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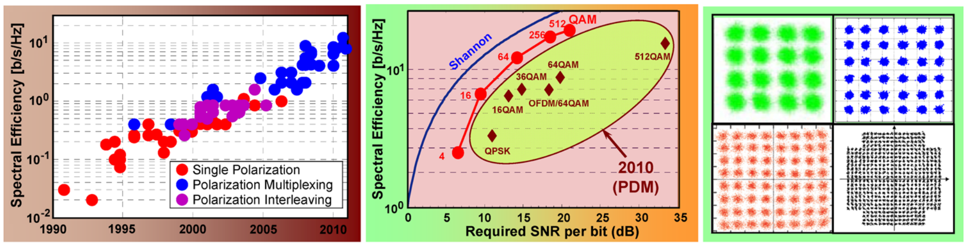

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Toward the Shannon Limit of Spectral Efficiency

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(Invited Paper)

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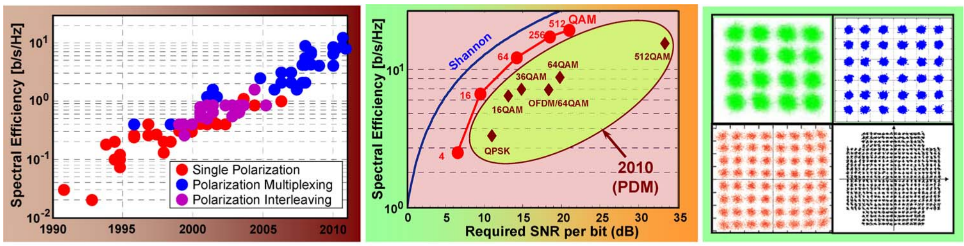
Abstract: Progress in high-capacity optical communication systems in 2010 is reviewed, with spectral efficiency (SE) as the main figure of merit. Advanced modulation formats, such as quadrature amplitude modulation (QAM) and orthogonal frequency-division multiplexing (OFDM), together with polarization-division multiplexing (PDM) and digital coherent detection, are playing key roles in approaching the Shannon limit of SE for optical fiber communication. Photonics is now entering into a new era of high SE on par with electronics (wireless), yet with orders of magnitude higher overall system capacity.

Index Terms: Fiber optics, optical fiber communication, Shannon limit, spectral efficiency.

Ever since Shannon disclosed the information capacity limit in a noisy communication link [1], researchers have put tremendous effort into approaching it in both wireless and optical links over the past few decades. Optical fiber communication systems and networks have been playing important roles in supporting the exponentially increasing information traffic around the globe [2], [3]. To grasp the sustainability of the capacity growth, the Shannon limit in optical fiber networks has been theoretically studied [4]–[8] and experimentally explored. There have been multiple “hero” experiments setting new records in high-capacity optical communication every year over the past three decades, and the year of 2010 was no exception. These recent advances are underpinned by various key technologies, including advanced modulation, polarization-division multiplexing (PDM), digital coherent detection, digital signal processing, advanced coding, advanced fiber technologies, and photonic integration. Among these technologies, advanced modulation combined with digital coherent detection is the key enabler. Quadrature amplitude modulation (QAM) and coherent optical orthogonal frequency-division multiplexing (CO-OFDM) are the two popular modulation formats explored in lab demonstrations, with high potential to be commercially deployed in the near future.

In this paper, we give a brief review on the major breakthroughs in the field of optical fiber communications in 2010, highlighting the enabling techniques and demonstrations with a focus on high spectral efficiency (SE). The intent of this review is not to present the pros and cons of various technologies, but rather to provide a literature survey for the photonics community.



(a) (b) (c)

Fig. 1. (a) Historical evolution of spectral efficiency (updated figure from [8]). (b) Major high spectral-efficiency demonstrations in 2010 showing the trend toward the Shannon limit. (c) Signal constellations of 16-QAM [33], 36-QAM [28], 64-QAM [29], and 512-QAM [30] demonstrated in 2010.

