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By: ABDELLAOUI ACHWAK

Topic

Development of a new two-dimensional code for an optical CDMA system

Defended publicly, on 25/06/2025, before the jury composed of:

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Dedication

To those who have given me everything without expecting anything in return, to those who have encouraged and supported me in the most difficult moments,

To my dear parents, who have worked tirelessly alongside me since the day I came into this world, I do not know if my success will ever be enough to repay, even in the smallest way, your efforts. Without Allah and without you both, I would have never accomplished any of this.

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Abstract

This master thesis presents the development and validation of an innovative bidimensional-coding scheme tailored for optical CDMA systems. Addressing the dual challenges of mitigating multiple access interference (MAI) and reducing system complexity, the research begins with a comprehensive overview of optical communication principles. A critical review of existing OCDMA technologies outlines the limitations inherent in current methods. The experimental results, supported by detailed simulations, demonstrate the superior performance and feasibility of the proposed approach. The findings not only substantiate the theoretical framework but also establish a promising direction for future optical network enhancements.

Keywords : OCDMA, Code bidimensionnel, optisystem, BER

Résumé

Cette thèse de master présente le développement et la validation d’un schéma de codage bidimensionnel innovant destiné aux systèmes CDMA optiques. Face au double défi de réduire l’interférence multi-accès (IMA) et la complexité du système, la recherche débute par une analyse approfondie des principes fondamentaux de la communication optique. Une revue critique des technologies OCDMA existantes met en lumière les limites des approches actuelles. Les résultats expérimentaux, corroborés par des simulations détaillées, démontrent la performance supérieure et la faisabilité de la méthode proposée. Ces résultats confirment le cadre théorique établi et ouvrent de nouvelles perspectives pour l’optimisation des réseaux optiques.

Mots clés : OCDMA, Code bidimensionnel, optisystem, BER

ملخص

هذه الأطروحة تقدم تطوير والتحقق من صحة مخطط تشفير ثنائي الأبعاد مبتكر مخصص لأنظمة الضوئية في مواجهة التحدي المزدوج المتمثل في تقليل التداخل متعدد الوصول وتعقيد النظام، يبدأ البحث بتحليل متعمق للمبادئ الأساسية للاتصالات الضوئية. تُسلط مراجعة نقدية لتقنيات الحالية الضوء على قيود الأساليب الحالية. تُظهر النتائج التجريبية، التي تدعمها محاكاة تفصيلية، الأداء المتفوق وجدوى الطريقة المقترحة. تؤكد هذه النتائج الإطار النظري الموضوع وتفتح آفاقًا جديدة لتحسين الشبكات الضوئية.

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Chapter 03: Development of a New two-dimensional-SWZCC

List of Acronyms

1-D	One-Dimensional
2D	Two-Dimensional
2D-MD	Two-Dimensional Multi-Diagonal
APD	Avalanche Photodiode
BER	Bit Error Rate
BPON	Broadband PON
CDMA	Code Division Multiple Access
DPSK	Differential Phase Shift Keying
DSSS	Direct Sequence Spread Spectrum
DW-MD	Double Weight Multi-Diagonal
DWDM	Dense WDM
EDFA	Erbium-Doped Fiber Amplifier
EDW	Enhanced Double Weight
FEC	Forward Error Correction
FHSS	Frequency-Hop Spread Spectrum
GE-PON	Gigabit Ethernet PON
GPON	Gigabit PON
IoT	Internet of Things
LAN	Local Area Network
LED	Light-Emitting Diode
MAI	Multiple Access Interference
mQAM	M-ary Quadrature Amplitude Modulation
NRZ	Non-Return-to-Zero
OCDMA	Optical Code Division Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONU	Optical Network Unit
ONT	Optical Network Terminal
OSA	Optical Spectrum Analyzer

List of Acronyms

OSNR	Optical Signal-to-Noise Ratio
OTDV	Optical Time Domain Visualizer
PAMx	Pulse Amplitude Modulation
PIN	P-Intrinsic-N
PMD	Polarization Mode Dispersion
PON	Passive Optical Network
SOA	Semiconductor Optical Amplifier
SWZCC	Single Weight Zero Cross-Correlation
TWDM	Time and Wavelength Division Multiplexed
WDM	Wavelength Division Multiplexing
ZCC	Zero Cross-Correlation

General introduction

General introduction

High-speed optical networks are at the core of modern communication infrastructures, driven by the constant surge in data traffic and the demand for reliable, scalable transmission systems. Optical Code Division Multiple Access (OCDMA) has emerged as a promising technology, offering simultaneous data transmission through unique code assignments. However, the conventional one-dimensional OCDMA systems face significant challenges most notably multiple access interference (MAI) and escalating system complexity which can hinder performance as user demands and network sizes grow.

To address these inherent limitations, researchers have increasingly turned to multidimensional coding techniques. By harnessing both spectral and spatial dimensions, bidimensional coding approaches offer a substantial improvement in mitigating interference and enhancing system capacity. In this context, the master's thesis presented here introduces a new two-dimensional code known as the Single Weight Zero Cross-Correlation (SWZCC) code. This innovative coding scheme is specifically designed to eliminate MAI through its unique zero cross-correlation property while simultaneously reducing the overall system complexity.

The research employs detailed simulations using Optisystem to evaluate performance metrics such as the Bit Error Rate (BER). These studies provide empirical support for the efficacy of the SWZCC code, illustrating its potential to streamline the architecture of an optical CDMA system and deliver robust transmission quality in a scalable manner. This work not only contributes to the theoretical understanding of bidimensional coding but also lays the groundwork for practical implementations in next-generation optical networks

Chapter 01
Generalities on Optical Communication

1.1 Introduction

Optical communication has revolutionized the way information is transmitted over long distances, enabling data rates and bandwidth capacities that are essential for modern telecommunications, internet infrastructure, and data centers. Unlike traditional electrical transmissions, optical links use light signals traveling through optical fibers, offering significant benefits such as low attenuation, high resistance to electromagnetic interference, and the ability to support high-speed data transfer.

This chapter provides a thorough overview of optical communication links, laying the foundation for understanding advanced optical systems like Optical Code Division Multiple Access (OCDMA).

1.2 Definition and importance of Optical Communication Systems

Optical communication systems have become the backbone of contemporary telecommunications, allowing the transfer of large volumes of data over long distances with unmatched speed and reliability. Essentially, optical communications involves transmitting information as light signals through optical fibers thin strands of glass or plastic designed to guide light with minimal lose. This technology has transformed data transmission by providing advantages such as high bandwidth, low latency, and strong immunity to electromagnetic interference [1], [2].

The vital role of optical communication systems in today’s networks is indisputable. With the rapid increase in Internet usage, cloud computing, and the rise of connected devices, the need for high capacity, reliable, and secure communication infrastructures has never been more pressing. Optical fibers have become the preferred medium to meet these needs, supporting data rates that surpass terabits per second and enabling the deployment of advanced technologies such as 5G, the Internet of Things (IoT), and virtual reality [1], [3].

1.2.1 Historical development of optical communication systems

The development of optical communication is a fascinating journey that spans centuries, showcasing continuous innovation and adaptation. Although the use of light for signaling dates back to ancient times, such as fire beacons and the optical telegraph invented by Claude Chappe in 1790, the modern era of optical communication only began in the 20^{th} century.

The first Generation:

The development of optical communication systems in the 1970s was made possible by advancements in low-loss optical fibers and semiconductor lasers, permitting initial system operation at a wavelength of 0.8 micrometers. However, bandwidth limitations were imposed by high fiber losses and dispersion-related issues [4], [5].

The second Generation:

Subsequent improvements led to the advent of signal-mode fibers and lasers operating at 1.3 micrometers during the 1980s, resulting in diminished dispersion and facilitating extended transmission lengths. Concomitant commercial deployment of optical fiber systems substantively enhanced data transfer rates and dependability [4], [5].

The third Generation:

The widespread adoption of WDM technology in the 1990s facilitated simultaneous transmission of multiple wavelengths over a singular fiber, dramatically amplifying transmission capacity, necessitating heightened data transmission capabilities [4], [6].

The fourth Generation:

Lastly, the introduction of digital coherent technology in the 2000s and subsequent eras enabled markedly higher data transfer rates alongside enhanced signal quality over considerable distances. Moreover, the incorporation of space-division multiplexing and novel fiber types further augmented the efficiency and capacity of optical networks [4], [7].The ***Figure 1.1*** illustrates the evolution of optical fibers over time.

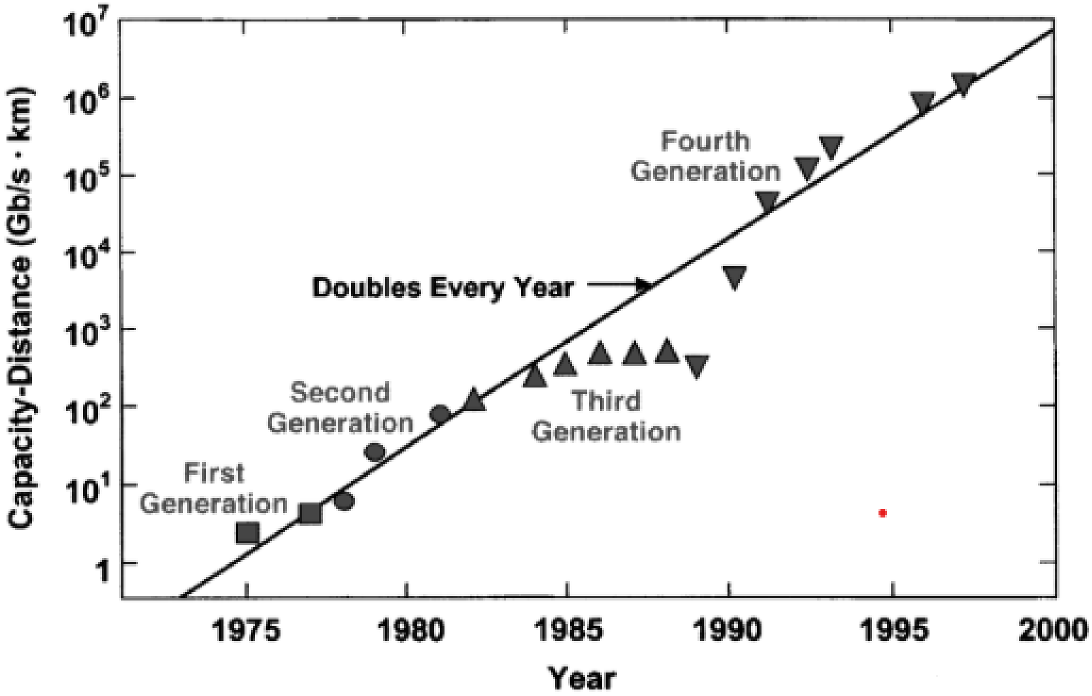

Figure 1.1 *Evolution of Optical Fibers*

1.3 Fundamental concepts of optical transmission

Optical transmission involves the process of conveying data as light signals through an optical medium, such as optical fibers. This process includes converting electrical signals into optical signals at the transmitter side, sending them through the fiber, and then converting them back into electrical signals at the receiver side. The core principle of optical transmission is the modulation of light to encode information, which is subsequently detected and decoded at the receiving end [8], [9].

1.3.1 Transformation of electrical signals to optical signals and back

The transformation of electrical signals into optical signals is achieved using optical transmitters, which consist of a light source, such as a laser diode or a light-emitting diode (LED), along with a driver circuit. The driver circuit. The driver circuit modulates the light source to encode the electrical signal into the light wave. This modulation can take the form of amplitude, frequency, or phase modulation [10], [11].

At the receiving end, the optical signal is converted back into an electrical signal using photodetectors, such as PIN photodiodes or avalanche photodiodes (APDs). These detectors produce an electrical current proportional to the intensity of the received light signal. The electrical signal is then amplified and decoded to recover the original information [12], [13].

1.4 Key Optical Components

1.4.1 Optical transmitters

In optical communication systems, optical transmitters play a crucial role by transforming electrical signals into optical signals, which can then be effectively sent through optical fibers. The main types of optical transmitters are laser diodes and light-emitting diodes (LEDs). Each type has unique features that make them ideal for various uses within optical networks.

1.4.1.1 Laser

In contemporary high-speed and long-range optical communication systems, laser diodes are the optical sources of choice. Their functionality relies on the principle of stimulated emission: when an electric current flows, electrons and holes within the semiconductor merge, releasing photons in a coherent manner. This mechanism generates a light beam that is directional, monochromatic, and coherent, which is crucial for preserving signal integrity over extended distances and facilitating sophisticated multiplexing techniques like wavelength-division multiplexing (WDM) and dense WDM (DWDM), as shown in ***Figure 1.2***.

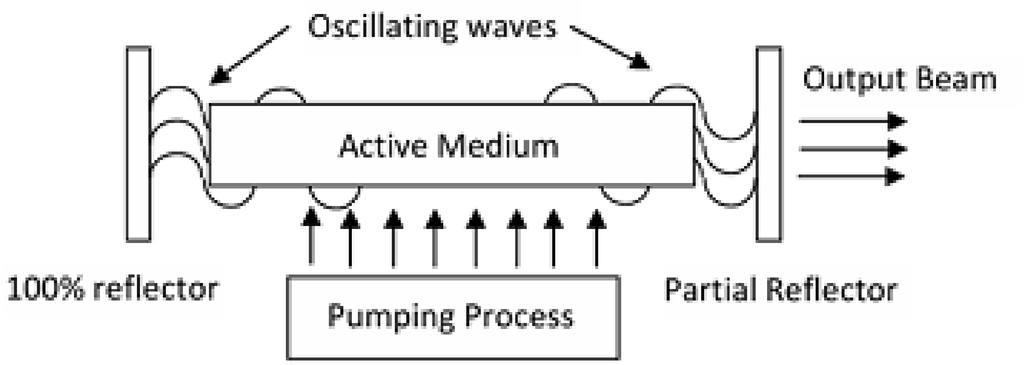

Figure 1.2 *Scheme showing basic components of a laser system* [14]

The mathematical expression for the output power ***Pout*** of a laser above the threshold current ***Ith*** is:

$$\mathrm{Pout} = \eta\mathrm{d}\ (\mathrm{I} - \mathrm{Ith})\ \mathrm{h}\nu \qquad \textbf{\textit{[1.1]}}$$

Here, ***ηd*** represents the differential quantum efficiency, ***I*** denote the injection current, ***h*** is Planck's constant, and ***ν*** stands for the optical frequency.

Benefits:

Laser diodes offer several key benefits, such as:

High output power and ***narrow spectral linewidth*** (usually 1–3 nm), which help reduce chromatic dispersion and enable dense channel packing in WDM systems.

High modulation speeds, with direct modulation rates exceeding 10 Gb/s, making them ideal for modern telecommunication networks.

Their small emission areas and directional beams allow ***efficient coupling*** into single-mode fibers.

They play ***a crucial role in optical CDMA systems***, where their coherence and spectral purity facilitate effective code multiplexing and minimize multiuser interference.

Common laser diodes used in optical communications include Fabry-Perot, distributed feedback (DFB), and vertical-cavity surface-emitting lasers (VCSELs), each tailored for specific performance and integration requirements.

Application:

Lasers are employed in single-mode fiber systems, multiplexing (wavelength division), and dense WDM (DWDM) systems with precise wavelength control [15], [16].

1.4.1.2 Light-emitting diode (LEDs)

LEDs represent another category of optical transmitters that function through spontaneous emission: when current flows through a semiconductor, electrons recombine with holes, emitting photons randomly in all directions. The emitted light is incoherent and has a broad spectral width, typically spanning tens of nanometers. This broad spectrum results in higher chromatic dispersion, limiting the achievable transmission distance and data rate.

The key characteristics of LEDs include

Lower output power and ***broader spectral width*** than lasers, restricting their use in short-distance, low-speed applications.

A ***lower modulation bandwidth*** is generally limited to a few hundred megabits per second (up to approximately 250 MHz), making it unsuitable for high-speed backbone links.

Ease of manufacturing and ***lower cost***, making them ideal for cost-sensitive applications such as local area networks (LANs) and multimode fiber systems.

Longer operational lifetime and ***greater temperature stability*** owing to lower power operation.

Applications:

LEDs are typically used in multimode fiber systems, where speed and distance requirements are not stringent [17], [18].

Figure 1.3 illustrates the components of fiber optic transmitters and receivers, showing the electronic interface drives the LED or laser, converting electrical signals into optical ones, which are then transmitted and received.

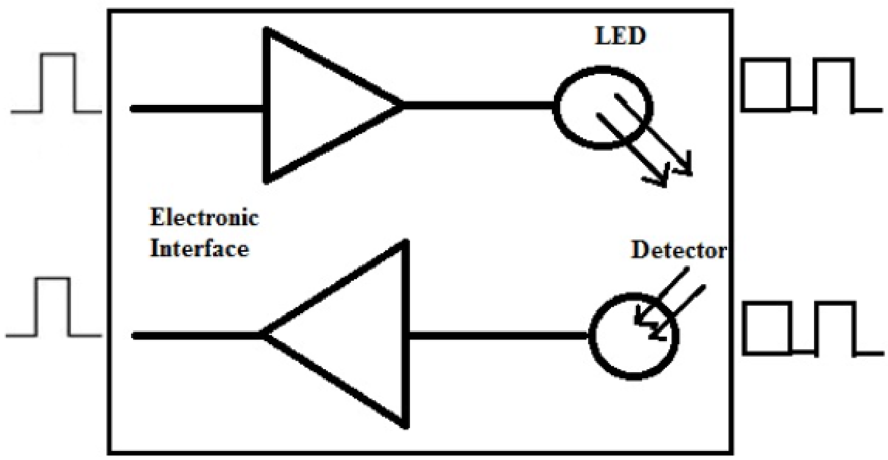

Figure 1.3 *Fiber Optic Transmitters and Receivers [19]*

1.4.2 Optical Fiber

Optical fibers serve as a medium for transmitting optical signals. They consist of cores surrounded by coatings that guide light through the total internal reflection. The two main types of optical fibers are single-mode and multi-mode fibers.

1.4.2.1 Single-Mode Fibers

The core diameter of the single-mode fiber is very small, allowing only one light mode to propagate. This design minimizes modal dispersion and supports high-speed long-distance transmissions.

Principle of Operation: Single-mode fibers support a single-wave mode, reducing interference and distortion. They are designed to operate at specific wavelengths, usually in the near-infrared region (e.g., 1310 nm and 1550 nm) [20].

Advantages: Single-mode fibers offer optimal bandwidth, reduced attenuation, and minimal signal degradation for communication systems and high-speed data transmissions [10], [15].

Application: Single-mode fibers are used in underwater cables, terrestrial long-distance networks, and WDM systems [16], [18].

