مجلة جامعة بني وليد للعلوم الإنسانية والتطبيقية
Bani Waleed University Journal of Humanities and Applied Sciences
تصدر عن– جامعة بني وليد – ليبيا
Website:https://jhas-bwu.com/index.php/bwjhas/index
المجلد التاسع ـ العدد الخامس ـ 2024 ـ الصفحات (181- 196)

ISSN3005-3900

الإرسال المتعدد الاستقطاب في الاتصالات البصرية: التقنيات والتطبيقات

نبيل عبد الجليل أبوجناح [1] *

[1]. قسم هندسة الاتصالات، كلية الهندسة، جامعة الزيتونة، ليبيا

n.abujnah39@gmail.com

Polarization Multiplexing in Optical Communications: Techniques and Applications

Nabeil A. Abujnah [1]*

Communication Engineering Department, Faculty of Engineering, Azzaytuna University, Libya

تاريخ الاستلام: 2024-10-22 تاريخ القبول: 2024-11-12 تاريخ النشر : 2024-12-04

الملخص:

الإرسال المتعدد الاستقطابي هو تقنية مبتكرة في أنظمة الاتصالات البصرية تستخدم خصائص الاستقطاب للضوء لتعزيز قدرة نقل البيانات بشكل كبير. من خلال الاستفادة من حالات الاستقطاب المتعامدة، يسمح الإرسال المتعدد الاستقطابي بنقل متزامن لتدفقات بيانات متعددة على نفس القناة البصرية، مما يضاعف معدل البيانات بشكل فعال دون الحاجة إلى عرض نطاق ترددي إضافي. تستعرض هذه الورقة أساسيات الإرسال المتعدد الاستقطابي، بما في ذلك مخططات التعديل الرئيسية مثل تحويل طور رباعي (QPSK) وتعديل سعة رباعي (16-QAM). كما تتناول التحديات المتضمنة، مثل انتشار وضع الاستقطاب واختلال التوازن في الاستقطاب، والتي يمكن أن تضعف أداء النظام. تبحث هذه الورقة بشكل أكبر في التطبيقات العملية للإرسال المتعدد الاستقطابي في أنظمة النقل عالية السعة وشبكات الألياف الضوئية ومراكز البيانات. بالنظر إلى المستقبل، من المتوقع أن يلعب الإرسال المتعدد الاستقطابي دورًا مهمًا في تلبية الطلب المتزايد على عرض النطاق الترددي في البنية التحتية للاتصالات الحديثة، وتقديم حلول قابلة للتطوير لتعزيز أداء النظام البصري.

الكلمات المفتاحية: الإرسال المتعدد الاستقطاب، الاتصالات البصرية، نقل البيانات، تقنيات التعديل، انتشار وضع الاستقطاب، الألياف البصرية، *QPSK*، *QAM*16-، الشبكات عالية السعة، اتصالات الألياف البصرية، كشف الاستقطاب والتنوع.

Abstract:

Polarization multiplexing is an innovative technique in optical communication systems that uses the polarization properties of light to significantly enhance the ability of data transmission. Taking advantage of orthogonal polarization states, polarization multiplexing allows simultaneous transmission of multiple data streams on the same optical channel, effectively doubling the data rate without the need for additional bandwidth. This paper reviews the fundamentals of polarization multiplexing, including key modulation schemes such as quadrater phase shift caning (QPSK) and quadrater amplitude modulation (16-QAM). It also addresses the challenges involved, such as polarization mode diffusion and polarization imbalance, which can impair system performance. This paper further investigates the practical applications of polarization multiplexing in high-capacity transmission systems, optical fiber networks, and data centers. Looking to the future, polarization multiplexing is poised to play an important role in meeting the growing demand for bandwidth in modern communication infrastructure, offering scalable solutions to enhance optical system performance.

Keywords: polarization multiplexing, optical communication, data transmission, modulation techniques, polarization mode diffusion, optical fiber, QPSK, 16-QAM, high-capacity networks, fiber-optic communication, polarization-diversity detection.

Introduction

In today's digital world, communication systems are expected to handle the growing demand for bandwidth. Our daily lives depend on fast, reliable data transmissionh whether it's video streaming, attending a virtual meeting, or simply sending an email. However, behind the scenes, there is an ongoing challenge: how to transfer more data through the same infrastructure, without compromising speed or quality. This is where polarization multiplexing comes into play in optical communication systems.

Optical communications, especially through fiber-optic networks, have revolutionized the way data is transmitted over long distances. Since the advent of optical fiber, the telecommunications industry has been able to send large amounts of data with minimal signal loss. Yet, as the demand for data continues to grow, the need for greater use of existing fiber networks has become more urgent than ever. This is where polarization multiplexing offers a beautiful solution.

The concept of polarization multiplexing is based on a simple but powerful idea: light waves can rotate in different directions or polarizations. Using two orthogonal polarization states often called vertical and horizontal or right and left rotational polarizations two data streams can be transferred simultaneously to the same fiber. Imagine that there are two separate highways within the same road, each traveling in a different direction, leading to a greater flow of information. This technique doubles the capacity of data transmission without the need for additional bandwidth, making it an incredibly valuable tool in today's telecommunications scenario.

But why is it so important? Let's put it into context. Every day, we generate and use amazing amounts of data. According to a 2020 report by Cisco, global internet traffic is expected to reach 4.8 zettabytes annually by 2022, an almost inconceivable number. To support this rapid growth, telecommunication providers must continuously innovate to improve efficiency and increase capacity. Polarization multiplexing allows for better utilization of available resources, making it a cornerstone in the development of next-generation optical communication systems.

However, the journey of implementing polarization multiplexing is not without its challenges. While this sounds theoretically promising, a number of obstacles need to be overcome for the real-world application of this technique. One such challenge is polarization mode dispersion (PMD), a phenomenon where different polarization modes travel at different speeds through the optical fiber, distorting the signal. This becomes a problem especially in long-distance networks. Additionally, polarization errors can occur due to the misalignment of polarization states between the transmitter and the receiver. And then there's the problem of cross polarization interference, where two data channels interfere with each other due to flaws in the fiber.

Despite these challenges, researchers have made significant progress in addressing these issues. For example, the development of modern polarization-retaining fibers and the introduction of polarization-diversity detection techniques have greatly improved the efficiency of the system. In fact, modern optical systems using polarization multiplexing such as polarization division multiplexing (PDM) are already deployed in high capacity transmission systems, especially in long-range fiber optic networks and data centers (Yang et al., 2020).

In this paper, we will dive into the principles behind polarization multiplexing, explore the various techniques used to implement it, and test its applications in real-world communication systems. We will also look at the ongoing challenges and the future of this technology as we continue to push the boundaries of optical communications. Polarization multiplexing isn't just a theoretical concept it's a proven technique shaping the future of communication, offering a broad solution to meet the demands of the next generation of global connectivity.

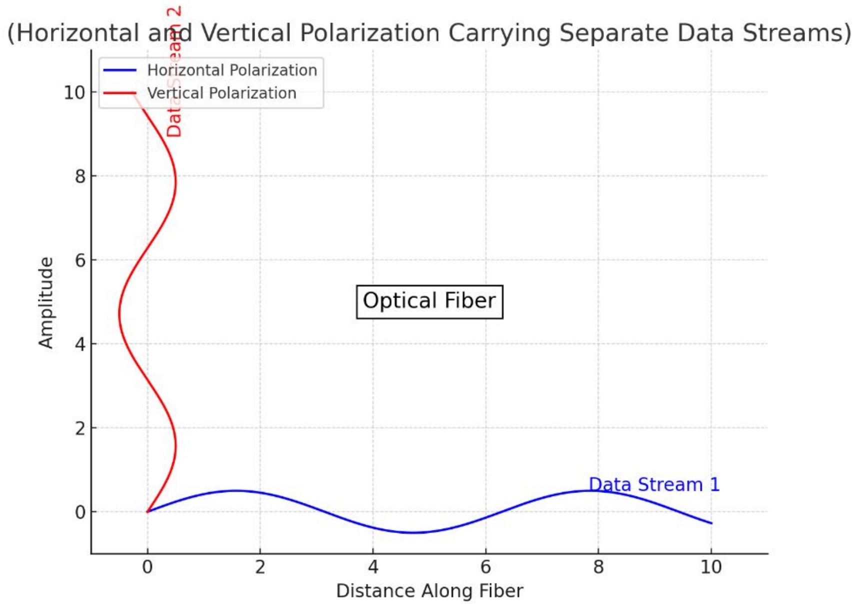


Figure 1 Basic outline of polarization multiplexing.