2. Device and Subsystem Improvements

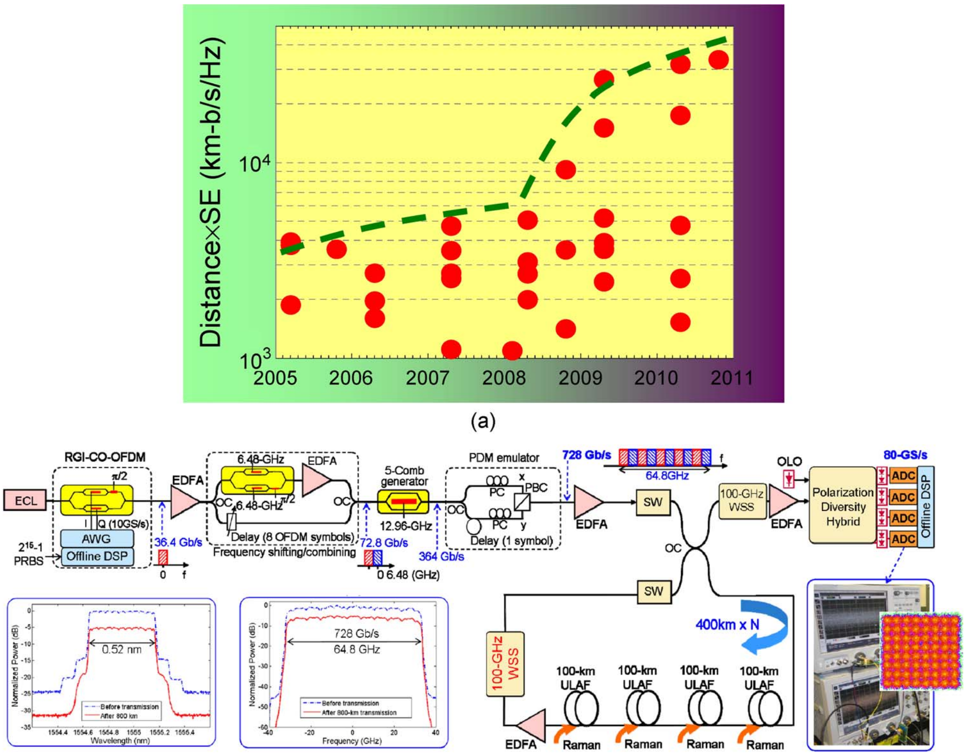
We begin with the enabling techniques at the device and sub-system levels that are fundamental to enhance system performance. In 2010, various noteworthy implementations were accomplished. For signal generation, i) Yamazaki *et al.* demonstrated a 64-QAM modulator based on silica photonic integrated circuits (PLCs) and LiNbO3 phase modulators [9]; ii) Winzer *et al.* generated a 56-Gbaud PDM 16-QAM data stream using a single I/Q modulator [10]; and iii) Yi *et al.* [11] and Hillerkuss *et al.* [12] showed Tb/s OFDM signal generation from frequency-locked optical combs. For signal reception, i) Nagarajian *et al.* reported a 10-channel (45.6-Gb/s/channel) PDM differential quadrature phase-shift keying (DQPSK) InP receiver based on PLCs [13]; ii) Fischer *et al.* demonstrated a 128-Gb/s QPSK digital coherent receiver with parallel optical sampling [14]; iii) Shen *et al.* designed a polarization demultiplexer and polarization-mode-dispersion (PMD) compensator for a 112-Gb/s direct-detected PDM return-to-zero (RZ) DQPSK system [15]; and iv) Kaneda *et al.* showed a real-time 2.5-GS/s coherent receiver for sub-band detection of a 53.3-Gb/s OFDM signal [16]. As a complementary approach to the high-speed electronic DSP-based PMD compensation and polarization demultiplexing, optical polarization tracking at a speed up to 59 krad/s was demonstrated in a 112-Gb/s PDM-RZ-DQPSK transmission experiment [17]. Another key breakthrough was the development of high-speed analog-to-digital converters (ADCs) at 56 Gb/s [18], which enabled the implementation of digital coherent receivers at 100-Gb/s and beyond [7].

3. Channel Data Rate Increase

It is desirable to increase the data rate per wavelength channel beyond the currently commercialized 100 Gb/s [8]. Using spectrally efficient reduced-guard-interval (RGI) CO-OFDM and high-speed ADCs, Liu *et al.* [19]–[21] demonstrated the detection of 448-Gb/s, 606-Gb/s, and 728-Gb/s signals with a single coherent detection front-end, which allows for a simple transceiver architecture for cost-effective system upgrade. As the data rate of a channel continues to increase, the sampling speed of ADC will eventually limit the data rate that can be received in a single-detection step, and this calls for banded detection or optical time-division multiplexing (OTDM). Several groups have achieved Tb/s transmission using CO-OFDM with banded detection [22], [23] and OTDM with multiple parallel receivers [24]. A comprehensive study on the use of OFDM to form high-SE superchannel was reported by Chandrasekhar *et al.* [25]. An interesting scheme to approach the SE of OFDM using Nyquist WDM was recently proposed and studied [26].

