Research Highlights

Modulation and multiplexing in optical communication systems

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Digital electronics and optical transport

The rapid transition from analog to digital systems over the past ~50 years has enabled universal processing of all kinds of information, fundamentally without loss of quality [1]. Breakthroughs in digital semiconductor technologies and their enormous ability to scale [2] have enabled cost-effective mass-production of richly functional yet highly reliable and power-efficient microchips that are found in virtually any electronic device today, from high-end internet routers to low-end consumer electronics.

Closely coupled to the generation, processing, and storage of digital information is the need for data transport, ranging from short on-chip [3] and board-level [4,5] data buses all the way to long-haul transport networks spanning the globe [6,7] and to deep-space probes collecting scientific data [8], cf. Fig. 1 [5,10]. Each of these very different applications brings its own set of technical challenges, which can be addressed using electronic, radio-frequency (RF), or optical communication systems. Among the different communication technologies, optical communications generally has the edge over baseband electronic or RF transmission systems whenever *high aggregate bit rates* and/or *long transmission distances* are involved. Both advantages are deeply rooted in physics: First, the high optical carrier frequencies allow for high-capacity systems at small relative bandwidths. For example, a mere 2.5% bandwidth at a carrier frequency of 193 THz (1.55 μm wavelength) opens up a 5-THz chunk of continuous communication bandwidth. Such "narrow-band" systems are much easier to design than systems with a large relative bandwidth. Second, transmission losses at optical frequencies are usually very small compared to baseband electronic or RF technologies. Today's optical telecommunication fibers exhibit losses of less than 0.2 dB/km; the loss of typical coaxial cables supporting ~1 GHz of bandwidth is 2 to 3 orders of magnitude higher. In free-space systems optical beams have much smaller divergence angles than in the microwave regime[1], at the expense of significantly exacerbated antenna pointing requirements, though. The narrow beam width favorably translates into the system's link budget, in particular in space-based systems where atmospheric absorption is less of a problem. Apart from the above two major advantages, other considerations sometimes come into play, such as the unregulated spectrum in the optical regime or the absence of electromagnetic interference.

The gradual replacement of electronic transport

The suitability of optical communications for different system scenarios can be further analyzed using the three basic transponder characteristics shown in Fig. 2: A transponder's *sensitivity* measures the minimum power (or the minimum signal-to-noise ratio) required by the receiver to close a digital communication link, which impacts the link distance that may be bridged. In this loosely defined context, the term "sensitivity" also includes the effect of linear and nonlinear signal distortions due to the transmission channel. The *capacity* of a system measures the amount of data that can be transmitted over the communication medium. Here, we think of the capacity *per waveguide*, with the understanding that parallel lanes (buses) are likely to be used in applications that require high aggregate capacities at tight transponder integration requirements. In many applications, *implementation* aspects of a transponder (including its physical dimensions, power consumption, cost, and reliability) are the most critical parameters and often delay the entrance of optics into a particular application space. The figure roughly indicates the relative