Through this discussion, we want to shed light on how this technique is helping to solve the capacity crisis in optical communications, ensuring that we can continue to continuously send large amounts of data over vast distances at lightning speeds.

Polarization multiplexing is an innovative technique within optical communication that takes advantage of the unique properties of light waves to transmit multiple data streams through a single optical fiber. Utilizing the different directional properties of light, polarization multiplexing provides an effective solution for the increased demand for high capacity, high-speed data transmission. This section covers the basic concepts of polarization and reviews how it is effectively used in multiplexing to increase communication efficiency and bandwidth usage.

Basics of polarization

In order to understand polarization multiplexing, we first need to test the concept of polarization in light waves. Light, as an electromagnetic wave, consists of rotating electric and magnetic fields that are longer than each other and in the direction of propagation. The direction in which the electric field rotates is called wave polarization. If the electric field vibrates at a certain surface, light is said to be linearly polarized, while if it rotates in a helical pattern, it is rotationally polarized (Kikuchi, 2016).

In the context of optical communication, polarization offers a unique degree of freedom, allowing light waves to carry more information. Traditional communication methods regulate amplitude or frequency to encode data, but polarization adds another layer of information without changing the amplitude or frequency of the signal. This capability is especially valuable in modern optical systems where bandwidth performance is essential. By encoding the data over two different polarization states often vertical and horizontal or right and left circular polarization it is possible to transfer two separate data streams simultaneously through the same optical channel. This method effectively doubles the data rate, maximizing the fiber's ability to carry information without the need for additional bandwidth (Kahn & Ho, 2004).

The practical implementation of polarization multiplexing includes modern devices capable of maintaining and detecting these distinct polarization states over long distances. A common method involves the use of polarization-retaining fibers and polarization controllers, which keep polarization states stable during transmission. However, it can be difficult to maintain different polarization states due to the natural tendency of light to change polarization within the fiber, an effect called polarization mode dispersion (PMD). This phenomenon occurs when different polarization modes travel through the fiber at slightly different speeds, leading to signal distortion over long distances. Resolving PMD is critical for maintaining data integrity in high-speed, long-range optical systems (IP & Kahn, 2008).

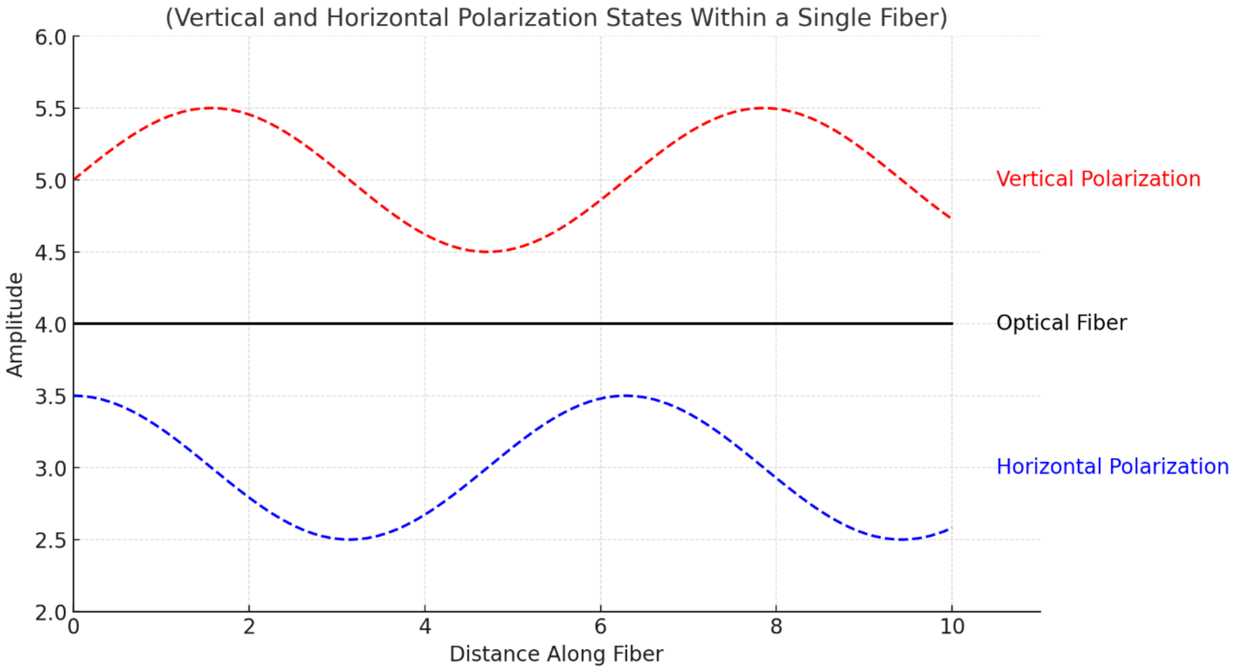


Figure 2 Example of polarization states in optical fibers.

These data can visually represent different polarization states such as vertical, horizontal, and rotational polarization showing how these states synchronize and travel through the fiber. A clear outline will help explain the concept of orthogonal polarization states and their role in carrying different data streams.

The importance of polarization in communication goes far beyond the ability to carry additional data. By allowing separate data channels within the same physical medium, polarization multiplexing directly contributes to the increase in spectral efficiency, which is an important factor in meeting the high needs of modern networks. As Winzer and Acembry (2006) explain, the main advantage of polarization multiplexing is the ability to double the data rate without extending bandwidth, making it indispensable for dense wavelength division multiplexing (DWDM) systems, where bandwidth constraints are prominent. Thus, polarization multiplexing plays an important role in the backbone of today's Internet infrastructure, enabling faster, more efficient data transmission in long-range and high-capacity optical networks.

Using polarization to incorporate "channels" of data within a fiber, polarization multiplexing offers a scalable solution to current communication challenges. While implementing polarization multiplexing in optical systems requires careful handling of factors such as PMD and polarization imbalance, technological advances continue to improve its reliability. Through these developments, polarization multiplexing is likely to remain at the forefront of high-capacity optical communications, paving the way for next-generation data transmission systems (Kikuchi, 2016;

There are two basic polarization states used in optical systems: linear and circular. Linear polarization occurs when an electric field rotates along a straight line, whereas rotational polarization refers to the rotation of the electric field in rotational motion. Polarization multiplexing uses these two orthogonal polarization states to transfer two separate data streams over the same optical channel.

Polarization states

Polarization in light waves can exist in several states, mainly classified as linear, round, or elliptical. In optical communications, the most commonly used states are linear polarization (e.g. vertical and horizontal) and rotational polarization (left-handed and right-handed). Each polarization state represents a different direction of the electric field vector, allowing multiple data streams to be carried within the same optical fiber. By encoding data at different polarization states, optical systems can effectively double their ability to carry data without the need for additional bandwidth, making polarization multiplexing a valuable asset in high-capacity communication networks.

