cellular technologies, satellite communication, and in some wireless LAN applications, serving as the foundation for various telecommunications standards, including GSM (Global System for Mobile communications).

Key Features of TDMA:

TDMA-based systems are characterized by several key features:

- **Time Slot Allocation:** The fundamental aspect of TDMA is the division of the communication channel into sequential time slots.
- **Synchronization:** Accurate timing is crucial for the operation of TDMA to prevent overlap between time slots.
- **Dynamic Allocation:** Some TDMA systems dynamically allocate time slots based on demand, improving flexibility and efficiency.
- **Error Detection and Correction:** TDMA systems often incorporate error detection and correction mechanisms to ensure the reliability of communications. [26]

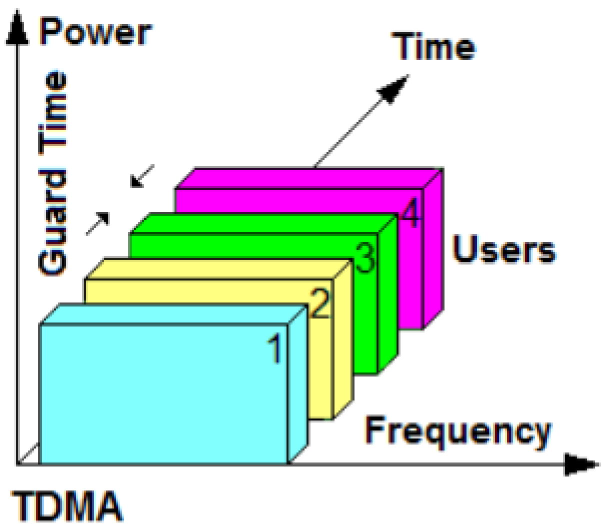


Figure I.23 : Diagram of TimeDivision Multiplexing (FDMA)

I.5.2.4 Code Division Multiple Access (CDMA)

CDMA (Code-Division Multiple Access) refers to any of several protocols used in second-generation (2G) and third-generation (3G) wireless communications. As the term implies, CDMA is a form of multiplexing, which allows numerous signals to occupy a single transmission channel, optimizing the use of available bandwidth. The technology is used in ultra-high-frequency (UHF) cellular phone systems in the 800-megahertz (MHz) and 1.9 gigahertz (GHz) bands.

CDMA employs analog-to-digital conversion (ADC) in combination with spread spectrum technology. Audio input is first digitized into binary elements. The frequency of the transmitted signal is then made to vary according to a defined pattern code. This enables the signal to be intercepted only by a receiver whose frequency response is programmed with the same code, following along with the transmitter frequency. There are trillions of possible frequency sequencing codes, which enhances privacy and makes cloning difficult [27].

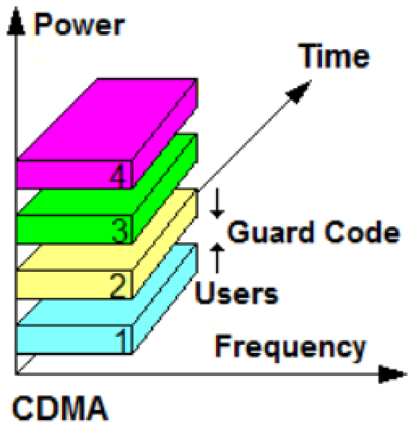


Figure I.24 : Diagram of Code division multiplexing (FDMA)

- **Code of Walsh: Also** known as "Walsh-Hadamard code," it is an algorithm that generates statistically unique sets of numbers for use in encryption and cellular communications. Known as "pseudo-random noise codes," Walsh codes are used in direct sequence spread spectrum (DSSS) systems such as Qualcomm's CDMA. They are also used in frequency hopping spread spectrum (FHSS) systems to select the target frequency for the next hop.

  Walsh Code Algorithm :

```
(a', b') = (a+b, a-b)
(a', b') = (a+b, a-b)
```

$$W_2=\begin{bmatrix}0&0\\0&1\end{bmatrix}\quad W_4=\begin{bmatrix}0&0&0&0\\0&1&0&1\\0&0&1&1\\0&1&1&0\end{bmatrix}\quad W_8=\begin{bmatrix}0&0&0&0&0&0&0&0\\0&1&0&1&0&1&0&1\\0&0&1&1&0&0&1&1\\0&1&1&0&0&1&1&0\\0&0&0&0&1&1&1&1\\0&1&0&1&1&0&1&0\\0&0&1&1&1&1&0&0\\0&1&1&0&1&0&0&1\end{bmatrix}$$

Figure I.25: Walsh code functions

I.6 Conclusion

Outlined the fundamentals of optical fibers and digital communication systems. Key topics included fiber types, signal modulation, and multiplexing methods, which collectively enhance data capacity and transmission efficiency. These principles underpin today's communication technologies.

We talked about key aspects examined included the structural types and transmission characteristics of optical fibers, such as attenuation and various dispersion mechanisms (chromatic, modal, PMD), alongside significant nonlinear effects (SPM, XPM, FWM). Essential components of the optical link, including sources, amplifiers, and detectors, were outlined. Finally, core digital communication concepts relevant to optical systems, namely modulation, multiplexing, and multiple access techniques, were surveyed. This foundational knowledge is essential for comprehending the design and limitations of modern optical communication systems.

CHAPTER II

Coherent Optical Orthogonal Frequency Division Multiplexing

II.1 Introduction

There are two trends which are ever evident in today's optical networks: (i) the transmission data rate per channel has been fast increasing and rapidly approaching 100 Gb/s, and (ii) the dynamically reconfigurable network has gradually become a reality thanks to deployment of optical Add/Drop Multiplexers (OADM). These trends place significant challenges to the high-speed transmission link for the optical networks. In particular, as the transmission rate approaches 100 Gb/s, conventional meticulous per-span optical dispersion compensation becomes too costly and time-consuming if not possible, as the dispersion compensation requires precise fiber dispersion measurement and precise matching of the dispersion compensation cross broad wavelength range. Most importantly, a dynamically reconfigurable network mandates a fast link setup and leaves the manual optical dispersion compensation impractical. Coherent optical orthogonal frequency-division multiplexing (CO-OFDM) has been recently proposed in response to the above-mentioned challenges. [28].

II.2 Introduction au CO-OFDM

II.2.1 Definition and Context

Although OFDM was standardized in wireless communications a long time ago, CO-OFDM was first presented by researchers in 2008 and is considered to be the latest model used in optical communication systems, The coherent optical OFDM (CO-OFDM) is a technique in which input data is modulated using light frequency, and demodulation is performed in a coherent mode [29].

Coherent optical orthogonal frequency-division multiplexing (CO-OFDM) has recently emerged as an attractive modulation format for optical communications, and significant progress has been made through theoretical analysis and experimental demonstration. CO-OFDM brings to optical communications the combination of two powerful techniques, coherent optical detection and orthogonal frequency-division multiplexing (OFDM). From the perspective of coherent optical detection in optical communications, the first wave of the intense interest appeared in the 1980s and early 1990s, when the coherent detection was viewed as a promising technique to improve the receiver sensitivity [30].

However, the ensuing invention of the erbium doped fiber amplifier (EDFA) reduced research on coherent communication to peripheral interest. In the early 21st century, the impressive record-performance experimental demonstration using a differential-phase-shift-keying (DPSK) system, in spite of an incoherent form of modulation by itself, reignited the interest in coherent communications. The second wave of research on coherent communications is highlighted by the remarkable theoretical and experimental demonstrations from various groups around the world. It is rather instructive to point out that the circumstances and the underlying technologies for the current drive for coherent communications are entirely different from those of a decade ago, thanks to the rapid technological advancement within the past decade in various fields. First, current coherent detection systems are heavily entrenched in silicon-based digital signal processing for high-speed signal phase estimation and channel equalization. Second, multicarrier technology, which has emerged and thrived in the RF domain during the past decade, has gradually encroached into the optical domain [31]. Third, in contrast to the optical system that was dominated by a low-speed, point-to-point, and single-channel system a decade ago, modern optical communication systems have advanced to massive wave-division-multiplexed (WDM) and reconfigurable optical networks with a transmission speed approaching 100Gbits/s. In a nutshell, the primary aim of coherent communications has shifted toward supporting these high-speed dynamic networks by simplifying the network installation, monitoring, and maintenance.

OFDM has emerged as the leading physical-layer interface in wireless communications in the past decade. It is a special form of a broader class of multicarrier modulation where a data stream is carried with many lower-rate subcarrier tones. OFDM has been widely studied in mobile communications to combat hostile frequency-selective fading and has been incorporated into wireless network standards (802.11a/g WiFi, HiperLAN2, 802.16 WiMAX) and digital audio and video broadcasting (DAB and DVB-T) in Europe, Asia, Australia, and other parts of the world. The synergies between coherent optical communications and OFDM are twofold. The coherent system brings OFDM a much-needed linearity in RF-to-optical (RTO) up-conversion and optical-to-RF (OTR) down-conversion. OFDM brings coherent system computation efficiency and ease of channel and phase estimation. In spite of the fact that all the current CO-OFDM experimental demonstrations use off-line signal processing [32], the complementary metal–oxide semiconductor (CMOS) application-specific integrated circuit (ASIC) chips recently demonstrated for single carrier coherent systems signify that the current silicon speed can support 40Gbit/s OFDM transmission systems. Because of its superior scalability with the bit rate of the transmission systems, CO-OFDM is well-positioned to be an attractive choice of modulation format for the next generation of 100Gbit/s transmission. [33]

II.2.2 Basic Principles

The principle of OFDM is to transmit the data through a large number of multiple orthogonal subcarriers. **FigureII.1** shows the time and frequency structure of the OFDM signal. The

OFDM signal in time domain consists of a continuous stream of OFDM symbols with a regular period T_S. The OFDM baseband signal $s(t)$is written as

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{k=1}^{N_{sc}} c_{ki} \exp\big(j2\pi f_k (t - iT_s)\big)\, f(t - iT_s) \quad (1)$$

$$f_k = \frac{k-1}{t_s}\ , \Delta f = \frac{1}{t_s} \quad (2)$$

$$f(t) = \begin{cases} 1, (-\Delta_G < t \leq t_s \\ 0, (t \ \leq -\Delta_G \ , t > t_s \end{cases} \quad (3)$$

where c_{ki} is the ith information symbol at the kth subcarrier, $f(t)$ is the pulse waveform of the symbol, f_k is the frequency of the subcarrier, and Δf is the subcarrier spacing, T_s, Δ_G and ts are the OFDM symbol period, guard interval length and observation period, respectively. A cyclic prefix associated with the guard interval is appended by cyclically extending the OFDM symbol into the guard interval **(FigureII.1)**. It can be easily shown that, if the maximum delay spread of multipath fading is smaller than the guard timeΔ_G, the cyclic prefix can perfectly eliminate the intersymbol interference (ISI). In the context of optical transmission, the delay spread due to the chromatic dispersion among the subcarriers should not exceed the guard time, and the fundamental condition for complete elimination of ISI in optical medium is thus given by: [34]

$$\frac{c}{f^2} |D_t| \ \cdot \ N_{sc} \ \cdot \ \Delta f < \Delta_G \quad (4)$$

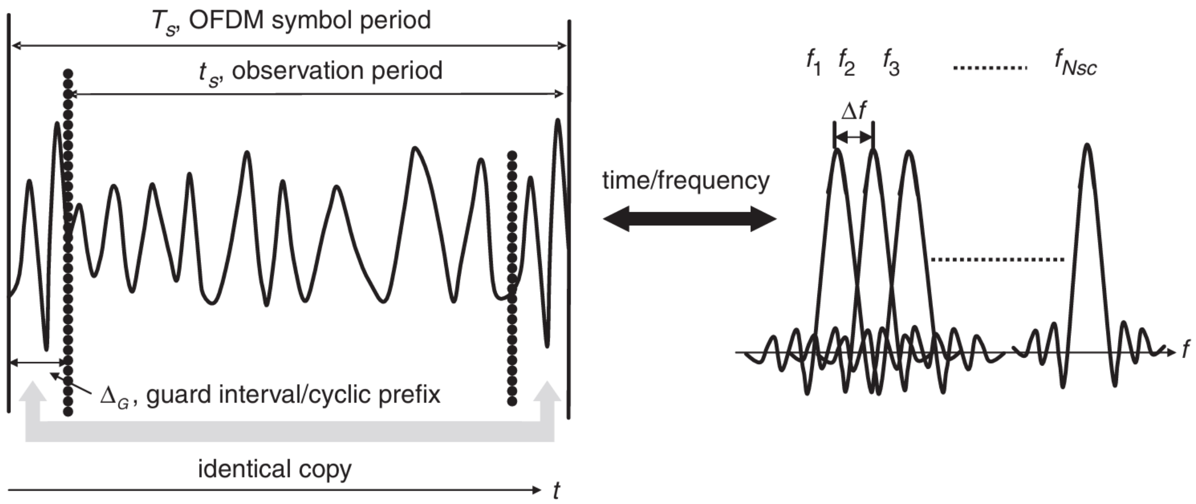


Figure II.1 : OFDM symbol in time and frequency domain

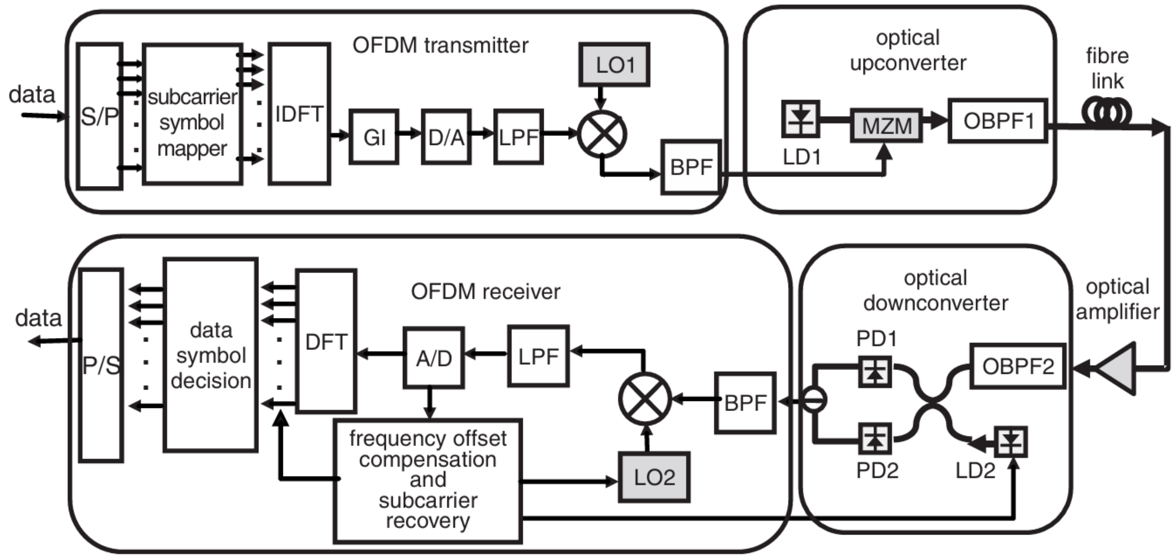


Figure II.2 : Conceptual diagram for complete CO-OFDM system

S=P: serial-to-parallel

Gl: guard interval insertion

D=A: digital-to-analogue

MZM: Mach-Zehnder modulator

LPF: lowpass filter

BPF: bandpass filter

(I)DFT: (inverse) discrete Fourier transform

OBPF: optical bandpass filter

PD: photodiode

LD: laser diode

FigureII.2 shows a conceptual diagram of a complete CO-OFDM system. The function of the OFDM transmitter is to map the data bits into each OFDM symbol, and generate the time series by inverse discrete Fourier transform (IDFT) expressed in **(1)**, including insertion of the guard interval, and then upconvert to an appropriate RF frequency to be fed into an optical upconverter. The function of the optical upconverter is to linearly shift the OFDM spectrum from the RF domain to the optical domain. **FigureII.2** shows an approach using a single optical Mach-Zehnder modulator. For instance, assuming LO1 of 15 GHz, and the OFDM baseband spectrum (f_1 to $f_{N_{sc}}$) spanning from 0 Hz to 10 GHz, two sidebands from 15 to 25 GHz away from the optical carrier will be generated. The modulation index can be as high as 0.5 without incurring significant penalty when the modulator is based at the zero-output point. One of the two sidebands, for instance, the higher sideband, can be conveniently selected with an optical bandpass filter (OBPF1 in **FigureII.2**) and all other sidebands plus the optical carrier are rejected. The field at the output of the optical upconverter is given by:

$$E_S = e^{j\{2\pi(f_{LD1}+f_{LO1})t+\phi_{LD1}\}} \cdot \sum_{k=1}^{N_{sc}} c_k e^{j2\pi f_k t} \qquad (5)$$

where f_{LD1} / f_{LO1} are the frequencies for optical carrier/local oscillator 1 (LO1), ϕ_{LD1} is the phase noise of the laser diode 1 (LD1). For simplicity, only one OFDM symbol is shown in **(5)**. The received optical signal after traversing through total chromatic dispersion ofD_t, can be approximated as

$$E_S \approx e^{j\{2\pi(f_{LD1}+f_{LO1})t+\phi_{LD1}\}} \sum_{k=1}^{N_{sc}} c_k e^{j2\pi f_k t} e^{j\Phi_D(k)},$$

$$\Phi_D(k) = \frac{\pi \cdot c}{f_{LD1}^2} D_t \cdot f_k^2 \qquad (6)$$

where $\Phi_D(k)$ is the phase dispersion of each subcarrier owing to the fibre chromatic dispersion. The signal then passes through an optical downconverter, which consists of a pair of balanced photodetectors. It is very critical to use an OBPF before the photodetectors to eliminate interference and optical noise from the image frequency to the OFDM spectrum. The detected signal at the output of the balanced receiver can be easily shown to be

$$P_S \propto e^{j\{2\pi(f_{LO}+f_{LD1}-f_{LD2})t+\phi_{LD1}-\phi_{LD2}\}} \cdot \sum_{k=1}^{N_{sc}} c_k e^{j2\pi f_k t} e^{j\Phi_D(k)} \qquad (7)$$

where f_{LD2} / $\phi_{LD2}$is the frequency=phase noise of LD2. The signal enters the OFDM receiver, is further downconverted to baseband with RF I/Q demodulation, sampled with sampling rate ofN_{sc}/t_s in the observation period, and the received information symbol c_k for each subcarrier k is then extracted by performing a DFT and is given by

$$c'_k = e^{j(\phi_{LD1}-\phi_{LD2})} \cdot c_k \cdot e^{j\Phi_D(k)} \qquad (8)$$

The advantage of the coherent detection becomes obvious in **(8)**: the system is simply a linear channel with a constant phase shift $\Phi_D(k)$as far as each individual subcarrier k is concerned. This constant phase will be automatically included in symbol decision on the individual subcarrier basis, resulting in superior dispersion tolerance for CO-OFDM format. [35]

II.3 Operating Principle of CO-OFDM

II.3.1 Digital Signal Processing (DSP):

II.3.1.1 Window Synchronization

The DSP begins with window synchronization in the OFDM reception. Its accu racy will influence the overall performance. Improper position of the DFT window on the OFDM signal will cause the inter-symbol interference (ISI) and ICI. In the worst case, the mis-synchronized symbol cannot be detected completely. The most commonly used method is Schmidl-Cox approach. In this method, a preamble consisting of two identical patterns is inserted in the beginning of the multiple OFDM symbols, namely, an OFDM frame. (**Figure II.3)** shows the OFDM frame structure.

The Schmidl synchronization signal can be expressed as

$$s_m = s_m + \frac{N_{SC}}{2}, m = 1,2, \dots, \frac{N_{SC}}{2} \quad (9)$$

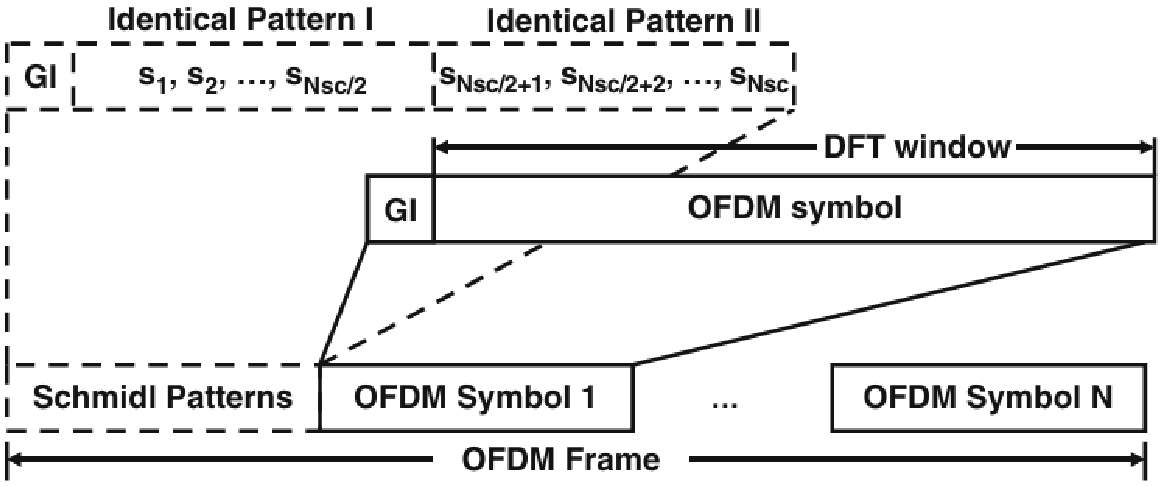


Figure II.3 :OFDM frame structure showing Schmidl pattern for window synchronization

Considering the channel effect, the received samples will have the form as

$$r_m = e^{j\Delta\omega t + \Delta\phi} \cdot s_m + n_m \quad (10)$$

Where $s_m = S_m(t) \otimes h(t) \cdot n_m$stands for the randomnoise.

The delineation of OFDM symbol can be identified by studying the following correlation function defined as

$$R_d = \sum_{m=1}^{N_{sc/2}} r_{m+d}^* r_m + d + \frac{N_{SC}}{2} \quad (11)$$

The principle is based on the fact that the second half of r_m is identical to the first half except for a phase shift. Assuming the frequency offset $\omega_{off}$is small to start with, we anticipate that when $d = 0$, the correlation function R_d reaches its maxi mumvalue [36].

II.3.1.2 Frequency Offset Synchronization

In wireless communications, numerous approaches to estimate the frequency offset between transmitter and receiver have been proposed. In CO-OFDM systems, we use the correlation from the window synchronization to obtain the frequency off set. The phase difference from the sampless_m to $s_m + N_{sc/2}$ is $\pi f_{offset} N_{sc}/S_{sampling}$, where $S_{sampling}$ is the ADC sampling rate. The formula in Equation **(11)** can be re-written as

$$R_d = \sum_{m=1}^{N_{sc/2}} |r_{m+d}^*|^2 \, e^{\pi f_{offset} N_{sc}/S_{sampling}} \qquad (12)$$

Consequently, from the phase information of the correlation, the frequency offset can be derived as

$$f_{offset} = \frac{S_{sampling}}{\pi N_{sc}} \angle R_d \qquad (13)$$

where $\angle R_d$ stands for the angle of the correlation function of R_d. Because the phase information $\angle R_d$ranges only from 0 to 2π , large frequency offset cannot be identified uniquely. Thus, this approach only supports the frequency offset range from $-f_{sub}$ to f_{sub} where f_{sub} is the subcarrier spacing. To further increase the frequency offset compensation range, the synchronization symbol is further divided into $2^k (k > 1)$segments. The tolerable frequency offset can be enhanced to a few subcarriers pacing [37]. Again, beside the Schmidl approach, there are other various approaches to perform the frequency offset estimation, such as the pilot-tone approach.