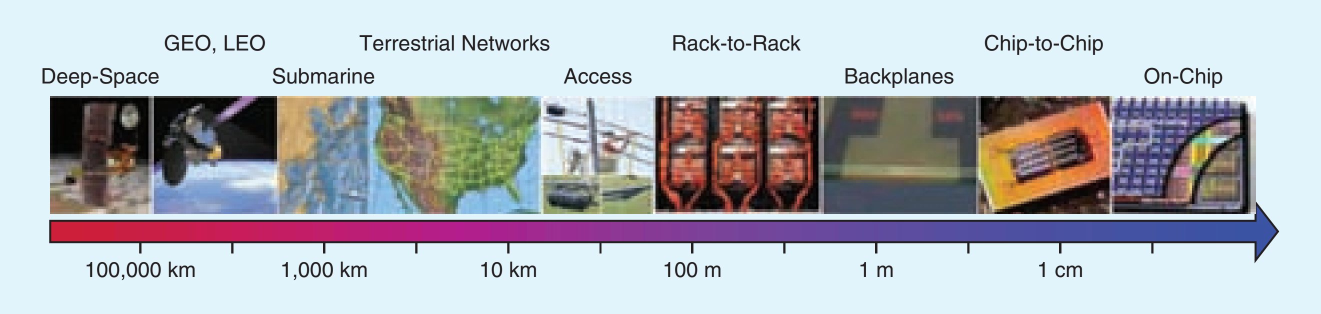

Figure 1. Digital communication distances can be over 100,000 km in deep-space missions and below 1 mm on-chip. (GEO: Geostationary satellite orbit; LEO: Low-Earth satellite orbit.) Figures reproduced with permission. From left to right, courtesy of (1) NASA/JPL-Caltech; (2) European Space Agency (ESA); (3) Alcatel-Lucent; (4) Alcatel-Lucent [11]; (5) Corning, Inc. [9]; (6) – (9) IBM [3].

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[1] The divergence angle of an antenna of diameter D operating at wavelength λ is given by λ/D. At 1μm, a telescope (=antenna) of 10 cm diameter has a divergence angle of 10 μrad (=0.6 mdeg).

importance of the three performance metrics for different communication applications.

As bandwidth demands have continuously increased and as opto-electronic device and integration technologies have advanced, optical communications has gradually replaced electronic (and to some extent directional[2] microwave) solutions. This process started on a large scale in the late 1970s and 1980s at the most demanding high-bandwidth/long-distance applications of terrestrial [6] and submarine [7] transport. With massive fiber-to-the-home (FTTH) deployments now underway world-wide, optics is currently capturing the access space [9], and rack-to-rack interconnects are starting to become optical [3]. The red application areas in Fig. 2 indicate well established optical communication technologies. The applications marked orange denote areas where optics can be found but is not yet used on a massive scale. The blue applications are still dominated by electronics, with research on optical successors being actively pursued. Despite the continuing improvement in electronic transmission techniques [12], optical solutions are expected to enter backplanes, paving the way to optical chip-to-chip and, eventually, on-chip communications once electronic transmission can no longer keep pace with the growing need for communication capacity, power consumption, or "escape bandwidth", i.e., the interconnect capacity per unit of interface area [3,4,5]. At the same time, areas where optical communications is already well established have to continue supporting ever-increasing capacity demands.

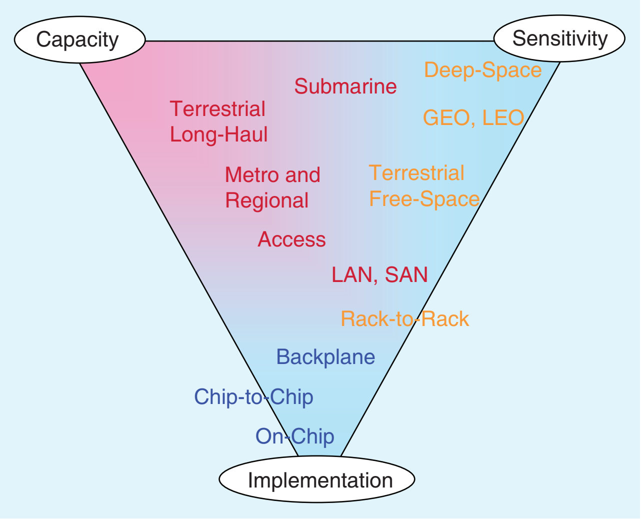

Figure 2. Sensitivity, capacity, and implementation aspects (physical dimensions, power consumption, and cost) are key factors behind the success of any communication technology. Starting from "high sensitivity / high capacity" applications (terrestrial and submarine long-haul), optical communications is steadily replacing electronic transmission technologies.