In a linearly polarized wave, the electric field rotates in the same surface, such as vertical or horizontal. This is especially beneficial in polarization multiplexing, as two orthogonal linear polarization states can act as separate channels for data transmission. Kikuchi (2016) highlights that these orthogonal linear polarization states are the basis of many modern optical communication systems, where they allow simultaneous, independent data streams without significant interference when properly organized.

In addition to linear polarization, circular polarization is often used in optical systems, where the electric field vector rotates in a rotational motion as the wave propagates. This is achieved by combining two orthogonal linear components with a phase difference of 90 degrees. Circular polarization, whether left-handed or right-handed, is valuable for minimizing certain types of interference and signal degradation, especially in dynamic environments where polarization alignment can change during transmission. According to Winzer and Esimber (2006), circular polarization states also resist certain types of distortion and can be used effectively in environments where it is difficult to maintain a fixed polarization state.

The choice between linear and circular polarization depends on the specific requirements of the communication system. Linear polarization is more common in fiber optic systems due to the ease of maintaining steady states over long distances, especially with polarization-retaining fibers. However, in free-space optical communications or satellite systems, circular polarization can provide better performance by reducing some alignment problems (Snyder & Low, 1983).

The real-world implementation of polarization multiplexing requires careful management of these states to prevent cross polarization interference. As described by IP and Kahn (2008), when two polarization states interact or flow, it can lead to signal distortion, reducing the effectiveness of the system. Modern modulation techniques and polarization control mechanisms, such as polarization controllers and polarizers, help mitigate these problems and ensure stable transmission.

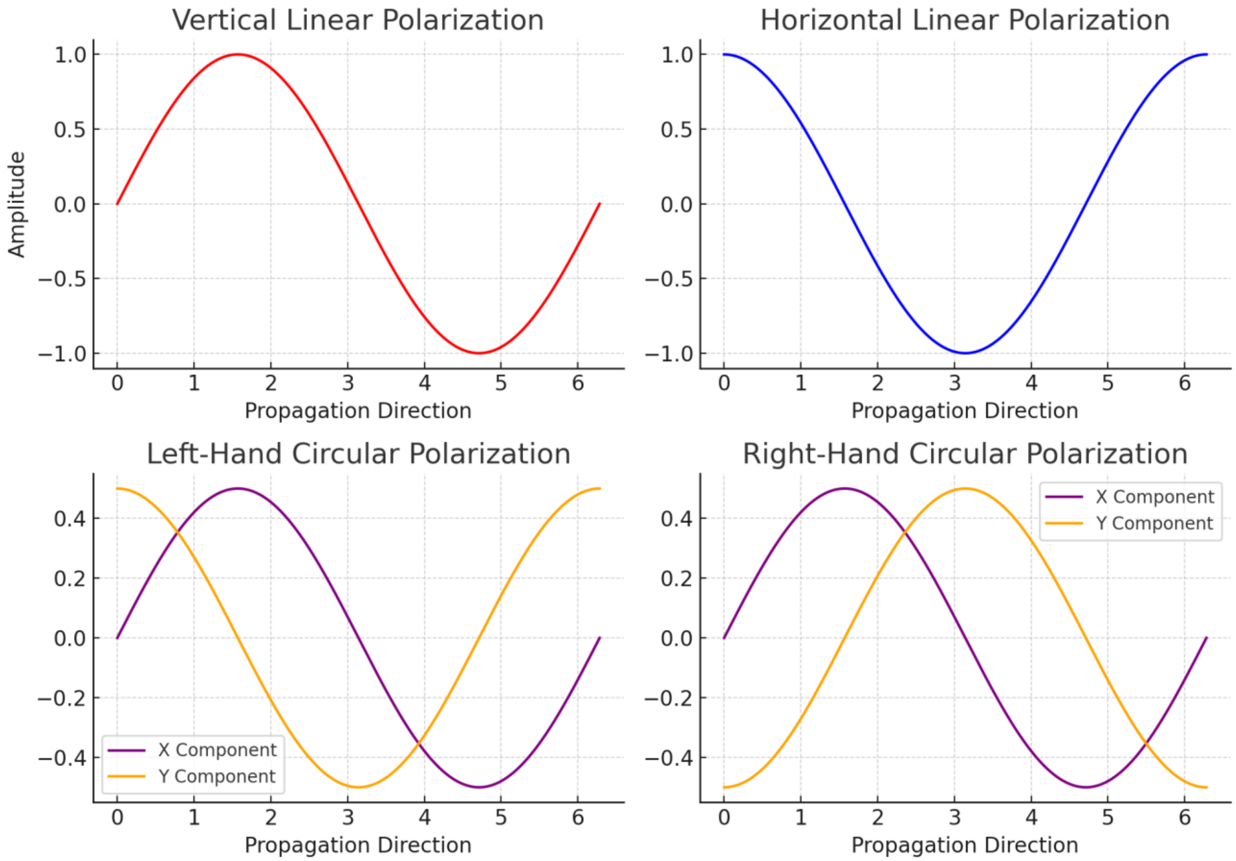


Figure3 Types of polarization states.

These data can provide examples of vertical and horizontal linear polarization, as well as examples of left-handed and right-handed rotational polarizations, providing visual representations about the appearance and spread of different polarization states.

Techniques for polarization multiplexing

- **Polarization Division Multiplexing (PDM)**

Polarization multiplexing significantly enhances data transmission by allowing multiple data streams to travel through a single optical fiber. This technique is important for high-capacity networks where bandwidth performance is essential. Polarization division multiplexing (PDM) has become particularly popular in various techniques of polarization multiplexing as it has acquired the ability to double the potential of data by taking advantage of orthogonal polarization states. This technique is widely applied in high-speed optical communications, including data centers, long-distance networks, and global Internet infrastructure, which is indispensable in managing today's large-scale data demands.

The basic principle of PDM involves encoding two independent data streams on two orthogonal polarization states, usually vertical and horizontal linear polarization. These states are mixed into an optical beam using a polarization beam combiner (PBC) and transferred to a fiber. Upon reaching the receiver, the polarization beam splitter (PBS) separates the two polarization states, allowing independent processing of each data stream and effectively doubling the data capacity of the fiber. However, maintaining polarization stability is important, as environmental factors such as temperature fluctuations and mechanical pressure can change polarization states, introducing potential interference between channels. Figure 1 below illustrates the setup of a typical PDM system, showing the process of coupling and separating orthogonal polarization to facilitate independent data channels.

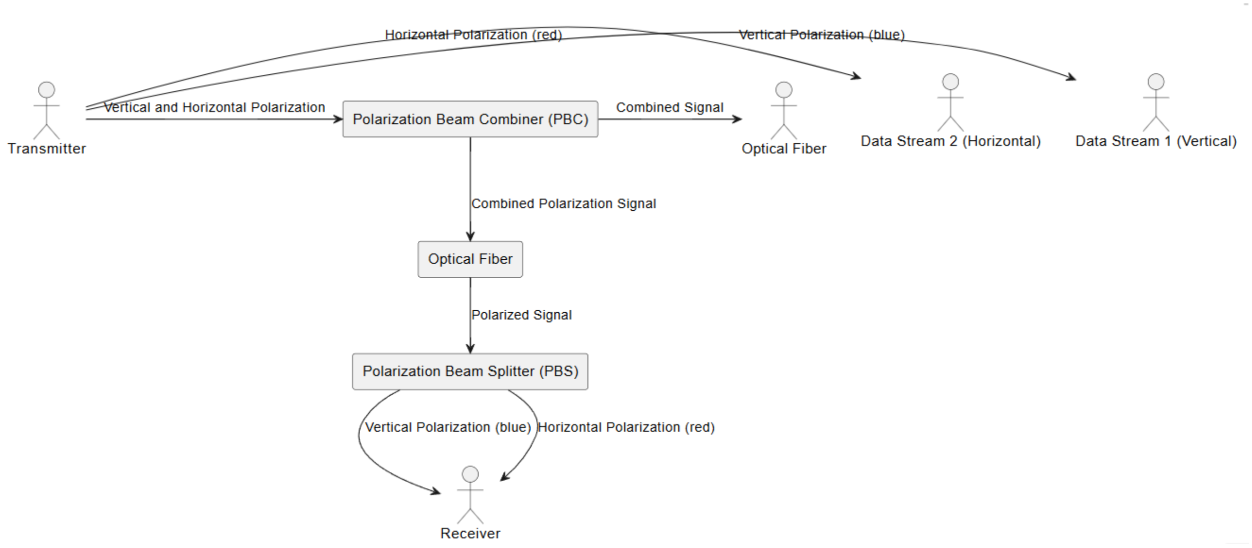


Figure 4 Basic setup of polarization division multiplexing (PDM).