II.3.1.3 Channel Estimation

Assuming successful completion of window synchronization and frequency offset compensation, the RF OFDM signal after DFT operation is given by

$$r_{ki} = e^{j(\phi_i)} h_{ki} s_{ki} + n_{ki} \qquad (14)$$

where s_{ki} (r_{ki}) is the transmitted (received) information symbol, ϕ_i is the OFDM common phase error (CPE), h_{ki} is the frequency domain channel transfer function, and n_{ki} is the noise. The commonphase error is caused by the finite linewidth of the transmitter and receiver laser.

An OFDM frame usually contains a large number of OFDM symbols. Within each frame, the optical channel can be assumed to be invariant. There are various methods of channel estimation, such as time-domain pilot-assisted and the frequency-domain assisted approaches.

Here, we are using the frequency domain pilot-symbol assisted approach. **Figure 20** shows an OFDM frame in a time-frequency two-dimensional structure.

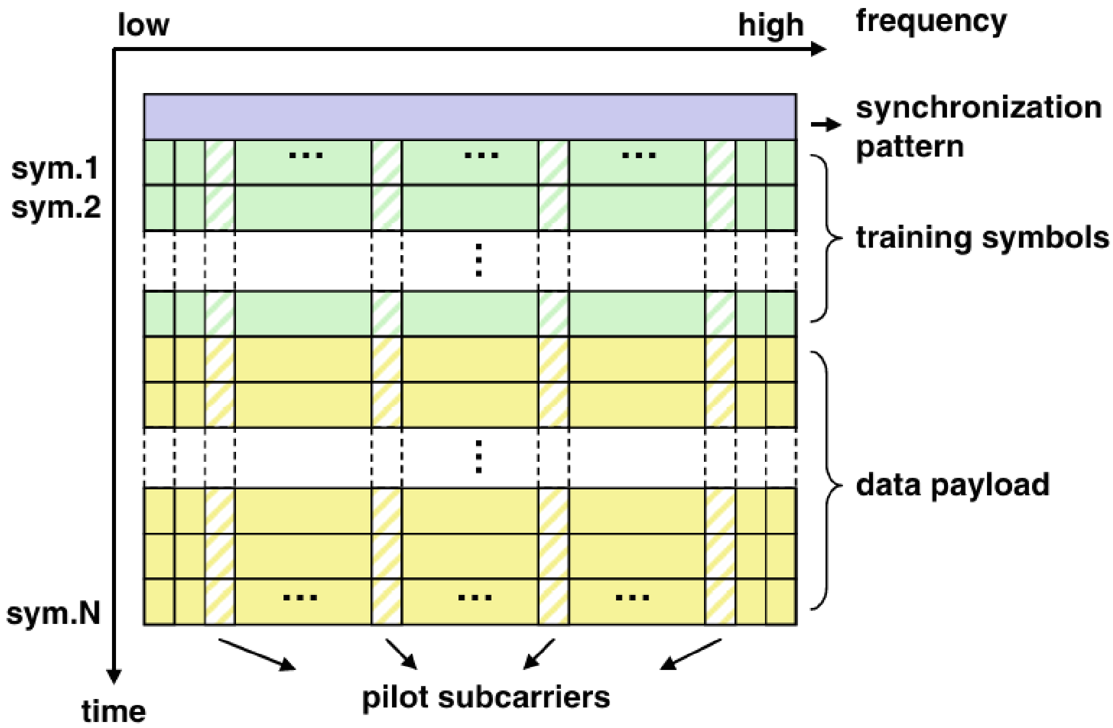


Figure II.4: Data structure of an OFDM frame

The first few symbols are the pilot-symbols or training symbols for which transmitted pattern is already known at the receiver side. The channel transfer function can be estimated as

$$h_{ki} = e^{-j\phi_i} r_{ki}/s_{ki} \qquad (15)$$

Due to the presence of the random noise, the accuracy of the channel transfer function h is limited. To increase the accuracy of channel estimation, multiple training symbols are used. By performing averaging over multiple training symbols, the in fluence of the random noise can be much reduced. However, training symbols also leads to increase of overhead or decrease of the spectral efficiency. In order to obtain accurate channel information while still using little overhead, interpolation or frequency domain averaging algorithm over one training symbol can be used.[38].

II.3.1.4 Phase Estimation

As we mentioned above, the phase noise is due to the linewidth of the transmitter and receiver lasers. For CO-OFDM, we assume that Np subcarriers are used as pilot subcarrier to estimate the phase noise. The maximum like lihood CPE is given as

$$\phi_i = arg\left(\sum_{k=1}^{N_p} r'_{ki} h_k^* s_{ki}^* / \delta_k^2\right) \quad (16)$$

Whereδ_k is the standard deviation of the constellation spread for the kth subcarrier. [39] After the phase noise estimation and compensation, the constellation for every subcarrier can be constructed and symbol decision is made to recover the transmitted data.

II.3.2 Polarization-Diversity Multiplexed OFDM

In Sect. **3.1**, the OFDM signal is presented in a scalar model. However, it is well known that SSMF supports two modes in polarization domain. To describe the multiple input multiple output (MIMO) model for CO-OFDM mathematically, Jones vector is introduced and the channel model is thus given by

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N_{sc}} c_k \Pi(t - iT_s) \exp\left(j2\pi f_k (t - iT_s)\right) \quad (17)$$

$$s(t) = \begin{bmatrix} s_x \\ s_y \end{bmatrix}, c_{ik} = \begin{bmatrix} c_x^{ik} \\ c_y^{ik} \end{bmatrix}$$

$$f_k = \frac{k-1}{t_s}$$

$$s(t) = \Pi(t) \exp(j2\pi f_k t) \quad (18)$$

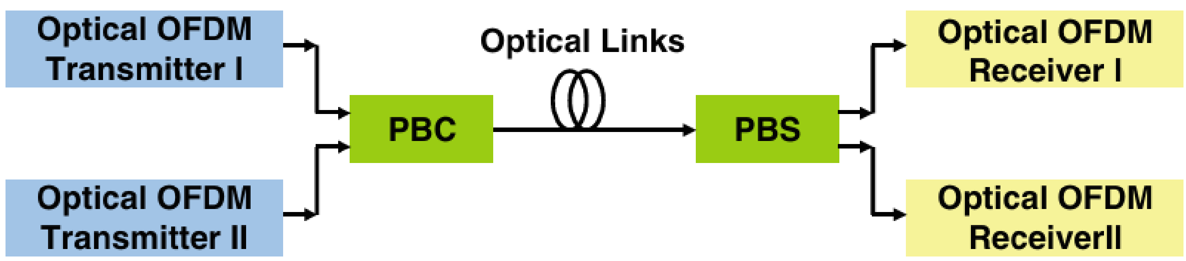


Figure II.5 :PDM-OFDM conceptual diagram

$$\Pi(t) = \begin{cases} 1, & (0 < t < T_s) \\ 0, & (t \le 0, \quad t > T_s) \end{cases} \quad (19)$$

Where s_x and s_y are the two polarization components for $s(t)$ in the time domain;c_{ik} is the transmitted OFDM information symbol in the form of Jones vector for the$k$th subcarrier in the ith OFDM symbol; c_x^{ik} and c_y^{ik} y are the two polarization components for c_{ik}; f_k is the frequency for the kth subcarrier; N_{sc} is the number ofOFDMsubcarriers; and T_s and t_s are the OFDM symbol period and observation period, respectively [40]. four CO-MIMO-OFDM configurations are described: (1) (1 × 1) single-input signle-output, SISO-OFDM; (4) (2 × 2) single-input multiple output SIMO-OFDM; (3) (2 × 1) multiple-input single-output MISO-OFDM; (4) .2 2/ multiple-input multiple-output MIMO-OFDM. Among those configurations, SISO-OFDM and MIMO-OFDM are the preferred schemes. MIMO-OFDM is also called polarization diversity multiplexed (PDM) OFDM. **Figure 21** shows the PDM-OFDM conceptual diagram.

In such scheme, the OFDM signal is transmitted via both polarizations, doubling the channel capacity compared to the SISO scheme. At the receiver, no hardware polarization tracking is needed as the channel estimation can help the OFDM receiver to recover the transmitted OFDM signals on two polarizations.

II.3.2.1 Single-Polarization CO-OFDM (SP-CO-OFDM)

The transmitted signal in an SP-CO-OFDM system is given by[41]:

$$x(t) = Re\left\{\sum_{k=0}^{N-1} X_k e^{j2\pi k\Delta f t} \cdot e^{j\phi_{laser}}\right\}$$

WhereX_k is Complex symbol on the kth subcarrier and N Number of subcarriers, Δf Subcarrier spacingϕ_{laser}Laser phase noise. At the receiver, coherent detection is performed using a single-polarization coherent mixer, followed by DSP for: CD compensation via frequency-domain equalization, Phase recovery (using pilot-aided or blind algorithms).

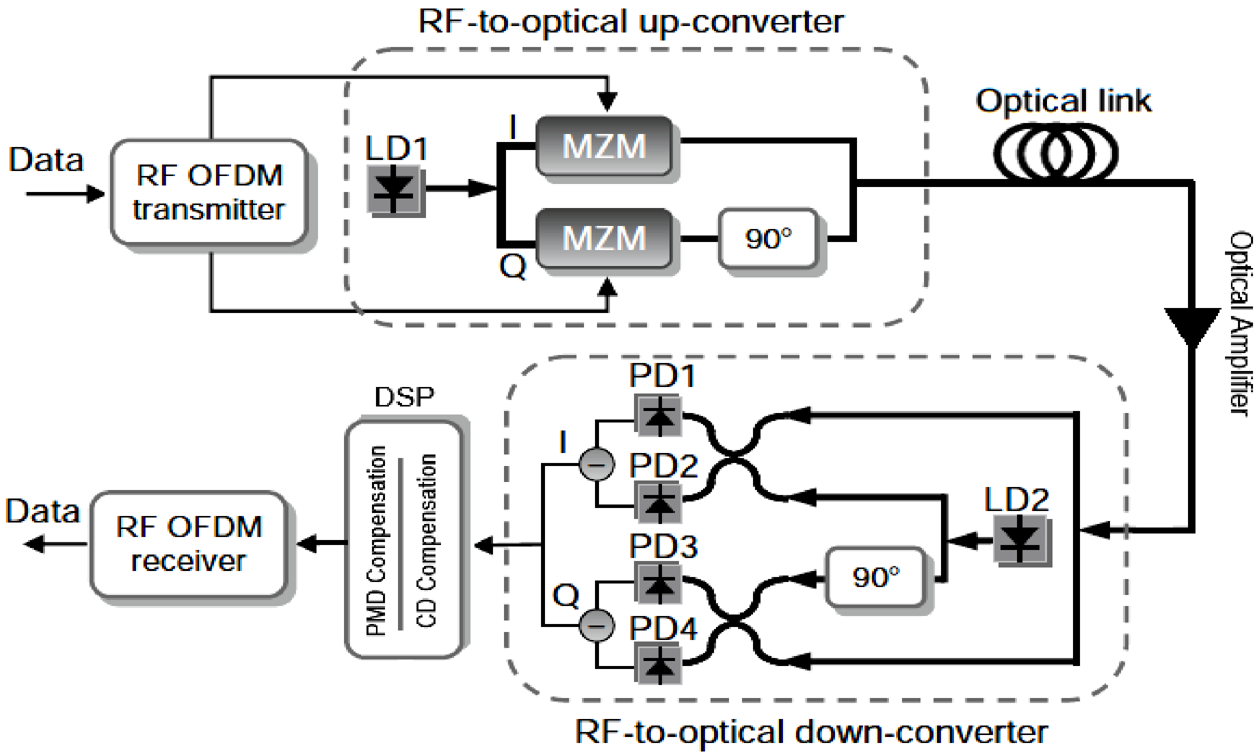


Figure II.6: CO-OFDM System with Single Polarization

A typical single-polarization CO-OFDM system on (**Figure II.6)**begins on the transmitter side with data mapping, where digital symbols (e.g., QAM) are mapped onto multiple subcarriers, followed by an IFFT to convert frequency-domain symbols to a time-domain OFDM signal, cyclic prefix (CP) addition to mitigate inter-symbol interference, and finally DAC and optical modulation to convert the signal to analog and modulate it onto an optical carrier (e.g., via IQ modulation) in one polarization. The signal then propagates through single-mode fiber before being processed at the receiver side, where coherent detection using a local oscillator recovers the field (amplitude and phase), followed by ADC and DSP (including FFT, CP removal, channel estimation, and equalization), and finally demodulation and decoding to recover the transmitted data.

II.3.2.2 CO-OFDM System with Dual Polarization (DP-CO-OFDM)

DP-CO-OFDM transmits independent OFDM signals on two orthogonal polarizations (X and Y). The transmitted signal is:

$$x(t) = \begin{bmatrix} x_X(t) \\ x_Y(t) \end{bmatrix} = Re\left\{ \sum_{k=0}^{N-1} \begin{bmatrix} x_{X,k} \\ x_{Y,k} \end{bmatrix} e^{j2\pi k \Delta f t} \cdot e^{j\phi_{laser}} \right\}$$

At the receiver, a polarization-diversity coherent detector is used, followed by 2×2 MIMO equalization to separate the two polarizations.

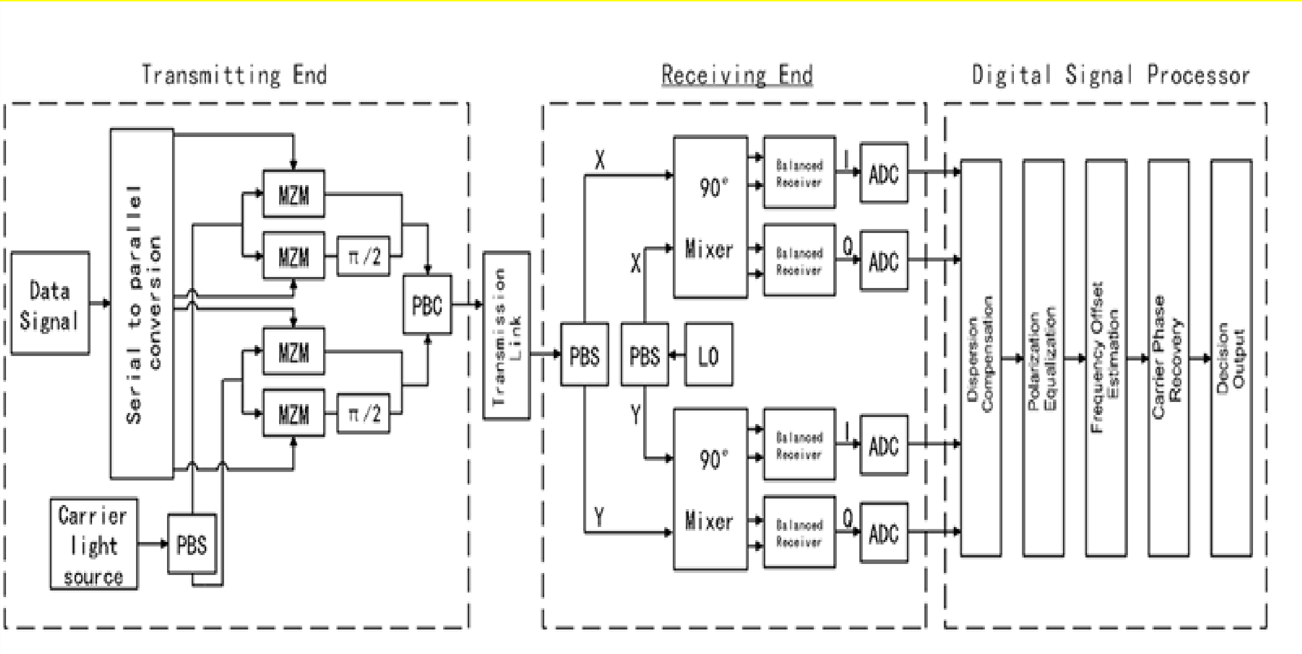


Figure II.7: CO-OFDM System with Dual Polarization

A dual-polarization coherent optical OFDM (DP-CO-OFDM) system enhances spectral efficiency by transmitting independent data streams on two orthogonal polarizations (X and Y). On the transmitter side, input data is split into two polarization streams, each mapped to digital symbols (QAM), converted to time-domain OFDM signals via IFFT, and appended with a cyclic prefix (CP) to mitigate ISI, before being converted to analog via DACs and modulated onto orthogonal polarizations of an optical carrier using a dual-polarization IQ modulator (with PBS and MZMs). The signal then propagates through single-mode fiber (SMF), experiencing chromatic dispersion (CD), polarization mode dispersion (PMD), and nonlinear effects. At the receiver side, a polarization-diverse 90° hybrid and balanced photodiodes perform coherent detection, recovering both polarizations and their I/Q components, which are then digitized by ADCs. DSP processes the signals—removing CP, applying FFT, and performing MIMO equalization (2×2 butterfly filter) to compensate for polarization rotation and impairments, followed by frequency/phase recovery to correct LO mismatches. Finally, the equalized symbols are demapped (QAM decoding), reconstructing the original data from both polarizations, doubling spectral efficiency while maintaining robustness against fiber impairments.

Table II.1 is detailed comparative table between Single-Polarization CO-OFDM (SP-CO-OFDM) and Dual-Polarization CO-OFDM (DP-CO-OFDM) systems:

Feature	Single-Polarization CO-OFDM (SP-CO-OFDM)	Dual-Polarization CO-OFDM (DP-CO-OFDM)
Polarization Channels	1 (Single polarization, e.g., X or Y)	2 (Orthogonal polarizations, X & Y)
Spectral Efficiency	Lower (Uses only one polarization)	2× Higher (Simultaneous X & Y transmission)
Data Rate	Limited by single-polarization capacity	Doubled (Two independent data streams)
Hardware Complexity	Simpler (No polarization multiplexing)	Higher (Requires dual-pol IQ modulator, PBS, MIMO DSP)
DSP Complexity	Lower (No polarization tracking needed)	Higher (Requires 2×2 MIMO equalization for polarization demuxing)
Data Rate (per wave-length)	Lower (e.g., 50 Gbps)	Higher (e.g., 100 Gbps or more)
Fiber Impairment Tolerance	Sensitive to PMD (Polarization Mode Dispersion)	More robust (MIMO equalization compensates PMD)
Local Oscillator (LO) Requirements	Standard coherent detection (single pol.)	Requires polarization-diverse 90° hybrid
Channel Estimation	Simpler (Single-channel equalization)	Complex (Butterfly filter for polarization crosstalk)
Phase Recovery	Standard (Single-carrier phase tracking)	More complex (Joint polarization/phase recovery)
Power Efficiency	More power-efficient (Lower DSP load)	Higher power consumption (Advanced DSP)
Cost	Lower (Simpler Tx/Rx components)	Higher (Dual-pol modulators, advanced DSP)
Applications	Short-reach, low-cost systems	Long-haul, high-capacity optical networks

II.3.3 Real-Time Coherent Optical OFDM

The real-time optical OFDM has progressed rapidly in OFDM transmitter, OFDM receiver, and OFDM transceiver. We are focused on the long-haul transmission; we will mainly discuss the real-time CO-OFDMtransmission in this subsection. With increased research interest in optical OFDM, numerous publications on this topic are being produced confirming the fast pace of research. However, most of the published CO-OFDM experiments are based on off-line processing, which lags behind single-carrier counterpart, where a real-time transceiver operating at 40Gb s^{-1} base don CMOSASIC shasal ready been reported. More importantly, OFDM is based on symbol and frame structure, and the required DSP associated with OFDM procedures, such as window synchronization and channel estimation, remains a challenge for real-time implementation. Among many demonstrated algorithms, only a few can be practically realized due to various limitations associated with digital signal processor capability. It is thus essential to investigate efficient and realistic algorithms for real-time CO-OFDM implementation in both FPGA and ASIC platforms [42].

II.3.3.1 Real-Time Window Synchronization

The first DSP procedure for OFDM is symbol synchronization. Traditional offline processing uses the Schimdl approach [43], where the autocorrelation of two identical patterns inserted at the beginning of each OFDM frame gives rise to a peak indicating the starting position of the OFDM frame and symbol. The autocorrelation output is

$$P(d) = \sum_{k=0}^{L-1} r_d^* + k^r d + k + L \tag{20}$$

and can be recursively expressed as

$$P(d+1) = P(d) + r_{d+L} * r_{d+2L} - r_d * r_{d+L} \tag{21}$$

An example of DSP implementation of **(21)** can be found in **Figure II.8**,where$L$ indicates the length of synchronization pattern, r_d indicates the complex samples, and $P(d)$indicates the autocorrelation term whose amplitude gives peak when the synchronization is found. The relatively simple equation **(21)** and the architecture in **Figure II.9**, however, assume that the incoming signal is a serial stream, and this implementation only works if the process clock rate is the same as the sample rate.