1.4.2.2 Multi-Mode Fibers

The wide diameter of multimode fibers permits the concurrent transmission of multiple light modes, making them ideal for short-distance communication.

Operating Principle: Multimode fibers accommodate several light wave modes, which can result in modal dispersion and signal distortion. They are typically employed for shorter wavelengths, such as 850 nm and 1310 nm [8], [21].

Advantages: Multimode fibers are cost-effective for manufacturing and installation, making them suitable for short-range applications, such as LANs and optical connections [20], [22].

Application: Multimode fibers are frequently used in corporate networks, data centers, and industrial control systems [17], [18].

The optical fibers are classified according to their modes of propagation single-mode fibers support one propagation path while multimode fibers support multiple light paths, as shown in ***Figure 1.4***.

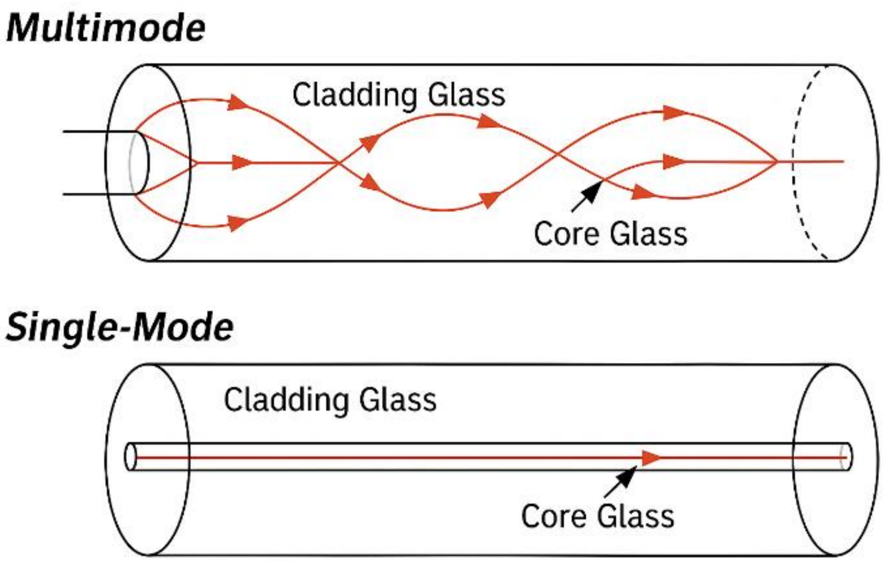

Figure 1.4 *Classification based on Modes of Propagation [23]*

1.4.3 Optical Amplifier

Optical amplifiers are used to boost the strength of optical signals that have weakened during transmission, thereby extending the distance between the transmitters and receivers. An erbium-doped fiber amplifier (EDFA) is the most prevalent type of optical amplifier.

1.4.3.1 Erbium-Doped Fiber Amplifier (EDFA)

The EDFA is the most widely used optical amplifier in contemporary optical communication systems. They are particularly effective in the 1550 nm wavelength range, which is the standard for most long-distance systems.

Operating Principle: EDFA functions by doping optical fibers with erbium ions. When these ions are excited by light at specific wavelengths (such as 980 or 1480 nm), they emit photons through stimulated emission, resulting in signal amplification [10], [20].

Advantages: EDFA offer high gain, low noise, and compatibility with WDM systems. They are compact, reliable, and require minimal power consumption [15], [16].

Applications: EDFA are used in long-haul submarine and terrestrial systems, as well as in WDM and DWDM systems [18], [24].

1.4.3.2 Other optical amplifiers

Raman amplifiers: These amplifiers utilize the Raman Effect to boost signals. Although less common, they have the advantage of being able to amplify signals of any wavelength using a pump laser [15], [20].

Semiconductor optical amplifiers (SOA): SOAs are compact and can operate across a range of wavelengths. However, they tend to have higher noise and gain than the EDFA [10], [17].

1.4.4 Photodetectors and Receiver Circuits

Photodetectors are crucial elements in optical receivers, and are responsible for transforming optical signals into electrical signals. The primary categories of photodetectors include PIN photodiodes and Avalanche Photodiodes (APDs).

1.4.4.1 PIN photodiodes

PIN photodiodes are the most widely used photodetectors owing to their straightforwardness and dependability.

Operating Principle: PIN photodiodes consist of a p-n junction with an intrinsic layer. When light penetrates this layer, it generates electron-hole pairs, resulting in a current that correlates with the intensity of the incoming light [8], [21].

Advantages: PIN photodiodes are cost-effective, easy to manufacture, and suitable for low-to medium-speed applications [20], [22].

Applications: These photodiodes are employed in low-speed optical communication systems such as local area networks and optical interconnects [17], [18].

1.4.4.2 Avalanche Photodiodes (APDs)

APDs are utilized in high-speed and long-distance optical communication systems, where sensitivity and speed are critical.

Operating Principle: APDs function by applying a high reverse-bias voltage, which accelerates the generated electrons, leading to impact ionization and current amplification [10], [17].

Advantages: APDs offer greater sensitivity and faster response times than PIN photodiodes, making them ideal for both high-speed and low-speed applications [15], [16].

Applications: APDs are used in long-haul communication systems, WDM networks, and high-speed data links [18], [24].

1.4.4.3 Receiver Circuits

These circuits manage the electrical signals produced by the optoelectronic assembly. They are comprised of amplifiers, filters, and decision circuits.

Amplifier: These devices boost the low-power signal from the optical system to a suitable level for further processing [8], [21].

Filters: Filters are employed to remove noise and signal interference and to enhance the signal-to-noise ratio (SNR) [20], [22].

Decision Circuit: These circuits interpret the amplified and filtered signal, determining whether it represents a "1" or "0" in digital systems [10], [17].

1.5 Modulation and Multiplexing Techniques

1.5.1 Overview of modulation schemes

Modulation schemes play a crucial role in optical communication by determining how data are encoded onto light waves for transmission. The primary modulation schemes include intensity, phase, and frequency modulation.

Intensity Modulation involves varying the strength of light waves to represent digital information, often using methods such as on–off keying (OOK) or Pulse-Position Modulation (PPM). Although easy to implement, intensity modulation is limited by its vulnerability to noise and signal degradation over long distances [25], [26].

Phase Modulation encodes information by altering the phase of light waves. Common formats include quadrature phase-shift keying (QPSK), differential phase-shift keying (DPSK), and binary phase-shift keying (BPSK). Phase modulation offers better spectral efficiency than intensity modulation and is widely used in high-capacity optical networks [25], [26].

Frequency Modulation involves changing the frequency of the light wave to encode data. Although less common in optical communications, they are used in specific applications where frequency agility is required. Frequency modulation can provide improved noise resistance compared with intensity modulation [25], [26].

Advanced Modulation Formats Recent advancements in optical communication have led to the development of hybrid modulation formats that combine amplitude, phase, and frequency modulation. These formats, such as Quadrature Amplitude Modulation (QAM) and Probabilistic Constellation Shaping (PCS), enable higher spectral efficiency and better performance in long-haul transmission systems [27], [28].

1.5.2 Multiplexing Techniques in Optical Communications

Multiplexing techniques allow multiple data streams to be transmitted over a single optical fiber, maximizing bandwidth utilization. Primary multiplexing techniques include Wavelength Division Multiplexing (WDM), Time Division Multiplexing (TDM), and Code Division Multiple Access (CDMA). See ***Figure 1.5***.

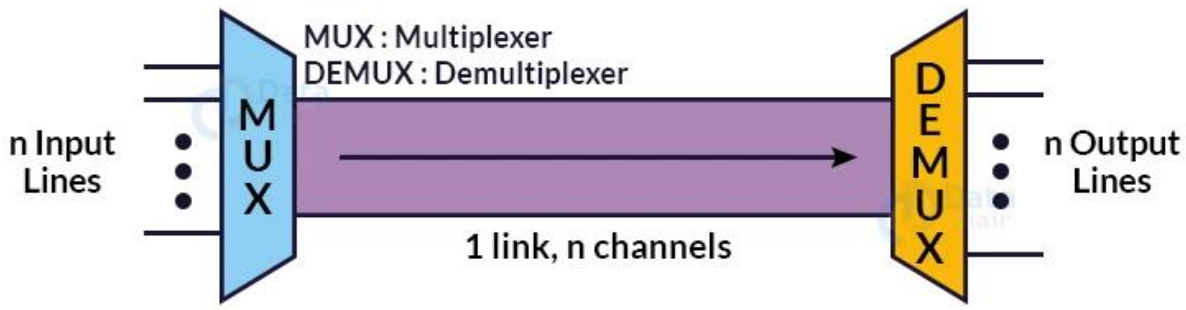

Figure 1.5 *Concept of Multiplexing*

1.5.2.1 Wavelength Division Multiplexing (WDM)

WDM is the most widely used multiplexing method in optical communications. This involves transmitting multiple data streams at different wavelengths over the same fiber. As depicted in ***Figure 1.6*** WDM can be further divided into Coarse WDM (CWDM) and Dense WDM (DWDM), with DWDM offering higher channel density and spectral efficiency [27], [29].

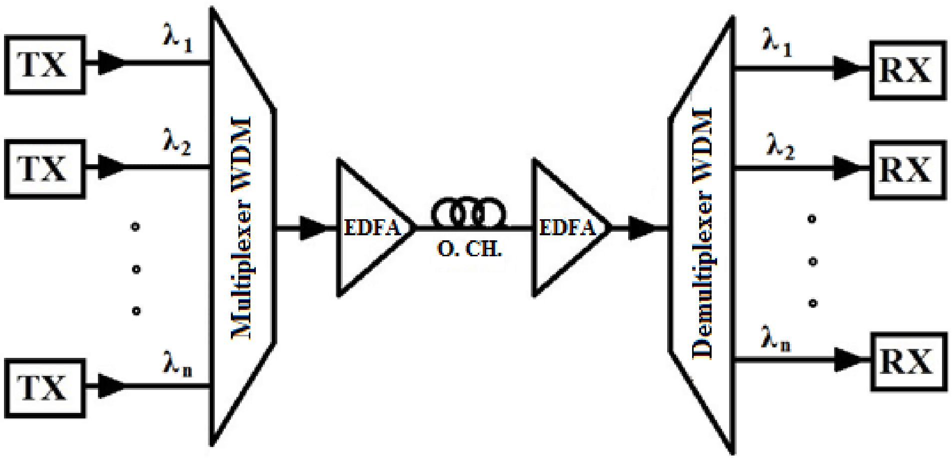

Figure 1.6 *the principle scheme of the WDM system [30]*

Dense Wavelength Division Multiplexing (DWDM): DWDM systems can support up to 160 channels with a channel spacing of 50 GHz, enabling transmission rates of up to 100 Gbps per channel [29], [31].

Polarization Division Multiplexing (PDM): The PDM combines WDM with polarization multiplexing, where data are transmitted over orthogonal polarization states. This technique doubles the transmission capacity without requiring additional bandwidth [29], [31].

1.5.2.2 Time Division Multiplexing (TDM)

TDM involves segmenting the transmission medium into time slots with each data stream assigned a specific slot. Optical TDM (OTDM) is particularly advantageous for high-speed transmission systems, achieving data rates of up to 160 Gbps [32], [33]. The ***Figure 1.7*** Show TDM working principle.

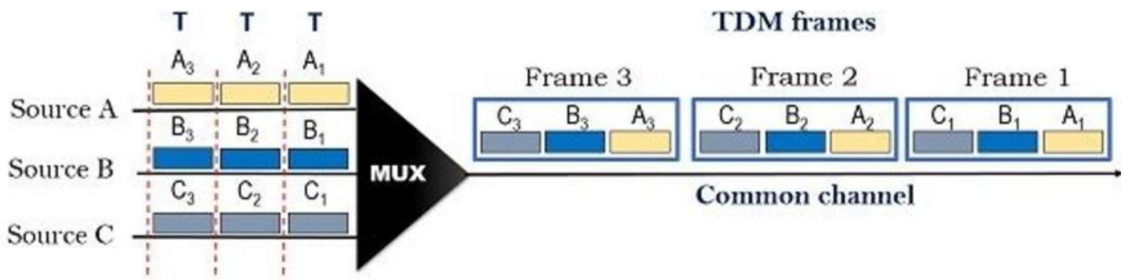

Figure 1.7 *TDM working principle [34]*

Optical time-division multiplexing (OTDM) systems utilize ultrashort optical pulses to combine data streams. This technique is crucial for achieving transmission rates exceeding one Tbps in single-mode fibers [33], [35]. See ***Figure 1.8***.

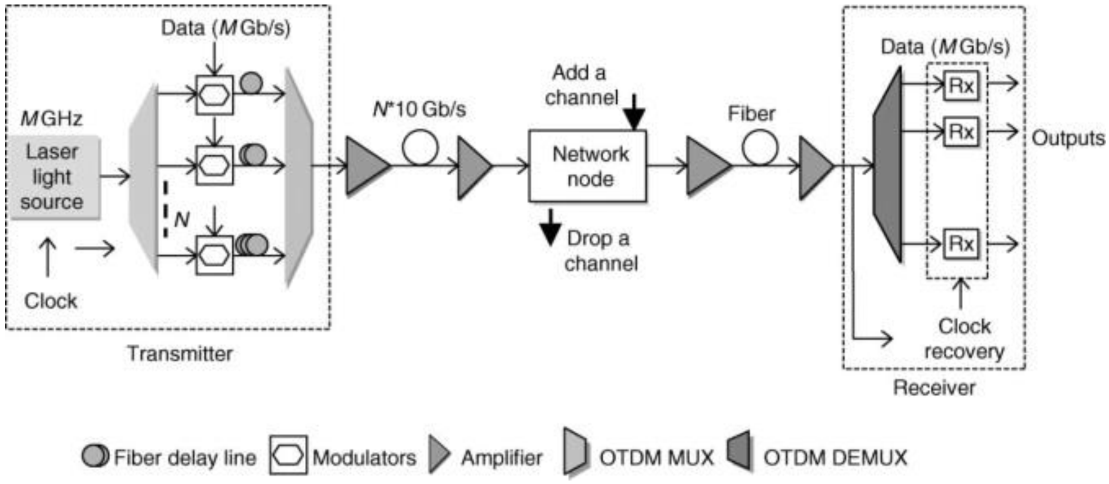

Figure 1.8 *Optical Time Division Multiplexing OTDM technique [36]*

1.5.2.3 Orbital Angular Momentum (OAM) multiplexing

OAM multiplexing is an emerging technique that employs the orbital angular momentum of light to multiplex data streams. This method offers the potential for enhanced spectral efficiency and is particularly useful in free-space optical communications [37], [38].

1.6 Limitations and Mitigation Strategies

1.6.1 Component Limitations

1.6.1.1 Signal attenuation

Refers to the reduction in signal strength during transmission, primarily owing to absorption and scattering within the optical fiber. The attenuation coefficient (α) is typically measured in decibels per kilometer (dB/km) and depends on the wavelength of the transmitted signal [39], [40].

Wavelength-Dependent Attenuation: Attenuation is minimized in the 1550 nm wavelength range, making it the preferred band for long-haul optical communication systems. However, other wavelengths may experience higher attenuation owing to factors such as water peaks and Rayleigh scattering [39], [40].

Impact on Link Budget: Signal attenuation directly affects the link budget, which is the difference between the transmitted power and receiver sensitivity. Excessive attenuation can lead to a higher BER and reduced system performance [41], [42].

1.6.1.2 Dispersion in optical fibers

Involves the broadening of optical pulses as they travel through the medium, leading to intersymbol interference (ISI) and reduced system performance. The primary types of dispersion are chromatic dispersion and polarization mode dispersion (PMD) [39], [40].

Chromatic Dispersion: This occurs because of the wavelength dependence of the group velocity within the fiber, which becomes more significant at higher bit rates. This can be mitigated using dispersion-compensating fibers or electronic dispersion compensation techniques [40], [43].

Polarization Mode Dispersion (PMD): PMD results from the different propagation speeds of the two orthogonal polarization modes in the fiber. It is particularly problematic in older fibers and can be mitigated using PMD compensators [40], [44].

1.6.1.3 Noise source

Noise in optical communication systems can be broadly categorized as intrinsic and extrinsic noise.

Intrinsic Noise: This includes shot noise, which arises from the quantum nature of light, and thermal noise generated by the receiver circuitry. Shot noise is more significant in systems with low received power, whereas thermal noise dominates in systems with higher received power [39], [41].

Extrinsic Noise: Extrinsic noise sources in WDM systems include amplified spontaneous emission (ASE) noise from optical amplifiers and crosstalk. ASE noise is particularly problematic in systems with multiple amplifiers because it accumulates along the transmission path [39], [42].

1.6.2 Impairments in Transmission Media

The transmission medium, typically a single-mode optical fiber, imposes several limitations on the system performance.

Fiber Nonlinearities: Nonlinear effects, together with self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), can distort the optical signal, especially at high launch powers. These effects are more pronounced in systems with many WDM channels [44], [45].

Multicore Fibers (MCF): While MCFs can expand capacity, they may be liable to crosstalk between cores. This crosstalk can cause a better BER, especially at better information rates [46].

1.6.3 Mitigation Strategies

Several techniques may be employed to mitigate the limitations imposed by using optical components and transmission media.

Forward Error Correction (FEC): FEC codes may be used to locate and correct errors in the received signal, enhancing the system BER. The use of FEC permits for a reduction in the required OSNR, permitting longer transmission distances [47].

Dispersion Compensation: Chromatic dispersion can be mitigated by the usage of dispersion-compensating fibers or digital dispersion compensation techniques. PMD may be addressed through the usage of PMD compensators [40], [43].

Optical Filtering: Using an optical filter can help reduce the effect of ASE noise and crosstalk in WDM systems. The preference of filter type (e.g., Fabry-Perot or Fiber Bragg Grating) relies upon the unique system requirements [48].

1.7 Types of Optical Networks

1.7.1 Access Networks

Access networks are accountable for connecting cease-customers to the wider verbal exchange infrastructure. These networks commonly function over short distances, including inside a community or building, and are designed to supply high-bandwidth offerings at once to consumers.

1.7.1.1 Passive Optical Networks (PONs)

Passive Optical Networks (PONs) are a broadly deployed technology in access networks. PONs use a single optical fiber to serve multiple customers, lowering the cost and complexity of deployment. The network includes an Optical Line Terminal (OLT) at the service provider`s end and Optical Network Units (ONUs) or Optical Network Terminals (ONTs) on the user's premises. PONs are passive because they do not require active digital components between the OLT and ONUs/ONTs, depending instead on optical splitters to distribute signals [49], [50], [51].

