ARTICLE IN PRESS

Optics Communications ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Invited Paper

Transmission of multi-dimensional signals for next generation optical communication systems

Anlin Yi, Lianshan Yan *, Yan Pan, Lin Jiang, Zhiyu Chen, Wei Pan, Bin Luo

Center for Information Photonics & Communications, School of Information Science & Technology, Southwest Jiaotong University, Chengdu, Sichuan, 611756, China

ARTICLE INFO

Keywords:
Optical communication
Multi-dimension
Polarization-division-multiplexing (PDM)
Pseudo-PDM

ABSTRACT

Over the past several decades, the data-carrying capacity of a single optical fiber have been increased significantly by fully exploring and optimizing physical dimensions of the light. Generally there are five major candidates of dimensions, including time, wavelength, polarization, space and quadrature (phase and amplitude). Multi-dimension, utilizing more than two dimensions of the light simultaneously, is one of the essential characteristics of next generation optical communication systems. We review recent advances in transmission of multi-dimensional signals, and highlight innovative ways of exploring the polarization dimension to further increase the capacity or spectral efficiency of a single optical fiber, a so-called pseudo-polarization-division-multiplexing (PPDM) technique. Related demonstrations include non-orthogonal PDM, PPDM of three and four states (PPDM-3 and PPDM-4). Brief discussions on trends of multi-dimensional signal transmission technologies are also presented.

1. Introduction

With the rapid development of Internet-driven services, especially the explosive increases of the Internet-based video and peer-to-peer interactive applications, the global IP traffic broke the Zettabyte (ZB) threshold at the end of 2016 and it will grow at a compound annual growth rate (CAGR) of 22 percent from 2015 to 2020. By the end of 2020, global traffic will reach 2.3 ZB per year, or 194.4 EB per month under Cisco's forecast and methodology (Fig. 1) [1]. As a result, a global community of researchers and engineers is relentlessly striving to improve the backbone and local network infrastructures that can carry more data, more efficiently than ever before. Over the last several decades, optical communication technologies have been advancing rapidly, supporting the ever-growing bandwidth requirements. The transmission capacity of a single optical fiber now is up to 2.15 Pb/s [2]. To increase this figure-of-merit, researchers have been striving to find innovative ways to explore and optimize the physical dimensions of optical light. As shown in Fig. 2, mainly five physical dimensions can be used for modulation and multiplexing to increase the capacity over optical fiber links, i.e. time, wavelength, polarization, space (multicore fiber, linearly polarized (LP) modes, orbital-angular momentum (OAM) and vector modes) and quadrature (phase and amplitude) [2–12]. Obviously, ***multi-dimension***, utilizing more than two dimensions of the light simultaneously to increase the overall capacity, is one of the essential characteristics of next generation optical communication systems.

In this paper, we first give a brief overview of recent advances in transmission of multi-dimensional signals for next generation optical communication systems, with an emphasis on optical time-division-multiplexing (OTDM), wavelength-division-multiplexing (WDM), space-division-multiplexing (SDM), quadrature modulation and polarization-division-multiplexing (PDM). In Section 3, we present recent advances of exploring polarization dimension to increase the transmission capacity over standard single-mode-fiber (SMF) links, including non-orthogonal PDM, pseudo-PDM (PPDM) of three and four polarization states (PPDM-3 and -4). In Section 4, before the summary, we will briefly discuss the trends and challenges of multi-dimensional signal transmission technologies.

2. Review of multi-dimensional signals transmission technologies

As shown in Fig. 2, five physical dimensions can be employed to carry optical signals: time, wavelength, space, quadrature and polarization. These dimensions can be utilized independently or simultaneously to increase the data-carry capacity of optical communication systems.