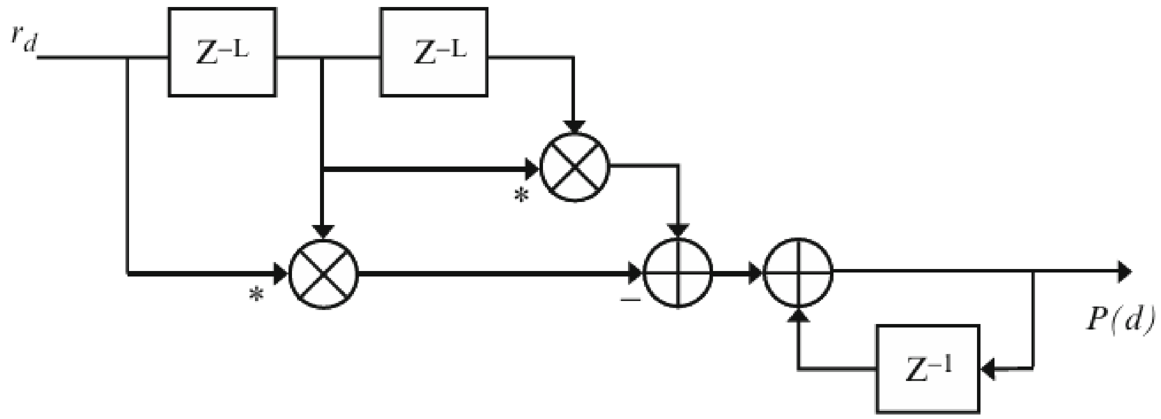


Figure II.8 :DSP block diagram of autocorrelation for symbol synchronization based on serial processing

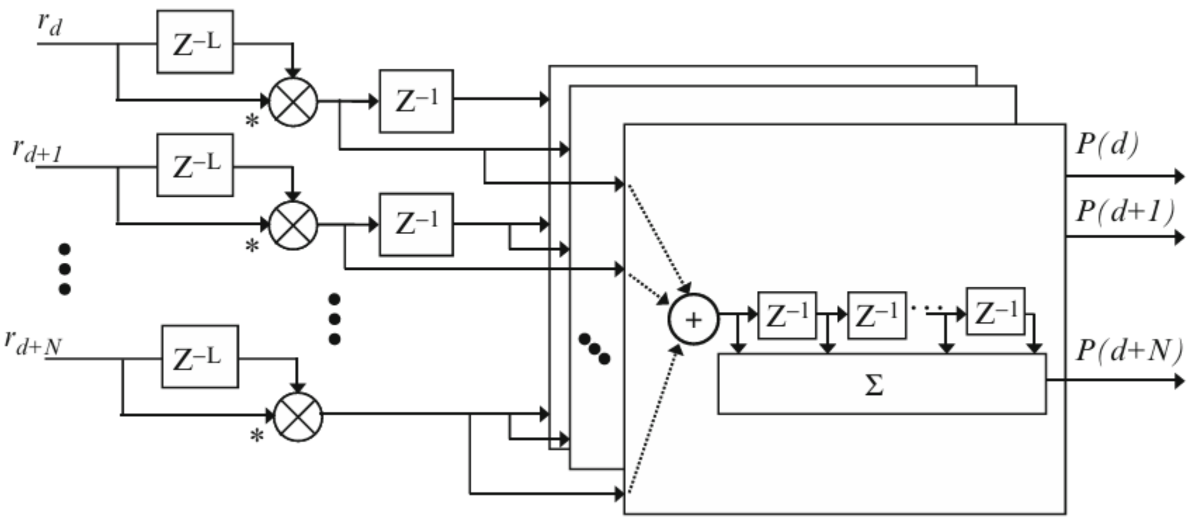


Figure II.9: DSP block diagram of autocorrelation for symbol synchronization based on parallel processing

This is because the moving window for autocorrelation needs to be taken sample by sample while multiple samples need to be processed simultaneously at a parallel process clock cycle. As there was no direct information available to indicate the frame starting point in the 16 parallel channels in our setup, locating the exact frame beginning would involve heavy computation that processes the data among all the channels. To illustrate this point, an implementation of the parallel autocorrelation can be constructed such that we can divide the autocorrelation of **(20)** by length N forthe N parallel processing:

$$P(d) = \sum_{k=0}^{(L/N)} \sum_{m=Nk}^{N(k+1)-1} (r^*_{d+m} r_{d+m+L}) \tag{22}$$

which does not have an apparent recursive equation. The DSP realization is presented in (**Figure.II.9)** As shownin **(22)** and (**Figure.II.9)**, by restricting the synchronization pattern length L to multiple of the number of de-multiplexed bits N, a simple implementation of autocorrelation suitable for parallel processing is realized. However, for the case of $N = 16$ and $L = 32$, the processing resource required in this parallel implementation is estimated as 16 complex multipliers and $16 \times 15 + 16 = 256$ complex adders at each clock cycle. This indicates further efficiency improvementof symbol synchronizationin parallel processing is desired.

II.3.3.2 Real-Time Frequency Offset Synchronization

Frequency offset between signal laser and local lasers must be estimated and compensated before further processing. The algorithm used in this stage is the same as **(13)**. In the experiment, the local laser frequency is placed within ± 2 subcarrier spacings from the signal laser, which guarantees that the phase difference $\hat{\phi}$ be tween these two synchronization patterns remains bounded within $\pm\pi$. It can be shown that the error of multiple of the subcarrier spacing has no significance. The frequency offset can be derived as:

$$f_{offcet} = \hat{\phi}/(\pi T/2) \tag{23}$$

The Coordinate-Rotation-Digital-Computer (CORDIC) algorithm is used to calculate the frequency offset angle and compensate input data in vectoring and rotation modes, respectively. **(Figure II.10)** shows the frequency offset angle output against the sampling points with the frequency offset normalized to $2/(\pi T)$. Once the timing estimate signal from window synchronization stage is detected, the current output value of **(23)** is the correct frequency offset.

Once the frequency offset is obtained, frequency-offset compensation will be started. The implementation of frequency offset compensation in real-time is to use the cumulative phase information. The DSP diagram for frequency compensation is shown in (**Figure II.11)**. Assuming that $\Delta\Phi$ is the phase difference between adjacent samples, which is derived from the auto-correlation, within one FPGA sampling period, N samples are distributed among the multiplexed channels. For the i th channel, the phase is cumulated as$i \times \Delta\Phi$, and then compensated for that channel.

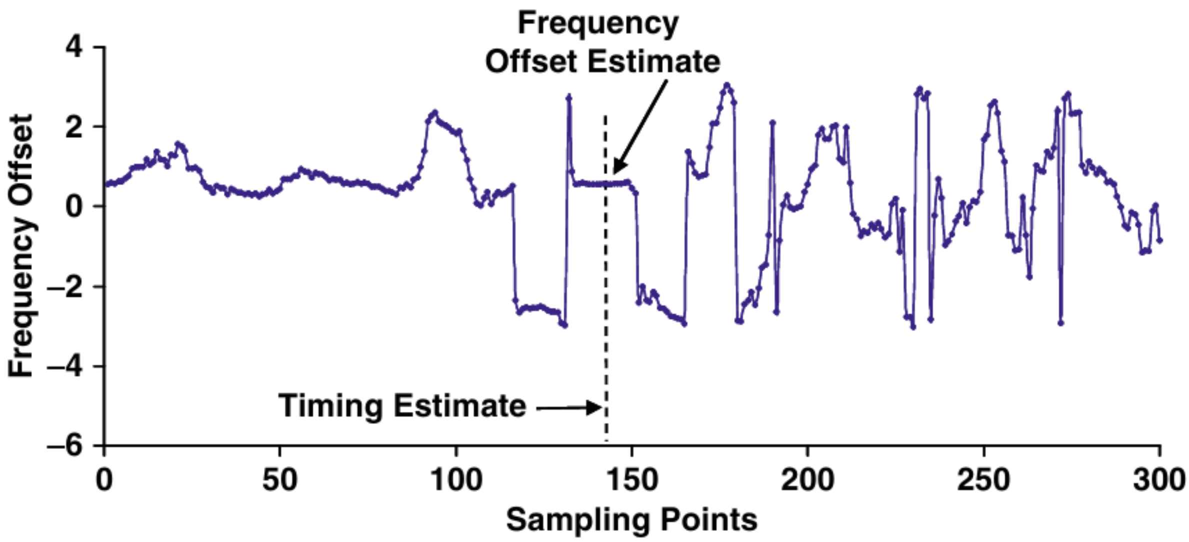


Figure II.10: Real-time measurement of frequency offset estimation for the OFDM signal. The frequency offset is normalized to $2/(\pi T)$

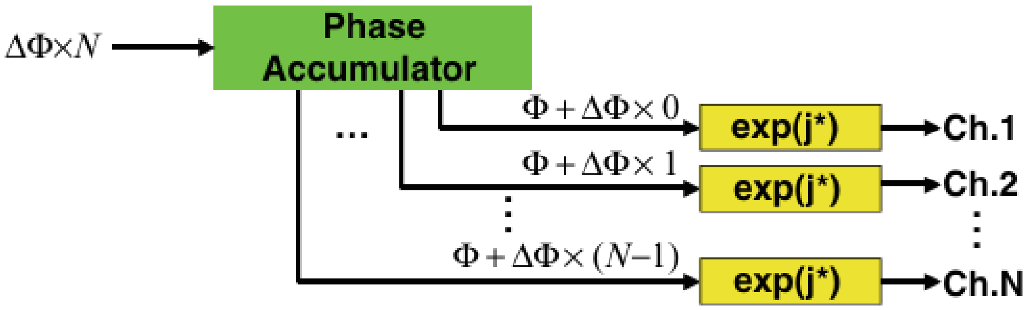


Figure II.11 : DSP diagram for frequency offset compensation

II.3.3.3 Real-Time Channel Estimation

(Figure II.12) shows the diagram for real-time CO-OFDM channel estimation. Once the OFDM window is synchronized, an internal timer will be started, which is used to distinguish the pilot symbols and payload. Two steps are involved in this procedure, channel matrix estimation and compensation. In the time slot for pilot symbols, the received signal is multiplied with locally stored transmitted pilot symbols to estimate the channel response. The transmitted pattern typically has very simple numerical orientation. Thus, multiplication can be changed into addition/subtraction of real and imaginary parts of the complex received signal, which can give additional resource saving. Taking average of the estimated channel matrixes over time and frequency can be used to alleviate error due to the random noise. Then the averaged channel estimation will be multiplied to the rest of the received payload symbols to compensate for the channel response. It is worth pointing out that one complex multiplier can be composed of only three (instead of four) real number multipliers.

To further save the hardware resources, the realization of the channel estimation can be done in a simple lookup table when pilot subcarriers are modulated with QPSK as in (**Table II.2**), avoiding the use of costly multipliers.

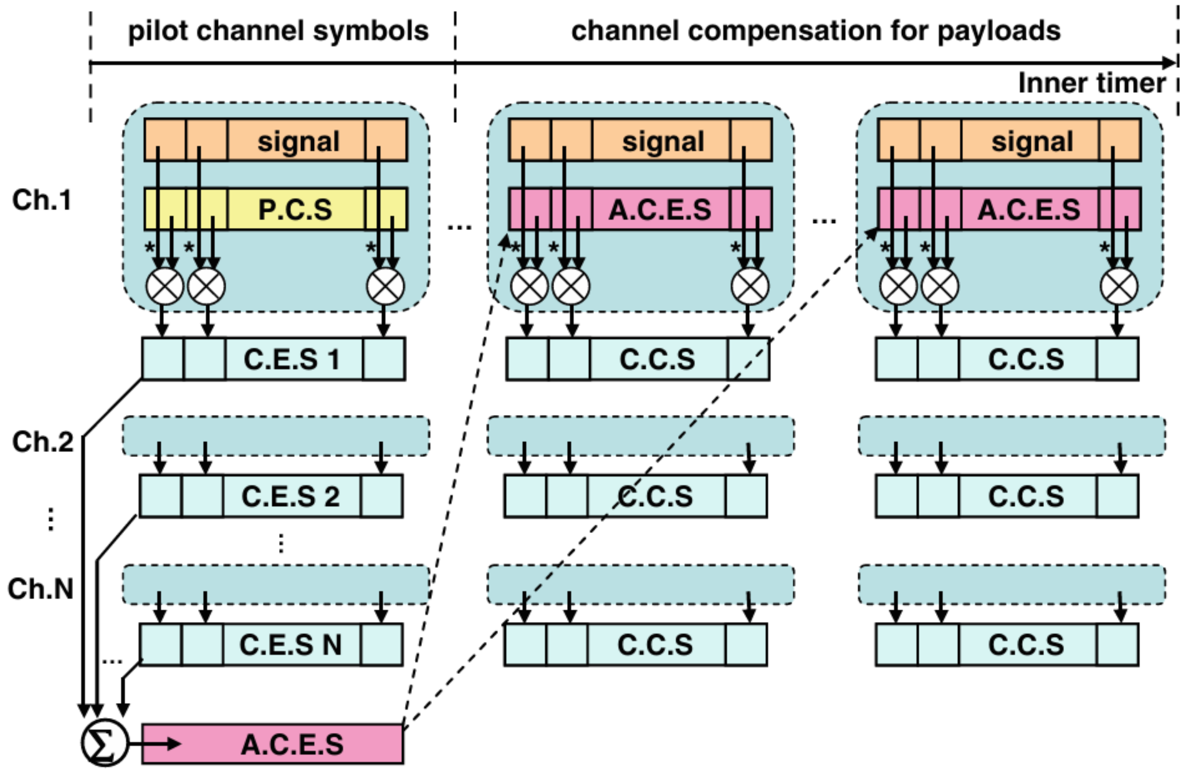


Figure II.12 : Channel estimation diagram. P.C.S Pilot channel symbol; *C.E.S* Channel estimated symbol; *A.C.E.S* Averaged channel estimated symbol; *C.C.S* Compensated channel symbol

Message symbols of pilot	Modulatedsymbols of pilot	$\frac{H^{-1} or B^{-1}}{Real}$	Imaginary
0	$-1+j$	$-a-b$	$a-b$
1	$-1-j$	$-a+b$	$-a-b$
2	$1+j$	$a-b$	$a+b$
3	$1-j$	$a+b$	$-a+b$

Table II.2 Lookup table for channel and phase estimate in case of QPSK pilot subcarrier. Received signal is $R = a + jb$

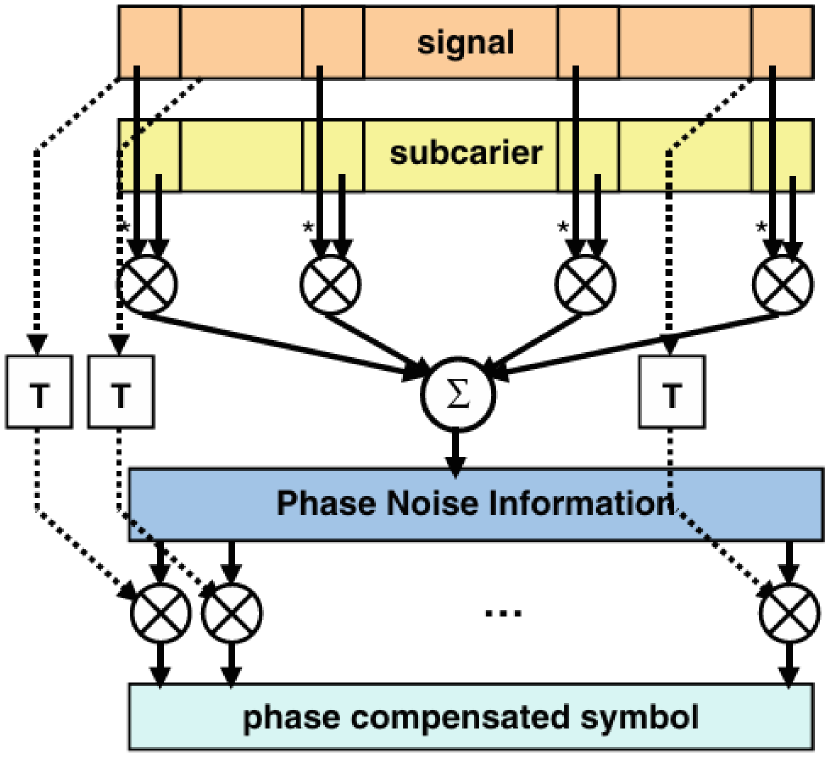


Figure II.13 : Phase estimation diagram

II.3.3.4 Real-Time Channel Estimation

Similar to channel estimation, phase estimation procedure can also be divided into estimation and compensation parts, which is shown in (**Figure II.13).** These pilot subcarriers then are compared with local stored transmitted pattern to obtain the phase noise information. These pilot subcarriers then are compared with local stored transmitted pattern to obtain the phase noise information. The same symbol and then compensated with the estimated phase noise factor.[44]

II.3 Conclusion

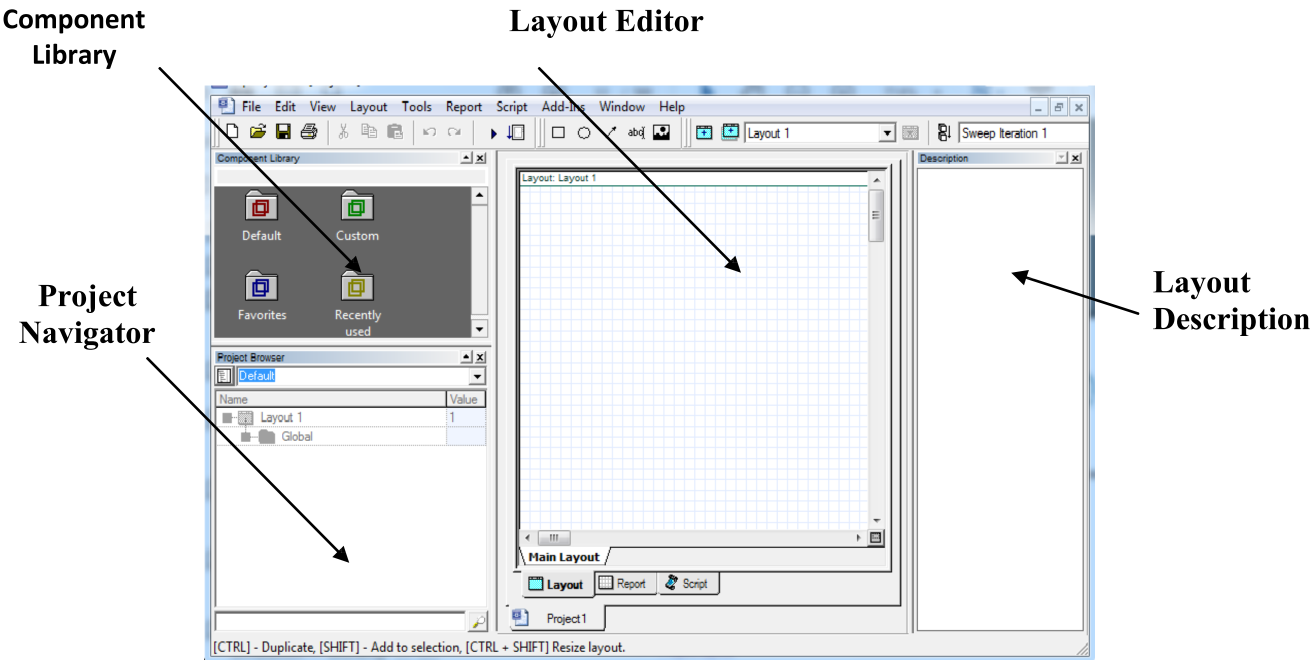
By conducting simulations in these areas, valuable data can be obtained to understand the behavior of the **CO-OFDM** system under different conditions, optimize the system design and parameters, and identify trade-offs between different performance metrics such as capacity, range, robustness, and complexity.

CHAPTER III

Simulations and results

III.1 Introduction

In this chapter, we will proceed to the simulation of the entire transmission chain and to allow the visualization of the diagrams of the eye, the Q quality factor, the BER, the OSNR, ... Which are the performance criteria).



FigureIII.1 :Diagram of the Optisystem interface

III.2 Simulation tools :

III.2.1OptiSystem Software Overview[45]

OptiSystem is a software developed by the Canadian company Optiwave, specialized in the design and simulation of optical transmission systems. It provides engineers and researchers with a complete environment to design, test, and optimize a wide range of optical links.

Thanks to its modular architecture, OptiSystem not only enables the realistic simulation of Fiber optic communication systems, but also the integration of user-created custom components, making it a particularly flexible and extensible tool.

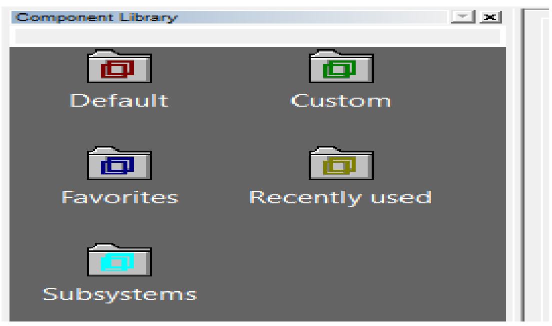


Figure III.2: Component Library.

III.2.2 Python:

The use of **Python** in the **simulation of a CO-OFDM** (Coherent Optical Orthogonal Frequency Division Multiplexing) system is very common, especially in research and development. Python offers a powerful ecosystem of libraries for numerical simulation, signal processing, optics, and communications.

III.2.2.1 Typical tools used

Here are the main Python libraries useful for simulating a CO-OFDM system:

Library	Usage
NumPy	Manipulation of signaux, FFT/IFFT, modulation
SciPy	Signal processing, filtering
Matplotlib / Seaborn	Visualisation des constellations, spectres, BER
Commpy	QAM/PSK modulation, BER calculation
PyTorch / TensorFlow	For machine learning if needed (e.g. dispersion compensation, channel estimation)
Optics / bibliothèques custom	For Optical modeling (fiber, attenuation, dispersion, etc.)

Table III.1 : the main Python libraries useful for simulating a CO-OFDM system

III.2.2.1 Typical steps of a CO-OFDM simulation

Here's an example of a **simplified pipeline** for a CO-OFDM simulation in Python:

1. **Data generation**
    1. Random bits to be transmitted.
2. **Modulation**
    1. QAM (e.g. 16-QAM), complex mapping.
    2. IFFT to generate the OFDM signal.
3. **Added cyclic prefix**
    1. To avoid inter-symbol interference (ISI).
4. **Propagation in the fiber**
    1. Chromatic dispersion (CD) modeling, modal polarization dispersion (PMD), ASE noise, etc.

5. **Consistent reception**
    1. FFT, channel equalization (e.g. MMSE equalizer or machine learning), demodulation.
6. **Analysis**
    1. Constellation, spectrum, bit error rate (BER), signal-to-noise ratio (SNR), etc.

5-Possible extensions to CO-OFDM:

1. Fiber **optic modelling** (dispersion, Kerr nonlinearity).
2. Simulation of **coherent reception** (local receiver, phase detection, etc.).
3. Addition of **digital compensation** (CMA, LMS, adaptive equalizers).
4. Use of **advanced DSP** for synchronization, channel estimation.

The complementarity between Python and OptiSystem in the simulation of (CO-OFDM).

1. OptiSystem: Physical and Visual Simulation

OptiSystem is ideal for modeling the complete optical transmission chain because it provides

Élément	Utilisation
Laser, MZM, fibre optique, EDFA	Modélisation physique précise
Détecteur cohérent	Simulation réaliste de la réception
Visualisateurs	Eye Diagram, Q-factor, BER Analyzer, OSNR
Compensation numérique (DSP)	Modules intégrés ou codés via Matlab/Script

Table III.2 the element of measurement

Measured Performance Criteria:

- Eye Diagram (temporal quality of the signal)
- **Q-factor (signal quality)**
- **BER (Bit Error Rate)**
- **OSNR** (Optical signal-to-noise ratio)

2. Python: digital processing, DSP, automation

Python can intervene **before**, **during**, or **after** a simulation in OptiSystem:

a) Before: Signal generation

1. QAM/OFDM Data Generation
2. Creation of injectable CSV or binary files in OptiSystem via *"User Defined Bit Sequence"*

b) Pendant : Co-simulation

1. Python can communicate with OptiSystem via external scripts, for example using **COM interface** (on Windows).
2. It is also possible to use **Matlab Component** in OptiSystem, and call Python code via an interface.

c) After: Analysis of results

1. Extraction of results (BER, Q, OSNR) generated in OptiSystem
2. Processing and visualization with pandas, matplotlib, etc.