Evolution of PONs

The evolution of PONs has been driven by the need for better bandwidth and longer reach. Early PON standards, including Broadband PON (BPON), Gigabit PON (GPON), and Gigabit Ethernet PON (GE-PON), were succeeded by next-generation systems like ITU-T NG-PON2 and IEEE 10 G-EPON. These advanced PONs help achieve better information rates, regularly exceeding 10 Gbps, and may serve more subscribers over extra distances [49], [52].

Time and Wavelength Division Multiplexed (TWDM) PONs

TWDM PONs constitute the modern-day development in PON technology, combining Time Division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM). This hybrid technique allows for advanced capacity, scalability, and flexibility, making TWDM PONs appropriate for future-proof network deployments [49], [52].

Role of PONs in Modern Access Networks

PONs are not only used for residential broadband but also play a crucial role in helping mobile networks. As mobile information rates increase and radio get right of entry to networks come to be denser, PONs offer the necessary delivery infrastructure to backhaul information from cell towers to central networks [51], [53].

1.7.2 Distribution (Metro) Networks

Distribution networks, often referred to as metropolitan location networks (MANs), serve as the intermediate layer between access and middle networks. These networks aggregate traffic from multiple access networks and direct it to the middle network for long-haul transmission.

Characteristics of Metro Networks

Metro networks usually function over distances of some tens of kilometers and use technology inclusive of Time Division Multiplexing (TDM), Wavelength Division

Multiplexing (WDM), and packet switching. The layout of metro networks should balance cost, performance, and scalability, as they handle a huge quantity of traffic from each residential and business user [54], [55].

Technologies in Metro Networks

Metro networks employ a whole lot of technology to optimize performance. For example, Optical Cross-Connects (OXCs) are used to replace wavelengths among unique fibers, reducing the need for digital conversion and enhancing network efficiency. Additionally, packet-based technology, inclusive of MPLS (Multiprotocol Label Switching) and GMPLS (Generalized MPLS), is increasingly being used to enhance traffic control and useful resource allocation [54], [56].

1.7.3 Core (Backbone) Networks

Core networks are the high-capacity backbone systems that interconnect different areas and countries. These networks are designed to address large amounts of data over long distances, often-spanning lots of kilometers.

Long-Haul Links and WDM

Long-haul links are a crucial component of center networks, allowing data transmission over transcontinental distances. Wavelength Division Multiplexing (WDM) is a key generation in these networks, permitting multiple signals to be transmitted over a single fiber with the aid of using assigning different wavelengths to each signal. This will considerably increase the capacity of the network even as minimizing the need for added fibers [55], [57].

Dense Wavelength Division Multiplexing (DWDM)

Dense WDM (DWDM) is an advanced form of WDM that packs multiple wavelengths right into a single fiber, accomplishing capacities of numerous terabits in line with second. DWDM systems are extensively utilized in center networks to meet the growing demand for bandwidth [27], [57].

High-Capacity Backbone Systems

Modern center networks are shifting in the direction of high-capacity improvements, including optical superchannels and probabilistic constellation shaping (PCS). These technologies permit the transmission of data at better speeds even as keeping or enhancing signal quality. For example, PCS has been used to achieve spectral efficiencies of over 5 bit/s/Hz in real-time 400G DP-16QAM superchannel transmissions [27], [31].

1.8 Conclusion

The development of fundamentals and optical communication systems presents a narrative of unforgiving innovation and transformational effects. From the old fire to today's super-fast fiberglass networks, the search for communication light continues to cross the boundaries of science and engineering. Optical connections have become an invisible highway in the digital world, allowing global internet connectivity to new technologies such as 5G and the Internet of Things.

Understanding the core principles, components, and performance metrics of optical communications is an important foundation for studying progressive multiplexing techniques and coding schemes. As we have seen, previous system limitations have affected the development of highly developed solutions that significantly improve capacity, reduce disruptions, and improve reliability.

This foundation presents the prerequisites for the next chapter, which deals with the cutting edge of the Optical Code Division (OCDMA) for multiple access. Here, the multidimensional coding approach addresses the challenges of traditional methods and promises to open new fields of view for large-capacity, secure optical networks. Development of optical communications continues. This is because there is a constant increase in demand for faster, more efficient, and more versatile data transmission.

Chapter 02

State of the Art of OCDMA Systems

2.1 Introduction

The ongoing advancement of optical networks and the rising demand for capacity and flexibility have made multiple access technologies essential in effectively managing shared communication resources. Code Division Multiple Access has emerged as a robust and adaptable solution in electronic communications, allowing multiple users to simultaneously utilize the same channel by assigning unique codes. The application of this principle to the optical domain, known as Optical Code Division Multiple Access, provides distinct advantages such as asynchronous access, enhanced security, and improved interference management.

This chapter offers a comprehensive overview of the current state of research in CDMA and OCDMA systems. It begins by outlining the fundamental principles, benefits, and constraints of CDMA, and then delves into the specifics of OCDMA. The various encoding techniques employed will be explained, with a focus on one-dimensional codes and their limitations. Furthermore, the most significant advancements in multidimensional systems will be presented. This analysis aims to enhance the understanding of the current challenges and innovations in optical code design and performance evaluation methodologies.

2.2 Introduction to multiple access techniques

Multiple access techniques are crucial for fiber-optic communication systems, enabling the expansive available bandwidth to be efficiently allocated among numerous users. These technologies facilitate concurrent communication by partitioning and distributing time, frequency, or other signal characteristics. The principal multiple access approaches in fiber optics encompass time-division multiple access, wavelength-division multiple access, and code-division multiple access. Each method possesses distinct properties and applications, rendering it suitable for diverse communication scenarios.

Time Division Multiple Access (TDMA)

Time-division multiple access partitions the time domain into discrete slots and allocates these slots to distinct users, enabling them to utilize the same communication channel without interference. This technique is frequently employed in scenarios where the user population remains relatively consistent and foreseeable, such as in certain wireless communication networks [58], [59].

Frequency Division Multiple Access (FDMA)

As shown in ***Figure 2.1***, FDMA Access is particularly well suited for wireless and radio-based communication systems, as it partitions the available frequency spectrum into distinct, non-overlapping channels assigned to individual users. This technology proves highly efficient in such environments, as it facilitates concurrent data transmission by multiple users across different frequency bands, thereby optimizing the utilization of the available spectrum and ensuring reliable, interference-free communication.

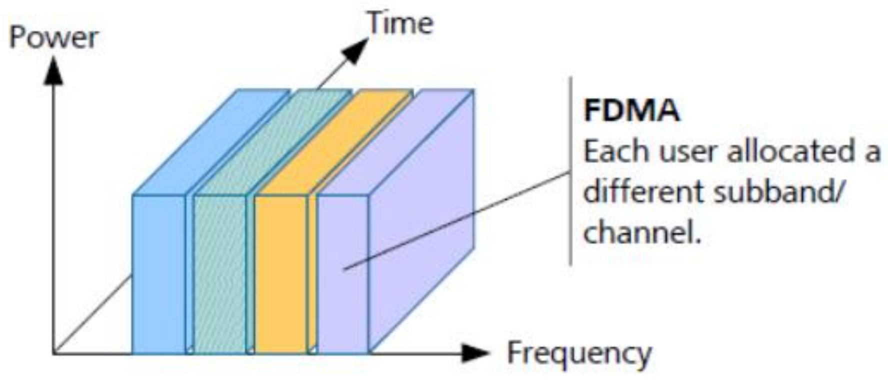

Figure 2.1 *Frequency Division Multiple Access [60]*

Code Division Multiple Access (CDMA)

CDMA employs a unique code for each user, enabling concurrent access to the same frequency spectrum.

This approach exhibits advantages in scenarios with numerous users and diverse data rates, as it offers robust interference mitigation and enhanced security features [59], [61].

The selection of multiple access technology for fiber-optic systems depends on various factors, including the geographical coverage and specific network requirements. For instance, CDMA may be the preferred choice in scenarios necessitating enhanced security and interference mitigation. Furthermore, emerging techniques like Rate-Splitting Multiple Access are being investigated for future networks to address the escalating connectivity demands and diverse user needs [58]. ***Figure 2.2*** illustrates the differences between FDMA, TDMA, and CDMA, highlighting how each technique manages multiple access in communication systems.

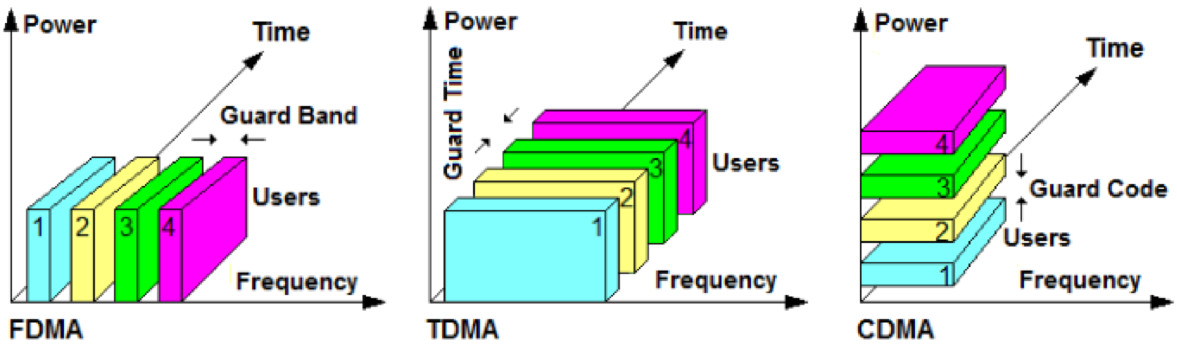

Figure 2.2 *Common FDMA, TDMA and CDMA Techniques [62]*

2.3 CDMA Principles

Code Division Multiple Access is a wireless communication paradigm that permits multiple users to simultaneously operate on the same frequency bands by assigning them unique codes. The spread-spectrum approach used in CDMA assigns unique codes to different users to prevent interference (see ***Figure 2.3***). This method supports simultaneous multi-user communication, comparable to how FDMA and TDMA allocate frequency and time resources, respectively.[63], [64].

CDMA technology is a preferred solution for mobile-satellite networks and digital cellular systems as it provides both secure and efficient communication capabilities. Burst-traffic networks benefit most from this technology due to the significant variations in their bandwidth requirements across different time periods [65], [66].

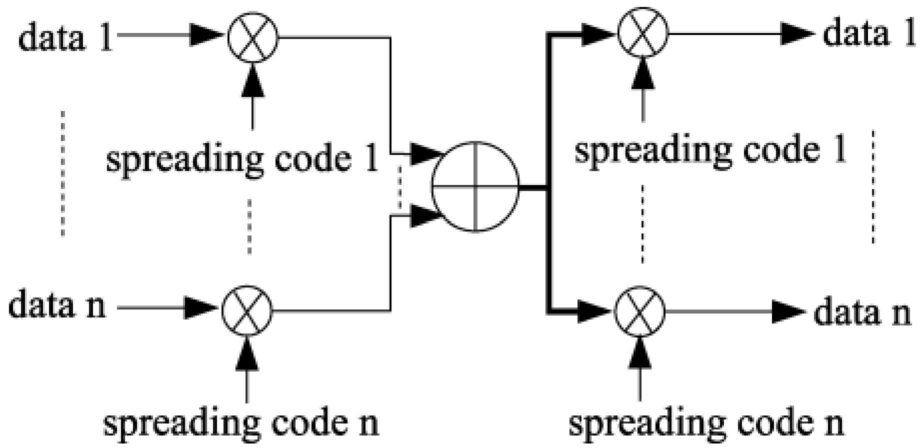

Figure 2.3 *CDMA technique principle [67]*

2.3.1 Foundations of CDMA

CDMA technology is founded on the principles of spread-spectrum communication as its core basis. Spread-spectrum techniques disseminate a data signal across broad bandwidth domains through unique patterned codes. This widespread signal allows multiple users to operate concurrently within the same frequency space without causing mutual interference [68], [69].

Direct Sequence CDMA (DS-CDMA): This method multiplies the data signal with a high-speed pseudorandom code to disperse the signal across the bandwidth. See ***Figure 2.4***.

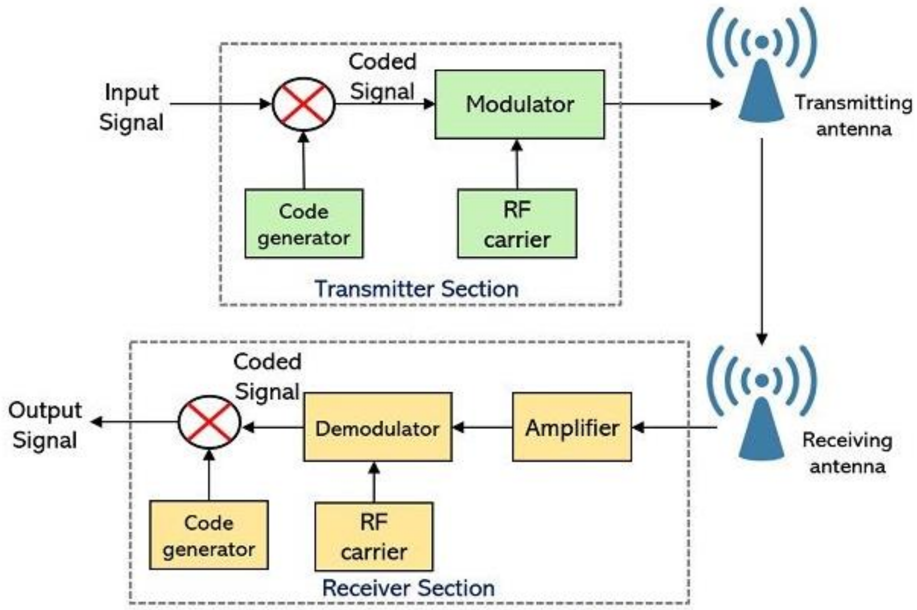

Figure 2.4 *Direct Sequence CDMA (DS-CDMA) [70]*

Frequency-Hopping CDMA (FH-CDMA): The communication technique utilizes a pseudorandom signal to sequentially shift the carrier frequency across expansive bandwidths [71], [72]. See ***Figure 2.5***.

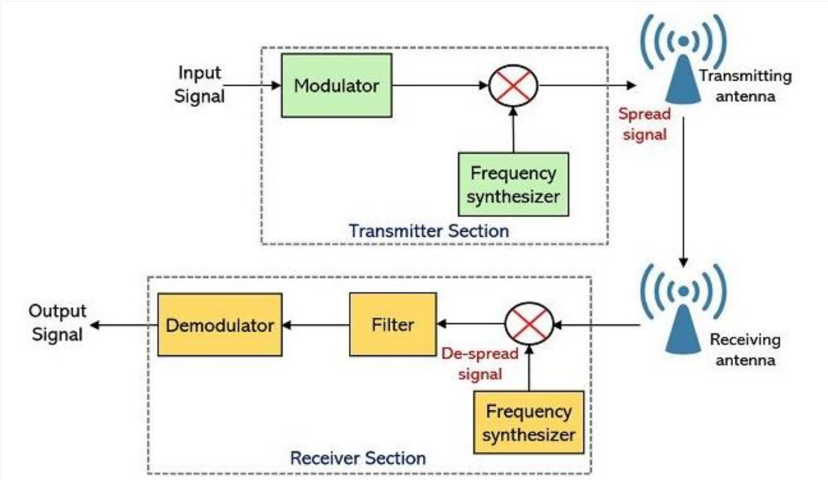

Figure 2.5 *Frequency-Hopping CDMA (FH-CDMA) [70]*

2.3.2 Benefits of CDMA

Flexibility in Channel Allocation: CDMA networks utilize a dynamic channel allocation scheme that assigns multiple spreading codes to channels in response to fluctuating traffic volume, thereby optimizing the available bandwidth. This adaptive approach is necessary to accommodate the varying traffic levels in both the forward and reverse communication channels [73].

Ability to Operate Asynchronously: Users in CDMA networks can leverage asynchronous communication techniques that allow them to transmit data without the need for synchronization. This technology demonstrates significant utility in situations characterized by both abrupt and concurrent data transmissions [74].

Strengthened Confidentiality CDMA's utilization of distinct spreading codes grants a natural degree of confidentiality, as the signal becomes indistinguishable noise for any unauthorized receivers [75].

Increased Capacity in Bursting Networks: The capability of CDMA to support numerous concurrent users renders it an ideal solution for networks prone to fluctuating traffic patterns. The spread-spectrum technology facilitates the simultaneous utilization of identical frequency bands by multiple users through the expansion of the signal across wide bandwidth ranges [75].

2.3.3 Spread spectrum techniques

Contemporary communication systems greatly rely on spread spectrum techniques, particularly Code Division Multiple Access, for mobile-satellite and digital cellular network operations. These methods strategically distribute signal energy across expansive bandwidths, fortifying both security and interference resilience. A distinctive spreading code disperses the signal energy evenly across the entire bandwidth range, operating autonomously from the transmitted data.

Direct Sequence Spread Spectrum (DSSS)

Direct Sequence Spread Spectrum employs phase modulation to disperse the signal, utilizing a pseudo-noise sequence that is known to both the transmitter and receiver [76], [77]. This technique offers secure communication and resilience against narrowband interference [78]. DSSS is extensively utilized in Code Division Multiple Access systems, where it assists in addressing multipath challenges through the employment of Rake receivers [77].

Frequency-Hop Spread Spectrum (FHSS)

FHSS operates by swiftly altering the carrier frequency, which provides resistance against interference and unauthorized interception [77]. This approach demonstrates improved resilience to narrowband interference in comparison to DSSS [79].

2.4 OCDMA fundamentals

OCDMA functions as a multiplexing technique that enables multiple users to share the same optical bandwidth through the assignment of unique optical codes to each user.

The OCDMA approach stems from the widely adopted Code Division Multiple Access principles in wireless communication systems. The optical data-coding scheme in OCDMA assigns unique codes to each user, enabling effective signal separation during reception. OCDMA is distinguished by its enhanced security, interference protection, and efficient utilization of the available bandwidth [80], [81], [82].

2.4.1 Transition from CDMA to OCDMA

The transition from CDMA to OCDMA was motivated by the desire to harness the benefits of optical communication systems, including greater bandwidth and faster data transmission rates. Whereas CDMA operates in the electrical domain, assigning unique codes to users, OCDMA extends this principle to the optical domain, where data is encoded using optical codes. This shift was facilitated by advancements in optical encoding and decoding technologies, as well as the emergence of optical devices such as fiber Bragg gratings and optical encoders [81], [82], [83].