Orthogonal dimensions and multiplexing

In order to meet the application-specific requirements on sensitivity and capacity under the respective implementation constraints, one has to choose the best suited *modulation* and *multiplexing* techniques based on the available physical dimensions shown in Fig. 3 [13].

Of particular importance in this context is the notion of *orthogonality* [15]. Loosely speaking[3], two signals are orthogonal if messages sent in these two dimensions can be uniquely separated from one another at the receiver without impacting each other's detection performance. This way, independent bit streams can share a common transmission medium, which is referred to as *multiplexing*. The amount of individual bit streams that can be packed onto a single transmission medium determines a system's *aggregate capacity*. The most advanced multiplexing techniques are therefore found in capacity-constrained systems, such as long-haul fiber-optic transport (cf. Fig. 2).

Multiplexing is performed by exploiting orthogonality in one or more of the physical dimensions shown in Fig. 3. Sending signals in disjoint frequency bins on different optical carrier frequencies is called wavelength-division multiplexing (WDM), cf. Fig. 4. Such signals are orthogonal, and individual bit streams can be recovered using optical bandpass filters or electronic filters following a coherent receiver front-end [16]. If signals leak energy into neighboring frequency bins, orthogonality is degraded and perfect reconstruction is no longer possible ('WDM crosstalk'). As shown in Fig. 4, a possible counter-measure, which has been used in some research demonstrations, is alternating the polarization of adjacent channels to re-establish orthogonality in the polarization dimension ('polarization interleaving').

Using true *polarization-division multiplexing* (PDM, cf. Fig. 4), one sends two independent signals on both orthogonal polarizations supported by a single-mode optical fiber. In order to recover these polarization-multiplexed bit streams, one either uses a polarization beam splitter whose axes are constantly kept aligned with the signal polarizations ('polarization control'), or one detects two arbitrary orthogonal polarizations ('polarization diversity') using coherent detection. Since upon fiber transmission the polarization axes at the receiver will be randomly rotated compared to the transmitter, one electronically back-rotates the detected signals using the (estimated) inverse Jones matrix of the transmission channel. This is the approach taken by modern coherent receivers [16].

Another way of achieving orthogonality in the frequency domain is by letting the signal spectra at adjacent wavelengths overlap but choosing the frequency spacing to be exactly $1/T_S$, where T_S is the symbol duration, synchronized across the individual (sub)carriers. This approach is visualized in time and frequency domain in Fig. 5. Although the superposition of the three modulated signals (examples shown are '1+2+3' and '1−2+3') looks unintelligible at a first glance, a receiver can uniquely filter out the information transported by each subcarrier by first multiplying the superposition with a sine wave of the desired subcarrier's frequency and then integrating over the symbol duration. This operation can be particularly efficiently done in the electronic domain using the fast Fourier transform (FFT). This kind of multiplexing is known as orthogonal frequency division multiplexing (OFDM) [17] or coherent WDM

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[2] Owing to the inherently high directionality of optical antennas, microwave systems will likely continue to be the solution of choice for mobile environments requiring omni-directional reception and transmission.

[3] A rigorous definition of orthogonality in the context of optical communications is given in, e.g., [13,14].