Despite its advantages, implementing PDM introduces challenges, especially polarization mode dispersion (PMD) and polarization-dependent loss (PDL). PMD occurs when different polarization modes travel at different speeds, leading to pulse expansion and intersymbal interference (ISI), which can significantly reduce signal clarity. The effects of PMD are magnified in long-distance transitions where slight velocity changes accumulate over the distance. Furthermore, PDL results in an unequal reduction of polarization states due to defects in optical components, leading to an imbalance in signal-to-noise ratio (SNR) between channels. These challenges require advanced digital signal processing (DSP) techniques on the receiver to correct polarization-related defects. DSP algorithms adjust the phase and time of each polarization channel to counterACT PMD, while synchronous parity helps reduce PDL by dynamically balancing power levels and SNRs in both polarization states.

Table 1 Summary of the basic challenges in PDM and the DSP-based solutions commonly used to address them.

Challenge	Description	Solution
Polarization Mode Dispersion	Different propagation speeds cause inter-symbol interference (ISI)	DSP with phase and timing adjustments

Polarization-Dependent Loss	Unequal attenuation leads to imbalance in signal-to-noise ratio (SNR)	Adaptive equalization

PDM has found a wide range of applications in high-speed optical networks, particularly in dense wavelength division multiplexing (DWDM) systems. DWDM maximizes spectral efficiency by transferring multiple wavelengths over the same fiber, and combining PDM with DWDM makes it possible to further increase capacity by doubling the data rate for each wavelength. This setting is common in undersea cables and intercontinental optical links that carry large amounts of global Internet traffic.

PDM is also invaluable in data centers and cloud computing environments, where the use of high data throughput and efficient bandwidth is important to manage large amounts of information transmitted between servers and storage systems. The implementation of PDM in data centers enables faster data handling on existing fiber infrastructure, making it a cheaper solution to increase capacity. In addition to ground fiber networks, PDMs are increasingly searched for free space optical (FSO) communications and satellite systems, although these applications face unique challenges, such as environmental turbulence, which can unexpectedly alter polarization states. Advances in polarization-agnostic technologies and adaptive DSP are enabling more reliable PDM deployment in these non-fiber environments, expanding its application.

Recent advances in PDM technology focus on increasing data rates and improving polarization flexibility. By combining PDM with higher-order modulation formats, such as 64-QAM (quadrater amplified modulation), the data rate can be further increased without additional bandwidth requirements. However, advanced modulation requires state-of-the-art integrated detection systems to accurately decode complex signals. Machine learning (ML) algorithms are also being integrated into the DSP process within the PDM system. ML-powered DSP can detect and adapt to polarization changes in real time, reduce processing loads on traditional DSP techniques and increase reliability under different conditions.

Additionally, researchers are looking for multidimensional PDM, which combines polarization states with local division multiplexing (SDM) to further amplify data channels within a fiber. Multidimensional PDM is still experimental but has significant potential for future data infrastructure, where extreme data capability is needed. Multidimensional PDM settings can become important for future global networks, allowing data rates to reach abnormal levels.

- **Modulation formats**

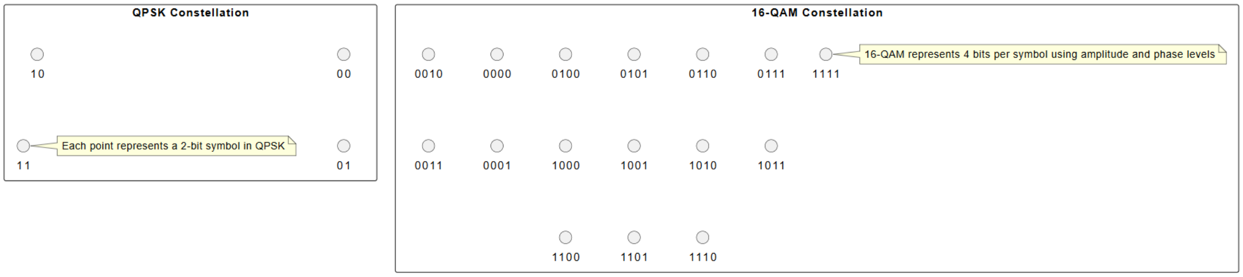
In polarization multiplexing, modulation formats play an important role in encoding information on light signals to maximize data transmission rates while balancing robustness and spectral performance. The two commonly used modulation formats are quadrater phase shift keying (QPSK) and quadrater implementation modulation (16-QAM), each offering unique advantages and tradeoffs in optical communication systems. These formats are essential for high-speed networks where sound capability and flexibility are important, especially in long-distance and data center applications.

Quadrature phase shift keying (QPSK) is a widely adopted modulation scheme that transmits two bits of information per symbol by changing the phase of the optical signal. QPSK has four different phase states (usually 0°, 90°, 180°, and 270°), each representing a unique two-bit binary combination (00, 01, 10, or 11). In polarization-multiplexed systems, QPSKs can be used at both polarization states (e.g. vertical and horizontal), allowing two independent two-bit channels to be simultaneously transferred to the same fiber. Thus, the use of QPSK in a polarization-multiplex setup effectively doubles the data throughput, enabling four bits per sign in two orthogonal polarizations.

The advantage of QPSK lies in its spectral performance and flexibility for noise. Since QPSK transmits two bits per symbol with only four phase states, it requires a relatively low signal-to-noise ratio (SNR) for accurate demodulation compared to higher-order formats. This makes QPSK especially suitable for long-distance transmission, where optical signals are subjected to different perturbations and noise over wide distances. In such situations the polarization of QPS combined with multiplexing provides a balanced solution for maintaining high data rates while ensuring strong performance. Research shows that QPSK, when combined with digital signal processing (DSP) and integrated detection, can effectively reduce disturbances such as polarization mode dispersion (PMD) and phase noise, thereby increasing the quality of long-distance transmission (IP & Kahn, 2008).

On the other hand, 16-QAM (quadrater amplitude modulation) is a more complex and advanced modulation scheme that increases data capacity by changing both the amplitude and phase of the light signal. In 16-QAM, each symbol represents one of 16 unique states, corresponding to a different combination of amplitude and phase levels. This setting allows 16-QAM to carry four bits per symbol, as each state can represent a separate four-bit binary combination. When applied in a polarization multiplexed system, the 16-KAM enables each polarization state to carry four bits, resulting in a total of eight bits per symbol in the two polarization channels. This significantly increases data rates, making 16-QAM the preferred choice for applications that require high spectral performance, such as data center interconnections and metropolitan area networks.