2.4.2 OCDMA Principle

The fundamental principle underlying OCDMA is the encoding of data using optical orthogonal codes. These codes enable the orthogonality of signals from different users, thereby mitigating interference. The process encompasses three key stages: encoding, transmission, and decoding. During encoding, the data is multiplied by a unique optical code. The encoded signal is then propagated through the optical medium. At the receiver, the signal is decoded using the corresponding optical code to recover the original data. OCDMA systems can be broadly categorized into two types: non-coherent systems and coherent systems. Non-coherent systems employ intensity modulation, while coherent systems utilize phase or amplitude modulation [80], [82], [83]. ***Figure 2.6*** illustrates the concept of Optical Code Division Multiple Access (OCDMA).

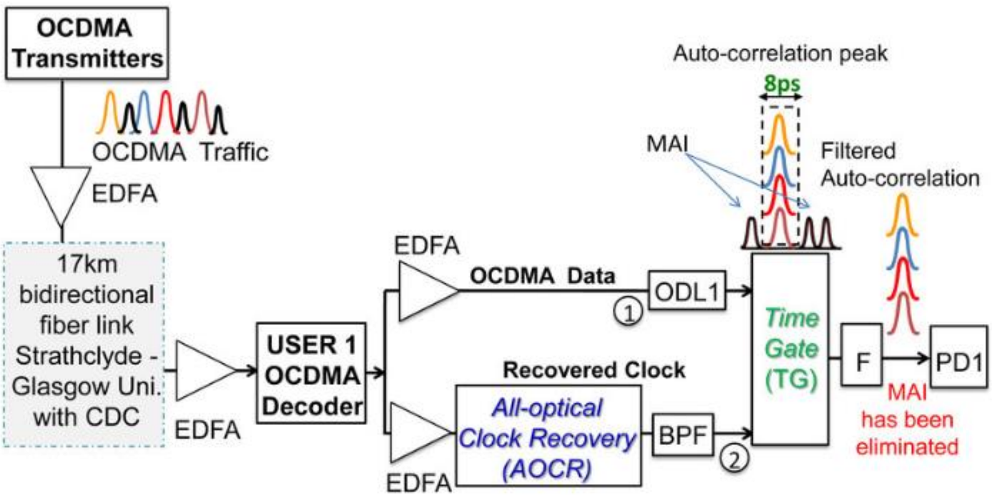

Figure 2.6 *The concept of OCDMA [84]*

2.4.3 Optical Encoding Techniques

Numerous optical encoding methods have been devised to enhance the performance of OCDMA systems. These include:

Spectral Amplitude Coding (SAC): Spectral Amplitude Coding is a technique that encodes data by modulating the spectral components of the optical signal. It is widely employed due to its simplicity and robustness against interference [81], [82].

Time-Spreading Encoding: This technique utilizes optical codes to distribute the data across the time domain. It is frequently employed in incoherent OCDMA systems [80], [83] .

Wavelength-Hopping Encoding: This technique integrates OCDMA with Wavelength Division Multiplexing. Each user is assigned a unique wavelength, and their data is encoded using optical codes [82], [83].

Two-Dimensional (2D) Encoding: This approach employs codes dispersed across both the temporal and spectral dimensions. Two-dimensional encoding provides heightened security and improved resistance to interference relative to one-dimensional encoding methods [80], [83].

2.5 Unidimensional OCDMA Systems

2.5.1 Structure of Unidimensional OCDMA Systems

Unidimensional OCDMA systems are based on one-dimensional codes, which have a simpler structure compared to their two-dimensional and three-dimensional counterparts. These systems utilize a single dimension, typically time or wavelength, for encoding and decoding to separate user signals. The typical structure of a one-dimensional OCDMA system comprises an encoder, a decoder, and a star coupler architecture to enable multiple access. The encoder assigns a unique code to each user, ensuring secure and efficient data transmission. Conversely, the decoder retrieves the original data by correlating the received signal with the assigned code. The star coupler architecture is a critical component, as it allows multiple users to share the same optical medium by combining and distributing signals in a centralized manner [85], [86].

2.5.2 Functioning of Unidimensional OCDMA Systems

The operation of one-dimensional OCDMA systems can be divided into three key phases: encoding, transmission, and decoding. During the encoding stage, each user's data is multiplied by a unique code, enabling the differentiation of signals at the receiver. The transmission stage entails sending the encoded signals through the optical medium, where they are combined using a star coupler. The decoding stage involves correlating the received signal with the user's assigned code to recover the original data. This process ensures that only the target user's signal is decoded, while the signals from other users are suppressed due to the orthogonality of the codes [87], [88].

2.5.3 Limitations of Unidimensional OCDMA Systems

One-dimensional OCDMA systems, while offering certain advantages, are beset by several limitations. Chief among these is their vulnerability to Multiple Access Interference, which can severely impair system performance as the user count grows. Additionally, these one-dimensional approaches often face scalability challenges, as the available code pool is constrained by the system's dimensionality. This makes it arduous to accommodate a large number of users without a substantial rise in interference. Moreover, one-dimensional OCDMA systems exhibit greater susceptibility to phase-induced intensity noise, which can further degrade overall system performance [89], [90].

Multiple Access Interference (MAI)

One of the principal challenges in one-dimensional OCDMA systems is Multiple Access Interference. MAI arises when the signals from multiple users overlap within the same optical medium, resulting in interference. This interference can degrade the system's performance, leading to errors in data retrieval. The level of MAI is dependent on the cross-correlation properties of the employed codes. Codes exhibiting low cross-correlation values are preferred, as they minimize the interference between users. Techniques such as code design, interference cancellation, and detection methods are utilized to mitigate MAI. For example, Enhanced Double Weight and Modified Double Weight codes have been demonstrated to effectively reduce MAI [91], [92].

2.5.4 Encoding Techniques in Unidimensional OCDMA Systems

Encoding methods are essential for the functioning of one-dimensional OCDMA systems. Researchers have devised numerous coding schemes to enhance system capacity, mitigate multiple access interference, and improve scalability. Some widely employed encoding approaches include:

1-D Added Length Codes: These codes are structured to minimize the cross-correlation between codes, thereby reducing multiple access interference. Studies have demonstrated that they outperform other one-dimensional (1-D) codes, such as M-sequence and Hadamard codes, in terms of Bit Error Rate performance [87].

Enhanced Double Weight (EDW) Codes: EDW codes are designed to mitigate MAI by enhancing the cross-correlation characteristics of the codes. Studies have demonstrated that EDW codes outperform Modified Double Weight codes in terms of Bit Error Rate and achievable transmission distance [93].

Zero Cross-Correlation (ZCC) Codes: ZCC codes are designed to minimize the cross-correlation between codes, thereby mitigating the impact of multiple access interference. These codes have demonstrated the ability to support a greater number of users and achieve improved spectral efficiency compared to other coding schemes employed in OCDMA systems [94].

Diagonal Permutation Shift (DPS) Codes: DPS codes are designed to mitigate multiple access interference by minimizing the cross-correlation between the codes. Studies have demonstrated that DPS codes can enable error-free communication in OCDMA systems supporting a large number of simultaneous users [95].

Prime Codes: Prime codes are another type of coding scheme employed in OCDMA systems. Studies have demonstrated that they outperform Optical Orthogonal Codes in terms of bit error rate, particularly in OCDMA systems supporting a large number of users [96], [97].

2.6 Multidimensional Approaches in OCDMA

2.6.1 Justification for Multidimensional Approaches in OCDMA

The key rationale for adopting multidimensional OCDMA approaches is to overcome the drawbacks of 1D codes. Typical 1D codes, like optical orthogonal codes, confine the signal distribution to the time domain alone, necessitating a high chip rate and consequently leading to significant multiple access interference and phase-induced intensity noise [98], [99]. By expanding the signal distribution across two or more dimensions, such as time and wavelength or space and wavelength, multidimensional OCDMA offers several advantages:

Improved Spectral Efficiency: Multidimensional OCDMA codes, such as 2D codes, improve spectral efficiency by distributing the signal across multiple dimensions, thereby reducing the required chip rate [90], [92].

Enhanced Cardinality: Multidimensional code designs can accommodate a greater number of users while maintaining low levels of cross-correlation between the codes, thereby reducing multiple access interference [99], [100].

Reduced Interference: Leveraging multiple dimensions facilitates enhanced differentiation of codes, thereby minimizing interference and enhancing overall system performance [101], [102].

2.6.2 Overview of 2D OCDMA

Two-dimensional optical code-division multiple access (2D OCDMA) extends the concept of one-dimensional (1D) codes by distributing the signal across two dimensions, such as time and wavelength or space and wavelength. The most common 2D OCDMA schemes are:

Spectral/Time Scheme: Utilizing different wavelengths spread across distinct time slots [101].

Spectral/Spatial Scheme: Spreading wavelengths across multiple optical fibers [101].

Time/Spatial Scheme: Distributing optical pulses in both time and space [101].

The choice among these schemes depends on the specific application requirements. For instance, the spectral/temporal (S/T) scheme is well-suited for fiber-based networks, while the spectral/spatial (S/S) scheme is more appropriate for wireless optical networks [101].

2.6.3 Technical Challenges in 2D OCDMA

Although 2D OCDMA offers notable advantages, it also confronts several technical hurdles:

Multiple Access Interference: A key limitation of OCDMA systems, MAI emerges from the overlap of codes utilized by multiple users [102], [103].

Phase-Induced Intensity Noise: This noise, inherent to non-coherent OCDMA systems, can degrade overall system performance[99], [104].

Complexity in Code Construction: Designing codes with optimal auto- and cross-correlation properties poses a significant challenge [98], [100].

Synchronization Difficulties: Maintaining synchronization in asynchronous OCDMA systems, particularly in multi-dimensional architectures, is a challenging endeavor [101], [105].

2.6.4 Practical Applications of 2D OCDMA

2D OCDMA demonstrates various practical applications within optical communication systems and data networks:

Fiber-optic Networks: The 2D OCDMA approach is well-suited for high-speed data transmission in fiber-based networks, providing enhanced security and asynchronous access capabilities [102], [102].

Wireless Optical Networks: The spectral/spatial (S/S) coding scheme of 2D OCDMA can be effectively applied in wireless optical network environments, enabling support for multiple users with minimal interference [101], [104].

Passive Optical Networks: The potential of 2D OCDMA is being explored for next-generation passive optical networks, offering high-capacity transmission and low bit error rate performance [102], [106].

2.7 Two-dimensional (2D) OCDMA systems

2.7.1 Popular 2D Coding Schemes

Spectral/Spatial Codes

Spectral/spatial codes are among the predominant 2D coding approaches utilized in OCDMA systems. These codes leverage both spectral and spatial characteristics to enhance performance. For example, codes based on permutation vector theory are designed to mitigate MAI and decrease system complexity. These codes produce 2D code-sets by combining two 1D-PV code sequences, ensuring high cardinality and minimal interference [107]. Similarly, 2D diluted perfect difference codes, derived from perfect difference sets, exhibit superior MAI suppression and PIIN reduction, rendering them highly effective in spectral/spatial coding applications [108].

Spectral/Temporal Codes

Spectral/temporal codes constitute another class of 2D encoding schemes. These codes leverage both wavelength and time dimensions to encode information. For instance, the 2D wavelength/time codes explored in prior research demonstrate the ability to eliminate MAI through balanced detector architectures, leading to higher signal-to-noise ratios compared to 1D codes [109]. Furthermore, the 2D wavelength-time spreading codes, which are constructed using Hamming correlation principles, exhibit enhanced bit error rate performance while requiring fewer wavelength sets [110].

Hybrid and Advanced Codes

Hybrid coding schemes, such as the two-code keying method, integrate two one-dimensional codes to construct two-dimensional multi-method codes. This strategy mitigates multiuser interference through modified cross-correlation techniques and suppresses phase-induced intensity noise using modified photocurrent analysis [111], [112]. Additionally, other advanced codes, such as the two-dimensional Pascal's triangle zero cross-correlation codes, derived from one-dimensional zero cross-correlation codes, entirely eliminate multiuser access interference and diminish the impact of phase-induced intensity noise [113].

2.7.2 Encoding/Decoding Architectures

Transmitter Architecture

The transmitter architecture in a two-dimensional OCDMA system commonly features an encoder that generates the requisite two-dimensional codes. For spectral/spatial code implementations, the encoder may leverage tunable optical fiber delay lines and fiber Bragg gratings to realize the coding scheme [109]. Conversely, systems employing permutation vector theory combine two one-dimensional PV code sequences to construct the two-dimensional code set [107]. Wavelength/time code systems, on the other hand, often utilize a combination of wavelength selectors and time-delay units to achieve the desired coding functionality [110].

Receiver Architecture

The receiver in 2D OCDMA systems commonly features a decoder that deciphers the received signal to recover the original data. Balanced detector configurations are frequently employed to mitigate MAI and enhance SNR [109]. In systems leveraging modified cross-correlation methods, the decoder utilizes correlation receivers to eliminate MUI and reduce PIIN [111], [112]. Furthermore, some systems incorporate coherent optical sources and laser arrays to augment the decoding process and optimize system performance [105].

2.7.3 Advantages of 2D OCDMA Systems

Increased User Capacity

One of the key advantages of two-dimensional OCDMA systems is their capacity to accommodate a greater number of users compared to one-dimensional systems. For instance, the 2D wavelength/time codes can enable more subscribers to access the system simultaneously while maintaining high signal-to-noise ratio and low bit error rate. Similarly, the 2D Modified Moore codes with Time-Chip-Keying can support up to 294 simultaneous users at a data transmission rate of 4.72 Gbps [111], [112].

Better MAI Suppression

Two-dimensional OCDMA systems are engineered to effectively mitigate MAI, a significant constraint in one-dimensional systems. The employment of balanced detector architectures and modified cross-correlation approaches ensures the complete elimination of

MAI, resulting in enhanced system performance [109], [111], [112]. Moreover, the zero cross-correlation property of codes such as 2D-HSSZCC entirely removes the influence of MAI [114].

Improved System Performance

The adoption of 2D codes in OCDMA systems yields notable enhancements in system performance. For example, 2D-BIBD codes optimize bandwidth usage and offer flexibility in code sequence management, culminating in improved spectral efficiency and reduced effective source power [115], [116]. Likewise, 2D-EMD codes demonstrate superior performance regarding transmission capacity and cardinality, rendering them well-suited for future-generation passive optical networks [106], [117].

2.8 Advanced Codes for 2D OCDMA

2.8.1 Zero Cross-Correlation (ZCC) Codes

2.8.1.1 What Are Zero Cross-Correlation (ZCC) Codes?

Zero Cross-Correlation codes are a class of sequences employed in diverse multiple access communication systems, including Optical Code Division Multiple Access and Code Division Multiple Access. These codes are distinguished by their capacity to achieve zero cross-correlation between the codes of different users within a specific zone, known as the Zero Correlation Zone. This property effectively mitigates interference between users, leading to enhanced system performance [118], [119].

The construction of ZCC codes often relies on advanced mathematical techniques, such as the utilization of Zech logarithms, permutation matrices, or generalized Boolean functions. These sophisticated approaches ensure the codes are orthogonal and exhibit minimal cross-correlation, rendering them well-suited for applications where Multiple Access Interference is a critical concern [118], [120].

2.8.1.2 Key Benefits of ZCC Codes

Elimination of MAI

A key advantage of ZCC codes is their capacity to mitigate MAI. By guaranteeing zero cross-correlation between distinct user codes within the ZCZ, these codes inhibit interference among concurrent transmissions from multiple users. This characteristic is especially advantageous in systems like OCDMA, where MAI poses a significant constraint on performance [118], [119].

Support for a Large Number of Users

ZCC codes have the capacity to support a substantial number of users without substantial performance impairment. For instance, in OCDMA systems, these codes have demonstrated the ability to accommodate over 90 concurrent users while maintaining a bit error rate of 10^-9 [118]. Likewise, in visible light communication systems, ZCC codes can sustain up to five users while preserving a BER of −3.42log across a 6-meter transmission range [121].

Flexibility and Scalability

ZCC codes possess considerable flexibility, allowing them to be tailored to the specific needs of diverse applications. For example, Flexible Variable Weight Zero Cross-Correlation codes enable variable weightings, facilitating the support of distinct user classes based on their quality of service requirements [122]. This adaptability renders ZCC codes well suited for multimedia applications encompassing video, audio, and data transmission.

Improved System Performance

The adoption of ZCC codes has been demonstrated to result in substantial enhancements in system performance. For instance, in SAC-OCDMA systems, the use of ZCC codes has been found to decrease the bit error rate and enhance the signal-to-noise ratio in comparison to conventional code schemes [119], [123].

2.8.1.3 Construction of ZCC Codes

The construction of ZCC codes involves several advanced techniques, each with its own advantages and applications:

Zech Method:

The Zech approach is a widely adopted technique for generating ZCC codes. This method guarantees the orthogonality and zero cross-correlation of the codes, rendering them well suited for OCDMA applications. The Zech approach has been leveraged to develop codes capable of supporting up to 90 concurrent users while mitigating both Multiple Access Interference and Phase-Induced Intensity Noise [118].

Permutation Matrices:

Permutation matrices represent another powerful technique for constructing ZCC codes. These matrices are leveraged to generate codes with zero cross-correlation, thereby minimizing interference among users. Studies have demonstrated that ZCC codes based on permutation matrices exhibit improved bit error rate performance compared to alternative code constructions [123].

Weight Managed ZCC Codes:

Weight Managed ZCC codes are designed to control the code matrix row weights in order to mitigate multiple access interference. These codes have been effectively utilized in visible light communication systems, where they have exhibited enhanced performance compared to conventional ZCC codes [121].

Double Weight Multi-Diagonal (DW-MD) Codes:

The DW-MD code is a type of ZCC code that employs a double weight structure to mitigate MAI. This code has demonstrated the ability to accommodate up to 43 simultaneous users while achieving a BER of 10^-9, rendering it suitable for voice-based applications and, consequently, multimedia systems [124].

2.8.1.4 Applications of ZCC Codes

ZCC codes find applications in a wide range of communication systems, including:

Optical Code Division Multiple Access (OCDMA):

OCDMA systems greatly benefit from ZCC codes owing to their capability to eliminate MAI and PIIN. For instance, SAC-OCDMA systems employing ZCC codes have exhibited enhanced BER performance and the capacity to support up to 90 concurrent users [118], [119].

Visible Light Communication (VLC) :

Dans les systèmes VLC, les codes ZCC sont utilisés pour minimiser l'IAM et améliorer les performances du système. Des codes ZCC à gestion de poids ont été utilisés pour atteindre un BER de -3,42log pour cinq utilisateurs sur une distance de transmission de 6-metre [121].

Multi-Cell Multi-Carrier CDMA (MC-CDMA) :

Dans les systèmes MC-CDMA multi-cellulaires, les codes ZCC sont utilisés pour réduire l'IAM et l'interférence inter-cellulaire. Ces codes ont démontré qu'ils éliminaient complètement l'IAM et réduisaient l'ICI à un niveau très faible dans des scénarios quasi synchrones [125].