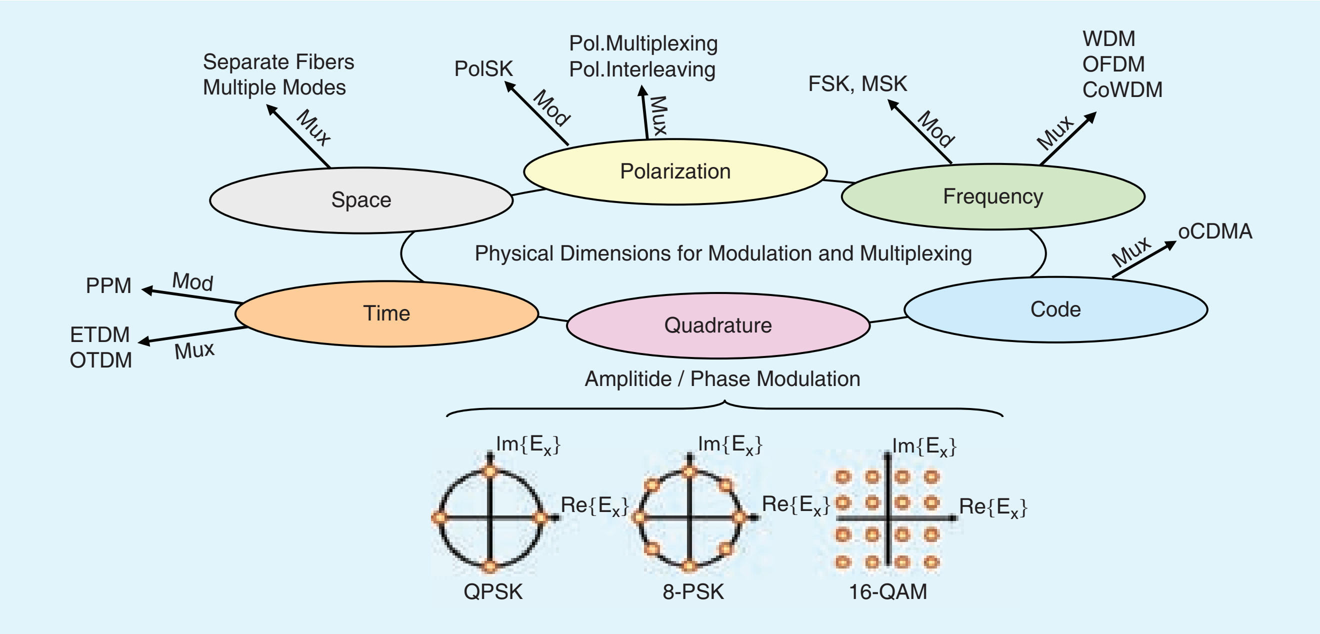

Figure 3. Physical dimensions that can be used for modulation and multiplexing in optical communications. (OTDM: Optical time-division multiplexing; ETDM: Electronic time-division multiplexing; oCDMA: Optical code-division multiple access; PPM: Pulse position modulation; PolSK: Polarization shift keying; FSK: Frequency-shift keying; MSK: Minimum-shift keying; WDM: Wavelength-division multiplexing; CoWDM: Coherent WDM; OFDM: Orthogonal frequency-division multiplexing; PSK: Phase shift keying; QPSK: Quadrature PSK; QAM: Quadrature amplitude modulation; E_x: Optical field (x polarization).)

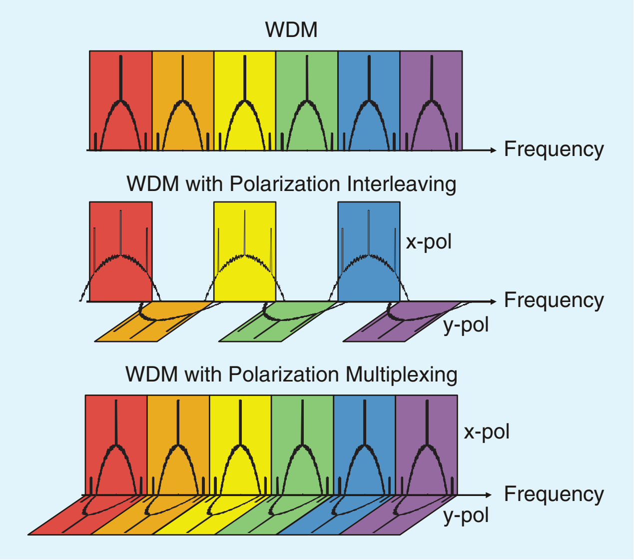

Figure 4. Orthogonality through disjoint frequency bins (WDM) can be combined with orthogonality in the polarization dimension.