III.3 Performance criteria

In order to evaluate the transmission quality of simulated WDM optical links, several performance criteria are taken into account. These indicators make it possible to analyse the degradation of the signal during propagation and the effectiveness of the modulation and compensation techniques used. Among the main criteria used:

- **Eye diagram**
- The **eye diagram** is a temporal representation of the received signal. It allows you to evaluate signal distortion, noise, jitter, and inter-symbol interference (ISI). A well-open eye is a sign of quality transmission, while a closed eye indicates strong signal degradation. **(figure III.3)**

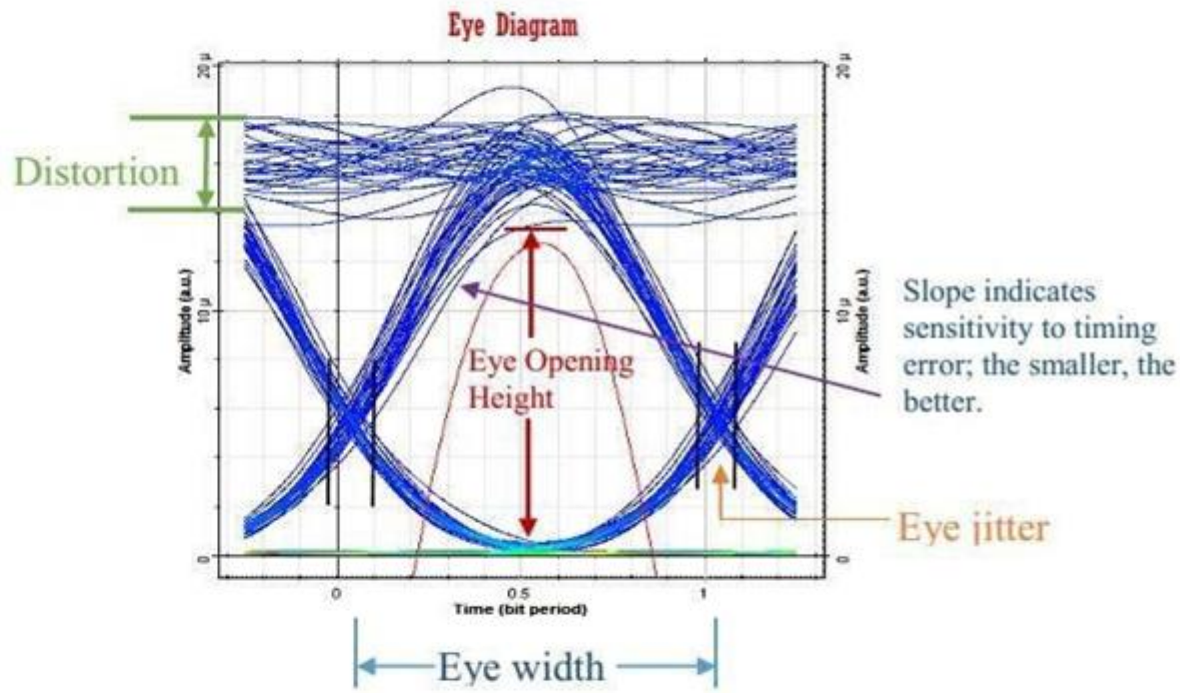
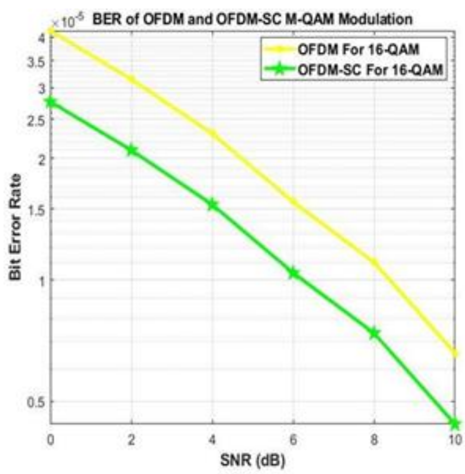


Figure III.3 : Eye diagram

- **Bit Error Rate (BER)**

The **BER** quantifies the percentage of bits received incorrectly in relation to the total number of bits transmitted. It is a direct indicator of the performance of a transmission system. A low BER reflects better link reliability.



FigureIII.4: Bit Error Rate (BER)

- **Constellation Diagram**

The **constellation diagram** allows you to visualize the modulated signal in complex domains (In-Phase and Quadrature). It provides a graphical representation of transmitted and received symbols, making it easy to identify modulation errors, phase effects, or distortions due to Fiber or channel.**(figureIII.5)**

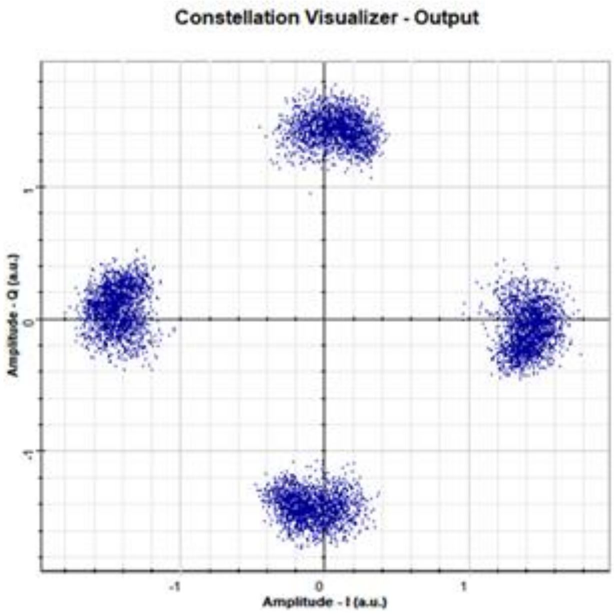


Figure III.5 :constellation diagram

III.4 Impact of Fiber Length on the CO-OFDM System

The length of the optical Fiber is a critical parameter directly influencing the performance of a **CO-OFDM** (Coherent Optical Orthogonal Frequency Division Multiplexing) system. Indeed, as the transmission distance increases, the effects of **dispersion**, **power loss** and **Non-linearities** become important, which can greatly degrade the quality of the received signal.

- **Chromatic dispersion**

Over long distances, **chromatic dispersion** causes optical pulses to spread out over time, leading to symbol overlap and increased inter-symbol interference (ISI). In OFDM systems, although this technology is naturally robust to dispersion, digital compensation is still required beyond certain lengths.

Attenuation

Power **loss** (attenuation) increases linearly with Fiber length. This decreases the signal-to-noise end-of-line ratio (OSNR), negatively affecting the **BER** (Bit Error Rate) and **the Q factor**. Optical amplifiers (such as EDFAs) are often used to compensate for this loss, but they also introduce additional noise.

- **Optical nonlinearities**

With the increase in distance (and therefore often the launch power), non-linear effects such as **the Kerr effect**, **cross-phase modulation (XPM)** or **stimulated Raman scattering** can appear. These phenomena distort the optical signal and reduce the efficiency of the decoding algorithms in reception.

- **Degradation of performance criteria**

In summary, an increase in Fiber length impacts the following criteria:

1. **Eye diagram : becomes more closed, indicating a temporal degradation of the signal.**

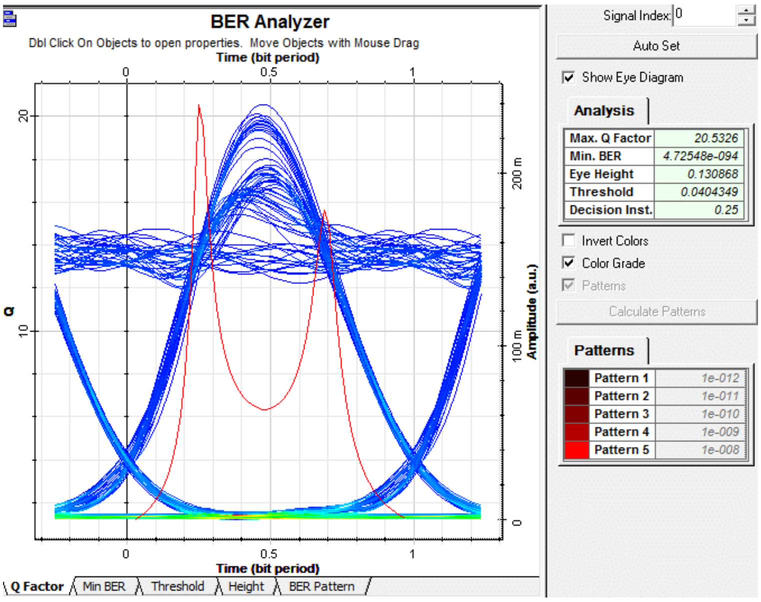
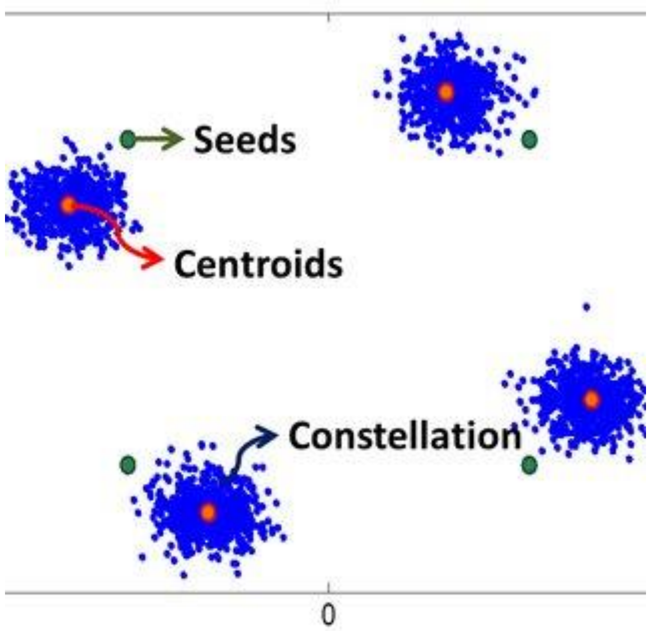


Figure III.6 : Eye diagram BER Analyzer

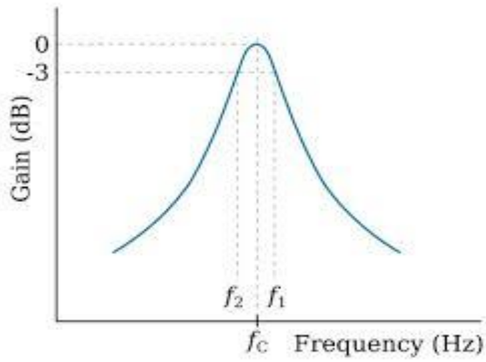
2. **Constellation diagram** : Dots become blurred and scattered, a sign of noise and distortions.



FigureIII.7:Constellation diagram

3. **Q-factor** : Decreases with distance, indicating a decrease in signal quality

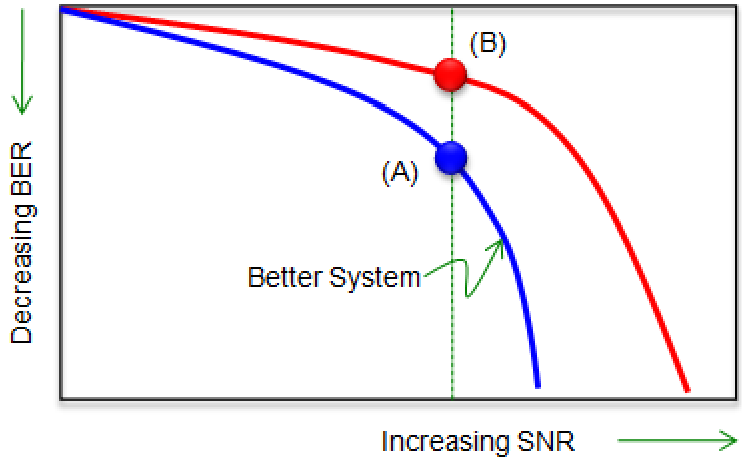
$$\boldsymbol{Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}} \quad (24) \ldots\ldots\ldots\ldots [53]$$



FigureIII.8: Q-factor

4. **BER**: increases, reflecting a less reliable transmission

$$BER = \frac{1}{2} \cdot erfc\left(\frac{Q}{\sqrt{2}}\right)$$



figureIII.9: BER analyzer diagram

Experimental analysis (to be integrated with results)

A comparative study by varying the length of the Fiber (e.g., 50 km, 100 km, 150 km, etc.) makes it possible to quantify these effects and evaluate the performance limits of the CO-OFDM system, while testing compensation solutions (DSP, pre-equalization, etc.).

III.4.1 Impact of Laser Power on the CO-OFDM System

The **power of the emission laser** plays a fundamental role in the overall performance of a **CO-OFDM system**. It determines the level of the signal injected into the optical fiber, thus influencing both the **signal-to-noise ratio (OSNR)** and the **nonlinear effects** that can occur during propagation.

- **Too low power**

When the launch power is insufficient:

1. The **optical signal** becomes vulnerable to thermal and quantum noise,
2. The **OSNR ratio** is low at Fiber output,
3. There is an **increase in BER** and a **reduction in Q-factor**,
4. The eye and constellation diagrams show increased dispersion and lack of clarity.

- **Optimal power**

There is an **optimal launch power** that allows a good compromise to be achieved between a high OSNR and a limitation of nonlinear effects. At this power:

1. The Q factor is maximum,
2. The BER is minimal,
3. The transmission quality is stable over several tens or hundreds of kilometres.

- **Too much power**

When the laser power exceeds a certain threshold:

1. Optical **nonlinear effects** appear (Kerr effect, phase auto-modulation, FWM, etc.),
2. The signal undergoes spectral and phase distortions,
3. The constellation diagram becomes blurred or exploded,
4. **BER** rises again despite high NSNO,
5. The **Q factor** decreases due to signal distortion.

Typical behaviour (Q vs. power curve)

Experimental analysis of the CO-OFDM system as a function of laser power usually reveals a **bell curve** of the Q factor: it increases with power, reaches a maximum, and then falls again under the effect of nonlinearities.

III.4.2 Impact of Chromatic Dispersion (CD) on the CO-OFDM System

In high-capacity optical transmission systems such as **CO-OFDM**, dispersion effects are major limiting factors, especially over long distances. Two types of dispersion play a critical role: **chromatic dispersion (CD)** and **modal polarization dispersion (PMD).**

- **Chromatic Dispersion (CD)**

Chromatic dispersion is due to the dependence of the speed of propagation of light on its wavelength. It causes the **optical pulses to spread out over time**, which can lead to symbol overlap (inter-symbol interference, or ISI).

In traditional systems, CD causes **severe distortion** of the signal. However, **CO-OFDM** is inherently robust against DC thanks to the use of narrowband OFDM symbols, and the possible digital compensation via DSP (Digital Signal Processing) techniques.

Affects observed :

1. Without compensation: closure of the eye diagram, increase in BER
2. With DSP: significant reduction of the impact of the CD, stability of the transmission up to several hundred km

III.4.3 Impact of Nonlinear Effects (SPM and XPM) on the CO-OFDM System

In high-power or long-distance optical transmission systems, the **non-linear effects of Fiber** become significant. The main mechanisms affecting **CO-OFDM (Coherent Optical OFDM)** are:

- **SPM – Self-Phase Modulation**

Definition:
SPM results from the variation of the refractive index of the Fiber with the optical power of the signal. This variation induces **intensity-dependent phase modulation**, directly affecting the signal spectrum.

Effects on CO-OFDM :

1. Distortion of OFDM subcarriers, especially on signal strength peaks,
2. Spectral broadening, which may result in inter-subcarrier overlap,
3. Degradation of the Q factor and increase of the BER, especially in the absence of input power control.

- **XPM – Cross-Phase Modulation**

Definition:
XPM is caused by **the interaction between multiple WDM channels** : the signal in one channel affects the phase of the signals in the other channels, via the same Kerr effect as SPM.

Effects on CO-OFDM :

1. Random phase fluctuations on subcarriers,
2. Increased sensitivity to power variations between channels,
3. Risks of inter-channel degradation (cross-interference), especially in dense WDM systems.

Over all performance implications

Parameter	With unmanaged SPM/XPM effects	With optimization (DSP + power control)
Signal spectrum	Widening, nonlinearities	Controlled spectrum
Constellation Diagram	Blur, phase distortion	Regular form (with precompensation)
Q-factor	Degradation	Improvement after non-linear equalization
BER	Signification crease	Partial reduction

Table III.3 Overall performance implications

◆ **Single Polarization (SP) Architecture**

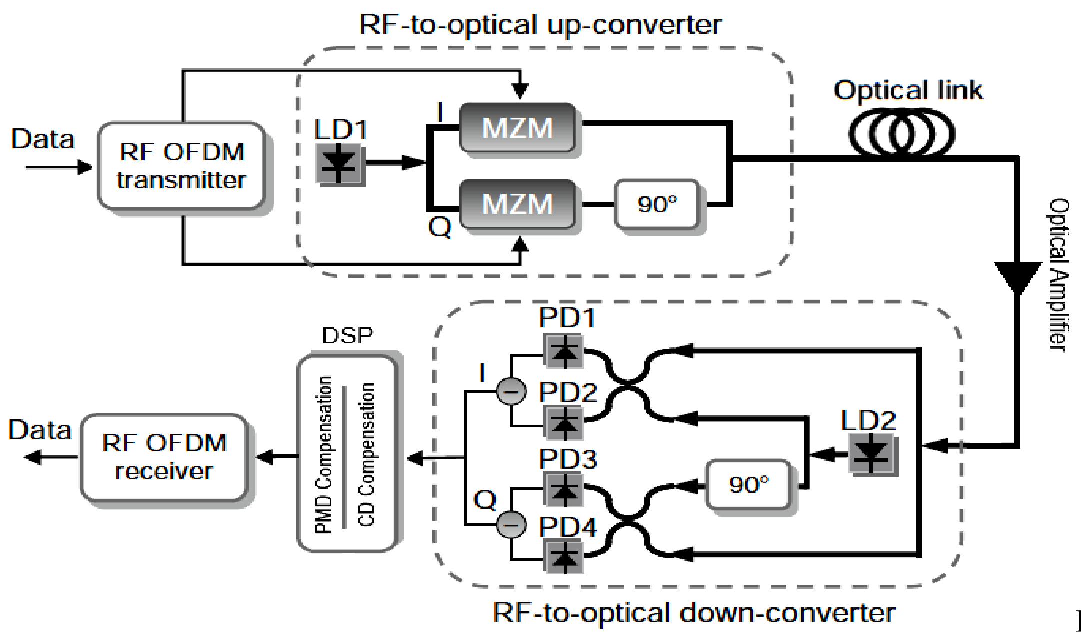


Figure III.10: CO-OFDM System with Single Polarization

Principle:

The optical signal is modulated and transmitted on only one polarization component (typically horizontal or vertical).

Advantages :

- Simple implementation,
- Lower complexity at the receiver and DSP level,
- Less sensitive to PMD (under short or medium distance conditions).

Disadvantages :

- Bit rate is limited to a single polarization,
- Lower spectral efficiency,
- Less robust for long-distance or high-capacity transmissions.

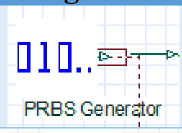
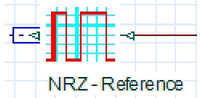
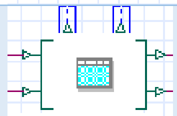
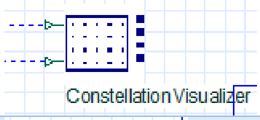
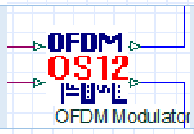
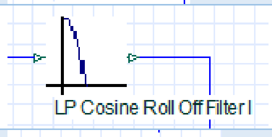
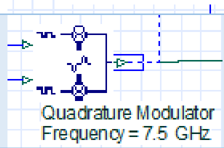
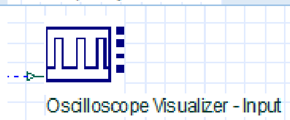
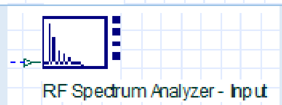
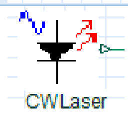
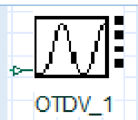
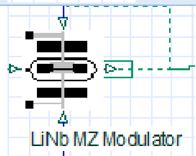
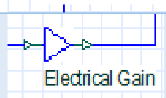
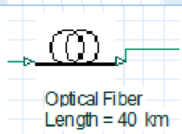
III.5 OFDM Coherent Detection Single Port Single Polarization 4-QAM

III.5.1 Parameters of simulation :

Parameter	Value
Length of Optical fiber	L = 10 km to 100 km.
Power laser	0 dBm.
EDFA Gain	12 dB
CD	16.75 ps/
Attenuation	0.2 dB/km
Number of user OFDM	512
Digital Modulation	QAM-4, QAM-16.
Diagram Constellation	Squar/Circular

Table III.4 : parameters of simulation

III.5.2 Components of architectures :

Components	Images	Rules
Pseudo-Random Bit Sequence Generator.		Generatesrandom bit stream
NRZ Pulse Generator.		Converts bits into NRZ pulses
Optical Time-Domain Visualizer		allows engineers to visually inspect the shape, delay, rise/fall time
MZM Modulator		Modulates an optical signal using a Mach-Zehnder Modulator.
OFDM Modulator		Modulates data using Orthogonal Frequency-Division Multiplexing (OFDM).
LP Cosine Roll Off Filter		Low-pass filter with raised cosine response to reduce inter-symbol interference.
Quadrature Modulator Frequency=7.5 GHz		Performs quadrature modulation to transmit data over in-phase and quadrature carriers.
Oscilloscope Visualizer-input		Displays input signals in real-time for visual analysis.
RF Spectrum Analzer-input		Analyzes the frequency spectrum of the input signal.
CW Laser		Must be connected to a modulator or directly to a fiber.
OTDV_1		(Function not specified — likely a test element or optical visualization tool.)
MZM Modulator		Modulates an optical signal using a Mach-Zehnder Modulator.
Electrical Gain		Electrically amplifies the signal before processing or modulation.
SMF Fiber		Single-mode fiber used for long-distance optical transmission.

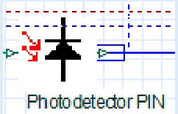
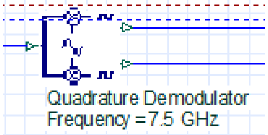
PIN Photodetector		Converts the received optical signal into an electrical signal.
Quadrature Demodulator		Demodulates the in-phase and quadrature components to retrieve data.