However, the higher data rate of 16-QAM comes at the expense of a higher sensitivity to noise and distortion. Since 16-KAM includes multiple dimensions and phase levels, it calls for high SNR for reliable demodulation. This greater need for SNR makes 16-QAMs more susceptible to disorders such as cross-phase modulation, polarization-dependent loss (PDL) and nonlinear effects, especially in long-range transmission where signal degradation is evident. Advances in DSP and integrated detection techniques have made 16-QAM more feasible for high-capacity systems by providing methods to compensate for these drawbacks. Integrated receivers, in particular, are equipped with DSP algorithms that can correct amplitude and phase errors, increasing the stability and accuracy of 16 QAM signals in polarization multiplexed systems (Winzer and Acembry, 2006).



5.

The choice between QPSK and 16-KAM depends on the system's requirements, as each modulation format has specific tradeoffs about data rate, robustness, and implementation complexity. QPSK is generally preferred for long-range applications where robustness and error flexibility are important. Its low SNR requirements and easy demodulation process make it ideal for highly reliable, long-range optical links, such as intercontinental and submarine communication systems. In contrast, 16-QAM is more commonly used in metropolitan and data center networks, where shorter distance signals allow for higher data rates with a lower sensitivity to degradation. The increased data rate of 16-QAM, combined with polarization multiplexing, is beneficial in an environment where bandwidth efficiency must be maximized.

Recent research shows that both QPSK and 16-QAM play important roles in high-capacity optical networks, with ongoing progress aimed at increasing their application. For example, multidimensional modulation formats that combine QPSK or 16-QAM with additional degrees of freedom, such as local or time multiplexing, are being developed to further advance data rates. This allows the creation of highly efficient and flexible optical communication systems that can meet the growing demand for global data traffic (Acembry & Takach, 2012).

Table 2 Comparison of QPSK and 16-KAM in Polarization Multiplexing.

Modulation Format	Bits per Symbol	Polarization States	Total Bits per Symbol in PDM	Advantages	Challenges	Typical Applications
QPSK (Quadrature Phase Shift Keying)	2	Vertical & Horizontal	4	High noise resilience; suitable for long-haul	Limited spectral efficiency	Long-distance, high-reliability

				links		transmission
16-QAM (Quadrature Amplitude Modulation)	4	Vertical & Horizontal	8	High spectral efficiency; higher data rates	Requires high SNR; more sensitive to impairments	Data centers, metro networks

- **Polarization-diversity detection**

Polarization-diversity detection is an important technique in polarization-multiplexed systems, which facilitates accurate separation and decoding of data transmitted to two orthogonal polarization states – usually vertical and horizontal. This approach ensures that every data stream carried over individual polarization states is processed and stored independently, even when signal degradation, cross-talk, or polarization fluctuates due to environmental factors or long-range transmission. By separating and decoding these data streams, polarization diversity detection increases data transmission capability and preserves signal quality.

In practical implementation, polarization diversity detection uses a polarization beam splitter (PBS) to separate the incoming light signal into its orthogonal polarization components. This separation is fundamental because each polarization stream is directed toward its own detector, which captures the specific polarization state independently of the other. This setup allows the receiver to prevent interference between polarization channels, thus maintaining the integrity of the transferred data. After separating the polarization channels, integrated receivers play an important role by capturing the phase and amplitude of the incoming signals. This capability is important for the interpretation of complex modulation formats such as QPSK and 16-QAM, which are common in high-speed optical communication systems. The integrated detection process provides accurate data retrieval by interpreting both phase and amplitude variations in each polarization stream.

Digital signal processing (DSP) is another cornerstone of polarization-diversity detection, which provides real-time correction for any misalignment or malfunction that occurs during transmission. DSP algorithms adjust phase and amplitude variations to compensate for polarization-related effects such as polarization mode dispersion (PMD) and polarization-dependent loss (PDL). These adjustments are dynamically accurate for polarization drift and signal errors, allowing the receiver to reconstruct the original data streams with high accuracy even over long transmission distances. Real-time optimization capability is important in DSP, as it enables polarization-diversity detection to work effectively in a variety of situations where polarization changes and distortions are inevitable. Research shows the importance of DSP for reducing PMD and PDL, especially in long-range transmission systems where optical signals experience accumulated disturbances (IP & Kahn, 2008).

In addition to DSP, polarization controllers are often integrated to monitor and synchronize the polarization state of the incoming signal at the receiver's end. These controllers dynamically adjust the detector parameters of the receiver to maintain alignment with the original transferred polarization states, which is essential because polarization changes can occur unexpectedly due to fiber properties and environmental effects. To counter minor flaws, synchronized equation techniques are also used in some systems, which further increases signal stability and flexibility. The synchronous equation is particularly beneficial in long-range optical networks where even minor polarization errors can accumulate at a distance and affect the quality of the data. As Winzer and Esimber (2006) state, the synchronized equation combined with DSP is highly effective in high-capacity optical networks, where continuous adjustments are necessary to ensure stable performance under different polarization conditions.

In systems using high-order modulation formats such as 16-QAMs, polarization-diversity detection becomes even more important. High-order modulation schemes are inherently more sensitive to noise and signal degradation, making accurate polarization separation and detection necessary to prevent data loss. For such cases, polarization diversity detection, combined with modern DSP, provides the flexibility necessary to accurately isolate and decode each polarization state. By ensuring that dense modulation formats are correctly interpreted, polarization diversity detection maintains data accuracy in challenging transmission conditions (Kikuchi, 2016).

Polarization-diversity detection applications extend to high-capacity optical communication systems, including long-range transmission, metropolitan networks, and data center interconnection. Its ability to maintain data integrity across different polarization states makes it valuable in a dense wavelength division multiplexing (DWDM) system, where each wavelength can carry independent polarization states without cross-talk. In DWDM, where it is important to maximize spectral efficiency, polarization-diversity detection ensures that each channel remains separate, maintaining the integrity of high throughput, multi-channel data transmission. For these applications, integrated detection combined with polarization diversity methods can enable better performance, as integrated receivers allow systems to handle more complex modulation formats while maintaining signal clarity (Acembry & Takach, 2012).

Despite its advantages, the implementation of polarization-diversity detection presents some challenges, especially regarding the sensitivity of polarization changes. Maintaining accurate alignment in real time requires complex DSP and polarization control mechanisms, which increase the cost and complexity of the system. Polarization states can change due to unpredictable environmental effects, demanding continuous adjustment by DSP and adaptive control systems. Future advances in machine learning (ML) and artificial intelligence (AI) are promising in addressing these challenges, as compatible ML algorithms can predict polarization changes and dynamically adjust recipient parameters. This approach can simplify hardware requirements and increase flexibility in polarization-diversity detection systems, making them more receptive to volatile environments (Kahn & Ho, 2004).

Challenges in polarization multiplexing

While polarization multiplexing enables higher data rates and improved spectral performance, it also introduces a set of unique challenges that must be carefully managed to maintain signal quality and reliability in optical networks. These challenges are mainly related to the physical properties of light and flaws in optical fibers that can distort or interfere with polarization states during transmission. Major challenges include polarization mode dispersion (PMD), polarization interaction, and cross polarization interference (XPI).

One of the most important problems in polarization multiplexing is polarization mode dispersion (PMD), which is caused by a slight difference in the propagation speed of different polarization modes within the optical fiber. In an ideal fiber, light waves of different polarizations will travel at the same speed. However, in reality, fiber defects cause one polarization mode to travel slightly faster or slower than the other. This velocity change results in a temporary expansion of optical pulses, a phenomenon known as pulse propagation. Over long distances, PMD can significantly distort the transmitted signal, as it causes individual pieces of information to spread and potentially overlap. This overlap leads to intersemble interference (ISI), where the bits of a pulse interfere with the adjacent pulse, making it difficult for the recipient to accurately interpret the transmitted data. PMD quickly becomes a problem at high data rates and long-distance transmission, where even minor time discrepancies can cause a substantial decline in signal quality. To deal with PMD, modern digital signal processing (DSP) techniques, such as synchronized equations, are applied to the receiver's end to dynamically correct these timing discrepancies. However, while DSP provides some level of compensation, it cannot completely eliminate PMD, especially when data rates continue to increase and signal pathways become longer (Winzer, 2017).