(CoWDM) [18,19], depending on whether the (de)multiplexing operations are performed electronically or optically (equivalent to the distinction between ETDM and OTDM in the time domain). If the orthogonal waveforms are not sine waves but orthogonal sequences of short pulses ("chips"), we arrive at optical code-division multiple access (oCDMA) [20].

Finally, one can make use of the spatial dimension, in its most obvious form by sending different signals on parallel optical waveguides, sometimes referred to as *spatial multiplexing*. Using parallel waveguides is particularly attractive for implementation-constrained systems (rack-to-rack interconnects and shorter), where frequency stable lasers and filters operating over a significant temperature range lead to bulky and power-consuming solutions, and coherent signal processing becomes problematic for the same reasons. Here, coarse WDM (CWDM) with uncooled components allows for channel spacings of typically 20 nm and can be an attractive multiplexing solution. In contrast, for long-haul transport systems, which are the most capacity-constrained systems existing today, spatial multiplexing is not cost efficient, and dense WDM is a requirement, recently even in combination with PDM. The key parameter characterizing such systems is the *spectral*

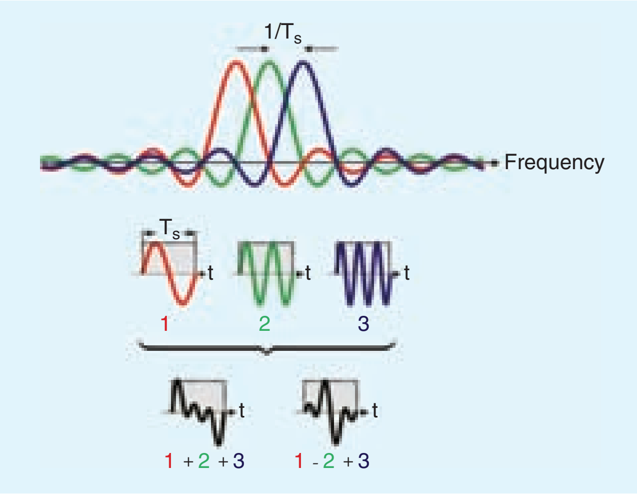

Figure 5. Orthogonal frequency spacings of 1/T_s lead to OFDM or CoWDM.

efficiency (SE), defined as the ratio of per-channel bit rate to WDM channel spacing.

Modulation and coding

Modulation denotes the method by which digital information is imprinted onto an optical carrier, and in its most general sense also includes *coding* to prevent transmission errors from occurring ('line coding') or to correct for already occurred transmission errors ('error correcting coding').

Uncoded *on/off keying* (OOK, cf. Fig. 6) in its various flavors [21] has been used in optical communications for decades because it is by far the simplest format in terms of hardware implementation and integration and exhibits a good compromise between complexity and performance. Those applications in Fig. 2 that are identified to be implementation-constrained, especially if integration and power efficiency weight heavily, are likely to employ uncoded OOK until capacity or sensitivity requirements dictate the use of more sophisticated formats or computationally intensive error correcting coding.

For sensitivity-dominated applications, in particular for space-based laser communications, binary *phase shift keying* (PSK, cf. Fig. 6) was studied intensively and set several sensitivity records [22,23,24]. Further sensitivity improvements can be obtained at the expense of modulation bandwidth, either by *M-ary orthogonal modulation* or by *coding*.

Orthogonal modulation formats employ $M > 2$ orthogonal signal dimensions, such as M non-overlapping time slots per symbol duration (*pulse position modulation,* PPM, cf. Fig. 6 for $M = 4$) [8,14,25] or M orthogonal frequencies (*M-ary frequency-shift keying*, FSK) [14]. In PPM, an optical pulse is transmitted in one out of M slots per symbol. The occupied slot position denotes the bit combination conveyed by the symbol. Both PPM and FSK expand the signal bandwidth by $M/\log_2 M$ compared to OOK. For example, using 64-PPM, sensitivity is improved by 7.5 dB at a bit error ratio (BER) of 10^{-16} at the expense of a 10-fold increase in modulation bandwidth [15].