Table III.5: Components of architectures

I.3 Architecture :

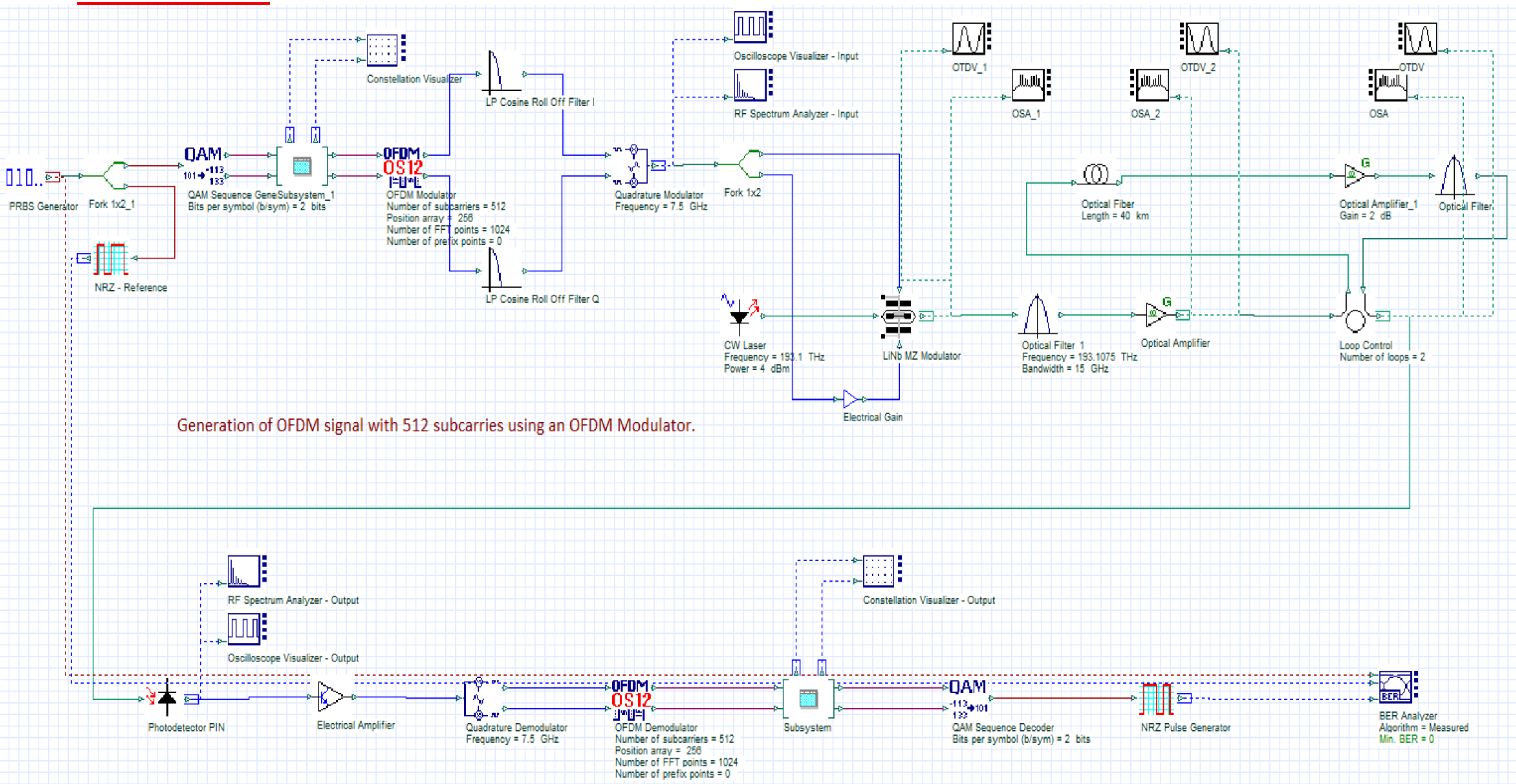
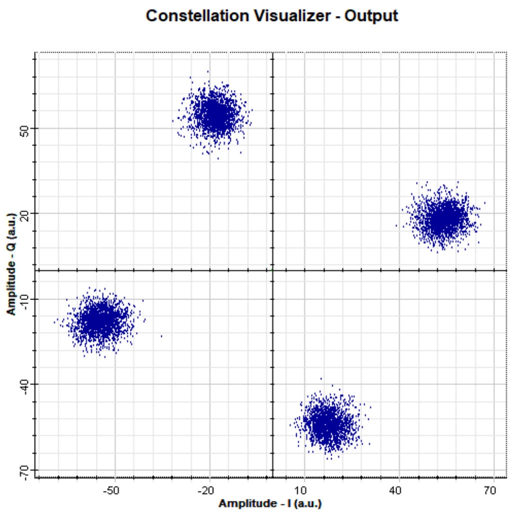


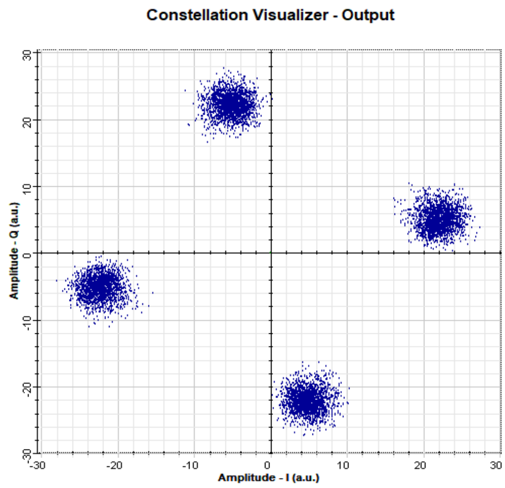
Figure III.11 : Architecture of CO-OFDM with Single Polarization.

III.6 Impact of length in system CO-OFDM, QAM-4

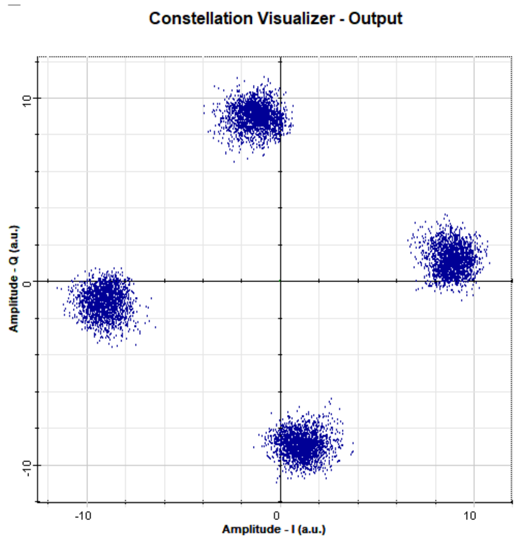
OFDM Coherent Detection Single Port Single Polarization 4QAM without CD and NL



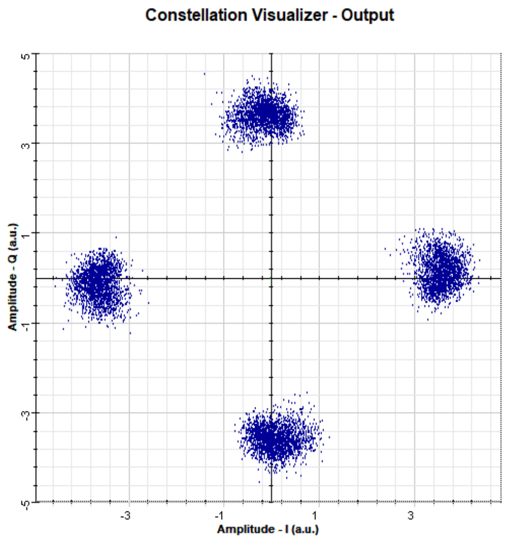
Length =20km



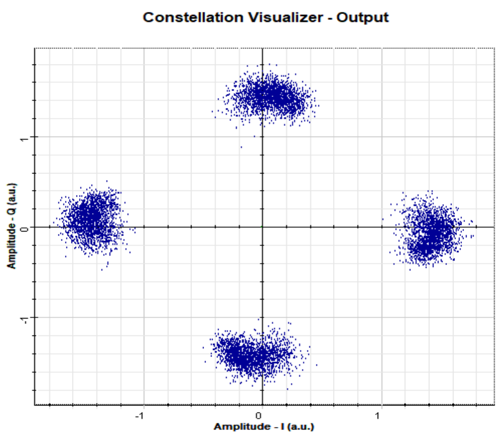
Length = 10 km



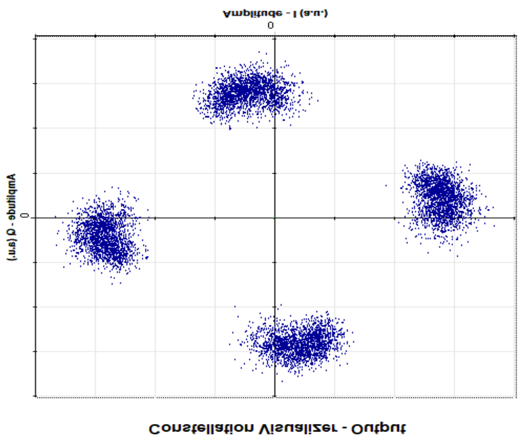
Length = 30 km



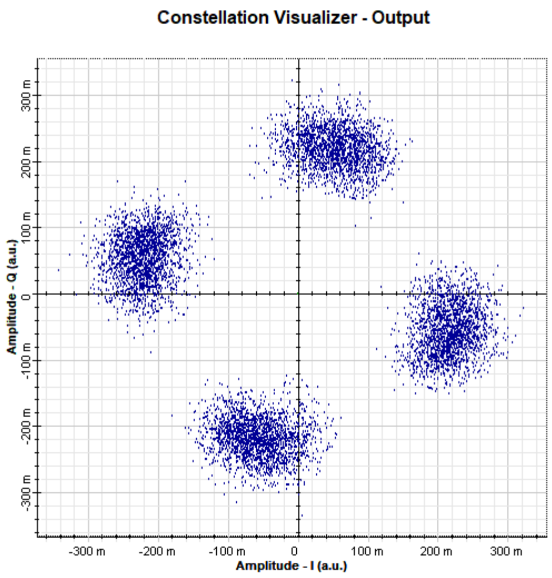
Length = 40 km

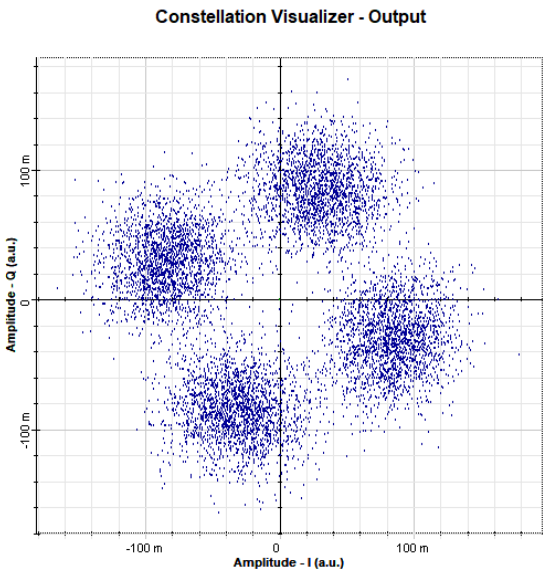


Length = 50 Km

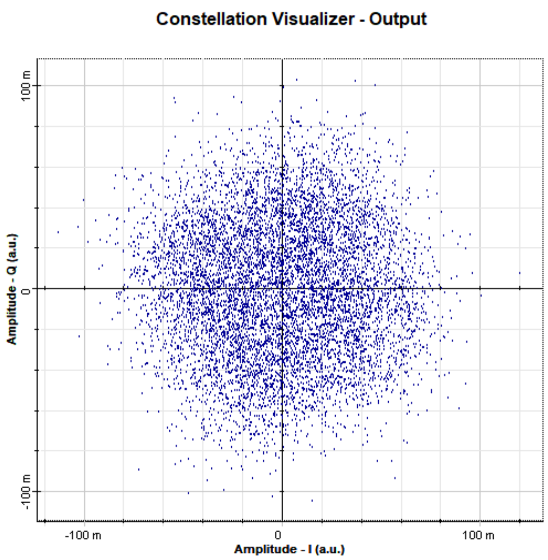


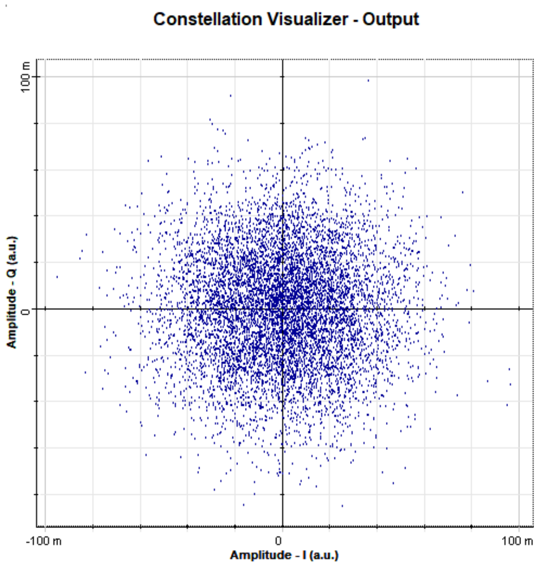
Leng= 60Km



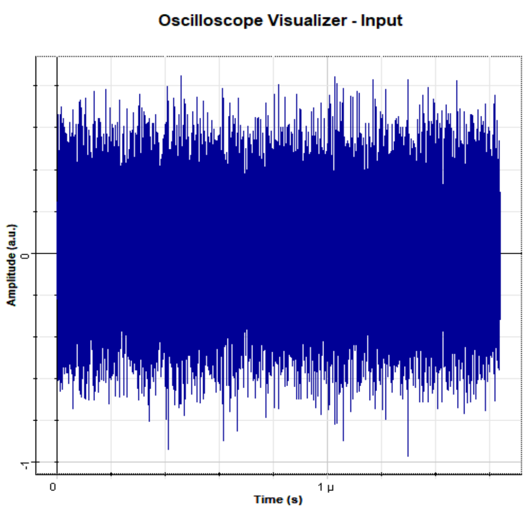


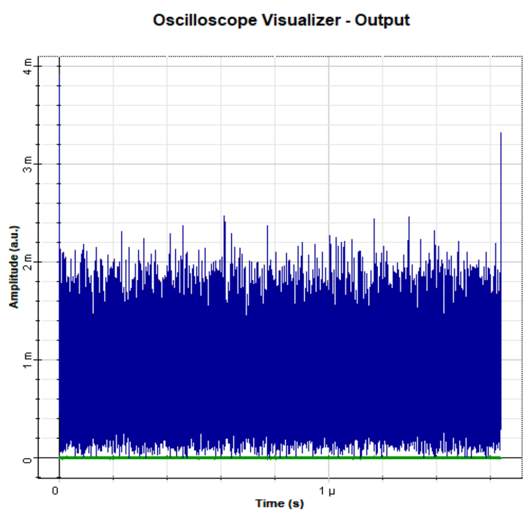
Length = 70 km **Length =80 km**





Length = 90 km **Length =100 km**





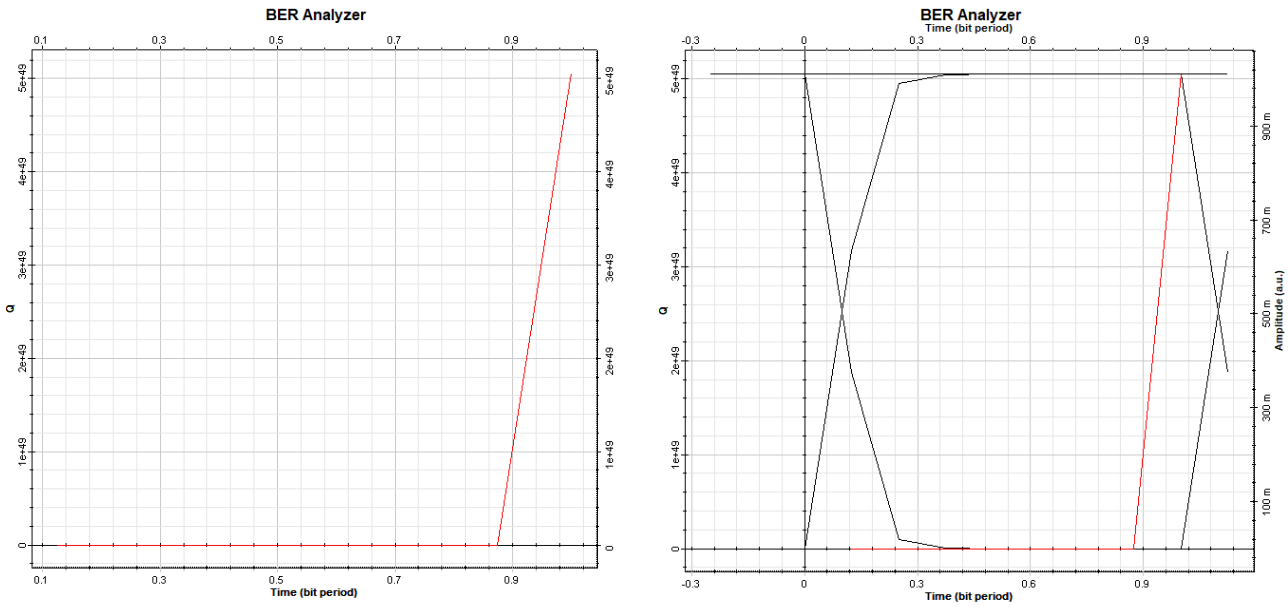
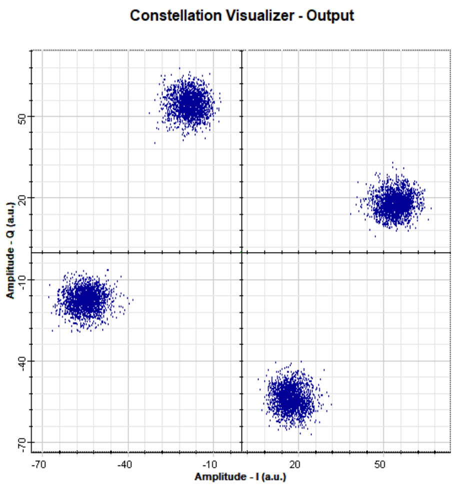


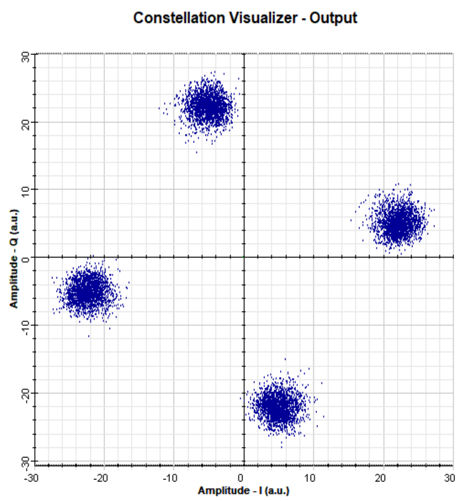
Figure III.12 : OFDM Coherent Detection Single Port single Polarization 4 QAM with CD and NL

CO-OFDM Coherent Detection Single Port Single Polarization 4 QAM -With CD and NLThe effect of distance is shown by the quality of the radio signal / communication.

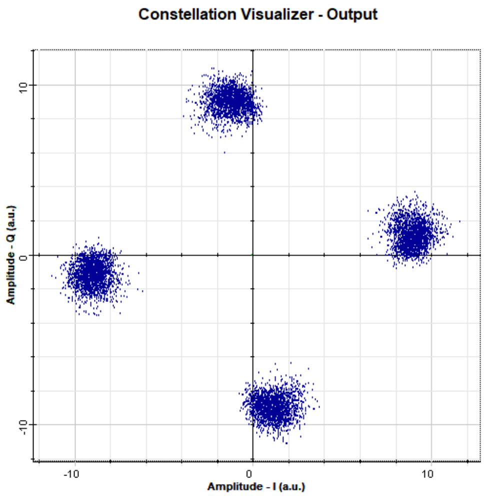
III.7 CO-OFDM Coherent Detection Single Port Single Polarization 4 QAM -Without CD and NL :