Another major challenge in polarization multiplexing is polarization mismatch, which refers to misunderstanding between polarization states on the transmitter and those found on the receiver. Ideally, polarization states should remain stable during transmission, allowing the receiver to independently isolate and decode the data performed at each polarization. However, in practical scenarios, several factors can disrupt polarization alignment, including temperature fluctuations, mechanical pressure on the fiber, and internal defects in the fiber itself. Even minor errors can lead to signal degradation, as the receiver may fail to properly distinguish between the two polarization states, resulting in data loss or errors. Polarization incompatibility is particularly challenging in systems that use advanced modulation schemes, such as 16-QAM or 64-QAM, where accurate alignment must be maintained for the correct interpretation of dense signal constellations. To reduce polarization imbalances, polarization controllers are often deployed on the receiver. These devices monitor incoming polarization states and automatically adjust the detection parameters so that the transmitted polarization can be matched as closely as possible. While effective, polarization control systems add complexity and cost to the overall system, and achieving real-time alignment is an ongoing technical challenge (Richardson et al., 2013).

Cross polarization interference (XPI) is another important issue that can affect the performance of polarization multiplexed systems. XPI occurs when two orthogonal polarization channels interfere with each other due to defects in the optical fiber, such as birefringence – asymmetry in the refractive index of the fiber. The light in one polarization state is partially converted to another polarization channel due to polarization, leading to interaction between channels. This cross-talk disrupts the freedom of polarization states, making it difficult for the recipient to accurately separate and decode each data stream. XPI can be particularly harmful in systems that use higher-order modulation formats, as closely packed signal points are more vulnerable to interference. XPI reduction techniques include the use of polarization-retaining fibers, which are specifically designed to maintain the stability of polarization states, and DSP algorithms that dynamically adjust for cross-talk on the receiver. However, managing XPI is a complex task, as complete elimination of two-way interference is not possible, especially in long-range and high-capacity optical networks where minor defects can accumulate and affect overall system performance (Kikuchi, 2016;

Addressing these challenges requires an integrated approach that combines advanced DSP, polarization control mechanisms, and improved fiber design. Innovation in integrated detection and machine learning-based adaptive control systems is also showing promise in better dealing with polarization-related glitches. By dynamically predicting and compensating PMD, polarization imbalance, and XPI, these technologies can increase the stability and efficiency of polarization multiplex systems. As optical networks continue to scale to meet the growing data demand, it will be important to manage these challenges to ensure the reliability and efficiency of next-generation communication infrastructure.

Polarization multiplexing has become an important technology in optical communications, especially as demand for data continues to grow. Using orthogonal polarization states, polarization multiplexing enables simultaneous transmission of two independent data streams over the same optical fiber, effectively doubling the transmission capacity without the need for additional spectral resources. This capability has made polarization multiplexing invaluable in high-capacity transmission systems, where the use of efficient bandwidth is most important to support innovative applications.

High-capacity transmission system

One of the primary applications of polarization multiplexing is in high-capacity transmission systems, where large-scale data must be transmitted over wide distances. As global data traffic increases, long-distance and trans-oceanic fiber optic networks should be able to handle sufficient bandwidth requirements. Polarization multiplexing plays an important role in these systems by effectively doubling the data rate on a fiber, making it possible to maximize the use of existing infrastructure rather than laying new, expensive cables. This capacity enhancement is particularly beneficial in dense wavelength division multiplexing (DWDM) systems, which already maximize spectral efficiency by transferring multiple wavelength channels over a single fiber. In DWDM systems, each wavelength can carry two polarization states (usually vertical and horizontal polarization) thanks to polarization multiplexing, further increasing the data potential without additional spectral demands.

For a typical DWDM setup that involves polarization multiplexing, two independent polarization channels are assigned to each wavelength, resulting in significantly higher data throughput. This approach is particularly beneficial for high-capacity backbone networks and intercontinental fiber optic cables, where adding new fibers is financially and technically difficult. Figure 1 below shows how DWDM polarization combined with multiplexing allows each wavelength channel to carry two distinct polarization states, ultimately improving fiber utilization and transmission efficiency.

Table 3 Combined benefits of DWDM and polarization multiplexing in high-capacity systems.

System	Component	Role
DWDM	Wavelength Channels	Enables multiple wavelengths on a single fiber
Polarization Multiplexing	Vertical & Horizontal Polarizations	Doubles data capacity per wavelength

In addition to DWDM, polarization multiplexing contributes to integrated optical communication systems, which use modern modulation formats to further increase data rates. Coherent systems, using modulation formats such as quadrant phase shift caning (QPSK) and 16-quadrater amplitude modulation (16-QAM), capture both the amplitude and phase of optical signals, allowing each polarization channel to carry more complex modulated signals. In polarization-multiplex integrated systems, this setup effectively doubles the data rate for a specific modulation format by enabling each polarization state to carry an independent data stream. This combination of polarization multiplexing with integrated modulation formats has enabled high-capacity transmission systems to achieve unprecedented levels of data throughput, making it ideal for long-distance communication networks and dense urban environments where efficient data transfer is essential (Acembry & Takach, 2012;

Polarization multiplexing also helps reduce some of the fundamental problems in traditional single-channel transmission, where signal degradation and interference increase with distance. In polarization-multiplex systems, independent polarization channels reduce cross-channel interference, which helps to maintain signal clarity over long distances. Furthermore, when combined with digital signal processing (DSP), polarization multiplexing can help correct transmission defects such as polarization mode dispersion (PMD) and polarization-dependent loss (PDL). DSP algorithms allow the receiver to adjust for variations in polarization states, dynamically compensating for errors that might otherwise impair data quality. This ability is especially important in long-range systems, where even minor disturbances can accumulate and affect signal integrity (IP & Kahn, 2008).

In addition to long-distance networks, polarization multiplexing is becoming increasingly important in metro networks and data center interconnects, where high-speed, high-capacity transmission is required at short distances. In metro networks, polarization helps meet the growing demand for multiplexing data services, such as 5G backhaul, streaming, and cloud connectivity. Polarization multiplexing provides a cheap solution to increase network capacity in densely populated areas by enabling rapid data transfer without increasing spectral demand. Similarly, in data centers, where large amounts of data are constantly transferred, polarization increases data throughput between multiplexing servers and storage facilities. This capability allows data centers to handle large-scale data replication and processing tasks without the need for extensive hardware upgrades, making it a valuable asset in high-demand environments (Kikuchi, 2016).

In integrated optical networks, polarization multiplexing is combined with high-order modulation formats to increase data rates. High-order modulation formats, such as 16-QAM or 64-QAM, allow each symbol to represent more bits by different dimensions and phases. When combined with polarization multiplexing, each polarization channel can carry independent, complex modulated signals, effectively doubling the data throughput. This setup enables networks to achieve much higher spectral performance, which is important for applications of 5G and beyond, where efficient use of spectrum is essential. DSP-equipped integrated receivers detect complex modulated signals and separate polarization channels, allowing accurate data retrieval even in difficult situations, such as dense urban deployment or long-distance transmission (Winzer, 2017).

Optical fiber networks

In optical fiber networks, polarization supports the growing need for multiplexing bandwidth as more devices, applications, and services rely on faster connectivity. In these networks, the ability to transfer two separate data streams on orthogonal polarizations such as vertical and horizontal effectively increases the data rate of fibers without the need for new physical infrastructure. This advantage has made polarization multiplexing a popular choice for enhancing the efficiency of optical fiber networks in both urban metro areas and long-distance links.