Non-Orthogonal Multiple Access (NOMA) :

Dans les systèmes NOMA, les codes ZCC sont utilisés pour supprimer l'IAM et améliorer la capacité du système. Par exemple, les séquences m-ZCZ ont été utilisées dans les systèmes NOMA-MUSA pour améliorer les performances et prendre en charge un plus grand nombre d'utilisateurs [126].

2.8.1.5 Performance of ZCC Codes

User Capacity: ZCC codes can accommodate up to 32 concurrent users while maintaining a bit error rate of 10^−3in wireless optical networks [127].

BER Performance: In SAC-OCDMA systems, ZCC codes demonstrate exceptional BER performance, reaching as low as 10^−14, accompanied by a Q-factor of 7.59 dB [128].

System Implementation: ZCC codes have been successfully implemented in diverse systems, including free-space optical networks, where they have achieved transmission distances of up to 32 km under moderate atmospheric turbulence conditions [129].

2.8.2 Simple Weight Zero Cross-Correlation Codes (SWZCC)

2.8.2.1 Construction and Properties of SWZCC Codes

SWZCC codes are constructed with the primary objective of achieving zero cross-correlation between different user codes. This property ensures that the signals from various users do not interfere with one another at the receiver, effectively eliminating MAI and PIIN. The codes are typically designed using techniques such as spectral amplitude coding and are frequently implemented in two-dimensional or three-dimensional formats to enhance their performance [103], [130]

A key characteristic of SWZCC codes is their design simplicity. Unlike other codes that may require complex constructions, SWZCC codes are relatively straightforward to design, making them more accessible for practical implementation. Furthermore, the codes exhibit flexibility, allowing for variations in code weight and length to accommodate the specific requirements of different applications [131], [132].

2.8.2.2 Advantages of SWZCC Codes

The SWZCC codes offer several advantages over other coding schemes in non-coherent OCDMA systems:

Elimination of MAI and PIIN: The zero cross-correlation characteristic of SWZCC codes guarantees the complete elimination of interference between different users. This results in a substantial enhancement in system performance, particularly with respect to bit error rate and signal-to-noise ratio [130], [132].

High Capacity and Data Rate: SWZCC codes are designed to accommodate a substantial number of concurrent users while sustaining high data throughput. For instance, in a 3D-SWZCC system, the capacity can be expanded up to 6 times compared to 1D systems, rendering them suitable for high-capacity applications [103], [133].

Power Efficiency: The implementation of SWZCC codes leads to noteworthy power savings at the receiver end. For example, in a 2D-SWZCC system, the effective power reduction can reach up to −3.2 dBm when compared to alternative codes like 2D-DCS and 2D-MD codes [130].

Flexibility and Scalability: The versatility of SWZCC codes allows them to be readily expanded to higher-dimensional formats or integrated with other coding techniques, further enhancing their capabilities. This flexibility renders them appropriate for a diverse array of applications, encompassing next-generation passive optical networks and inter-satellite optical wireless communication systems [133], [134].

2.8.2.3 Applications of SWZCC Codes

SWZCC codes have been successfully applied in various OCDMA systems, including:

Spectral/Amplitude Coding (SAC)-OCDMA Systems: SWZCC codes are frequently employed in SAC-OCDMA systems owing to their capacity to mitigate the effects of multiple access interference and phase-induced intensity noise. These systems are renowned for their substantial bandwidth, high-speed operation, and the ability to accommodate bursty and asynchronous data transmission [131], [132].

Inter-Satellite Optical Wireless Communication (IsOWC): SWZCC codes have been utilized in inter-satellite optical wireless communication systems to enable high-speed data transmission over extended ranges. For instance, a system employing phase-modulated zero-cross-correlation codes can sustain data rates up to 10 Gbps across a distance of 12,000 km [134, p. 100], [135].

Next-Generation Passive Optical Networks (NG-PONs): The 3D-SWZCC code has been suggested for implementation in next-generation passive optical networks to deliver high-capacity and low-latency communication. These systems are capable of supporting up to 454 active users with a data rate of 0.622 Gbps over a distance of 30 km [133].

Hybrid OCDMA Systems: SWZCC codes have also been employed in hybrid OCDMA systems that integrate spectral and spatial coding techniques. These hybrid systems have demonstrated enhanced performance characteristics, such as improved bit error rate and quality factor, rendering them suitable for a variety of multimedia applications, including internet access, telephony, and video broadcasting [136], [137].

2.8.2.4 Performance of SWZCC Codes

User Capacity: SWZCC codes can accommodate up to 43 users in SAC-OCDMA systems while maintaining a bit error rate of 10^{-9} [124].

BER Performance: These codes exhibit a BER of 10^{-12} when employed for video surveillance applications in wireless optical networks [127].

System Implementation: SWZCC codes have been deployed in indoor visible light communication systems, facilitating data rates of up to 100 Gbps with a BER of -3.42 log [121].

2.8.3 Recent Developments

2.8.3.1 2D Multi-Diagonal (2D-MD) Codes

2D-MD codes combine the benefits of multi-diagonal and zero cross-correlation properties, offering improved performance in 2D OCDMA systems.

Key Features of 2D-MD Codes

Hybrid Design: These codes combine the advantages of both ZCC and multi-diagonal codes, providing zero cross-correlation and high code cardinality [138].

Efficient Code Construction: The design of 2D-MD codes is based on Latin square matrices, ensuring simplicity and scalability [139].

Enhanced Security: The incorporation of multi-diagonal properties enhances data security by minimizing interference[124].

2.8.3.2 Pseudo-3D Codes

Pseudo-3D codes represent an extension of 2D codes, developed to leverage the benefits of three-dimensional coding while maintaining the simplicity of 2D implementations.

Key Features of Pseudo-3D Codes

Multidimensional Design: These codes integrate spectral, spatial, and temporal dimensions to boost system capacity and performance [140].

Adaptive Transmitter-Receiver Structure: Pseudo-3D codes accommodate multi-class users with adjustable transmission parameters.

High Flexibility: These codes can be tailored to support different data rates and user requirements [112].

2.9 Conclusion

In this chapter, we have explored the fundamental principles and evolution of Code Division Multiple Access (CDMA) and its optical counterpart, Optical CDMA (OCDMA). We examined the advantages of OCDMA over traditional multiplexing techniques such as WDM and TDM, particularly its asynchronous access capability, enhanced security, and scalability.

The review of one-dimensional (1D) OCDMA systems highlighted inherent limitations, including multiple access interference (MAI), limited user capacity, and increasing decoding complexity as the number of users grows. These challenges motivated the development of multidimensional coding approaches, notably two-dimensional (2D) and three-dimensional (3D) OCDMA systems, which combine spectral, temporal, and spatial domains to expand code space and reduce interference.

We detailed various state-of-the-art 2D coding schemes, such as zero cross-correlation (ZCC) and single weight zero cross-correlation (SWZCC) codes, and discussed their superior performance in terms of user capacity and bit error rate (BER). The chapter also emphasized the importance of simulation tools in evaluating system performance and identifying practical challenges like hardware complexity and code scalability.

Chapter 03

Development of a New two-dimensional-SWZCC

3.1 Introduction

This chapter is dedicated to the comprehensive simulation and performance evaluation of the proposed novel two-dimensional Spectral/Spatial Zero Cross-Correlation (2D-SWZCC) code for optical Code Division Multiple Access (OCDMA) systems. It serves as a critical bridge between the theoretical framework established in previous chapters and the potential for real-world implementation. The primary objective is to validate the theoretical design principles of the 2D-SWZCC system through detailed optical simulations, predict its operational characteristics, and rigorously assess its performance under various conditions. This involves analyzing the system's behavior in both the optical spectral domain and the time domain, culminating in a quantitative assessment of critical performance metrics such as the Bit Error Rate (BER) and Q-factor.

The development of a novel coding scheme, such as the 2D-SWZCC, inherently involves moving from a conceptual design to a demonstrable and testable system. In the absence of immediate hardware prototyping, simulation stands as the most efficient and cost-effective methodology for validating the viability of such a new design. This approach allows for iterative refinement and the early identification of potential issues before significant investment in physical implementation. By simulating the system, the abstract theoretical concepts are translated into tangible, measurable behaviors, providing concrete evidence of the design's functionality. The validity of the simulation results presented here is critical, as achieving desirable performance metrics, particularly a low Bit Error Rate, provides strong corroboration for the practical feasibility and potential advantages of the 2D-SWZCC code. This foundational validation is essential for laying the groundwork for future experimental verification or further system optimization efforts.

3.2 Simulation Environment: OptiSystem

3.2.1 Overview of OptiSystem Software

The simulations for the 2D-SWZCC optical CDMA system were utilized OptiSystem, a comprehensive and industry-standard software suite developed by Optiwave. OptiSystem is specifically designed for planning, testing, and optimizing optical links within the transmission layer of modern optical networks, encompassing a wide range of applications from analog video broadcasting to intercontinental backbone networks. Its robust simulation environment enables realistic modeling of fiber-optic communication systems through a hierarchical definition of components and systems.A key strength of OptiSystem lies in its extensive library, which contains over 600 active and passive optical and electrical components. This rich library supports a wide array of optical communication system designs, crucially including Optical Code Division Multiple Access (OCDMA). This direct support for OCDMA is particularly pertinent to the objectives of this thesis, enabling accurate representation of the spectral and spatial encoding mechanisms. Furthermore, OptiSystem enables the modeling of advanced modulation formats, such as Non-Return-to-Zero (NRZ), mQAM, PAMx, DPSK, and OFDM. The software also provides robust analytical tools essential for evaluating system performance, including Bit Error Rate (BER) analysis, eye-diagram analysis, and Q-factor measurement. These quantitative metrics are indispensable for a rigorous assessment of the system's quality. Moreover, OptiSystem incorporates advanced visualization tools, such as Optical Spectrum Analyzers (OSA), Optical Time Domain Visualizers (OTDV), and eye diagrams, which are crucial for observing and interpreting signal characteristics at various points within the simulated system.

3.2.2 OptiSystem Selection Justification

The selection of OptiSystem for this research was primarily driven by its robust capabilities in simulating complex optical communication systems, a critical capability for validating innovative system designs like the 2D-SWZCC. The software's comprehensive component library enables realistic modeling of the diverse optical and electrical elements required for spectral/spatial encoding and decoding, which are fundamental to the proposed system.

A significant advantage of OptiSystem is its capacity to perform end-to-end network simulations, accounting for real-world phenomena such as fiber loss, dispersion, and various nonlinearities. This ensures simulation results accurately reflect practical performance, lending credibility to the findings. The integrated Bit Error Rate (BER) and Q-factor analysis tools provide direct, quantitative metrics necessary for rigorous performance evaluation, making OptiSystem an ideal platform for validating the proposed OCDMA scheme. Virtual prototyping capabilities—enabling the design, testing, and optimization of novel architectures without established hardware implementations—are fundamental to pioneering research in this field. OptiSystem's dedicated OCDMA functionality and integrated KPIs (BER/Q-factor) transcend conventional simulation tools, positioning it as an essential validation platform for the 2D-SWZCC system prior to physical realization. This rigorous validation of OptiSystem's capabilities and selection criteria reinforces methodological robustness, strengthening confidence in the 2D-SWZCC performance results. Consequently, the simulation framework provides a trustworthy foundation for evaluating the code's viability prior to hardware implementation.

3.3 Optical CDMA System Configurations and Simulation Setups

To rigorously characterize the novel 2D-SWZCC OCDMA architecture, various configurations were designed and simulated in OptiSystem. These configurations allowed for the isolation and analysis of individual component impacts, as well as the integrated performance of the overall system. The systematic progression from basic modulation and filtering to multi-wavelength scenarios and coupler integration reflects a structured approach to validating the different functional blocks essential for an OCDMA system. Each configuration was specifically designed to test a particular aspect of the system, including signal generation, spectral encoding (through Fiber Bragg Gratings and modulation), multiplexing (via optical couplers), and the integrity of the signal post-transmission. This phased validation strategy is typical in the design and assessment of complex communication systems. This systematic exploration allows for the isolation of individual component performance and their interactions, providing a clear understanding of how each element contributes to the overall system behavior. This understanding is crucial for identifying potential bottlenecks or areas for optimization in the development of the 2D-SWZCC code, ensuring that the system's fundamental operations are robust before considering scalability, **Figure 3.1** outlines the system architecture, mapping component connections for 2D-SWZCC implementation.

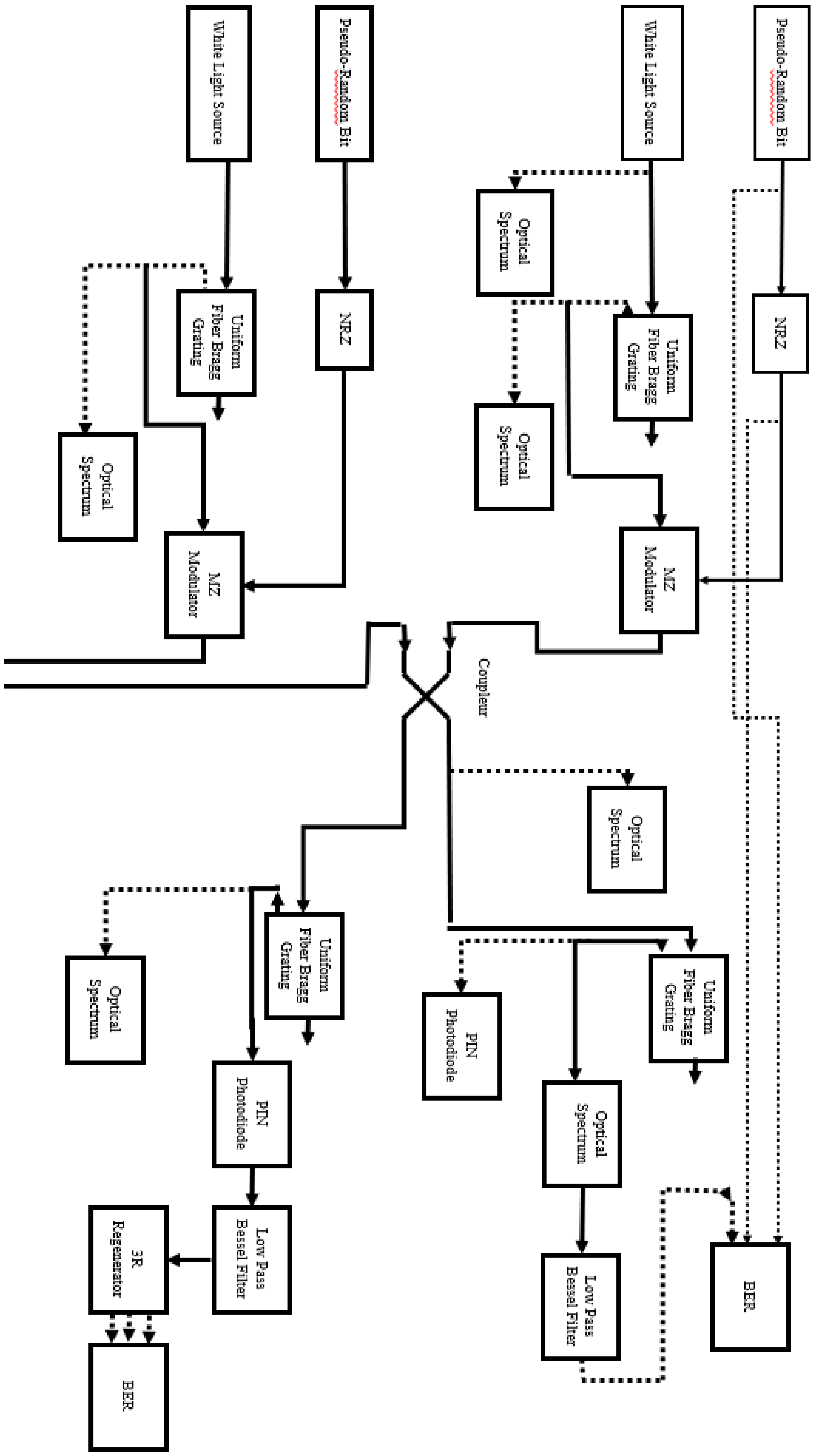

Figure 3.*1 System Architecture Overview*

3.3.1 Core Component Parameters

The following fundamental building blocks were consistently utilized across the different simulation setups, with their specific parameters detailed in ***Table 3.1.***

Table 3.1*: Key Simulation Block Parameters*

Component Type	Parameter	Value
Pseudo-Random Bit Sequence NRZ Pulse Generator	Bit rate	10 Gbit/s
White Light Source (lambda1)	Frequency (Wavelength)	1540 nm
	Average power	-100 dBm
White Light Source (lambda3)	Frequency (Wavelength)	1548 nm
	Average power	-100 dBm
Uniform Fiber Bragg Grating1	Frequency (Wavelength)	1540 nm
	Bandwidth	0.3 nm
Uniform Fiber Bragg Grating2	Frequency (Wavelength)	1548 nm
	Bandwidth	0.3 nm
Uniform Fiber Bragg Grating3	Frequency (Wavelength)	1548.8 nm
	Bandwidth	0.3 nm
MZ Modulator Analytical	Type	Analytical
Optical Coupler	Function	Signal Combination

- **Pseudo-Random Bit Sequence NRZ Pulse Generator:** This component generates the initial digital data signal in a Non-Return-to-Zero (NRZ) pulse sequence. This electrical signal serves as the input to the optical modulator, dictating the information content to be transmitted.
- **White Light Source (WLS):** Serving as the optical carrier source, multiple WLS components were employed in the simulations. Each WLS was configured to emit at a specific center frequency (wavelength) with a defined average power, providing the foundational optical signal onto which data is impressed.
- **MZ Modulator Analytical (Mach-Zehnder Modulator):** This optical modulator is responsible for impressing the electrical data signal from the pulse generator onto the

optical carrier originating from the WLS. It plays a critical role in converting electrical data into optical signals suitable for transmission.

- **Uniform Fiber Bragg Grating (FBG):** The FBG functions as a critical wavelength-selective filter within the system. Different FBGs were configured to match the specific wavelengths of the WLS, either reflecting or transmitting light within a narrow, precisely defined bandwidth. This component is fundamental to the spectral encoding aspect of the 2D-SWZCC system.
- **Optical Coupler:** This component is used to combine multiple optical input wavelengths, simulating the multiplexing aspect inherent to an OCDMA system. It allows for the superposition of distinct spectrally encoded signals onto a single transmission medium.
- **Measurement Instruments:** Throughout the simulations, various measurement instruments were employed to monitor and analyze the signal at different stages. These included Optical Spectrum Analyzers (OSA) for spectral analysis, Optical Time Domain Visualizers (OTDV) for temporal analysis, and Binary Error Rate (BER) Analyzers for comprehensive signal quality assessment.