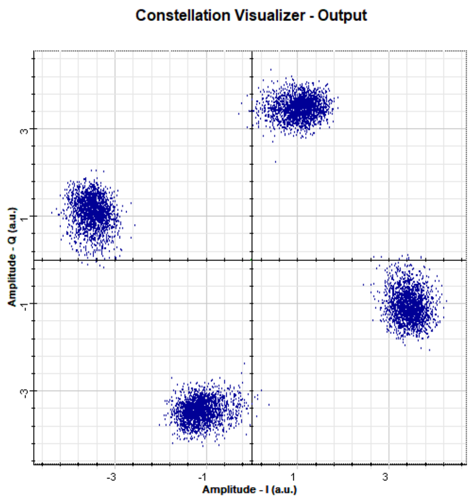
L=10km



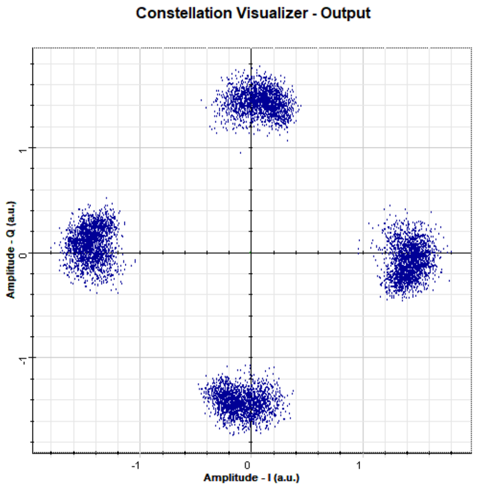
L=20 km



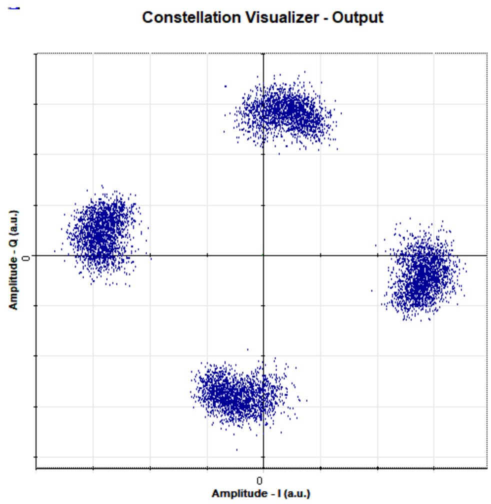
L=30km



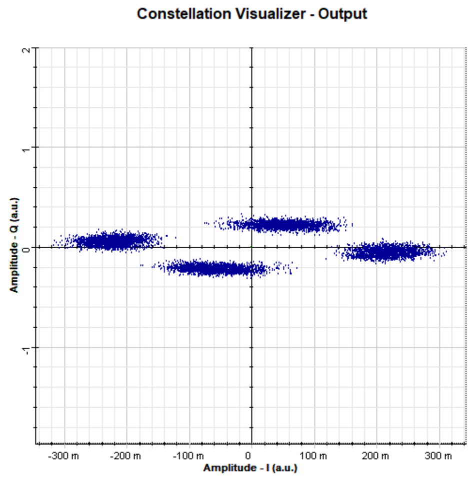
L=40km



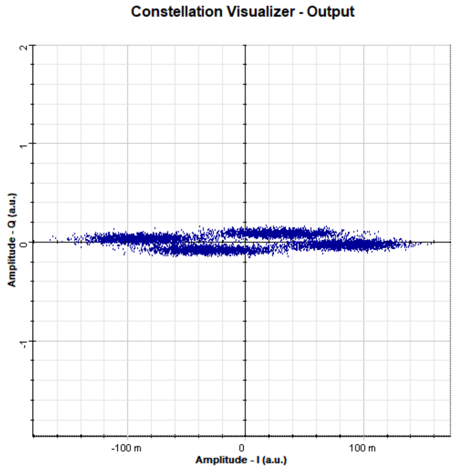
L =50km



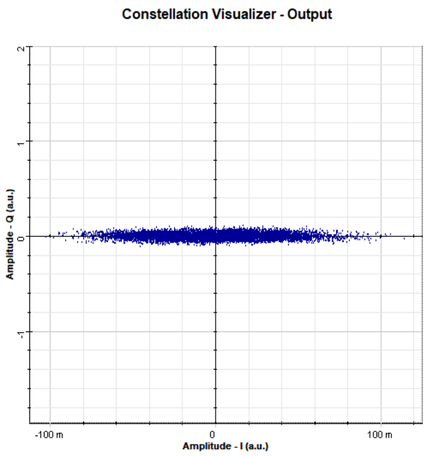
L=60km



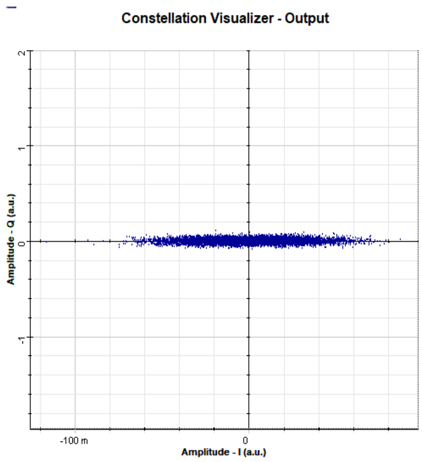
L = 70km



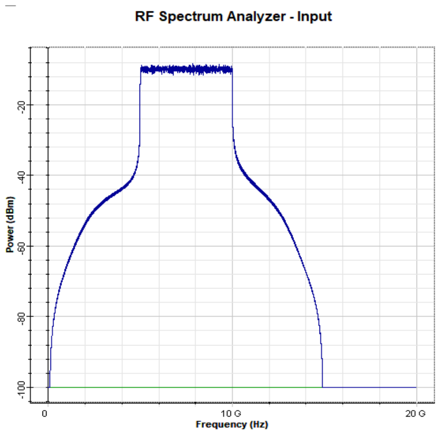
L=80km



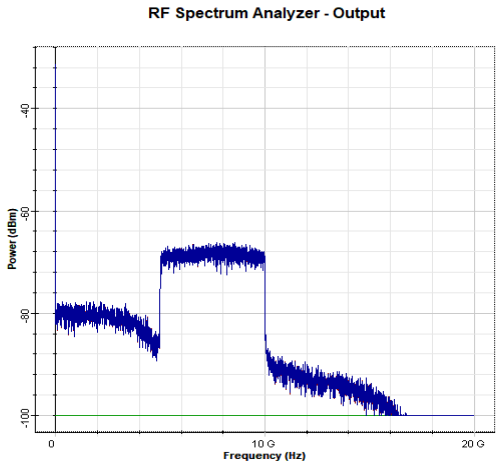
L=90km



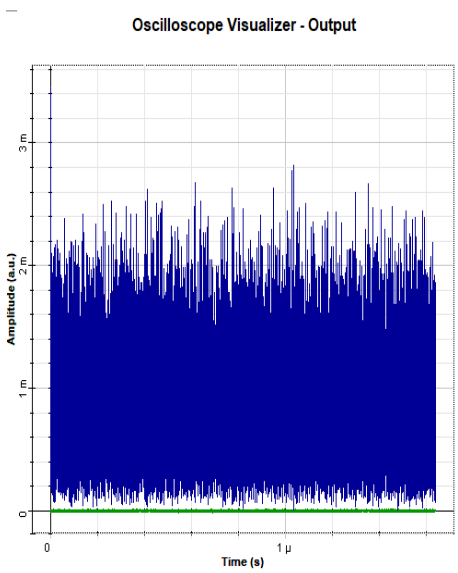
L=100km



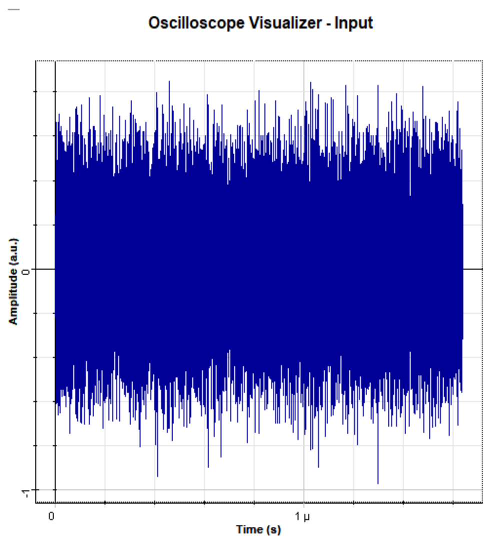
Length = 50 km



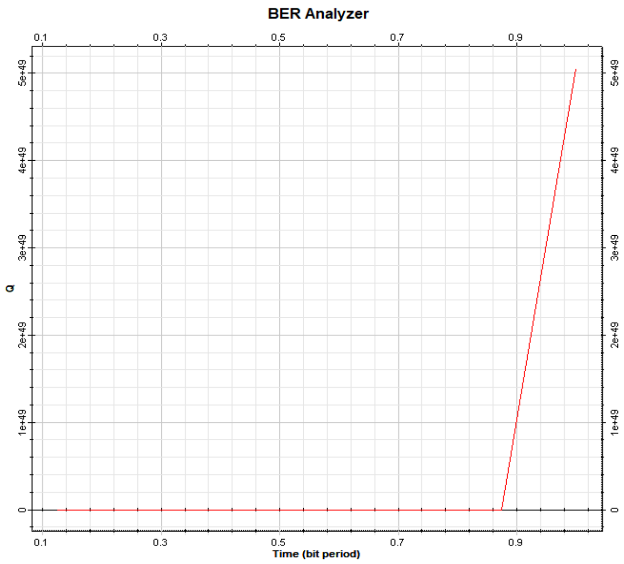
Length = 50 km



Length = 50 km



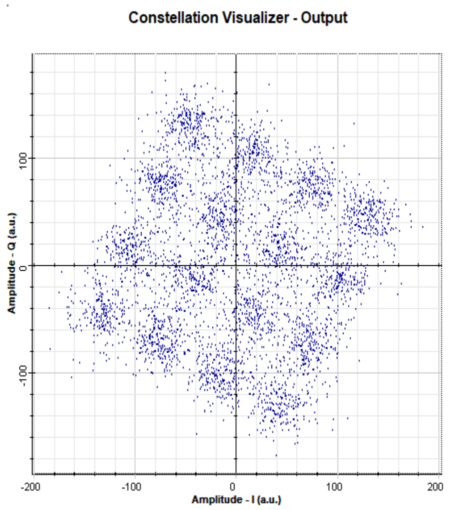
Length = 50 km



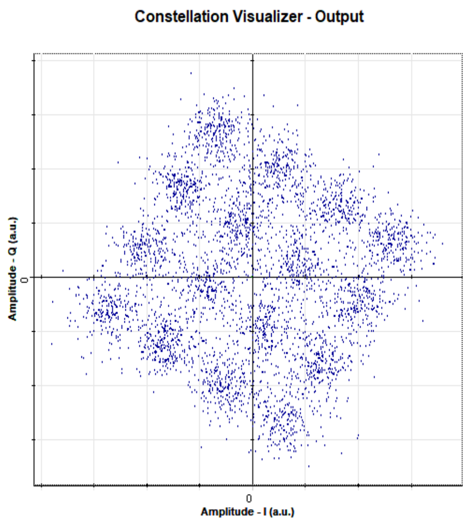
CO-OFDM Coherent Detection Single Port Single Polarization 4 QAM -Without CD and NLThe effect of distance is shown by the quality of the radio signal / communication

III.8 OFDM Coherent Detection Single Port Single Polarization 16-QAM

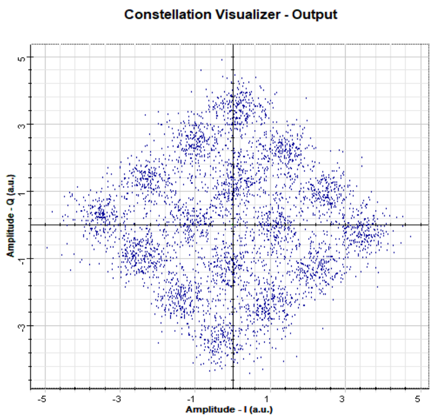
III.8.1 Impact of Length, Power=-4 dBm, Gain =12 dB EDFA:



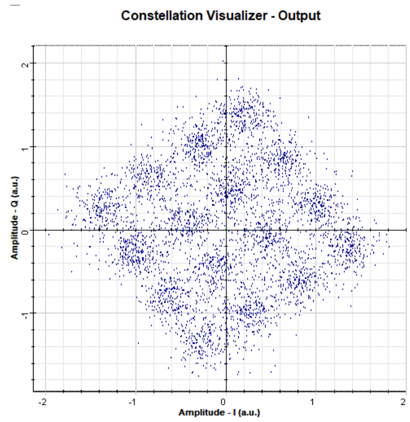
L =10 km



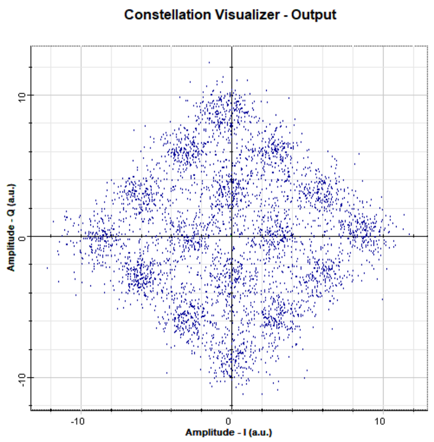
L=20 km



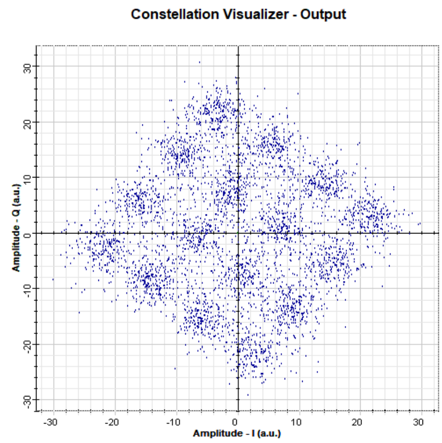
L=30 km



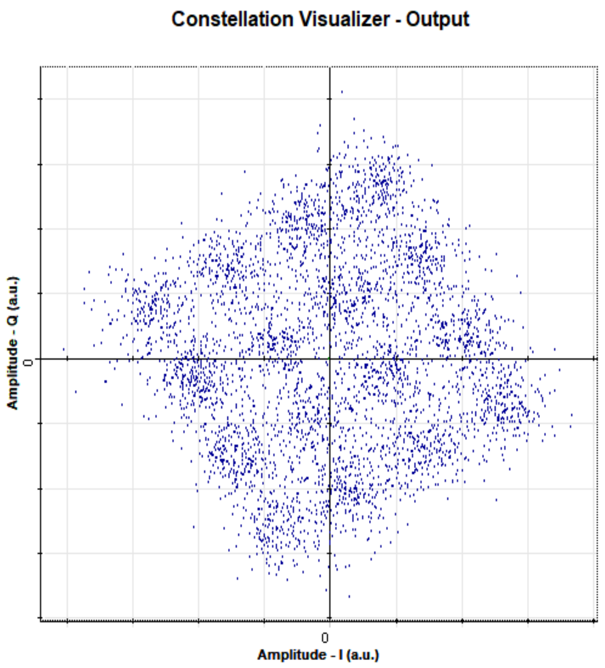
L =40 km



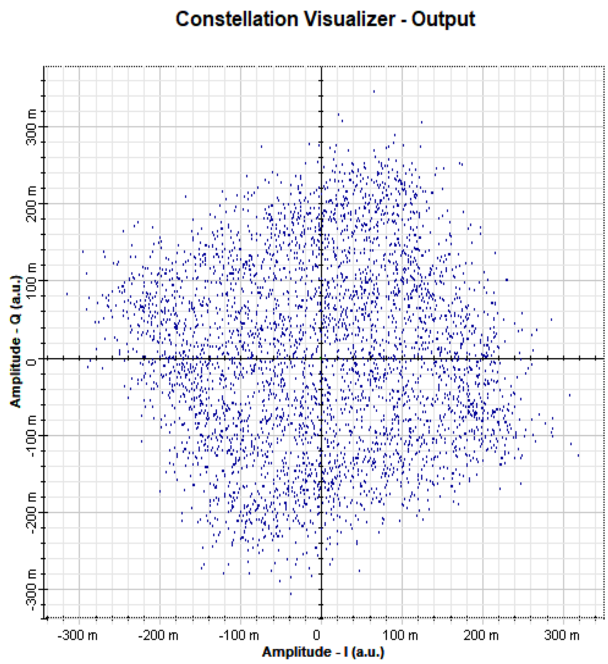
L= 50 km



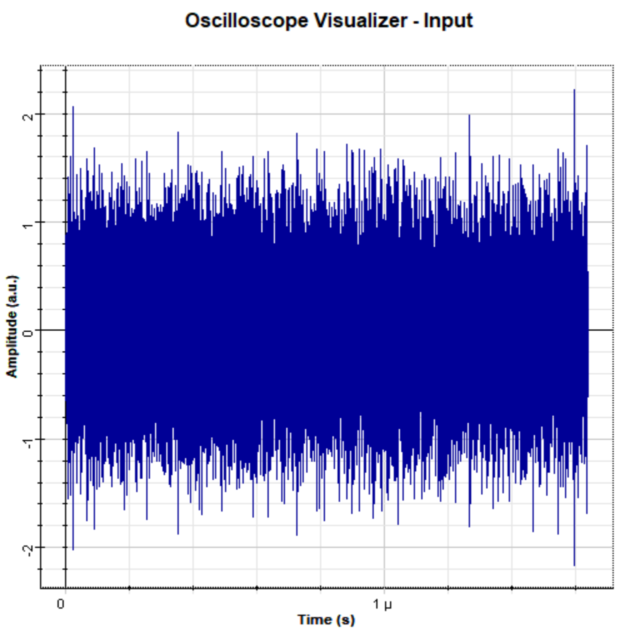
L=60 km



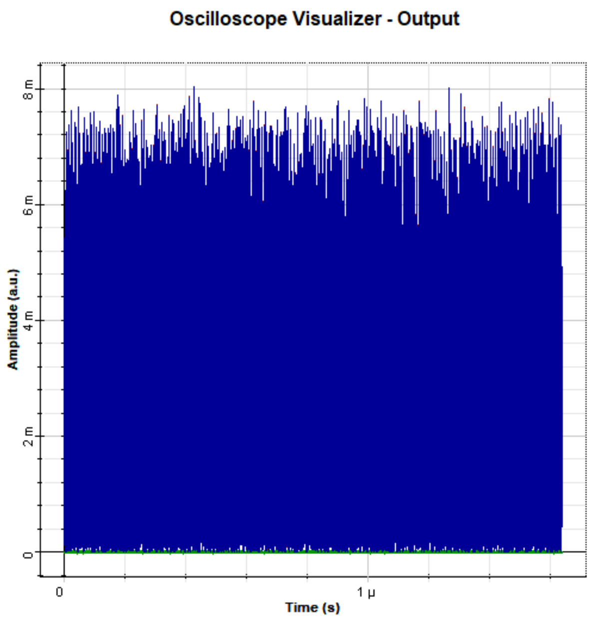
L=70 km



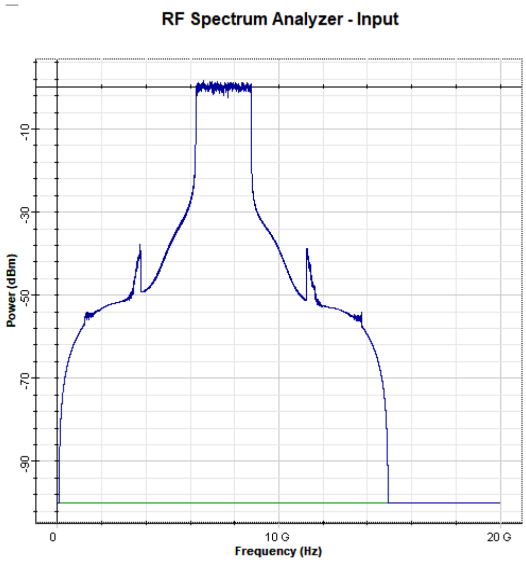
L= 80 km

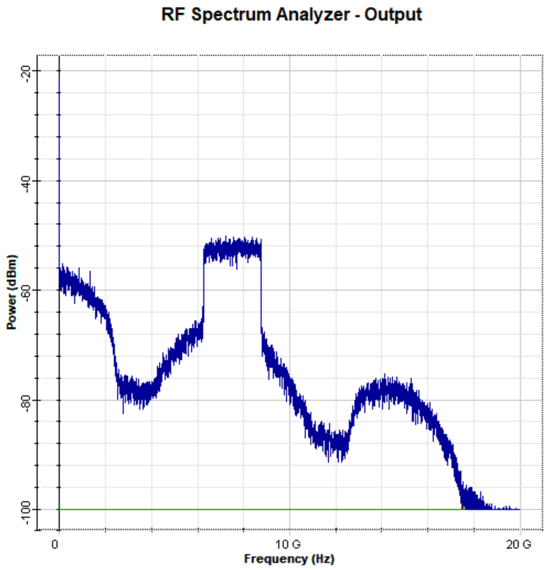


L =40 km

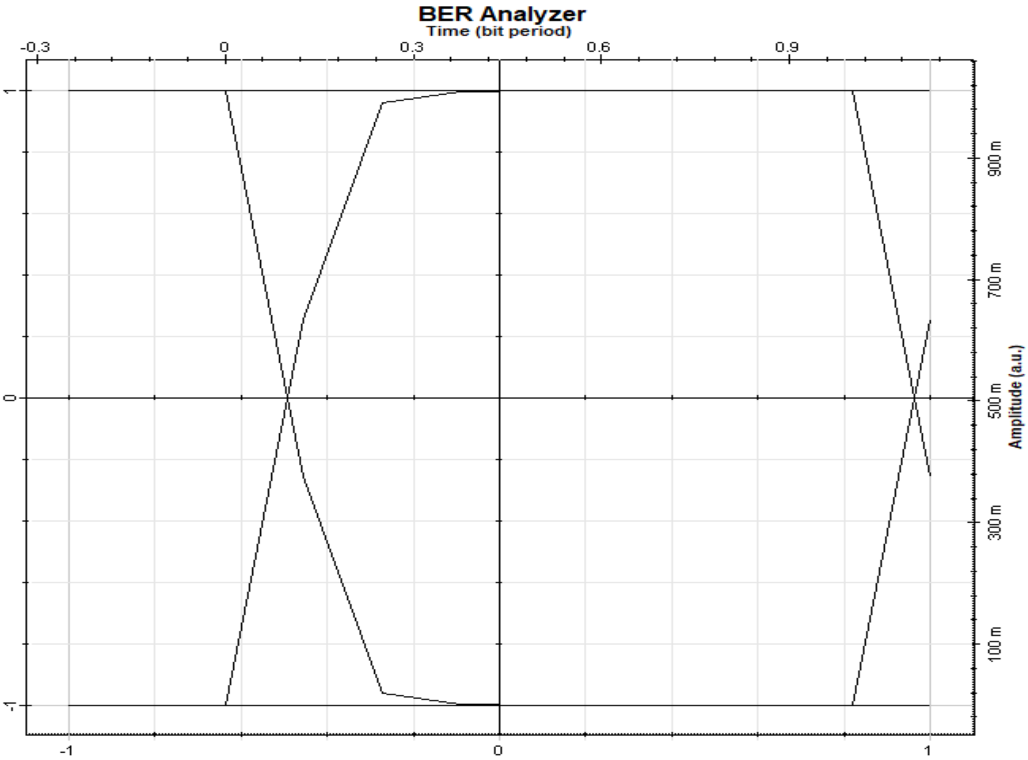


L =40 km



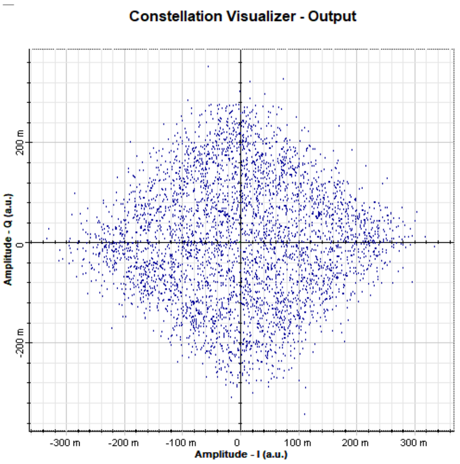


L = 40 km **L=40 km**

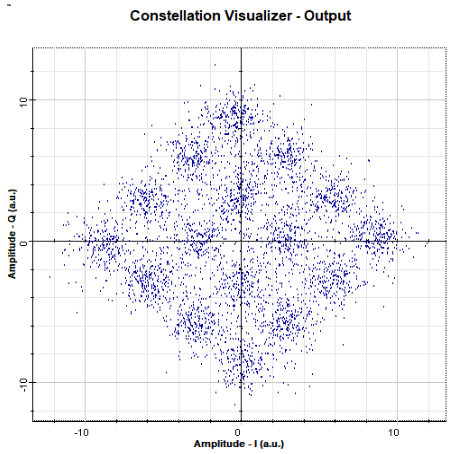


The Bit Error Rate (BER) is a key metric for assessing the reliability of optical communication systems. It is influenced by various factors such as attenuation, dispersion, receiver noise, and system nonlinearities. A high Signal-to-Noise Ratio (SNR) typically results in a lower BER, making SNR optimization essential. Forward Error Correction (FEC) techniques help tolerate higher BER before correction, enhancing system robustness. BER increases with transmission distance if no compensation is applied. It can be measured using specialized testers or estimated via simulation tools. The Q-factor is also commonly used as an indirect indicator of BER in performance evaluations.