* Corresponding author.
E-mail address: lsyan@swjtu.edu.cn (L. Yan).

http://dx.doi.org/10.1016/j.optcom.2017.07.046
Received 6 May 2017; Received in revised form 3 July 2017; Accepted 16 July 2017
Available online xxxx
0030-4018/

Please cite this article in press as: A. Yi, et al., Transmission of multi-dimensional signals for next generation optical communication systems, Optics Communications (2017), http://dx.doi.org/10.1016/j.optcom.2017.07.046.

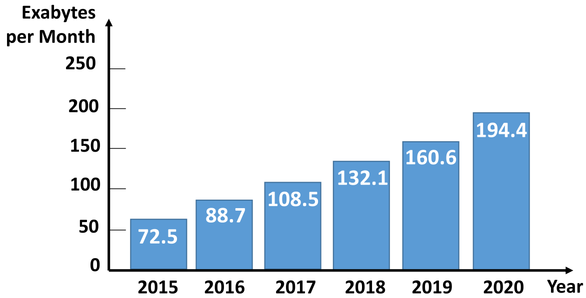

Fig. 1. Global IP traffic forecast and methodology (Source: Cisco VNI Ref. [1]).

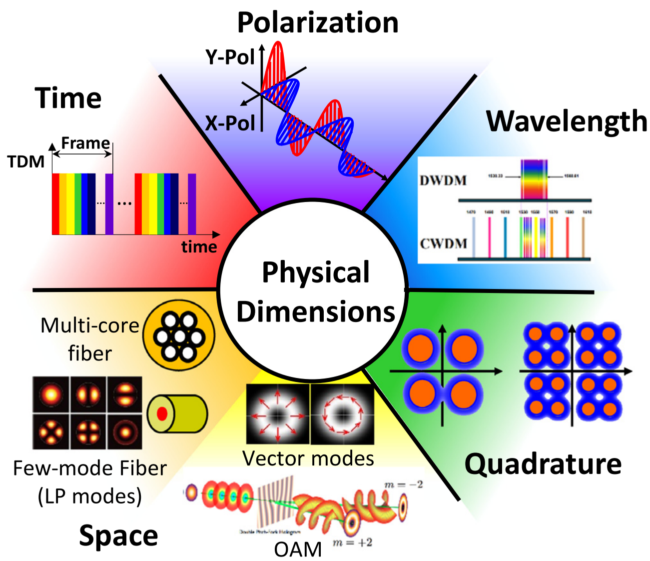

Fig. 2. Physical dimensions for optical communications.

2.1. Time dimension

The ***time dimension*** is exploited to increase the capacity over fiber by multiplexing signals in different bit slots in the time domain. In other words, it is practical to combine a set of low-bit-rate streams, each with a fixed and pre-defined bit rate, into a single high-speed bit stream that can be transmitted over fiber. This technique is well known as TDM. To optimize multiplexing in the time dimension, pulse shaping may be used to compress the spectrum of the temporal pulse subject to fundamental time-frequency constraints, and multi-level modulation formats may be employed to further increase bit-rate per pulse (e.g. PAM-4) [3,7]. TDM may be realized by electrical multiplexing (ETDM) or by optical multiplexing (OTDM) to a high-speed data signal [13–17]. Currently, almost all installed TDM optical communication systems are utilized ETDM. Experimental OTDM transmission was demonstrated as early as 1993 with bit rate of 100 Gb/s over 36 km fiber [15]. Since then, OTDM-transmission technologies have made a lot of advances toward much higher bit rates and much longer transmission links. 160 Gb/s transmission over a record length of 4320 km was reported in Ref. [16] and a record data rate of 2.56 Tb/s transmission over 160 km was reported in Ref. [17]. However, it is still a challenging task for OTDM technology to investigate the physical limits of ultra-high-speed and ultra-long haul fiber transmission and to search for appropriate and more practical techniques for data generation, transmission, and demultiplexing to extend these limits.