A major advantage of polarization multiplexing in optical fiber networks is its compatibility with dens wavelength division multiplexing (DWDM), a technology that already maximizes spectral efficiency by transferring multiple wavelength channels over a single fiber. When combined with polarization multiplexing, each wavelength channel can carry two distinct polarization states, resulting in a substantial increase in data throughput. Table 1 shows how combining DWDM with polarization multiplexing maximizes optical fiber usage, making it possible to handle significantly more data volumes on the same network infrastructure. This combination is particularly beneficial in high-traffic areas such as metropolitan networks, where existing fiber capacity needs to be increased to accommodate the high demand for internet, cloud services, and streaming applications.

Table 4 Combined advantages of DWDM and polarization multiplexing in optical fiber networks.

Technology	Function	Advantage
DWDM	Multiple wavelengths per fiber	Increased data channels
Polarization Multiplexing	Two polarizations per wavelength	Doubles data rate per wavelength channel
DWDM + Polarization Multiplexing	Combined wavelengths and polarizations	Maximizes data throughput per fiber

Furthermore, polarization multiplexing plays an important role in supporting integrated optical communication systems within optical fiber networks. Integrated systems use modern modulation formats to encode more data in each signal, such as quadrater phase shift keying (QPSK) and 16-quadrater amplified modulation (16-QAM). When polarization multiplexing is applied, each polarization channel can carry a separate modulated signal, which effectively doubles the data rate. Integrated receivers, equipped with digital signal processing (DSP) algorithms, can detect and isolate these signals by analyzing both their phase and amplitude, enabling accurate data retrieval. This capability allows optical fiber networks to achieve higher spectral efficiency, supporting a rapid increase in data demand without the need for expensive expansion of existing fiber infrastructure (Winzer, 2017;

Polarization multiplexing in metro networks enables high-speed data transfer in densely populated urban areas where internet usage, video streaming and cloud connectivity are high. Metro networks benefit from polarization multiplexing because it enables efficient use of limited fiber resources by doubling the data capacity on existing cables, reducing the need for additional fiber installations. This performance is particularly valuable in metropolitan areas, where adding new fiber infrastructure is often limited by physical space and financial constraints. Polarization therefore provides a cheaper way to increase the capacity of multiplexing networks and support high data demand in urban networks (Richardson et al., 2013).

Polarization is also important in multiplexing access networks, which connect end users to large metros and long-distance networks. In access networks, where infrastructure limitations are often more pronounced, polarization multiplexing allows network operators to provide high-speed services without extensive construction or deployment of additional fibers. By maximizing data throughput on existing fiber, polarization multiplexing supports the high-speed broadband, streaming, and communication services that consumers demand.

However, implementing polarization multiplexing in optical fiber networks introduces some technical challenges, including polarization mode dispersion (PMD), polarization imbalance, and cross polarization interference. These problems can affect the stability of polarization states, leading to signal degradation and statistical errors. To address these challenges, the DSP algorithm is used to dynamically adjust the parameters of the receiver, compensating for PMD and other drawbacks that may accumulate over long distances. Additionally, polarization controllers help maintain alignment between transmitter and receiver, ensuring that the two polarization channels remain separate during transmission. The combination of DSP and polarization control enables polarization multiplexing to work reliably, even in high-capacity optical fiber networks (IP & Kahn, 2008; Kikuchi, 2016).

Data centers and cloud computing

In data centers and cloud computing environments, where large amounts of data need to be transferred quickly and efficiently, polarization multiplexing plays an important role. As the demand for cloud services, data analytics, and distributed computing grows, the pressure on data centers to process and move large datasets has become more intense. Polarization multiplexing enables faster data rates in existing fiber infrastructure, helping data centers handle more traffic without the need for expensive upgrades or additional cables.

Data centers rely on high-speed optical interconnects to transfer data between servers, storage units, and networking devices. These interconnects should be able to handle large amounts of data to support tasks such as real-time data replication, machine learning processing, and backup services. By applying polarization multiplexing, each fiber link effectively doubles its data capacity, allowing data centers to maintain intense workloads more efficiently. Multiplexing in a large-scale cloud environment run by Google, Microsoft, and Amazon Polarization helps these companies meet high data demand without increasing physical infrastructure, reducing costs, and improving data transfer speed and reliability (Winzer, 2017).

An important area where polarization multiplexing proves particularly beneficial is in the Data Center Interconnect (DCI) system, which connects multiple data centers together. DCI is critical for cloud providers and businesses to ensure data requirement, disaster recovery and load balance in locations. Polarization multiplexing increases the potential of these interconnects, enabling them to support bandwidth-heavy applications such as artificial intelligence (AI) processing, big data analytics, and machine learning. This high capacity helps reduce the need for installation of new fiber cables, a process that can be both expensive and disruptive, especially in urban areas where data centers are often concentrated.

When used in conjunction with dense wavelength division multiplexing (DWDM), polarization multiplexing takes the performance a step further. DWDM allows multiple wavelengths of light to be transferred simultaneously to the same fiber, and with polarization multiplexing, each of these wavelengths can carry two separate data streams on each polarization axis. DWDM and polarization multiplexing together allow data centers to maximize data throughput, even as data traffic volumes increase rapidly due to cloud services, video streaming, and the Internet of Things (IoT). The table below summarizes the combined benefits of DWDM and polarization multiplexing, showing how these technologies work together to increase data center capacity.

Table 5 Combined benefits of DWDM and polarization multiplexing in a data center.

Technology	Function	Application in Data Centers
DWDM	Multiple wavelengths per fiber	Increases the number of channels per link
Polarization Multiplexing	Two polarizations per wavelength	Doubles the data rate per wavelength channel
DWDM + Polarization Multiplexing	Combined wavelengths and polarizations	Enhances data throughput for high-density links

Polarization multiplexing also helps data centers manage their energy consumption more efficiently. Transferring more data to the same infrastructure reduces the need for additional power and cooling, which are major contributors to the operating costs of the data center. As data centers grow, minimizing physical infrastructure can help regulate electricity usage, which is critical to meeting sustainable goals. With increasing pressure to improve energy efficiency, polarization multiplexing provides data centers with a way to achieve higher data rates with low energy demand.

Additionally, polarization enables multiplexing data centers to provide low-latency, high bandwidth connectivity, which is essential for emerging applications that require real-time data processing. Virtual reality (VR), augmented reality (AR) and cloud gaming all rely on fast, reliable data transmission to provide a seamless user experience. By increasing the data capacity of each fiberlink, polarization multiplexing helps ensure that these high bandwidth applications run smoothly. For example, in cloud gaming, where data must be processed and transmitted in real time to avoid delays, polarization multiplexing allows data centers to handle large amounts of connections simultaneously without compromising speed or quality (Acembry & Winzer, 2017).

Despite these advantages, polarization multiplexing in data centers is not without its challenges. Polarization misconceptions can be caused by environmental factors such as temperature changes or fiber defects, which potentially lead to signal degradation. To combat these problems, data centers rely on digital signal processing (DSP) to correct polarization-related errors and maintain stable transmission. DSP algorithms dynamically adjust for any variation in polarization, maintaining signal integrity even in fluctuating conditions (IP & Kahn, 2008;

Future Directions

Polarization multiplexing is poised for continued development as global data demand accelerates and new, more complex applications emerge. Researchers and industry leaders are looking for a number of innovative directions to enhance polarization multiplexing capability, stability and versatility, ensuring that it meets the needs of next-generation communication systems.