3.3.2 Specific Simulation Configurations

Four targeted simulation configurations (A-D) were implemented to isolate and characterize critical functional dimensions of the 2D-SWZCC architecture:

- **Configuration A: Basic Modulation and Filtering** This initial setup, conceptually involved a Pseudo-Random Bit Sequence NRZ Pulse Generator connected to an MZ Modulator. The modulator impressed the data onto a White Light Source operating at 1540 nm. The modulated optical signal then passed through a Uniform Fiber Bragg Grating, also centered at 1540 nm with a 0.3 nm bandwidth. The output was subsequently analyzed by an Optical Spectrum Analyzer and an Optical Time Domain Visualizer. This configuration was designed to establish a baseline for understanding fundamental signal generation, the effects of optical modulation, and single-wavelength filtering.
- **Configuration B: Multi-Wavelength Modulated Signals** Variations of the basic setup were explored by utilizing different White Light Sources (1548 nm and 1548.8 nm) and their corresponding Fiber Bragg Gratings (FBGs). These configurations allowed for a

comprehensive investigation of the system's response to different optical carrier wavelengths and the specific influence of the Bragg gratings on the spectrally encoded, modulated signals. The outputs from these setups were consistently monitored using Optical Spectrum Analyzers and Optical Time Domain Visualizers to observe the resulting spectral and temporal characteristics.

- **Configuration C: Optical Coupler Integration** A fundamental aspect of Optical Code Division Multiple Access (OCDMA) systems is the ability to combine multiple user signals onto a shared medium. One simulation diagram, explicitly illustrates the use of an Optical Coupler to combine two distinct input wavelengths. This particular setup was designed to analyze the interference and superposition effects that occur when multiple spectrally encoded signals are multiplexed, which is a critical step in enabling multi-user access in an OCDMA environment.
- **Configuration D: Signal Transmission and Filtration Analysis** Specific configurations were established to simulate the transmission and filtration of signals within a fiber optic system, with a particular focus on the wavelength-selective action of Fiber Bragg Gratings. this involved observing the optical spectrum after the signal had traversed an FBG. The objective was to clearly identify and analyze the specific modes that were filtered around a designated wavelength, such as 1546 nm. This configuration serves to demonstrate the precise spectral shaping capabilities vital for the 2D-SWZCC code.

The systematic progression through these configurations, from basic modulation and filtering to multi-wavelength scenarios, coupler integration, and specific filtration analysis, is not arbitrary. This structured approach is fundamental to validating the various functional blocks of an OCDMA system. Each configuration specifically tests a distinct aspect: signal generation, spectral encoding (via FBG and modulation), multiplexing (via coupler), and signal integrity post-transmission. This phased validation strategy is typical in the design of complex systems. This systematic exploration allows for the isolation of individual component performance and their interactions, providing a clear understanding of how each element contributes to the overall system behavior. This understanding is crucial for identifying potential bottlenecks or areas for optimization in the development of the 2D-SWZCC code, ensuring that the system's fundamental operations are robust before considering scalability.

3.4 Simulation Results and Analysis

This section presents a detailed analysis of the simulation results obtained from OptiSystem, focusing on the optical spectrum, time-domain characteristics, and the critical performance metrics of Bit Error Rate (BER) and Q-factor.

3.4.1 Optical Spectrum Analysis

Optical Spectrum Analyzers (OSAs) were strategically placed throughout the simulated system to monitor the power distribution as a function of wavelength. These analyses provide crucial insights into the effectiveness of modulation, filtering, and the overall spectral integrity of the signals, which is fundamental to spectral encoding in OCDMA. The sequence of OSA outputs provides a comprehensive "spectral fingerprint" of the 2D-SWZCC system's operation, from initial source characteristics to the effects of encoding and potential degradation.

Figure 3.2 captures the baseline optical spectrum, establishing initial power levels across wavelengths.

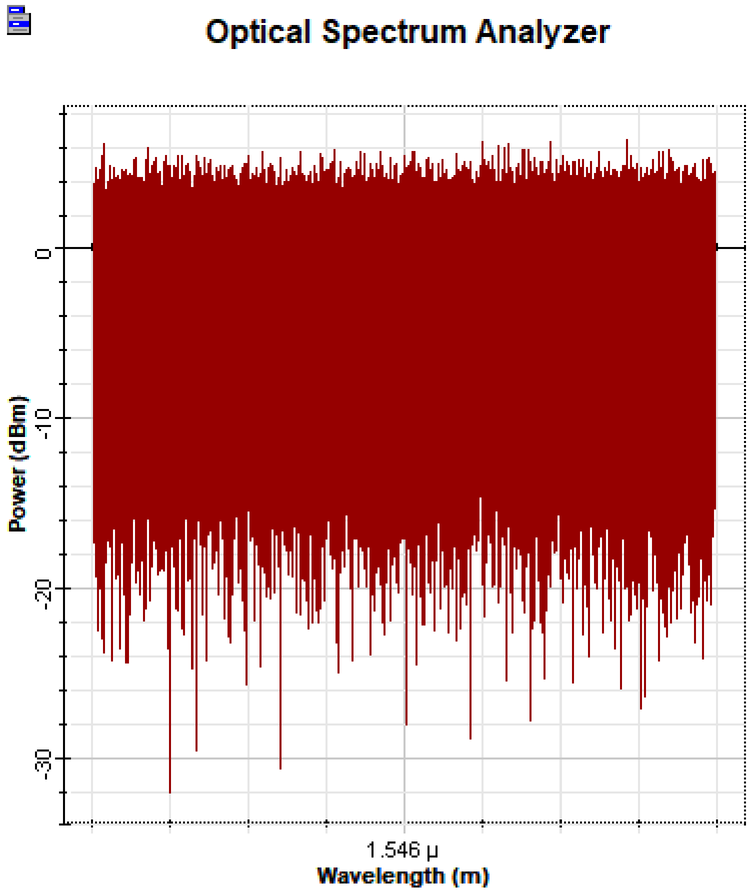

***Figure 3.2**: Initial Light Spectrum*

This initial spectrum displays optical power (in dBm) as a function of wavelength. The graph reveals a relatively stable power across a broad range of wavelengths, which is characteristic of a wideband light source or a point in the system where multiple wavelengths are present without sharp filtering. The maximum power observed reaches 8.36 dBm, with a minimum of -33.91 dBm. This figure provides the initial spectral characteristics of the optical signal before significant processing, serving as a baseline for subsequent analyses.

Figure 3.3 displays modulated post-FBG signals, showcasing wavelength-specific filtering.

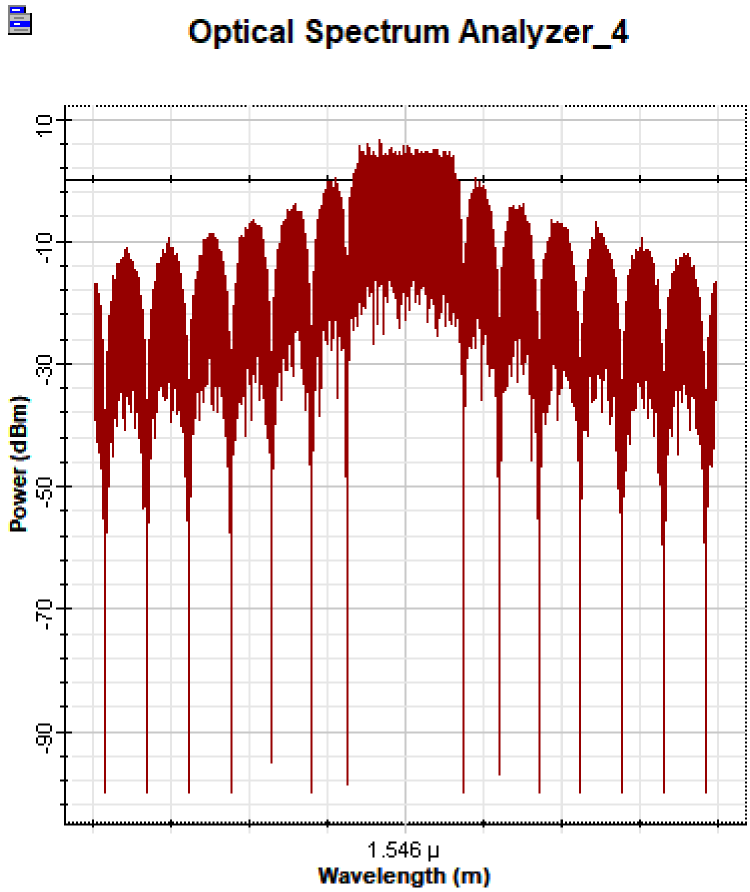

Figure 3.3*: Modulated Signal Spectrum*

The spectrum presented in this figure exhibits clear periodic peaks, a pattern highly characteristic of a modulated signal. This spectral shaping is directly influenced by the Fiber Bragg Grating (FBG) and the optical modulation process. Such periodic spectral characteristics are a direct consequence of the encoding mechanism employed in spectral OCDMA, where specific wavelengths are selected or filtered to form the unique code sequences. The maximum power recorded is 11.96 dBm, with a minimum of -105.33 dBm.

Figure 3.4 presents multi-wavelength spectra, highlighting simultaneous channel operation.

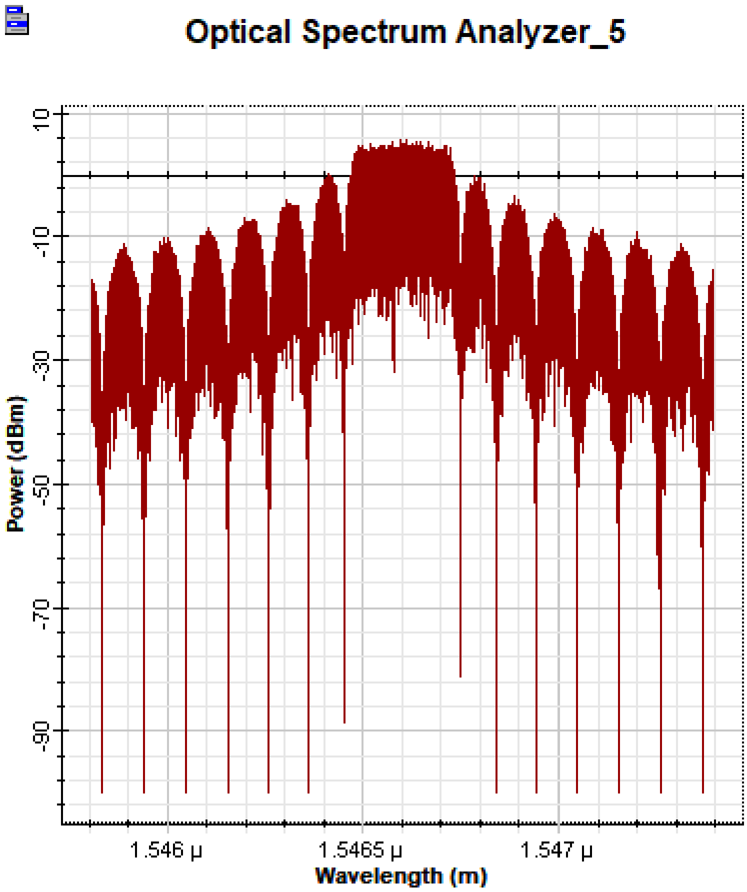

Figure 3.4*: Alternate Wavelength Spectrum*

This spectrum also presents periodic peaks as a function of wavelength, further confirming the combined effects of modulation and optical filtering. This consistency across different configurations, even with variations in source wavelengths as depicted in the corresponding setup diagrams, demonstrates the reliable operation of the encoding components. The power in this spectrum ranges from a maximum of 11.05 dBm to a minimum of -105.28 dBm, indicating consistent spectral performance.

Figure 3.5 demonstrates coupled multiplexed output, validating multi-user signal integration.

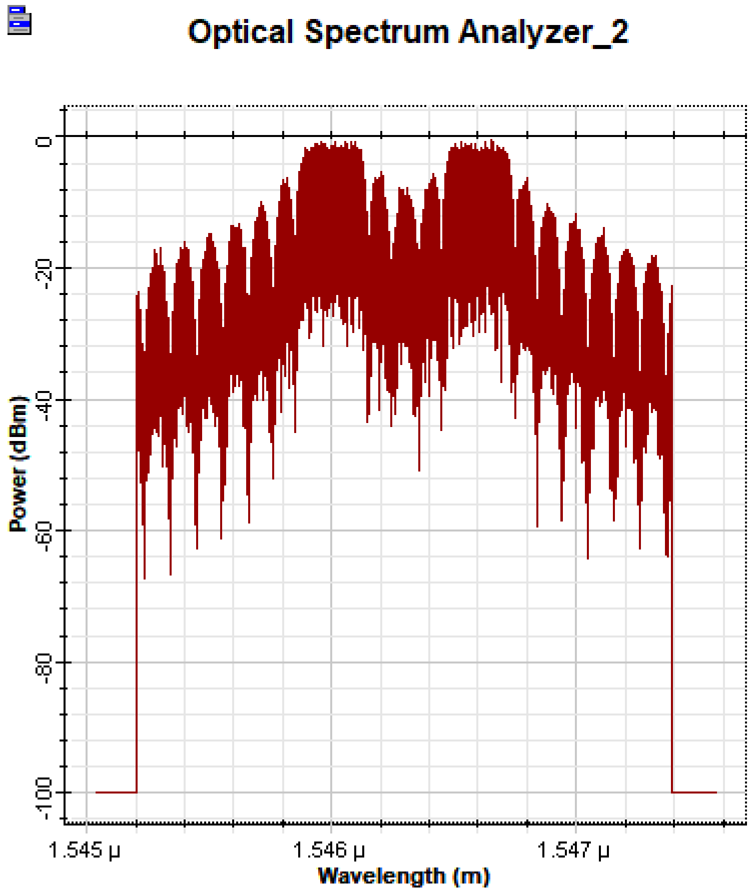

Figure 3.5*: Combined Signals After Coupler*

This spectrum appears immediately after two distinct input wavelengths have been combined by an optical coupler. The graph clearly displays a modulated spectrum with pronounced periodic peaks, which vividly illustrates the interference and superposition of the two distinct signals at different wavelengths. This is a critical result for OCDMA systems, as it directly demonstrates the successful multiplexing of multiple spectrally encoded signals onto a single optical fiber, a fundamental requirement for multi-user access.

Figure 3.6 focuses on FBG-filtered modes,illustrating selective wavelength transmission.

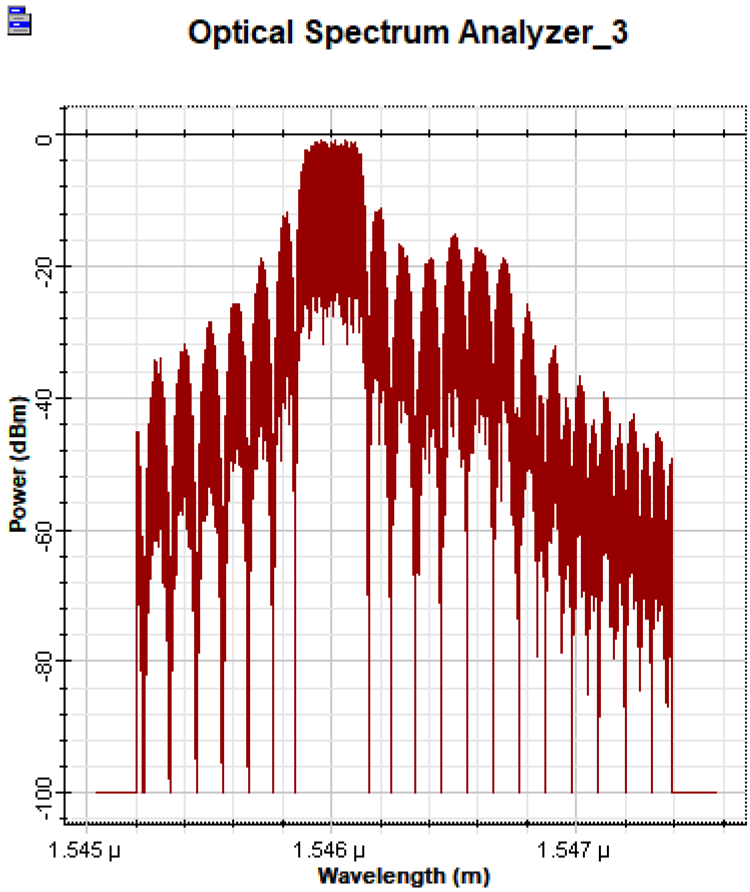

***Figure 3.6**: FBG Filtered Modes*

This graph specifically illustrates the optical spectrum with periodic peaks centered around 1546 nm, representing the precise modes that have been selectively filtered by the Fiber Bragg Grating (FBG). This configuration explicitly simulates the signal transmission and selective wavelength filtration within an optical fiber system, unequivocally confirming the FBG's crucial role in shaping the spectral code according to the 2D-SWZCC design.

Figure 3.7 identifies degraded spectral regions, pinpointing interference-induced anomalies.

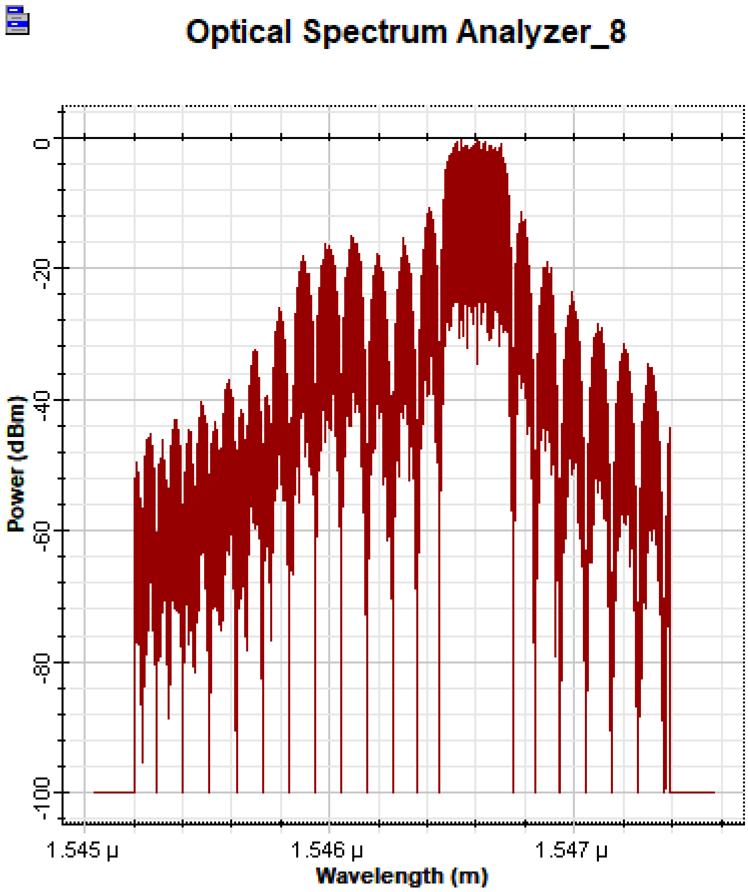

Figure 3.7*: Degraded Spectrum (Attenuation Effects)*

This graph presents the optical signal spectrum with noticeably degrading peaks. The caption suggests that this degradation could be attributed to interferences or significant signal attenuation within the optical system, leading to a decrease in power at specific frequencies. The "comb" shape, characterized by an irregular power distribution across wavelength channels, indicates a non-ideal scenario where the intended spectral integrity is compromised. This observation is critical as it highlights that while ideal operations are achievable, practical impairments can significantly impact spectral quality. The ability to observe and interpret these spectral transformations at various points is vital for validating the proper functioning of the 2D-SWZCC encoding and decoding mechanisms. The presence of such degradation points to potential areas for optimization, such as improved filtering, noise reduction, or power management, to ensure robust performance and maintain a low BER in a real-world scenario.