4. SE Increase

To increase the total capacity of optical fiber communication system within a limited bandwidth (generally determined by the bandwidth of optical amplifiers), one has to increase the channel SE. PDM is an effective technique to double the SE by carrying two independent data streams on two orthogonal polarization states at the same wavelength. Fig. 1(a) illustrates the SE increase enabled



(a)

(b)

Fig. 2. (a) Historical evolution of the distance-SE product (in km-b/s/Hz) over the last six years. (b) An exemplary experimental setup utilizing enabling techniques such as 64-QAM, RGI-CO-OFDM, PDM, digital coherent detection, and low-loss low-nonlinearity fiber (after [21]).

by polarization interleaving and PDM since 1990. Fig. 1(b) summarizes the major results on high-SE transmission obtained in 2010 [19]–[21], [27]–[30]. Typical recovered signal constellations of PDM-16QAM [27], OFDM/32QAM [20], PDM-64QAM [29], and PDM-512-QAM [30] are shown in Fig. 1(c). Note that the Shannon limit curve plotted in Fig. 1(b) is for the case with PDM but without the consideration of fiber nonlinearity. The nonlinear Shannon limit in the PDM case is still under active study [6]. Note also that the gap between the obtained SE and the Shannon SE limit becomes larger at higher SE, indicating larger fiber nonlinearity penalties and implementation penalties for signals with larger constellation sizes.

5. Overall Performance Increase

The results in Fig. 1 are plotted based on SE. Apparently the SE alone is not sufficient to evaluate the overall system performance. Here, we use two different figures of merit (FOMs): the product of transmission distance and capacity (Distance × Capacity) and the product of transmission distance and SE (Distance × SE). In addition to those already highlighted, there are also several "hero" experiments during 2010 achieving impressive overall performance, e.g., long transmission distance of a few thousands of kilometers and high capacity of tens of Tb/s with SE higher than 3 bit/s/Hz) [31]–[34]. Various enabling techniques are employed in these systems to achieve these levels of performance. We further draw the FOM in term of Distance × SE within the period of last five years (2005–2010) in Fig. 2(a). Notably, this FOM was essentially **flat** from 2005 to 2007 but **dramatically increased** after the emergence of the aforementioned enabling technologies such as QAM, OFDM, PDM, and digital coherent detection. An exemplary experimental setup [21] that utilized most of these technologies is shown in Fig. 2(b). In addition, ultra-large-area fiber (ULAF) was used to reduce both fiber loss and nonlinear coefficient in some of these hero experiments.

6. Other Highlights

As impressive as the above breakthrough lab demonstrations are field trials of high-speed (i.e., $>$ 100-Gb/s/channel) data transmission carried out over existing commercial links reported in March 2010 [35], [36], especially Verizon's test based on native internet protocol traffic at 100-Gb/s [35]. Such trials provide valuable information for the actual deployment of 100G Ethernet. More recently, a single-wavelength 112-Gb/s transceiver based on PDM-QPSK and digital coherent detection has become a commercial reality [37].

As more techniques are employed in optical communication systems to enhance the overall performance, some new challenging issues are appearing and have to be addressed. These include the well-known but complicated fiber nonlinearity issue. There are sustained efforts to mitigate or compensate certain types of fiber nonlinear effects [38], [39].

Another enabling technique that is worth mentioning is the optical signal processing approach in high-speed systems. In 2010, there were several papers covering different signal processing functionalities, such as phase-sensitive regeneration of DPSK signals [40], optical regeneration of PDM signals [41], and orthogonal tributary channel exchange for PDM signals [42]. Although these all-optical approaches are not yet sufficiently mature for practical implementations, they open new possibilities to further enhance the optical communication performance.

7. Concluding Remarks

In summary, numerous exciting advances took place in 2010 to push the limit of optical communication systems in terms of channel data rate, SE, overall capacity, and transmission distance. We highlighted these breakthroughs through several updated figures. Remarkably, recent optical fiber transmission demonstrations are already not too far away from the Shannon limit of single-mode fiber-optic transmission any more [6]. It is expected that riding on Moore's law, future advances in electronics [43] will continue to both demand and enable further capacity growth in optical communications. It may be desirable to relax the nonlinear Shannon limit by using new fibers with lower loss and/or lower nonlinear coefficients and developing nonlinearity mitigation strategies. Furthermore, potential utilization of the spatial degree of freedom through novel fibers, possibly by means of MIMO techniques, is a new direction worth exploring [2], [44]. With the increase in capacity, the cost per bit needs to be reduced as well in order to allow for sustainable capacity growth. Therefore, advances in the area of photonic integrated circuits are deemed to be essential.

Facing "the coming capacity crunch" [2], one can be assured that continued "research in this area is essential, challenging, and likely to be interesting" [3], as well as rewarding, both intellectually and economically.

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