With error correcting coding ('forward error control', FEC), redundancy is introduced at the transmitter and is used to correct for detection errors at the receiver [26]. Typical FECs for terrestrial fiber-optic systems today operate at up to 40 Gb/s with 7% overhead and are able to correct a channel BER of of 2×10^{-3} to 10^{-16}, yielding a sensitivity improvement of ~9 dB at a mere 7% bandwidth expansion. FECs with more than 11 dB of coding gain at BER $= 10^{-16}$ and at a 25% bandwidth overhead have been implemented at 10 Gb/s [26]. These high sensitivity gains achieved by FEC at a low bandwidth expansion in comparison with orthogonal modulation come at the expense of a significant increase in implementation complexity for FEC processing. Through the combination of modulation and coding, sensitivities of 1 photon/bit have been reported using PPM [27].

In contrast, capacity-constrained systems employ modulation formats that avoid an increase in modulation bandwidth to allow for dense WDM channel packing (high spectral efficiency). Narrow modulation spectra are accomplished by sticking to the two-dimensional quadrature signal space, i.e., by using multiple levels of real and imaginary parts (or magnitude and phase) of the complex optical field, as shown by the three examples in Fig. 3. In addition, low-overhead FEC (~7% to ~25%) is used to improve sensitivity. At currently investigated 100-Gb/s single-channel rates, quadrature phase shift keying (QPSK) [28,29], 8-PSK [30], and 16-QAM [31] have been reported, both on a single carrier and using CoWDM [32].

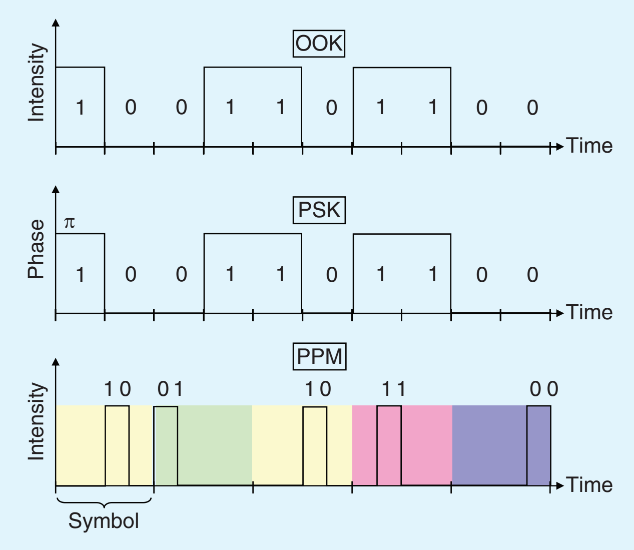

Figure 6. Waveforms associated with some optical modulation formats.