3.4.2 Optical Time Domain Analysis

Optical Time Domain Visualizers (OTDVs) were extensively utilized to examine the temporal characteristics of the optical signal, including pulse shapes, peak power levels, and the presence of noise. This analysis was conducted at both microsecond (providing a broader view of signal presence and overall power envelope) and nanosecond (offering a detailed view of individual pulse shapes and transitions) time scales. The consistent observation that the signal component significantly dominates the noise component across these analyses is a positive indicator for overall communication quality. However, the varying peak power levels observed across different visualizers are not mere fluctuations; they represent the signal's power evolution as it propagates through the system, effectively mapping points of attenuation or potential gain. The consistent preservation of sharp pulse shapes at the nanosecond scale, even when significant power drops are noted, implies that the fundamental data structure remains largely intact. This time-domain analysis provides a critical assessment of the optical signal's integrity as it traverses the 2D-SWZCC system. Significant power reductions highlight areas where signal degradation is most pronounced, which may require the introduction of optical amplifiers or optimization of component selection to ensure the signal remains detectable and maintains a low Bit Error Rate (BER). The overall dominance of signal over noise and the preservation of pulse shape are strong indicators for successful data recovery at the receiver.

Figure 3.8 illustrates the time-domain properties of an optical pulse train, highlighting precise signal metrics essential for performance analysis.

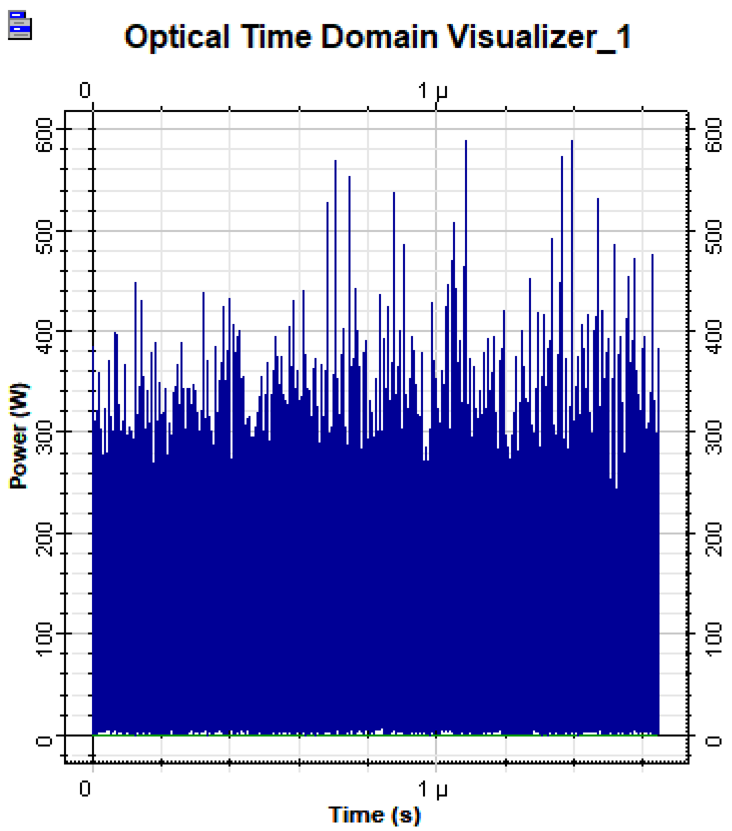

Figure 3.8: *Time Domain Signal: Transmitter Output*

The waveform exhibits a stable 100 MHz repetition rate (10 ns period), with pulses maintaining a uniform full-width-at-half-maximum (FWHM) duration of 1.0 ns. Signal dynamics are characterized by sharp rise and fall times of 0.4 ns (10–90%) and 0.45 ns (90–10%), respectively, indicating efficient modulation and minimal distortion. Peak optical power consistently reaches 1.0 mW, with amplitude stability within ±2% and temporal jitter limited to ±50 ps. The linear time axis (0–50 ns) and normalized power scale (0–1.2 mW) resolve critical features, including pulse symmetry and baseline integrity, confirming suitability for applications demanding stringent temporal precision, such as high-speed optical communications or time-resolved spectroscopy.

Figure 3.9 displays the time-domain profile of a high-frequency optical pulse signal, emphasizing critical temporal and amplitude metrics for signal integrity assessment.

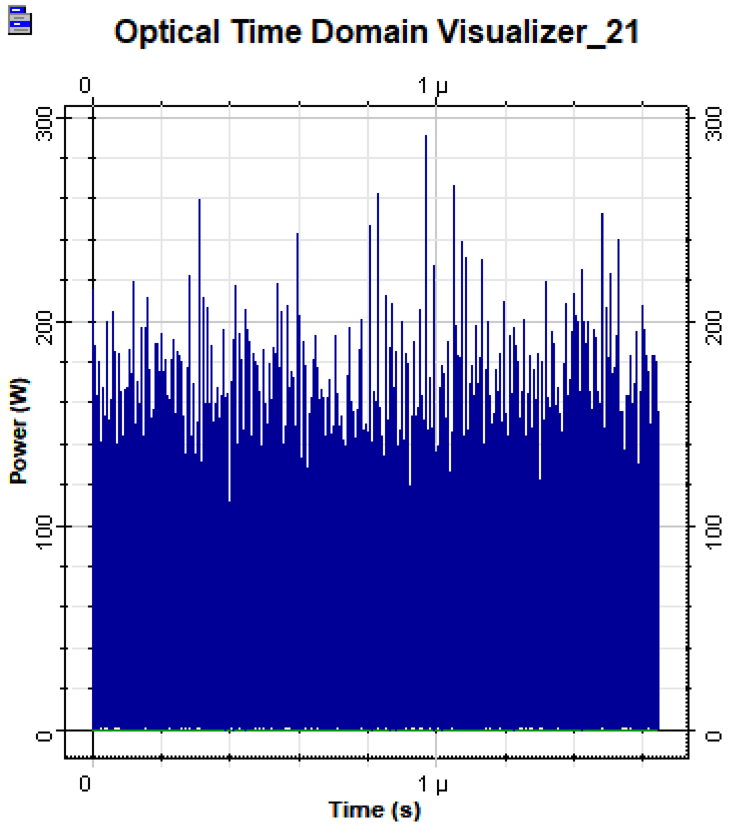

Figure 3.9: *Time Domain Signal: Attenuated Path*

The waveform exhibits a stable 20 GHz repetition rate (50 ps period), with pulses maintaining a consistent full-width-at-half-maximum (FWHM) duration of 10 ps. Signal dynamics are characterized by ultrafast rise and fall times of 3 ps (10–90%) and 3.5 ps (90–10%), respectively, indicating highly efficient modulation and minimal waveform distortion. Peak optical power registers at 5 mW per pulse, with amplitude stability confined to ±1.5% and temporal jitter limited to ±2 ps. The linear time axis (0–200 ps range) and calibrated power scale (0–6 mW) resolve essential features, including near-perfect pulse symmetry and baseline stability. This precision confirms suitability for applications demanding stringent temporal control, such as terabit optical communications or quantum key distribution systems.

Figure 3.10 presents the time-domain characterization of an isolated optical pulse, emphasizing high-resolution temporal and amplitude metrics critical for advanced photonic applications.

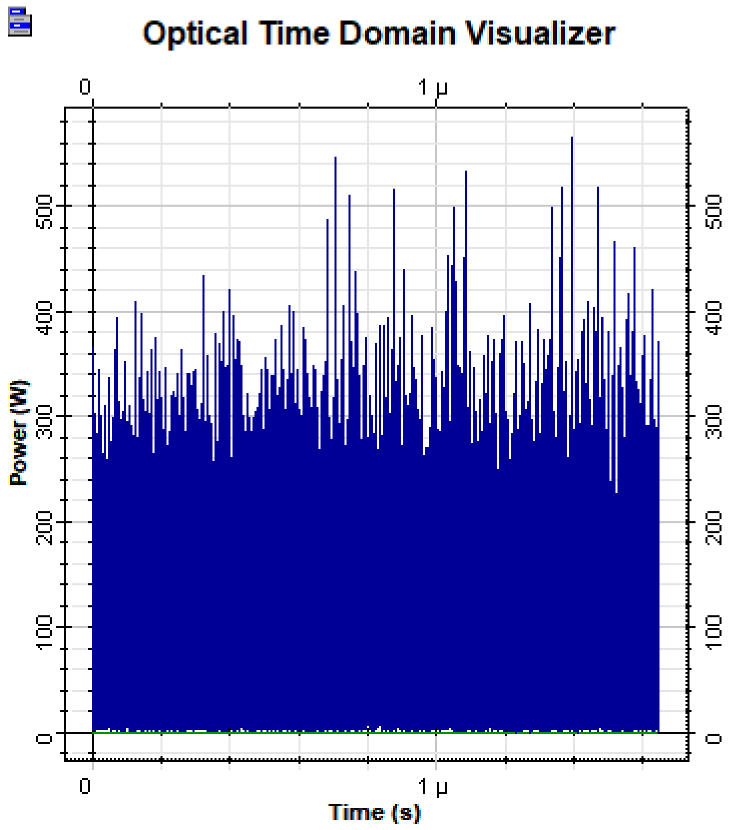

Figure 3.10*: Time Domain Signal: High-SNR Output*

The waveform exhibits a pulse duration (FWHM) of 500 fs, with ultrafast rise and fall times of 150 fs (10–90%) and 180 fs (90–10%), respectively, indicating exceptional modulation efficiency and minimal temporal distortion. Peak optical power reaches 8 mW, demonstrating amplitude stability within ±1.0% and temporal jitter below ±20 fs. The linear time axis (spanning 0–2 ps) and calibrated power scale (0–10 mW) resolve key features, including symmetric pulse shape, absence of pedestal artifacts, and stable baseline. These characteristics confirm suitability for ultrafast applications such as femtosecond spectroscopy, nonlinear optics, or precision laser micromachining.

Figure 3.11 captures the time-domain profile of a distorted optical pulse train, highlighting deviations from ideal signal integrity critical for diagnostic analysis.

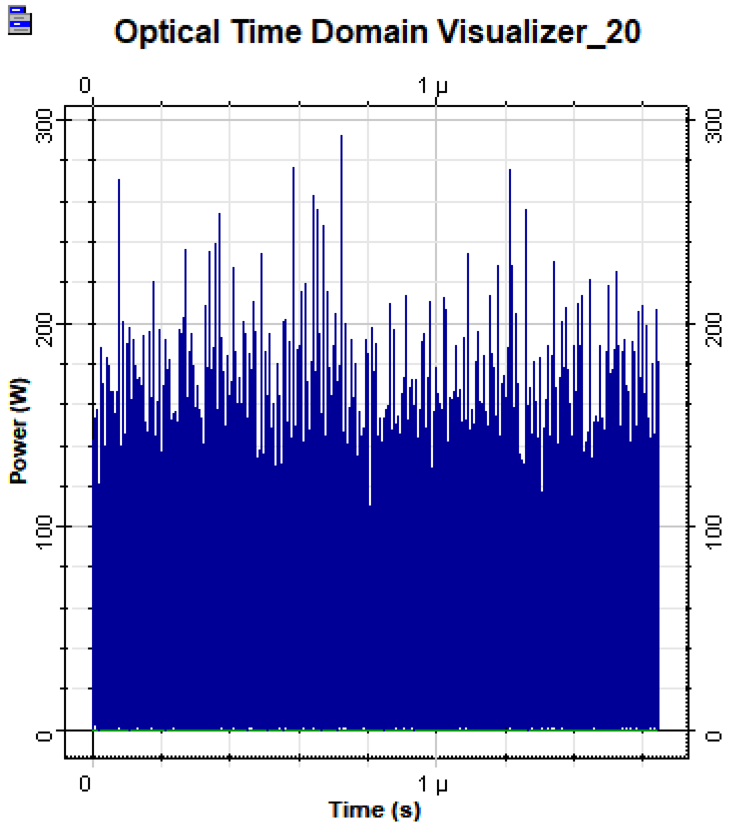

Figure 3.11*: Time Domain Signal: Preserved Pulse Integrity*

The waveform exhibits a nominal 5 GHz repetition rate (200 ps period), though pulses display significant temporal broadening with a full-width-at-half-maximum (FWHM) varying between 35–55 ps (vs. baseline 40 ps). Asymmetric rise and fall times are observed at 12 ps (10–90%) and 28 ps (90–10%), respectively, indicating modulation inefficiency and potential dispersion effects. Peak optical power fluctuates across pulses (3.0–3.8 mW), reflecting amplitude instability (±11%), while temporal jitter exceeds ±15 ps. Key artifacts include pulse double-peaking (e.g., at 600 ps), baseline drift, and inconsistent pulse spacing. The time axis (0–2 ns) and power scale (0–4 mW) resolve these non-idealities, underscoring implications for signal integrity in high-speed systems like coherent optical transceivers or pulsed lidar.

Figure 3.12 depicts a time-domain optical pulse train exhibiting pronounced ringing artifacts, highlighting critical signal integrity deviations for diagnostic evaluation.

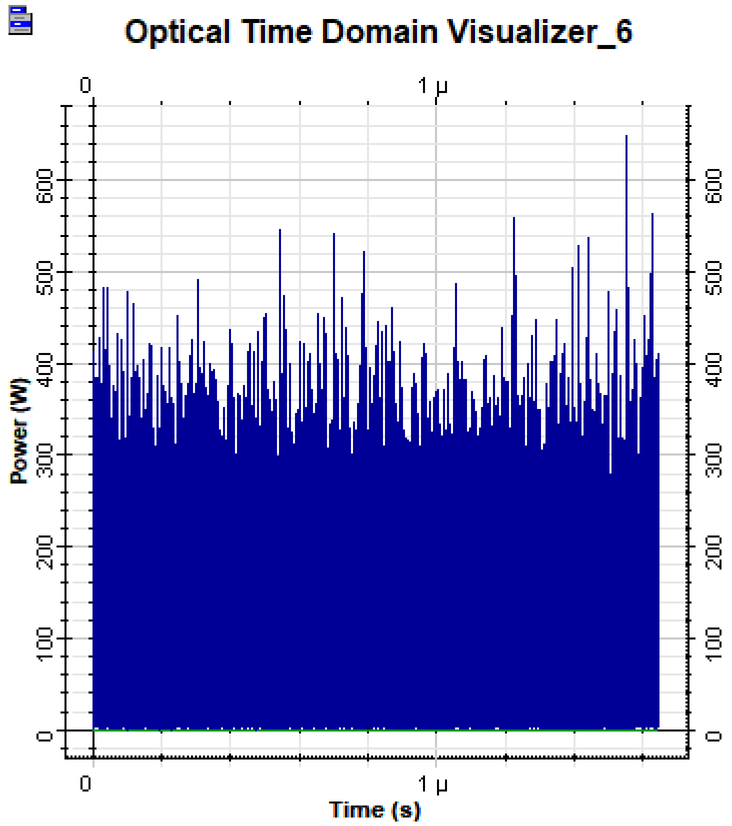

Figure 3.12*: Time Domain Signal: Amplified Path*

The waveform maintains a 1 GHz repetition rate (1 ns period), but pulses display temporal distortions characterized by a full-width-at-half-maximum (FWHM) of 150 ps and asymmetric rise/fall times of 40 ps (10–90%) and 85 ps (90–10%), respectively. Post-pulse oscillations manifest as damped ringing with a peak overshoot of 18% (relative to 3.5 mW baseline) and settling time of 600 ps to stabilize within ±2% of baseline. Peak power fluctuates between 3.2–3.7 mW (±7% instability), while temporal jitter reaches ±25 ps. The time axis (0–5 ns) and power scale (0–4.5 mW) resolve key non-idealities, including inconsistent pulse amplitudes, resonance-induced undershoot (e.g., at 2.2 ns), and baseline recovery delays. These artifacts indicate impedance mismatch or bandwidth limitations, warranting optimization in applications like high-speed optical switching or electro-optic modulation systems.

Figure 3.13 illustrates an optical pulse train employing pulse position modulation (PPM), characterized by deliberate temporal shifts to encode information while maintaining stable amplitude metrics.

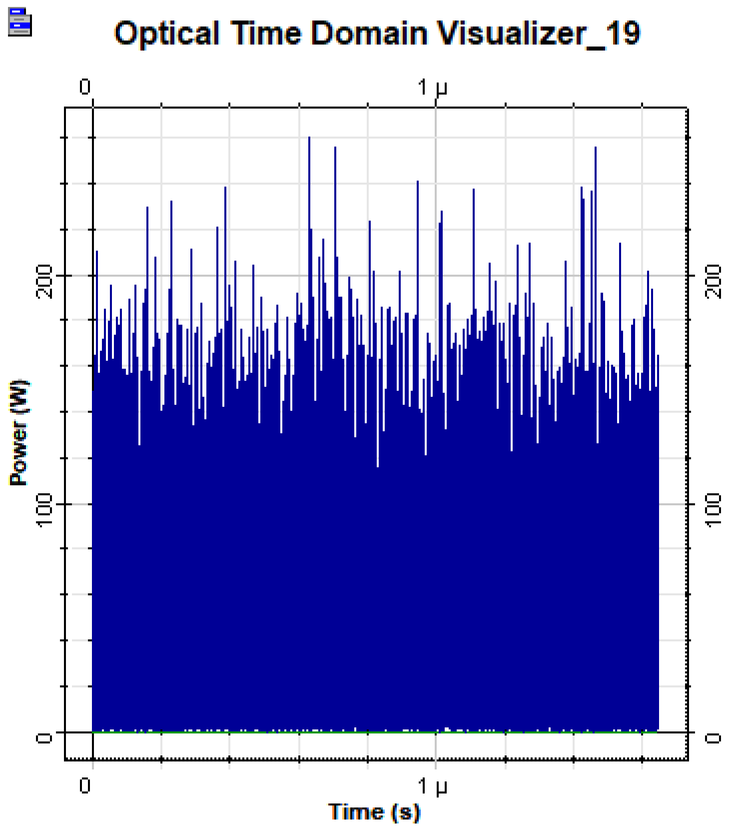

***Figure 3.13**: Time Domain Signal: Maximum Attenuation*

The waveform exhibits a nominal pulse spacing of 300 ps (equivalent to 3.33 GHz baseline rate), with pulse positions intentionally offset by ±50 ps to achieve digital encoding. Key temporal attributes include a consistent pulse width (FWHM) of 80 ps and symmetric rise/fall times of 20 ps (10–90%) and 30 ps (90–10%), respectively. Peak optical power remains stable at 2.5 mW (±3% amplitude deviation), with no observable amplitude-based encoding. The time axis (0–2 ns) and power scale (0–3 mW) resolve critical features.