An important area of focus is to increase data rates by combining polarization multiplexing with higher-order modulation formats, which is a promising solution for the future of 6G networks and beyond. As telecommunications move towards high-speed, low-delay networks, traditional methods are reaching their limits. Using higher-order modulation formats such as 64-QAM (quadrater amplified modulation) or even 128-QAM allows for more data to be encoded per symbol, increasing transmission capacity. When combined with polarization multiplexing, which doubles data streams on one fiber, these formats can provide the ultra-high capabilities needed for future wireless and fiber-optic networks. However, higher-order modulation introduces complications, as these formats are more susceptible to noise and signal degradation, which require highly accurate digital signal processing (DSP) and integrated detection techniques to maintain signal integrity over long distances (Richardson et al, 2013;

Another interesting approach is the use of machine learning (ML) and artificial intelligence (AI) to manage polarization changes in real time. One of the long-standing challenges in polarization multiplexing is the dynamic nature of polarization states, which can fluctuate due to environmental factors such as temperature changes or fiber defects. Currently, maintaining stable transmission involves complex DSP and polarization control systems, which increase cost and energy demand. ML and AI offer a more favorable approach: by predicting polarization changes based on previous data, artificial intelligence-powered systems can actively adjust alignment and reduce problems such as polarization mode dispersion (PMD) and cross polarization interference (XPI). These intelligent systems can improve polarization management autonomously, making polarization multiplexing more flexible, especially in high-capacity, long-range communication systems where stability is important (Zhong et al., 2020;

Another promising development is to integrate polarization multiplexing with space division multiplexing (SDM). While polarization multiplexing uses orthogonal polarization states, SDM works by transferring data through multiple local channels within a single fiber, such as in a multicore or multimode fiber. By combining polarization multiplexing with an SDM, each core or mode can carry two independent polarization states, rapidly increasing the data capacity of a fiber. This integrated approach can be especially effective for ultra-high-capacity networks, such as trans-ossine cables or inter-data center connections, where both space and capacity are at a premium (Winzer, 2017;

The potential for polarization multiplexing is also being investigated in free space optical (FSO) communications, a technology that uses light to transmit data through the atmosphere rather than fiber. FSO is gaining interest as a means of connecting satellites, ground stations and even ground networks without the need for physical infrastructure. Polarization can effectively double the data rate of the FSO system without increasing the multiplexing bandwidth a key advantage where the spectrum is limited. However, the FSO introduces unique challenges, such as environmental turbulence, that can disrupt polarization states. Researchers are looking for ways to adopt polarization control and stabilization techniques, such as adaptive optics, to mitigate these effects, making polarization multiplexing feasible in FSO environments where reliable high-speed data transfer is necessary (Kikuchi, 2016).

Energy efficiency is another area where polarization multiplexing has significant potential. As data centers and telecommunication networks expand, so does rising energy costs and the need for sustainable methods to manage carbon footprints. Future advances in polarization multiplexing are likely to focus on reducing the power consumption of related components, such as DSP units, polarization controllers, and integrated receivers. Efficient DSP algorithms and low-power AI solutions can streamline the polarization control process, adjust only when needed, and save energy. By making polarization multiplexing more energy efficient, data centers can better manage power and cooling requirements while continuing to support high-speed data operations (Yan et al., 2018).

Looking further into the future, researchers are also exploring how polarization multiplexing can be applied in quantum communications. Quantum key distribution (QKD) relies on polarization states to encode quantum bits (qubits) for highly secure data transfer, a technique that has already been proven in controlled experimental settings. By incorporating polarization multiplexing with QKD, it may be possible to produce safe, high-capacity quantum communication channels, where each polarization state independently encodes quantum information. This approach can revolutionize data security in sectors such as finance, government, and defense, where high data integrity and privacy are highest. Although practical, large-scale applications of polarization multiplexing in quantum communications are still in development, they represent an interesting frontier for both scientific exploration and applied technology (Bennett & Brassard, 1984;

As these advances unfold, polarization multiplexing will likely play an increasingly central role in enhancing the capabilities of optical networks and data centers. By combining traditional techniques with innovative methods such as machine learning, space division multiplexing and quantum applications, future polarization multiplexing technologies will be well equipped to meet the growing needs of our data-driven world. This ongoing evolution promises not only to enhance the efficiency and capacity of global communication networks but also to provide new opportunities for secure, sustainable and highly acceptable communication systems.

Conclusion

Polarization multiplexing has emerged as a key technology in optical communications, providing an effective solution to the growing demands for high-speed, high-capacity data transmission. Taking advantage of orthogonal polarization states, this technique enables the simultaneous transmission of multiple data streams over a single optical fiber, effectively doubling its capacity. Throughout this paper, we explore the applications, challenges, and future directions of polarization multiplexing, highlighting its role in various domains, including high-capacity transmission systems, optical fiber networks, , data centers, and cloud computing. In high-capacity transmission systems, polarization multiplexing seamlessly combines with dense wavelength division multiplexing (DWDM) and coherent detection, supporting the large data rates required for long-haul and trans-sea networks. does Optical fiber networks, particularly in metropolitan areas, benefit significantly from polarization multiplexing because it maximizes existing infrastructure without the need for expensive expansion. For data centers and cloud environments, polarization multiplexing facilitates faster and more efficient data transfer, meeting the demands of real-time applications and large-scale data processing while also promoting energy efficiency. is While polarization multiplexing offers considerable advantages, its implementation comes with inherent technical challenges, such as polarization mode dispersion (PMD), cross-polarization interference (XPI), and polarization mismatch. Addressing these issues requires ongoing improvements in advanced digital signal processing (DSP), polarization controllers, and optical fiber technology. Future advances in machine learning and AI are expected to enhance real-time polarization management, while integration with space-division multiplexing (SDM) and free-space optical (FSO) communications will further expand its potential applications. will give Moreover, the combination of polarization multiplexing with emerging quantum communication techniques offers exciting possibilities for secure, high-capacity quantum networks.

References

1. Winzer, P. J., & Essiambre, R. J. (2006). Advanced optical modulation formats. Proceedings of the IEEE, 94(5), 952-985.
2. Kahn, J. M., & Ho, K. P. (2004). Spectral efficiency limits and modulation/detection techniques for DWDM systems. IEEE Journal of Selected Topics in Quantum Electronics, 10(2), 259-272.
3. Kikuchi, K. (2016). Fundamentals of coherent optical fiber communications. Journal of Lightwave Technology, 34(1), 157-179.
4. Ip, E., & Kahn, J. M. (2008). Compensation of dispersion and nonlinear impairments using digital backpropagation. Journal of Lightwave Technology, 26(20), 3416-3425.
5. Cisco. (2020). Cisco Annual Internet Report (2018–2023). https://www.cisco.com/
6. Snyder, A. W., & Love, J. D. (1983). Optical Waveguide Theory. Springer Science & Business Media.
7. Essiambre, R. J., & Tkach, R. W. (2012). Capacity trends and limits of optical communication networks. Proceedings of the IEEE, 100(5), 1035-1055.
8. Shieh, W., & Djordjevic, I. B. (2010). Orthogonal frequency division multiplexing for optical communications. Academic Press.
9. Richardson, D. J., Fini, J. M., & Nelson, L. E. (2013). Space-division multiplexing in optical fibres. Nature Photonics, 7(5), 354-362.
10. Bennett, C. H., & Brassard, G. (1984). Quantum cryptography: Public key distribution and coin tossing. Proceedings of IEEE International Conference on Computers, Systems, and Signal Processing.
11. Gisin, N., Ribordy, G., Tittel, W., & Zbinden, H. (2002). Quantum cryptography. Reviews of Modern Physics, 74(1), 145-195.
12. Zhao, Y., Xue, X., Ren, X., Li, W., Guo, Y., Yang, C., ... & Huang, S. (2023). Optical switching data center networks: understanding techniques and challenges. Computer Networks and Communications, 272-291.
13. Kachris, C., Kanonakis, K., & Tomkos, I. (2013). Optical interconnection networks in data centers: recent trends and future challenges. IEEE Communications Magazine, 51(9), 39-45.