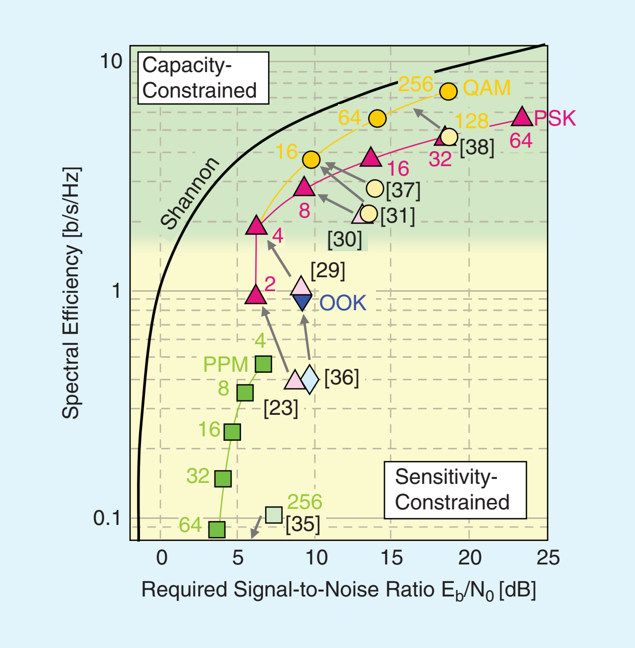

Figure 7. Trade-off between spectral efficiency (per polarization) and sensitivity of various modulation formats limited by AWGN. Modulation formats (bright: theoretical limits; faint: experimental results) are reported for a 7% overhead code at a pre-FEC BER of 2×10^{-3}. (Squares: PPM; triangles: PSK; circles: QAM; diamonds: OOK.)

Figure 7 visualizes the trade-off between sensitivity and spectral efficiency for the linear additive white Gaussian noise (AWGN) channel[4] [15]. The ultimate limit is given by Shannon's

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[4] Different limits are obtained for other channels, for example for the shot noise limited case. While the AWGN channel is the most relevant for optically amplified transmission systems [33], free-space systems can be shot-noise limited [25,34].

capacity. The lower portion of the figure belongs to the realm of sensitivity-constrained systems while the upper portion applies to capacity-constrained systems. The theoretically achievable sensitivity for four classes of modulation formats (OOK, PSK, QAM, PPM) are also shown, assuming the above mentioned 7% overhead FEC (2×10^{-3} pre-FEC BER). The performance of some recent experimental results is captured by the fainter colored symbols. It is evident that hardware implementation difficulties prevent the formats from performing at their theoretical limits, both in terms of sensitivity and spectral efficiency.

WDM system evolution

Fiber-optic transport systems are the most capacity-constrained of all optical communication systems. To assess technological progress at the forefront of transmission capacity, Fig. 8 compiles research experiments reported at the Optical Fiber Communication Conferences (OFC) and the European Conferences on Optical Communications (ECOC). The green data points show the experimentally achieved bit rates of electronically time-division multiplexed (ETDM) single-channel systems, which reflect the historic growth rate of the speed of semiconductor electronics. By 2005/2006, ETDM bit rates had reached 100 Gb/s [39,40].

By the mid 1990s, the erbium-doped fiber amplifier (EDFA) had made WDM highly attractive because it could simultaneously amplify many WDM channels. This allowed the capacity of fiber-optic communication systems to scale in the wavelength domain by two orders of magnitude compared to single-channel systems, as indicated by the red data points. Up until ~2000, achieving a closer WDM channel spacing was a matter of improving the stability of lasers and of building highly frequency selective optical filters; pre-2000, the increase in spectral efficiency, represented by the yellow data points in Fig. 8, was therefore due to improvements in device technologies.

When 40-Gb/s systems started to enter optical networking at the turn of the millennium, optical modulation formats [21,41] and coding[5] [26] became very important, first to improve sensitivity so that the reach of 40-Gb/s systems would not fall too short of that of legacy 10-Gb/s systems. With the simultaneous development of stable 100-GHz and 50-GHz spaced optics, the modulated optical signal spectra quickly approached the bandwidth allocated to a single WDM channel, which took the increase of spectral efficiency from a device design level to a communications engineering level, and made spectrally efficient modulation important, as it had traditionally been the case in electronic and RF communication systems. Using advanced communication techniques such as coherent detection (presently still with off-line signal processing instead of real-time bit error counting), PDM, OFDM, and pulse shaping, spectral efficiencies have continued to increase at multi-Gb/s rates, with today's records being at 4.2 b/s/Hz at 100 Gb/s [30, 31], 5.6 b/s/Hz at 50 Gb/s [37], and 9.3 b/s/Hz at 14 Gb/s [38]. Further scaling of spectral efficiency becomes increasingly more difficult, requiring exponentially more constellation points per modulation symbol[6]. Recent studies on the fundamental capacity limits of optical transmission systems over standard single-mode fiber predict a maximum capacity of about 11 b/s/Hz over 2000 km [33,43], assuming that PDM doubles capacity compared to the reported single-polarization case.