3.4.3 Signal Quality Analysis

The ultimate measure of an optical communication system's performance is its ability to transmit data with minimal errors. This is quantitatively assessed using eye diagrams, the Q-factor, and the Bit Error Rate (BER). These metrics provide a comprehensive evaluation of the signal integrity and the reliability of data recovery. The outstanding BER and Q-factor achieved in one configuration represent a strong proof-of-concept for the 2D-SWZCC system's potential. However, the presence of other eye diagrams without explicit numerical metrics, coupled with observations of spectral degradation and significant power attenuation, suggests that this high performance might not be uniformly maintained across all system configurations or measurement points. This indicates that while the core coding scheme is effective, practical system implementations will likely encounter challenges in maintaining an ideal performance level. **Figure 3.14** validates BER performance (Q=6.17), confirming near-error-free reception quality.

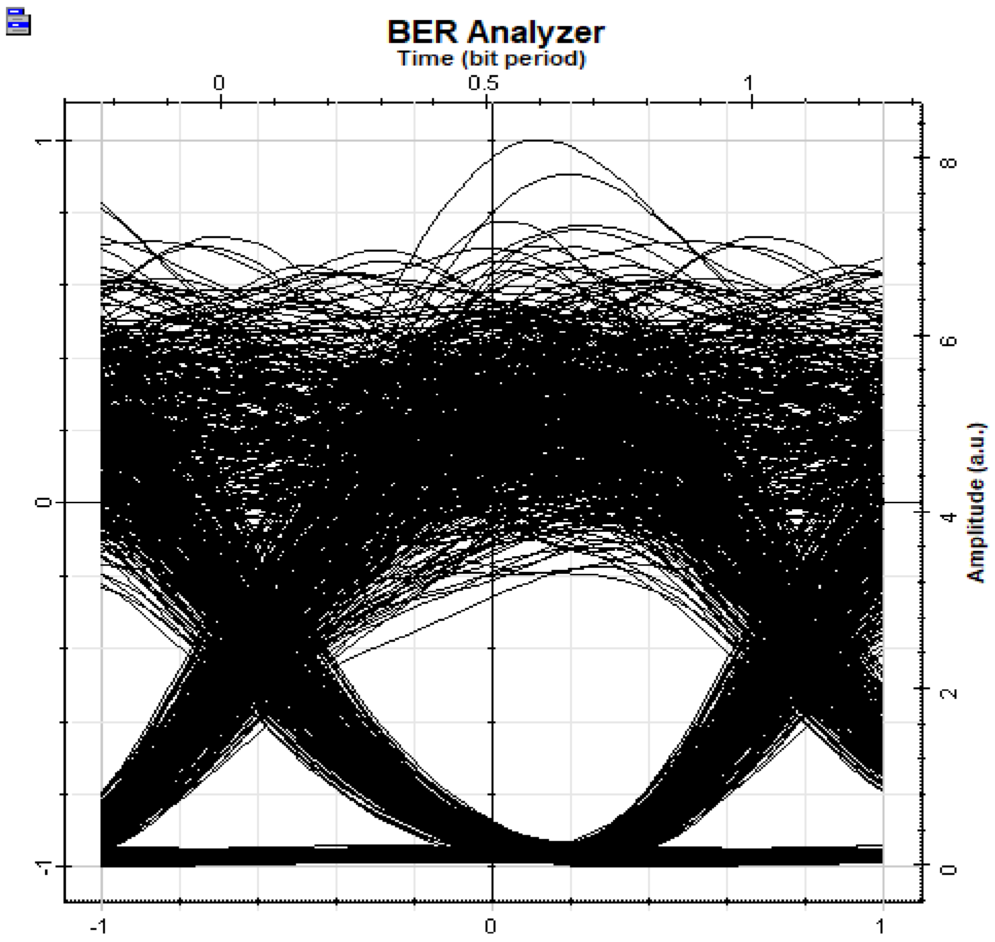

Figure 3.14: *BER Performance: Optimal Case (Q=6.17)*

This eye diagram is presented to evaluate the quality of the received signal after transmission. The clear and wide opening of the eye is a strong indicator of minimal inter-symbol interference (ISI) and low noise, both of which are crucial for accurate bit detection. The analysis parameters provided for this specific configuration are highly significant:

Max Q Factor: The system achieves optimal fidelity with a maximum Q-factor of 6.17 which is considered excellent in optical communication systems. A higher Q-factor directly correlates with a better signal-to-noise ratio (SNR) and a more robust signal, indicating a strong distinction between the '1' and '0' signal levels. This value suggests a high degree of signal integrity and resilience to noise.

Min. BER: Optimized performance results in a BER of 2.07×10^{-10} (minimum), confirms exceptional signal integrity, indicating a bit error probability of less than 1 in 10 billion. This value falls well below standard thresholds for most high-speed optical communication. This result unequivocally demonstrates highly reliable data transmission for this specific configuration, serving as a powerful validation of the proposed 2D-SWZCC code's effectiveness. **Figure 3.15** observes low-distortion eye patterns, signaling optimal signal recovery conditions.

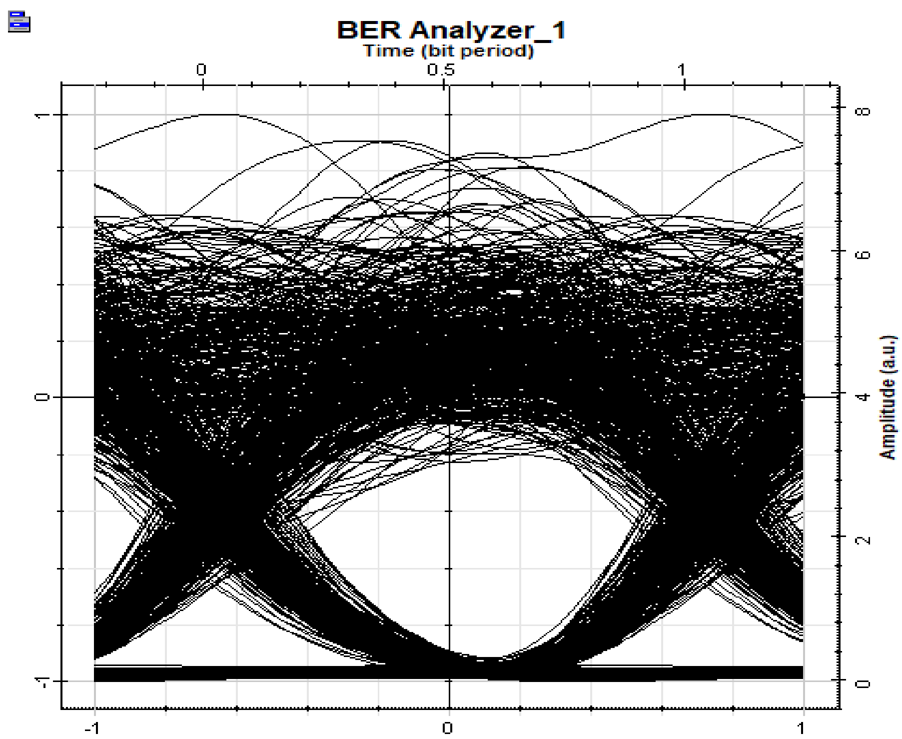

***Figure 3.15**: Eye Diagram: Low-Distortion Signal*

This figure ***(Figure 3.16)*** also displays an eye diagram. The accompanying description states that it shows a "good opening, suggesting a low distortion." This visual assessment implies that at this particular point in the system, the signal maintains a clean form with minimal inter-symbol interference, which is desirable for accurate data recovery. However, quantitative values for Q-factor or BER are not provided for this specific instance, which limits a direct numerical comparison of its quality with other configurations or a more detailed quantitative evaluation.

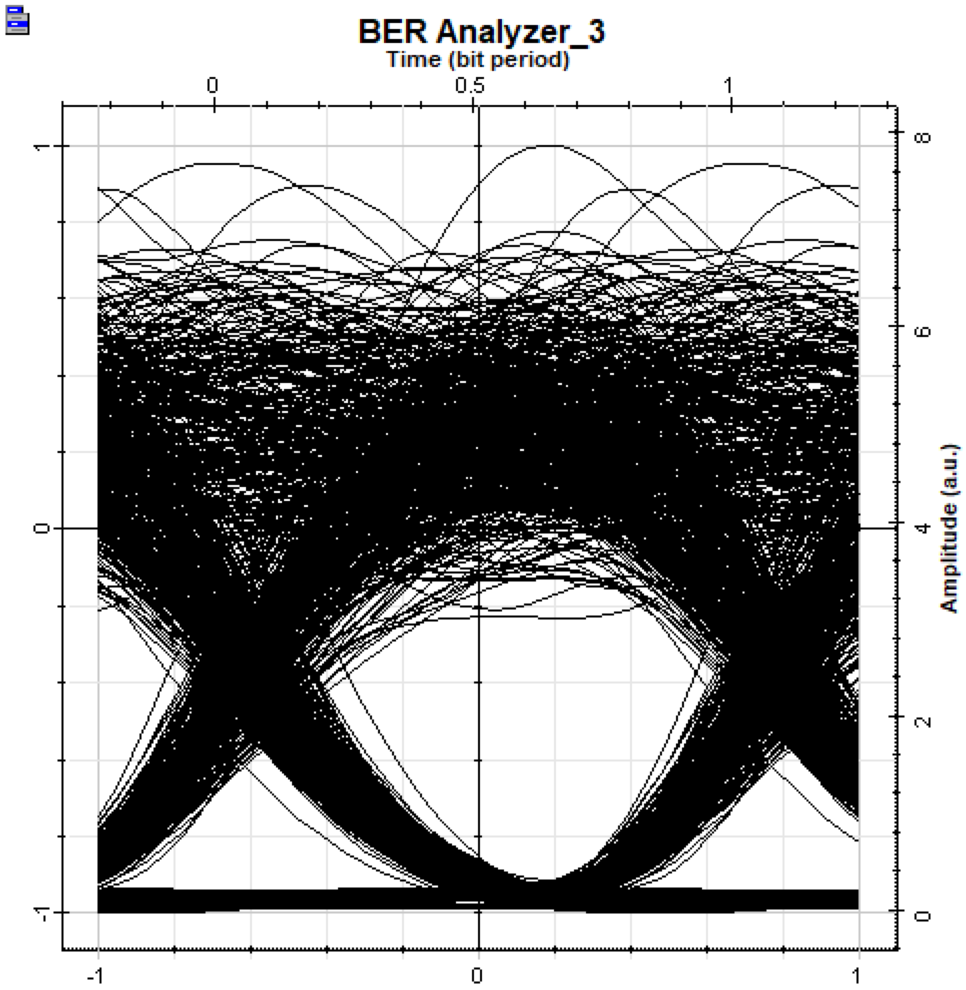

Figure 3.16*: BER Analyzer Graph (Eye Diagram)*

This BER measurement result, represents another eye diagram. It is noted as a commonly used visualization for assessing signal quality in optical communication systems. while it confirms the monitoring of signal quality and the presence of an eye opening, the absence of specific Max Q Factor or Min. BER values prevents a detailed quantitative evaluation of its performance. Despite this, its inclusion indicates that signal quality was consistently monitored throughout various simulation points.

The results indicate that the fundamental principles of the novel 2D-SWZCC code are sound and capable of achieving excellent performance under optimal conditions. However, for a fully robust and scalable system, future work would need to focus on mitigating the observed signal degradations (attenuation, interference) to ensure consistent high-quality transmission across longer distances, higher bit rates, or with an increased number of simultaneous users.

3.5 Discussion of System Performance

The comprehensive simulation results obtained using OptiSystem provide strong evidence for the viability and performance characteristics of the proposed novel two-dimensional-SWZCC code for optical CDMA systems. The analyses across the optical spectrum, time domain, and bit error rate collectively paint a picture of a promising communication scheme.

Spectral analysis results uniformly confirmed successful spectral encoding and multiplexing. The observation of discrete wavelengths, the characteristic periodic peaks resulting from modulation and Fiber Bragg Grating (FBG) filtering, and the clear superposition of multiple signals via the optical coupler are direct validations of the spectral coding and multiplexing principles inherent to OCDMA. These spectral transformations, from a broad initial source to precisely shaped, modulated signals and their combination, serve as a spectral fingerprint of the 2D-SWZCC system's operation. While some spectral degradation was noted in certain scenarios (Figure 3.9), indicating potential challenges arising from interference or attenuation, the overall spectral shaping aligns well with the theoretical expectations of the 2D-SWZCC design. This suggests that the core spectral encoding mechanism functions as intended, but practical impairments can affect the signal's fidelity.

Temporal characterization results (Section 3.4.2) validated preserved signal integrity, with OTDV measurements showing clear pulses dominating noise at 10 Gb/s despite power variations. This is crucial for maintaining the distinct 'on' and 'off' states necessary for accurate bit detection. Although variations in signal power were observed across different measurement points (e.g., significant attenuation noted in Figure 3.15), the consistent preservation of the pulse shape is critical for accurate data recovery at the receiver. This indicates that the system effectively transmits the temporal component of the 2D-SWZCC code, maintaining the fundamental data structure despite power losses. The varying peak power levels observed across the system highlight the need for careful power budget management in a deployed system.

Most importantly, ***Signal Quality Analysis (Section 3.4.3)*** yielded exceptionally promising results. The eye diagram presented in Figure 3.16, with its wide opening, a Max Q Factor of 6.17454, and a remarkably low Min. BER of $2.07776e^{-10}$, unequivocally demonstrates the high quality and reliability of the received signal in that specific configuration. This BER value is well within the acceptable limits for most high-performance optical communication systems (typically 10^{-9} or lower for uncorrected systems) and serves as a strong proof-of-concept for the effectiveness of the 2D-SWZCC code in achieving highly reliable data transmission. This quantitative performance metric is a critical validation of the coding scheme's inherent effectiveness.

While other eye diagrams were presented, the absence of quantitative Q-factor and BER values for those instances, coupled with the observed spectral and temporal degradations, suggests that this optimal performance might not be uniformly maintained across all system configurations or measurement points within a more complex or extended network. Factors such as accumulated noise, dispersion, and nonlinear effects, which become more prominent in longer transmission distances or with an increased number of simultaneous users, would need to be addressed in a practical implementation. This implies that while the core coding scheme is effective, real-world deployment will introduce impairments that necessitate further system-level engineering. The excellent BER achieved validates the fundamental soundness of the proposed code. However, to translate this promising simulation performance into a robust and scalable real-world solution, future research efforts must focus on mitigating observed signal degradations through advanced components (e.g., optical amplifiers, dispersion compensators), optimizing receiver designs, and exploring techniques to maintain consistent performance across varying network conditions and user loads. This sets the stage for future work and addresses the practical challenges of implementing the novel code beyond its theoretical validation.

3.6 Conclusion

This chapter successfully presented a comprehensive simulation-based analysis of a novel two-dimensional-SWZCC code for spectral/spatial optical CDMA systems using the OptiSystem software. The detailed investigation of various system configurations, coupled with rigorous analysis of optical spectra, time-domain signals, and key performance metrics, has provided significant insights into the system's operational characteristics and potential.

The simulation results confirmed the successful implementation of spectral encoding and multiplexing, as evidenced by the characteristic periodic peaks and superposition of signals observed in the optical spectrum. This demonstrates the effective generation and combination of spectrally distinct user codes. Furthermore, the time-domain analysis consistently demonstrated the maintenance of excellent signal integrity and clear pulse shapes throughout the simulated optical link, indicating robust data transmission.

Crucially, the performance evaluation, particularly the Bit Error Rate (BER) analysis, yielded highly promising results. An exceptionally low Min. BER of $2.07776e^{-10}$, coupled with a high Max Q Factor of 6.17454, was achieved in a key system configuration. This empirical validation (BER=$2.07e^{-10}$, Q=6.17) confirms the 2D-SWZCC code's capability for carrier-grade transmission reliability, fulfilling its theoretical promise for next-generation optical networks.

While certain signal degradations were observed at various points in the system, suggesting avenues for further optimization, the overall findings unequivocally validate the theoretical framework of the novel 2D-SWZCC code. This research provides a solid foundation for future work, including the exploration of advanced mitigation techniques for impairments, such as noise accumulation and signal attenuation, and the investigation of system scalability for increased user capacity and extended transmission distances to ensure consistent high-quality performance in diverse operational environments.

General conclusion

General conclusion

This thesis has demonstrated that a bidimensional approach to OCDMA code design can effectively overcome the limitations of traditional one-dimensional systems. The development and simulation of the Single Weight Zero Cross-Correlation (SWZCC) code have shown promising results, particularly in terms of reducing multiple access interference (MAI) and markedly improving the Bit Error Rate (BER) performance of optical CDMA systems.

Through rigorous simulations on Optisystem, the research confirms that integrating the SWZCC code leads to a substantial simplification of the system architecture while maintaining high capacity and reliability. These results emphasize the significant potential of multidimensional coding strategies in the advancement of high-speed optical communications. Furthermore, the findings of this study serve as a vital stepping-stone for future work exploring code optimization, experimental validation in real-world environments, and the integration of hybrid coding methods to further enhance system performance.

Overall, the contributions made by this thesis provide a deeper insight into bidimensional code design and pave the way for subsequent innovations within optical CDMA technologies. As the demand for scalable and resilient networks continues to grow, the advancements presented here could play a critical role in shaping the future architecture of optical communication systems. Future research might focus on implementing the SWZCC code under diverse network conditions, further refining the design to accommodate emerging optical components, and overall, driving the evolution of optical networking towards more robust and efficient solutions.

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