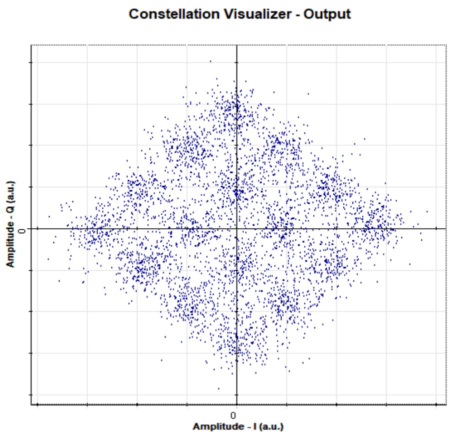
III.8.2 impact of Power, Length=40 km, Gain =2 dB EDFA:



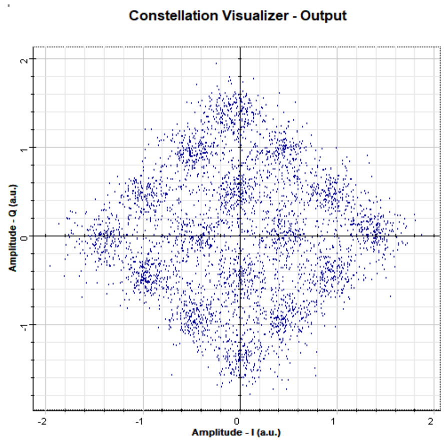
power = 0 dBm



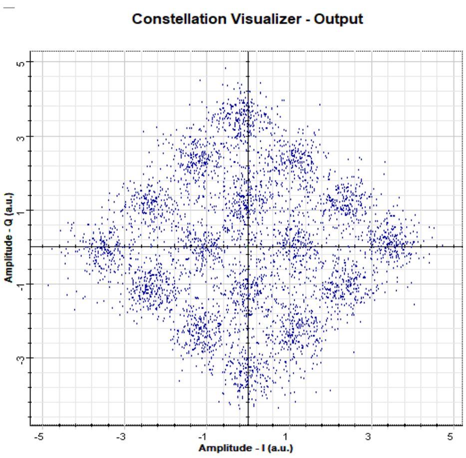
power= -4 dBm



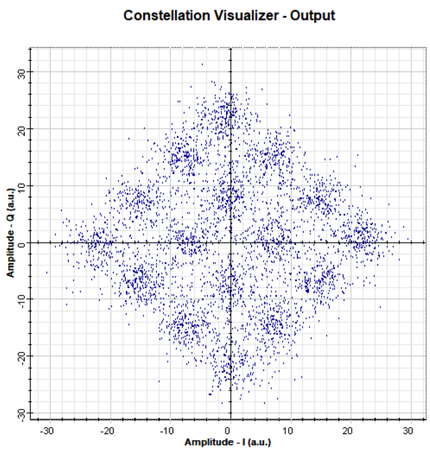
Power = +4 dBm



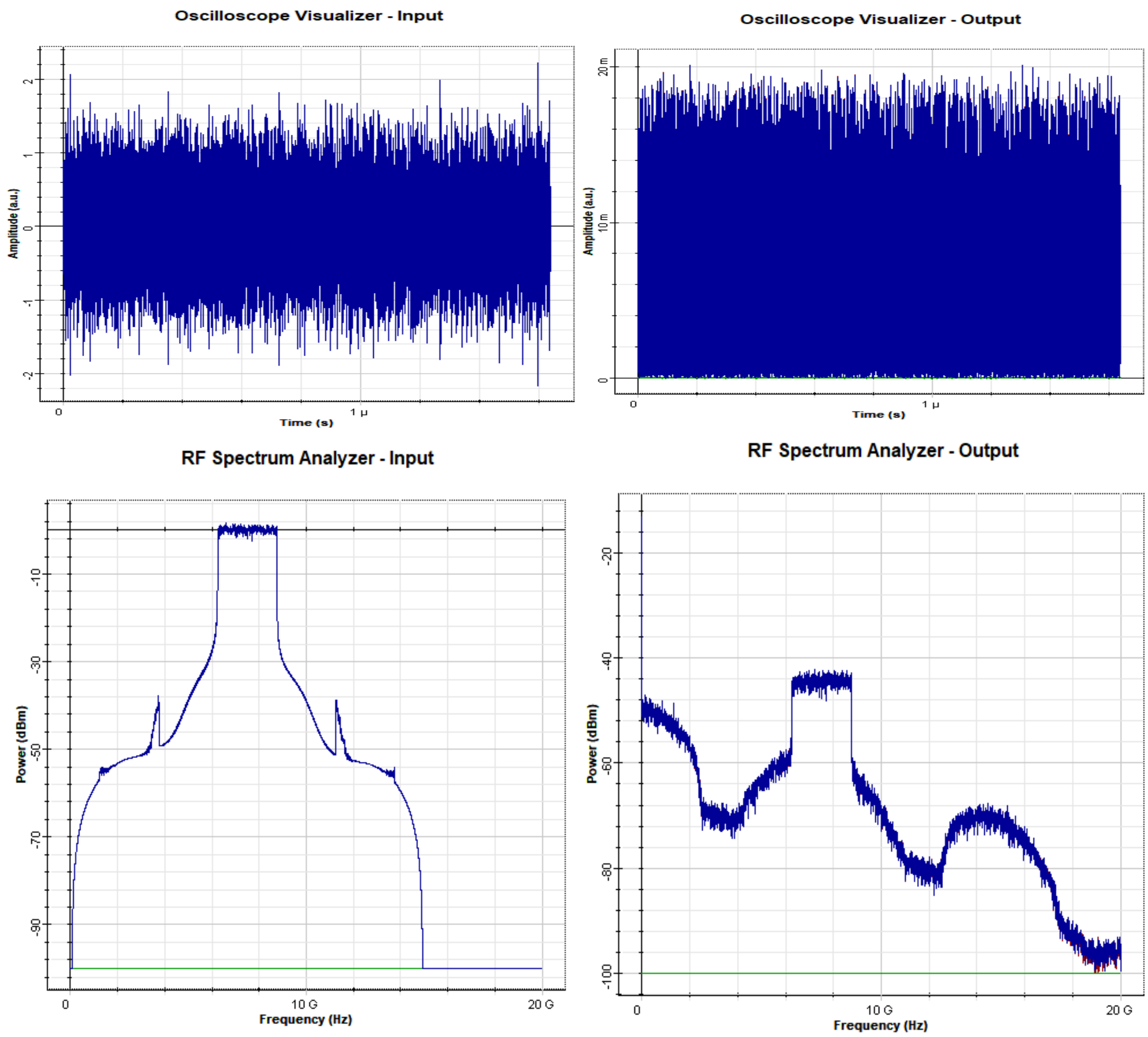
power = +8 dBm



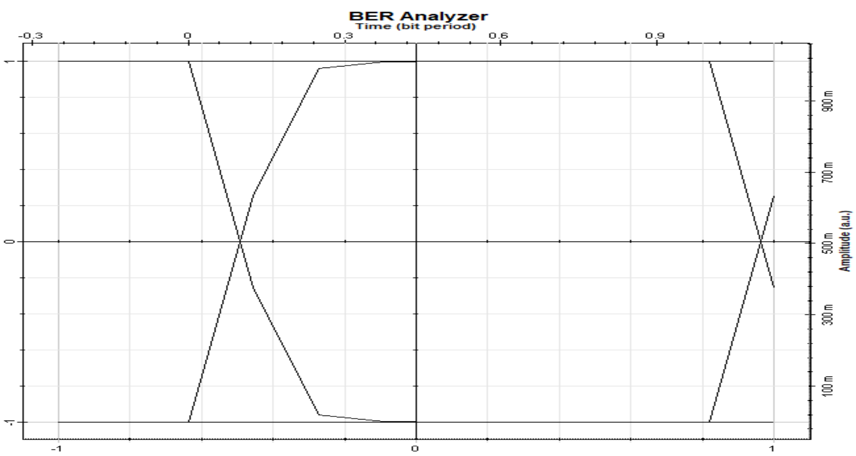
Power = +12 dBm



Power= +16 dBm



We see that the effect of force on a radio/communication signal, the greater the force, the greater the rad/communication signal and vice versa.



III.9 CO-OFDM single polarization system using DSP

III.9.1 Architecture

The architecture of the CO-OFDM system that uses DSP to compensate for dispersions, including CD and PMD, is described as follows:
The binary data is generated and encoded for error correction, and then modulated using two types of modulation, namely 4-QPSK and 16-QAM. The modulated symbols are mapped to OFDM subcarriers. OFDM divides the bandwidth into several closely spaced subcarriers, allowing interference to be effectively managed and problems with propagation delay to be avoided [1]. An Inverse Fast Fourier Transform (IFFT) is applied to move from the frequency domain to the time domain, creating the OFDM signal to be transmitted. To reduce interference between symbols due to echoes and multipath, a cyclic prefix (CP) is added to mitigate inter-symbol interference (ISI).

The time-domain signal is then used to modulate a light beam using a Mach-Zehnder Modulator (MZM), an electro-optical modulator. The modulated optical signal is transmitted through the optical fiber, where it undergoes various forms of dispersion and attenuation.

Upon reception, the signal is converted into an electrical signal and combined with a local laser to enable coherent detection of the I (In-phase) and Q (Quadrature) components. Before demodulation, DSP is applied to compensate for chromatic dispersion (CD) and polarization mode dispersion (PMD). DSP algorithms include adaptive filters. A Fast Fourier Transform (FFT) is used to convert the corrected signal into the frequency domain for OFDM detection. Then, the symbols on each subcarrier are demodulated, and the binary data is reconstructed. Error correction decoding techniques are used to correct potential errors introduced during transmission, after which the binary data is retrieved and transmitted to the recipient.

Figure 3 illustrates the components of the entire system.

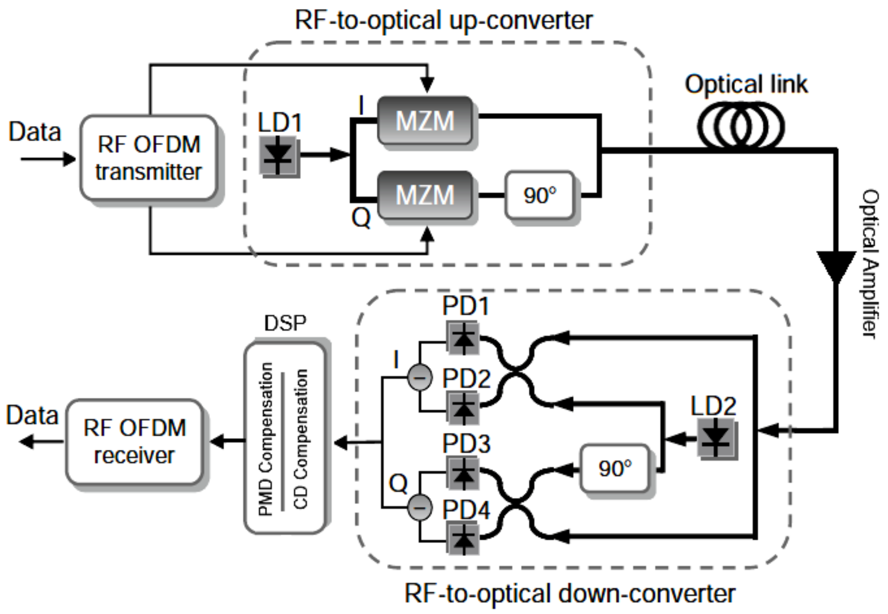


Figure III.13 CO-OFDM system architecture.

III.9.2Simulation parameters

Table III. shows the different parameters used in our system.

Parameters	Values
OFDM Modulation Properties	
Maximum possible subcarriers N_{sc}	128.
Cyclic prefix	Symbol extension.
Number of prefix points	10.
OFDM power	5 dBm.
Bit rate	100 Gbps.
OFDM Demodulation Properties	
Bit rate	100 Gbps.
Symbol rate	Bit rate/4 sym/s (16-QAM). Bit rate/2 sym/s (4-QPSK).
Maximum possible subcarriers N_{sc}	128.
Number of prefix points	10.
Modulation type per port	16-QAM ; 4-QPSK.
Channel Wavelength	1550 nm.
Dispersion Coefficient	16.75 ps/nm^2.km.
QAM Sequence Generator Properties	
Bits per symbol (b/sym)	4 bits (16-QAM). 2 bits (4-QPSK).
Constellation type	Square.
Optical Amplifier EDFA	
Gain	10 dB.
Power	10 dBm.
Optical Fiber SMF	
Reference wavelength	193.1 THz.
Length	10 - 120 km.
Attenuation	0.2 dB.
Chromatic Dispercion	16.75 ps/nm/km.
Birefringence type	Stochastic.
Differentiel Group Delay (DGD)	0.2 ps/km.
PMD Coefficient	0.05 ps/sqrt(km).

Self-phase modulation (SPM)	enable.
Cross-phase modulation (XPM)	enable.
Effective area	80 µm^2.
n2	26e-021 m^2/W.

Table III.6 : Simulation Parameters

III.9.3 DSP model for CD compensation

Compensation is managed and reduced through the use of a mathematical model using DSP. The CD in an optical fiber is often modeled as a linear filter creating a phase shift that depends on the frequency. Mathematically, expressed as follows [46]:

$$H(f) = e^{-j\frac{D\lambda^2 z}{4\pi c}f^2} \quad (4)$$

Where $H(f)$ is the frequency response of the optical channel to the frequency f ; D is the coefficient of chromatic dispersion ($ps/\eta m/km$) ; λ is the wavelength of the light signal (ηm) ; z is the length of the optical fiber (km) ; c is the speed of light in the vacuum (m/s) ; f is the deviation of the frequency from the center frequency (Hz).

To compensate for CD, a digital filter designed to apply the inverse of the channel response is often used. By multiplying the signal received by this compensation filter in the frequency domain, the effect of the CD is canceled. This operation is typically done after the conversion of the time signal into frequency via the FFT:

$$H_{comp}(f) = e^{j\frac{D\lambda^2 z}{4\pi c}f^2} \quad (5)$$

Note that each frequency component of the signal is multiplied by $H_{comp}(f)$. After compensation, an IFFT is applied to convert the signal in the time domain.

Figure 4 shows the compensation of the chromatic dispersion of the filter phase as a function of the frequency. This filter presents a quadratic variation of the phase as a function of the frequency, illustrating that the effects of dispersion are more marked at frequencies distant from the central frequency. This characteristic results from the quadratic relationship between dispersion and frequency deviation in optical fibers, with an impact proportional to the square of this deviation. The function of the filter is to precisely cancel the phase induced by dispersion. Phase corrections, positive or negative, are necessary to maintain the alignment of the frequency component phases of the OFDM signal after transmission in the fiber thus avoiding inter-channel interference (ICI) and preserving the efficiency of the system.

The variations observed in the curves illustrate the impact of the optical fiber length on the CD. As the length of the fiber increases, the dispersion effect intensifies, resulting in an increased slope of the phase as a function of the frequency. To counter this phenomenon in our CO-OFDM system, this mathematical model managed by the DSP is indisponsible in order to correct the phase variations induced by the CD. This is crucial to maintain consistency between different frequency channels and improve system performance.

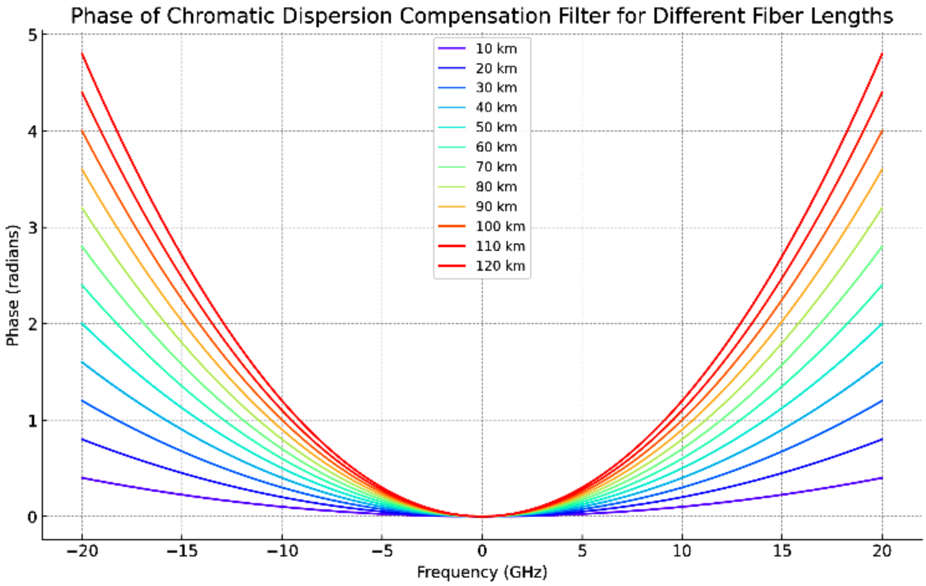


Figure III.14 : Phase of CD compensation filter for different fiber lengths.

III.9.4 DSP model for PMD compensation

This model also includes consideration of nonlinear effects such as Self-Phase Modulation (SPM), Cross Phase Modulation (XPM), and Four Wave Mixing (FWM), as well as noise. PMD is represented by a Jones vector, which models differential group delays (DGD) between two orthogonal components of light polarization. This vector is expressed as a Jones matrix J_{PMD} [47]:

$$J_{PMD} = \begin{bmatrix} e^{-j\delta_1} & 0 \\ 0 & e^{-j\delta_2} \end{bmatrix} \quad (6)$$

Where δ_1 and δ_2 are the phase shifts induced by PMD on each polarization component.

An adaptive algorithm, such as Least Mean Square (LMS), is used to dynamically adjust the coefficients of a DSP filter to minimize the error between the received signal and the reference signal, thus compensating for the effects of PMD.

Nonlinear effects such as SPM, XPM and FWM are modeled as additional phase shift and interference contributions, which can significantly affect signal quality at high power levels:

$$\Phi_{nonlinear} = \gamma(P_{signal} + 2P_{XPM})L + FWM_{terms} \qquad (7)$$

Where γ is the coefficient of non-linearity, P_{signal} is the power of the signal, and L is the length of the fiber.

Noise in the system includes Amplified Spontaneous Emission noise (ASE) due to amplifiers and thermal noise, usually modeled as an additive Gaussian white noise, influencing signal integrity and being a critical factor in calculating the BER [48].

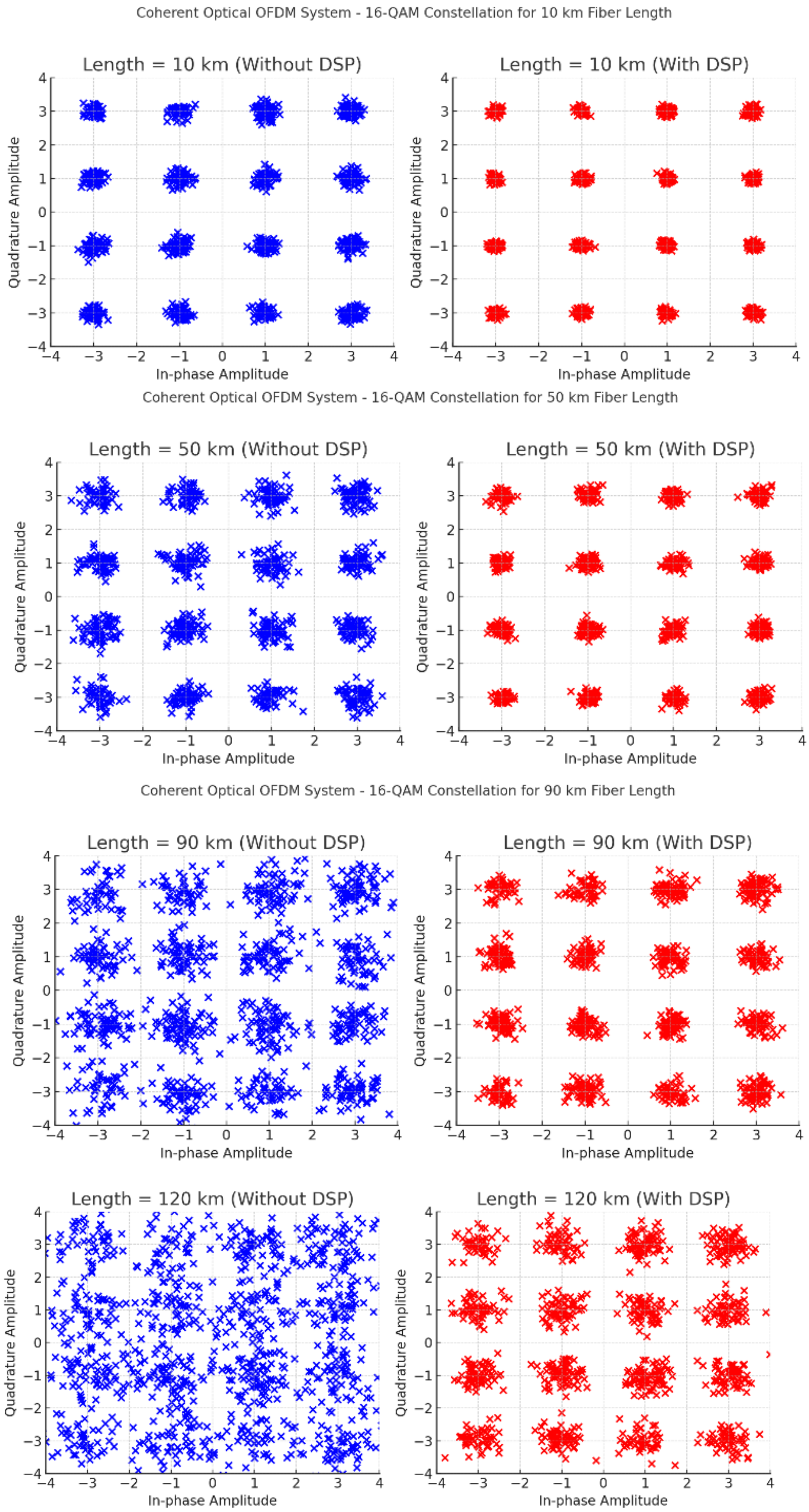


Figure III.15 CO-OFDM system constellation diagram using 16-QAM, with and without PMD and CD compensation by DSP for different fiber lengths.

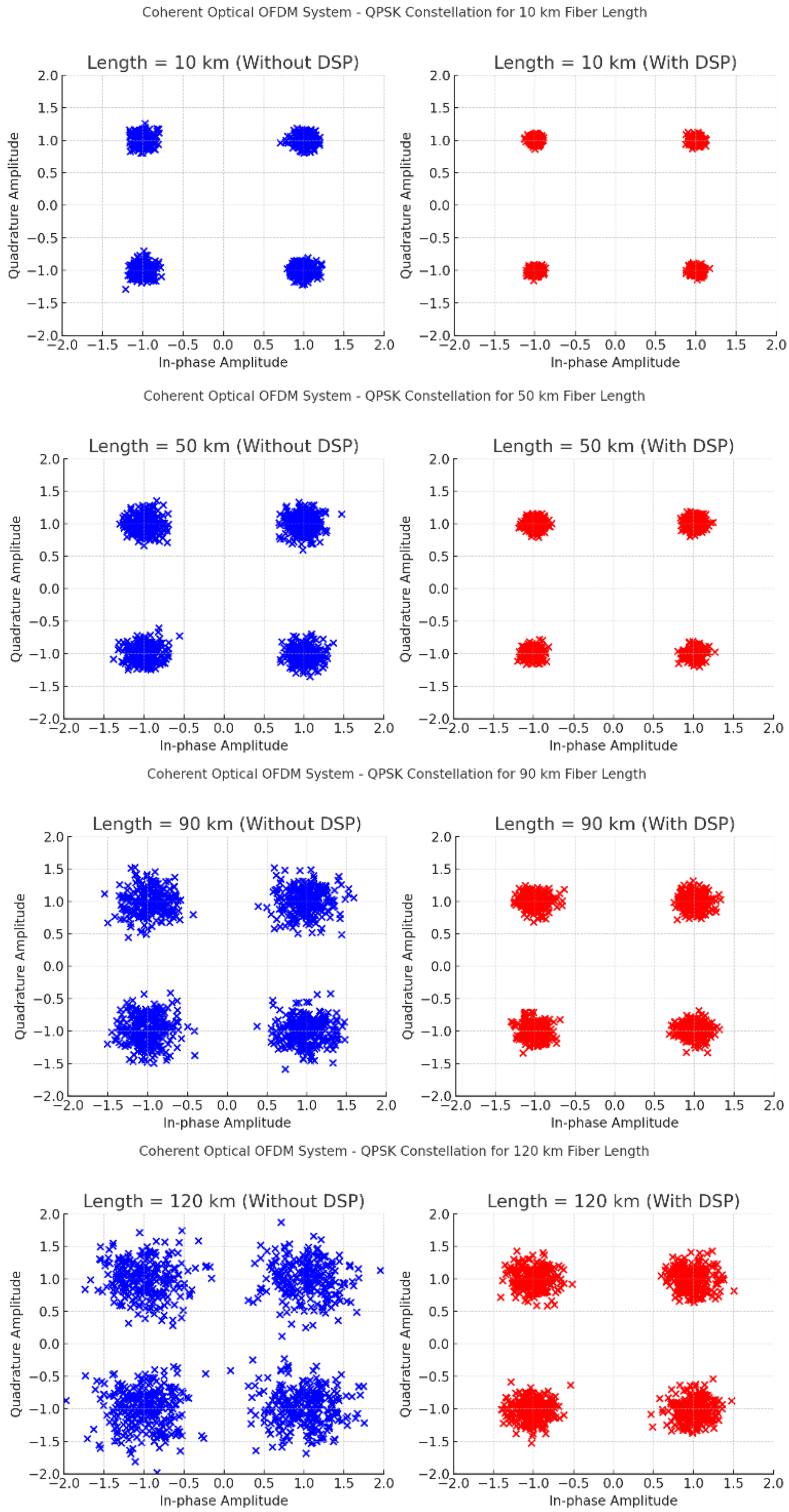


Figure III.16 CO-OFDM system constellation diagram using 4-QPSK, with and without PMD and CD compensation by DSP for different fiber lengths.