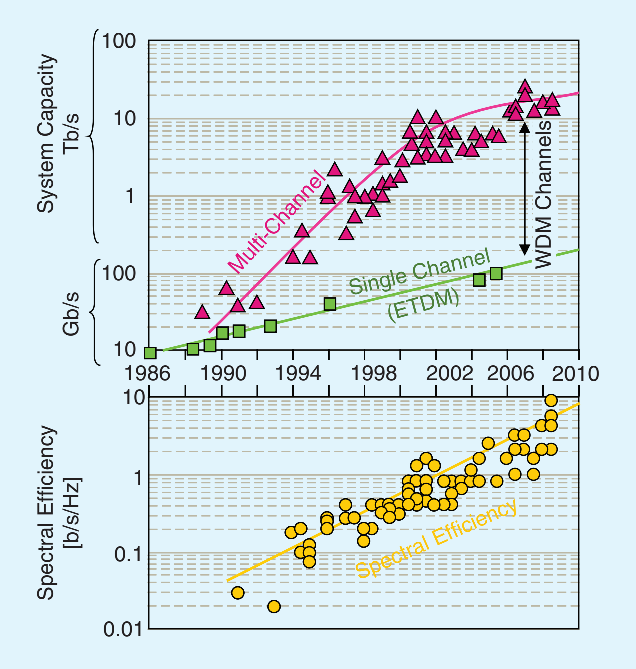

Figure 8. Progress in fiber-optic transmission capacities, as reported at post-deadline sessions of ECOC and OFC. (Green: Single-channel ETDM rates; red: WDM aggregate capacities on a single fiber; yellow: spectral efficiency.)

The experimentally demonstrated record for the *aggregate capacity* over a single optical fiber is currently at 25.6 Tb/s at a spectral efficiency of 3.2 b/s/Hz [42]. As evident from the red data points in Fig. 8, reported capacities have noticeably started to saturate over the last few years. With continuously increasing spectral efficiencies, this can be attributed, at least in part, to the slower growth rate of single-channel ETDM bit rates, which necessitates a large increase in the number of WDM channels to achieve record capacities and makes such experiments both time consuming and expensive. For example, the above mentioned 25.6-Tb/s experiment [42] used a total of 320 ETDM channels (2 optical amplification bands, 80 wavelengths per band, and 2 polarizations per wavelength, modulated at 80 Gb/s each).

All the above data indicate that WDM is still scaling in spectral efficiency and capacity at present but will likely reach fundamental as well as practical limits in the near future. Therefore, new approaches have to be explored in order to continue the scaling of capacity-constrained systems. Such approaches could include the use of lower nonlinearity or lower-loss optical transmission fiber [43], transmission over extended wavelength ranges, or even the use of multi-core or multi-mode optical fiber [44].

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[5] In submarine systems, coding was introduced well before 2000 [7,26].

[6] Transporting k bits of information per symbol (and hence per unit bandwidth in quadrature space) requires 2^k modulation symbols.

Conclusions

The success of digital information processing over the last century has triggered the demand to transport massive amounts of digital information, ranging from on-chip data buses all the way to inter-planetary distances. Optical communication systems have been replacing electronic and RF techniques starting at the most demanding *capacity-constrained* and *sensitivity-constrained* applications and are steadily progressing towards more *implementation-constrained* shorter-reach systems that require dense integration, low power consumption, and low cost.

Modulation and multiplexing techniques are key design elements of sensitivity-constrained and capacity-constrained systems, used to harvest the bandwidth advantages that optical technologies fundamentally offer. Spectrally efficient modulation will stay a key area of research for capacity-constrained systems. As WDM capacities over conventional fibers are approaching their fundamental limits, breakthroughs in fiber design and in complementary multiplexing techniques are expected to further scale capacity.

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