2.2. Wavelength dimension

Using the ***wavelength dimension***, one may multiplex a number of optical signals onto a single optical fiber by parallel using distinct wavelengths of the laser light, namely WDM in optical communications. In practical optical communication system, WDM technique, already an "inherited" one, usually combines with SDM, PDM, and quadrature modulation formats to increase the capacity of a single fiber. Additionally, to meet the bandwidth requirements, the capacity is increased by extending the WDM wavelength band from C-band to S-, L-, and U-band, as well as decreasing the channel space from 100 GHz to 50 GHz or even down to 25 GHz [9,18,19].

2.3. Space dimension

SDM, which utilizing the spatial dimension, refers to multiplexing techniques that establish multiple spatially distinguishable data paths through a single fiber. The SDM can be achieved by four ways, i.e. multi-core fiber (MCF), LP modes multiplexing using multi-mode-fiber (MMF), OAM and vector modes multiplexing. In the case of MCF, in which the distinguishable paths are defined by physically distinct single-mode cores (Fig. 2). The initial proposal of SDM using MCF were aimed at short-reach applications. *B. Rosinki* et al. firstly demonstrated 1 Gb/s data transmission over two cores of 4 core MCF at a wavelength of 850 nm [20]. Following greatly advances in the design and fabrication of single-mode MCF and related components (e.g. amplifier) [21–24], demonstrations of SDM transmission over MCF for long-haul applications have been showing impressive advances in terms of capacity, reach and spectral efficiency. Table 1 shows the mainly advances that have been made during the last few years. *H. Takara* and co-workers [25] firstly reported the Pb/s (1.01 Pb/s) capacity transmission experiment over 52 km 12 core MCF. Later, *H. Takahashi*' group demonstrated a long-haul (over 6160 km), WDM (40×103 Gb/s) transmission over MCF by firstly utilizing a multicore EDFA [26] and a record capacity-distance product of 1030.768 Pb/s × km was achieved [27]. *A. Turukhin* and co-workers transmitted a single wavelength and total capacity of 1.282 Tb/s 8D-APSK signal over the longest transmission distance over 14 350 km 12 core MCF by utilizing single mode EDFA [28]. *T. Mizuno* and co-workers reported a record 32 core long distance dense SDM (DSDM) transmission of over 1644.8 km using a crosstalk-managed transmission line [29]. Most recently, this group demonstrated the first 1 Pb/s DSDM unidirectional inline-amplified transmission experiment over 205.6 km of 32 core fiber using 100 GHz-spaced C-band WDM, utilizing a low crosstalk heterogeneous multi-core fiber [30].

MMF utilizes the linearly polarized modes to establish multiple spatially distinguishable data paths in a multi-mode fiber, which is well known as mode-division multiplexing (MDM). It is quite different from SDM transmission in MCF that the distinguishable mode paths have significant spatial overlap, and consequently signals are susceptible to coupling randomly among the modes during propagation [6–8]. To mitigate the crosstalk resulting from modes coupling during propagation, multiple-input multiple-out (MIMO) digital signal processing (DSP) techniques are needed at the receiver [31]. However, the DSP complexity requirements will increase rapidly with the multiplexed modes. Therefore, most significant MDM demonstrations have so far concentrated to few-mode fibers [32–42]. Table 2 shows the recent advances in MMF systems demonstrations. *R. Ryf* and co-workers transmitted 6 spatial modes and 32 WDM channels 16-QAM signals over 177 km FMF at spectral efficiency of 32 b/s/Hz [37], and 6 spatial modes and 32 WDM channels QPSK signals over 708 km FMF at a spectral-efficiency-distance product of 11 328 km × b/s/Hz [38]. A later, the longest transmission distance of 900 km for 32 WDM channels and 3 spatial modes with a 100 GHz channel spacing and a distance of 1500 km for a single wavelength channel 3 spatial modes experiment were achieved [39]. Most recently, the record of 15 spatial modes transmission over 23.8 km FMF was reported in Ref. [40]. The longest

Please cite this article in press as: A. Yi, et al., Transmission of multi-dimensional signals for next generation optical communication systems, Optics Communications (2017), http://dx.doi.org/10.1016/j.optcom.2017.07.046.