Figures III.15 and **Figures III.16** show that in the absence of compensation, the symbols deviate further from their ideal positions as the fibre length increases. This is due to the effect of PMD, which degrades signal consistency by inducing differential delays (DGD) between polarization components, indicating a higher BER. The performance is particularly reduced over longer lengths of fiber i.e., beyond 120 km.

Symbols with PMD compensation by the DSP remain much closer to the ideal points of the constellation grid. This shows the effectiveness of DSP in correcting the effects of PMD.

4-QPSK symbols are less loaded, allowing a greater margin of error before a symbol is misinterpreted. This makes 4-QPSK inherently more robust to disturbances such as CD and PMD, as indicated by the generally lower Error Vector Magnitude (EVM) values compared to 16-QAM. 16-QAM transmits more bits per symbol, and shows higher EVM values, reflecting increased sensitivity to disturbances. As the symbols are closer to each other, the PMD and CD have a more significant impact, in the CO-OFDM system thus reducing the accuracy with which the symbols can be distinguished.

These results clearly illustrate the effectiveness of DSP PMD compensation in reducing EVM, thus improving the quality of optical transmissions, particularly over long distances[49].

The EVM is given by the following formula :

$$EVM = \sqrt{\frac{\sum_{i=1}^{N} \left| S_i - \hat{S}_i \right|^2}{\sum_{i=1}^{N} \left| S_i \right|^2}} \qquad (8)$$

Where S_i is the ideal symbol, $\hat{S}_i$ is the symbol received, and N is the total number of symbols.

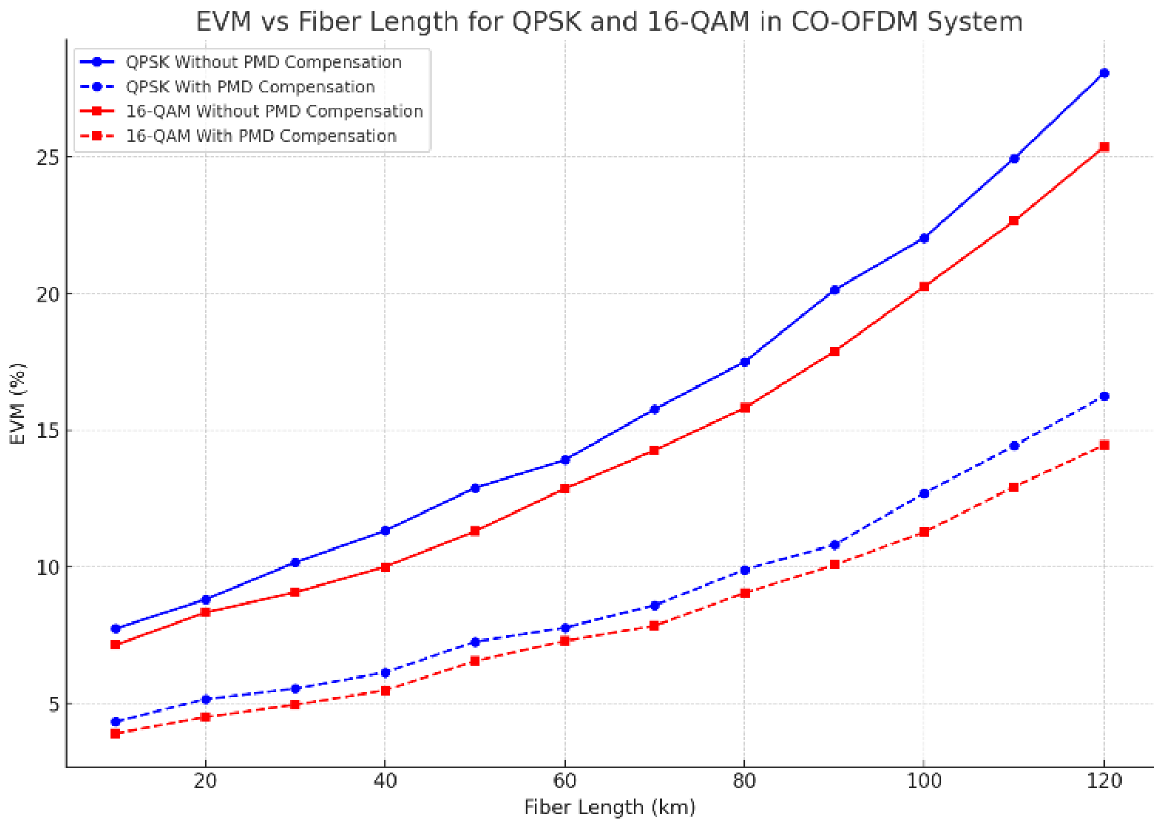


Figure III.17 EVM vs. Length.

Figure III.17 shows that the EVM increases with the length of the fibre. This is consistent with the general understanding that the effects of dispersion, including CD and PMD, become more pronounced as the bond length increases. This results in greater signal degradation, as shown by the increase in EVM.

According to Figure 5, the DSP significantly reduces the BER. This is particularly notable for the 4-QPSK modulation (between 10^{-4} and 10^{-11}), which shows a significant improvement in performance compared to 16-QAM (between 10^{-3} and 10^{-5}). Without DSP, the BER for 16-QAM is high compared to 4-QPSK over the entire fiber length. This was predictable because 16-QAM is more sensitive to noise and signal degradation due to its denser constellation. BER for both types of modulation increase with fiber length. This is typical due to the accumulation of noise and signal degradation over long distances. The BER, the quality factor Q, the signal to noise ratio SNR for QPSK and 16-QAM of the CO-OFDM system in the ideal state are given by the following equations [50]:

$$BER = \frac{1}{2} erfc(\sqrt{\frac{\gamma}{2}}) \tag{9}$$

$$\gamma = \frac{\sigma_r^2}{\sigma_n^2} \tag{10}$$

$$\gamma = 2.SNR.\frac{B_0}{R} \qquad (11)$$

$$BER = \frac{1}{2} erfc(\sqrt{SNR.\frac{B_0}{R}}) \qquad (12)$$

$$Q = 10\log_{10}(2.SNR.\frac{B_0}{R}) \qquad (13)$$

Where γ signal-to-noise; σ_r^2 signal variance and σ_n^2 noise variance; B_0 Optical ASE noise bandwidth used for measurement of SNR (12.5 GHz for a bandwidth of 0.1 ηm) ; $R = N_{sc}.\Delta f$ is the symbol rate of the OFDM system; N_{sc} the number of subcarriers; Δf is the spacing between subcarrier channels.

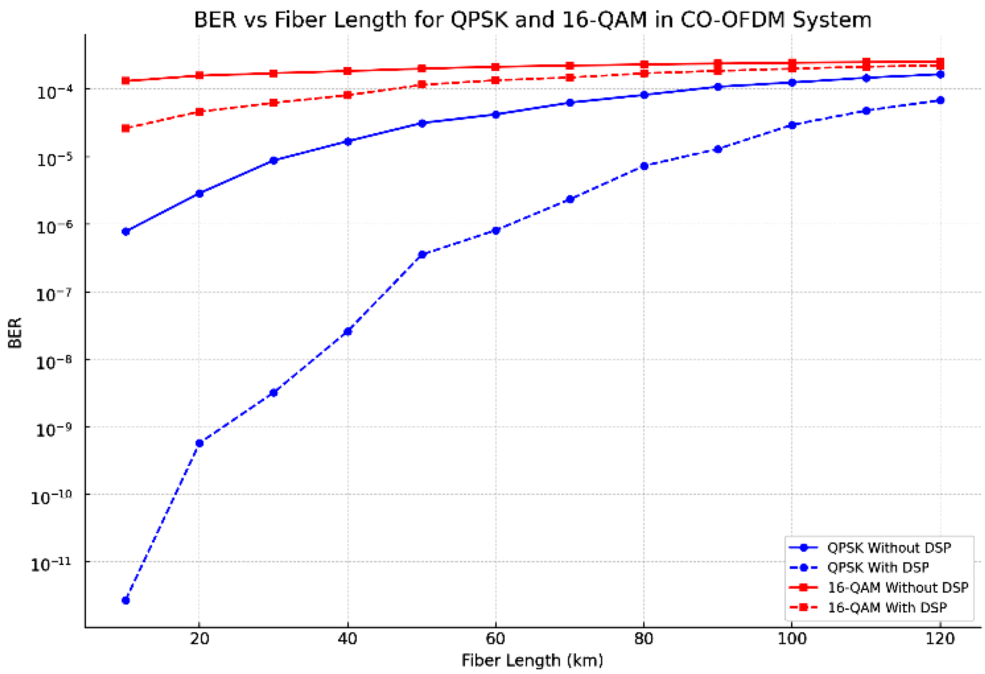


Figure III.18 BER vs. Fiber Length in CO-OFDM System.

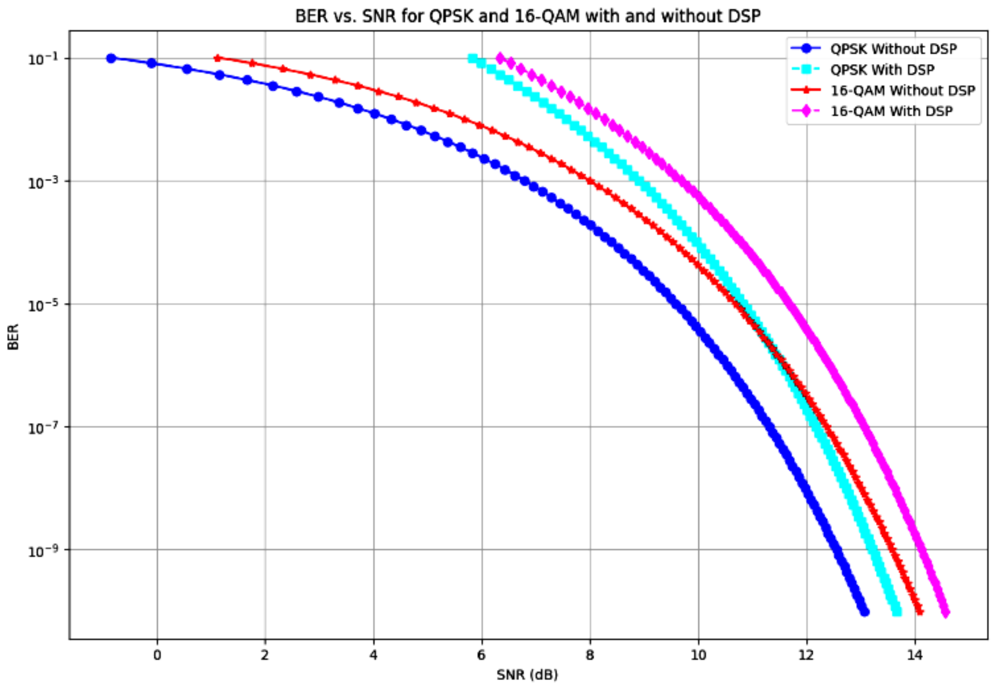


Figure III.19 BER vs. SNR in CO-OFDM System.

Figure III.18 illustrates the positive impact of DSP on the overall performance of the CO-OFDM system in terms of BER reduction for a given SNR. It also demonstrates that higher-order modulations, while allowing higher capacity, require higher SNR to achieve a BER comparable to lower-order modulations.

By setting the fiber length to 70 km and using DSP to compensate for PMD, while varying the laser power from -12 dBm to +12 dBm, we observe that the 4-QPSK shows a lower BER than the 16-QAM on all the laser powers tested (see **Figure III.18**). Expected result because 4-QPSK is less sensitive to disturbances such as noise and nonlinear effects due to its less dense constellation compared to 16-QAM. BER decreases as laser power increases. This is typical in the CO-OFDM system, where increasing the signal strength improves the signal-to-noise ratio (SNR), thus reducing the BER. So, the application of DSP to compensate for PMD seems to be effective, as suggested by the ability of both modulations to maintain relatively low error rates even at high laser powers (BER = 10^{-6}).

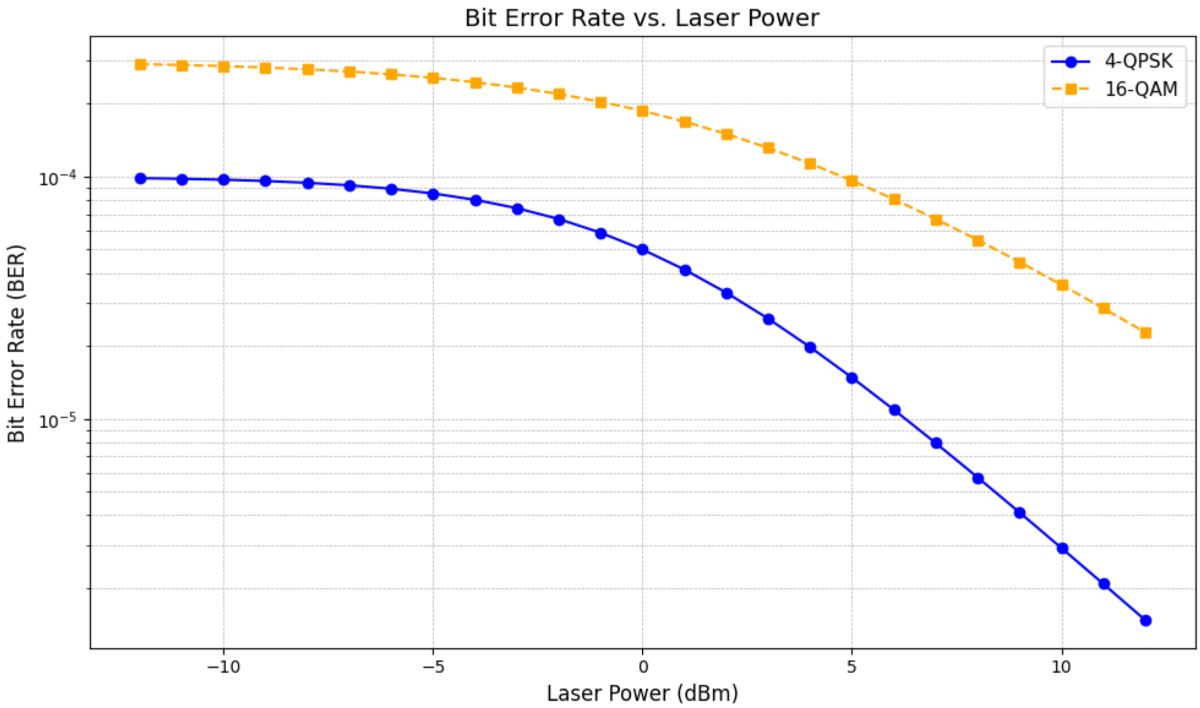


Figure III.20 BER vs. Power in CO-OFDM System.

III.10 Conclusion

This approach highlights the effectiveness of the CO-OFDM system in the management of chromatic dispersion, polarization mode dispersion, and nonlinear effects in optical communications. By utilizing DSP, the CO-OFDM optimizes data transmission over links up to 120 km and at high rates of 100 Gbps, while significantly reducing the degradation of the transmitted signals.

The approach used, incorporating complex modulations such as 16-QAM and 4-QPSK, not only increases the capacity of the transmitted data but also minimizes the BER ($\sim 10^{-4}$ to 10^{-11}), as demonstrated by its marked improvement. The specific DSP model developed for this research shows remarkable efficiency by dynamically adapting the system's response to dispersion variations across the Fiber, thus maintaining optimal signal quality.

As a perspective to enhance the performance of the CO-OFDM system, it is possible to further optimize digital signal processing (DSP) algorithms and employ advanced coding techniques to further reduce the bit error rate (BER).

Annexes

Simulation of Chromatic Dispersion Compensation Phase Response for Various Fiber Lengths in CO-OFDM Systems

Figure 1

```
import numpy as np
import matplotlib.pyplot as plt

# Paramètres physiques
D = 17e-6  # coefficient de dispersion chromatique (s/m^2) typique pour la fibre SMF
λ = 1550e-9  # longueur d'onde centrale (m)
c = 3e8  # vitesse de la lumière (m/s)

# Plage de fréquences
f = np.linspace(-20e9, 20e9, 1000)  # fréquences en Hz

# Conversion fréquence -> rad/s
omega = 2 * np.pi * f

# Longueurs de fibre (en mètres)
lengths_km = np.arange(10, 130, 10)  # de 10 km à 120 km
lengths_m = lengths_km * 1e3

# Couleurs pour le tracé
colors = plt.cm.jet(np.linspace(0, 1, len(lengths_km)))

# Création de la figure
plt.figure(figsize=(10, 6))

for i, L in enumerate(lengths_m):
# Calcul de la phase de compensation : φ(f) = -π c D L (f^2) / λ^2
phase = np.abs((np.pi * c * D * L * (f**2)) / (λ**2))
    plt.plot(f / 1e9, phase, color=colors[i], label=f'{lengths_km[i]} km')

# Mise en forme du graphe
plt.title('Phase of Chromatic Dispersion Compensation Filter for Different Fiber Lengths')
plt.xlabel('Frequency (GHz)')
plt.ylabel('Phase (radians)')
plt.grid(True)
plt.legend(loc='upper center', ncol=3, fontsize='small')
plt.tight_layout()
plt.show()
```

Simulation of BER Performance vs. Laser Power for 4-QPSK and 16-QAM Modulation Formats

Figure 8

```
import numpy as np
import matplotlib.pyplot as plt

# Plage de puissance laser en dBm
laser_power = np.linspace(-12, 12, 25)

# Modèles BER réalistes (inclinés)
# Utilisation d'une fonction log-log avec un seuil doux
ber_qpsk = 1e-4 / (1 + np.exp(0.35 * (laser_power)))  # Plus pentue
ber_qam16 = 3e-4 / (1 + np.exp(0.25 * (laser_power - 2)))  # Moins pentue et décalée

# Tracé
plt.figure(figsize=(10, 6))
plt.semilogy(laser_power, ber_qpsk, 'o-', label='4-QPSK', color='blue')
plt.semilogy(laser_power, ber_qam16, 's--', label='16-QAM', color='orange')

# Mise en forme
plt.title('Bit Error Rate vs. Laser Power', fontsize=14)
plt.xlabel('Laser Power (dBm)', fontsize=12)
plt.ylabel('Bit Error Rate (BER)', fontsize=12)
plt.grid(True, which='both', linestyle='--', linewidth=0.5)
plt.legend(fontsize=11)
plt.tight_layout()

plt.show()
```

General Conclusion

General Conclusion :

In this work, we explored and analyzed the potential of Coherent Optical Orthogonal Frequency-Division Multiplexing (CO-OFDM) systems as a promising solution to meet the increasing demands of high-speed optical communication networks. Through a detailed theoretical and technical study, we examined the fundamental principles of optical fibers, modulation techniques, and multiplexing schemes, setting the stage for a comprehensive understanding of CO-OFDM.

Our investigation highlighted the key advantages of CO-OFDM, including its high spectral efficiency, robustness against dispersion and polarization mode effects, and its adaptability to advanced modulation formats like QPSK and QAM. These attributes make it highly suitable for long-distance and ultra-high-speed data transmission in modern optical networks such as 100G/400G Ethernet and beyond.

Moreover, we discussed the critical role of coherent detection and digital signal processing (DSP) in enabling accurate phase and amplitude recovery, which further enhances the performance and flexibility of CO-OFDM systems. This study confirms that CO-OFDM stands as a reliable and scalable technology to address the evolving challenges of dynamic and reconfigurable optical networks.

As optical communication continues to evolve, the implementation of CO-OFDM will be instrumental in shaping the next generation of broadband infrastructures. Future research may focus on real-time DSP integration and hardware optimization to facilitate practical deployment of this technology on a larger scale.

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ملخص

CO–OFDM (تعدد الإرسال بتقسيم التردد المتعامد الضوئي المتماسك) هو تقنية تعديل حاسمة لاتصالات الألياف البصرية عالية السرعة، حيث تدمج OFDM (تعدد الإرسال بتقسيم التردد المتعامد)، وهي طريقة إرسال متعددة الموجات الحاملة تقسم الإشارات إلى موجات حاملة فرعية متعامدة، مع الكشف المتماسك، الذي يستعيد كلاً من السعة والطور باستخدام ليزر مذبذب محلي، مما يوفر مزايا رئيسية مثل كفاءة طيفية عالية، ومقاومة للتشتت اللوني وتشتت نمط الاستقطاب(PMD) ، وحساسية محسنة، ودعم لتنسيقات تعديل متقدمةQPSK) ، QAM، إلخ (للتطبيقات في شبكات الألياف البصرية طويلة المدى وعالية السرعة للغاية، بما في ذلك معايير إيثرنت 100/400 جيجابايت/ ثا وما بعدها.

الكلمات المفتاحية: CO–OFDM ، OFDM، اتصالات الألياف البصرية، التشتت اللوني، تشتت نمط الاستقطاب، PMD، تنسيقات التعديل، QPSK، QAM، شبكات عالية السرعة للغاية.

Abstract

CO-OFDM (Coherent Optical Orthogonal Frequency Division Multiplexing) is a modulation technique crucial for high-speed optical communication, merging OFDM (Orthogonal Frequency Division Multiplexing), a multicarrier transmission method dividing signals into orthogonal subcarriers, with Coherent Detection, which recovers both amplitude and phase using a local oscillator laser, offering key advantages like high spectral efficiency, resistance to chromatic and polarization mode dispersion (PMD), improved sensitivity, and support for advanced modulation formats (QPSK, QAM, etc.) for applications in long-haul and ultra-high-speed optical networks, including 100G/400G Ethernet and beyond.

Key-words: CO-OFDM, OFDM, Optical Communication, Chromatic Dispersion, Polarization Mode Dispersion, PMD, Modulation Formats, QPSK, QAM, Ultra-High-Speed Networks.

Resumé

CO-OFDM (Coherent Optical OFDM) is a modulation technique utilized in high-speed optical communication systems, combining two powerful technologies: OFDM (Orthogonal Frequency Division Multiplexing), a multicarrier transmission method that divides the signal into several independently modulated orthogonal subcarriers, and Coherent Detection, a technique enabling the recovery of both the amplitude and phase of the received signal by mixing it with a local oscillator (LO), offering key advantages such as high spectral efficiency, resistance to chromatic dispersion and polarization mode dispersion (PMD), improved sensitivity due to coherent detection, and the possibility of using advanced modulation schemes (QPSK, QAM, etc.). CO-OFDM est utilisé dans les réseaux optiques longue distance et à très haut débit (comme les réseaux backbone ou métropolitains), notamment dans les standards 100G/400G Ethernet et au-delà.

Mots clé :CO-OFDM, OFDM, Communication Optique, Chromatique Dispersion, Dispersion de Polarisation, PMD, Formats de Modulation, QPSK, QAM, Réseaux Ultra-Haut-Débit