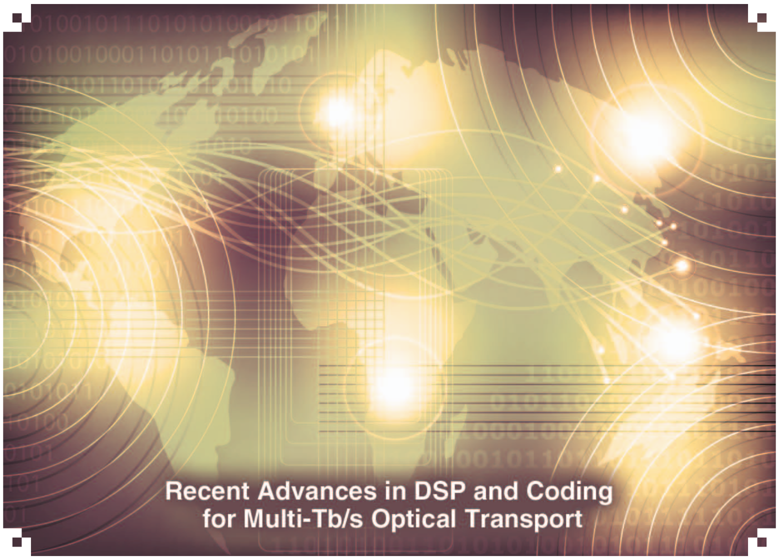
Xiang Liu, S. Chandrasekhar, and Peter J. Winzer

Digital Signal Processing Techniques Enabling Multi-Tb/s Superchannel Transmission

An overview of recent advances in DSP-enabled superchannels



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Digital signal processing (DSP) combined with coherent detection has played a central role in the recent capacity expansion of optical networks. Optical superchannels aim to increase per-channel interface rates as well as per-fiber capacities of wavelength-division multiplexed (WDM) systems in a cost-effective manner. Superchannels circumvent the electronic bottleneck via optical parallelism and provide high-per-channel data rates and better spectral utilization, especially in transparent optical mesh networks. This article reviews recent advances in the generation, detection, and transmission of optical superchannels with channel data rates on the order of terabits per second (Tb/s). Enabling DSP techniques such as Nyquist–WDM, orthogonal frequency-division multiplexing (OFDM), software-defined modulation and detection, advanced coding, and joint DSP among the superchannel constituents are presented. Future prospects of DSP techniques for high-capacity superchannel transmission are also discussed.

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SUPERCHANNEL TRANSMISSION

To satisfy the ever-increasing capacity demands of fiber-optic networks, the data rate carried by each wavelength channel in WDM

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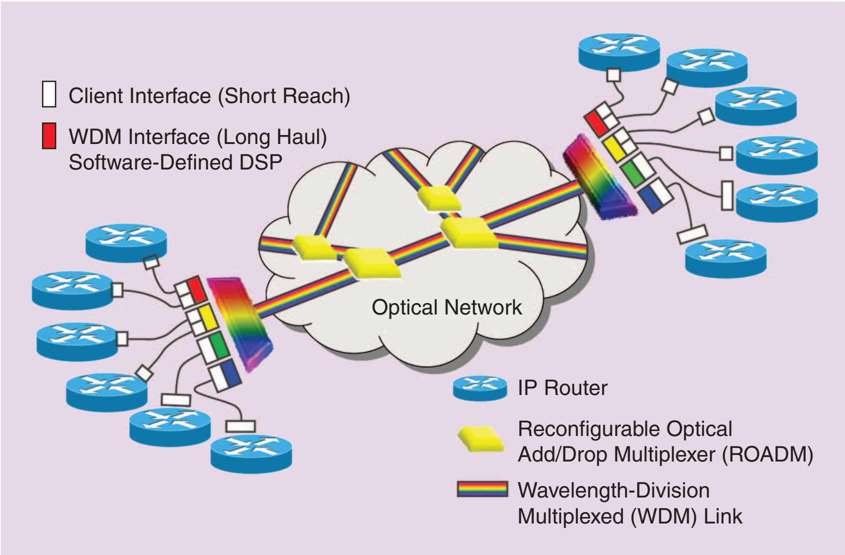
systems has been increasing exponentially for over two decades [1]. Figure 1 shows the schematic of a typical optical network, connecting Internet protocol (IP) routers via short-reach client interfaces to long-haul WDM transponders, which are wavelength multiplexed onto fibers making up an optically routed mesh network. The key enabling elements for the recent interface speed and fiber capacity expansion in optical networks are high-speed optical WDM transceivers based on coherent detection and advanced DSP [1]. High-speed digital-to-analog converters (DACs) and analog-to-digital converters (ADCs) built in 40-nm complementary metal–oxide–semiconductor (CMOS) technology are currently available up to 65 Gsamples/s with an effective number of bits (ENOB) of about six (e.g., see http://www.fujitsu.com/downloads/MICRO/fme/documentation/c63.pdf). Powerful digital signal processors, containing on the order of 100 million gates [2] and capable of operating at close to 100 tops/s, and form the basic building blocks of modern optical transceivers. Figure 2 shows the evolution of such application-specific integrated circuits (ASICs) for commercial optical communications applications, showing a gate count increase of ~70% per year. Single-carrier 100-Gb/s transponders have been commercially available since mid-2010 (e.g., see http://www3.alcatel-lucent.com/100g-coherent/). To scale to Tb/s interfaces and beyond (expected to be needed by 2015 [1]) in an economically attractive manner, however, optical superchannels that circumvent the electronic bottleneck via optical parallelism are the method of choice. Consequently, dual-carrier 400-Gb/s digital coherent transponders have been commercially available since early 2013 (e.g., see http://www3.alcatel-lucent.com/400g-pse/), and long-haul transmission with Tb/s superchannel data rates has been experimentally demonstrated [3]–[7]. In the context of optical transport networks, the term *superchannel* was first used in [3] to refer to multiple single-carrier-modulated signals that are seamlessly multiplexed under the coherent optical OFDM (CO-OFDM) conditions [3]–[5]. The superchannel concept was later generalized to any collection of optical signals that are

1) modulated and multiplexed together with high spectral efficiency (SE) at a common originating site
2) transmitted and routed together over a common optical link
3) received at a common destination site.

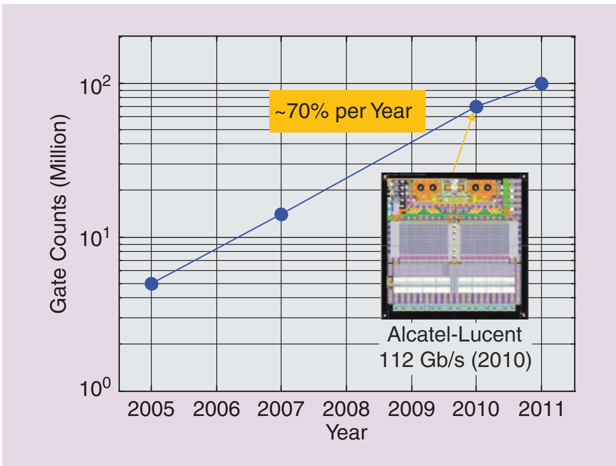
To achieve high-SE multiplexing, "Nyquist–WDM" and "quasi-Nyquist–WDM" with spectrally shaped single-carrier modulated signals have also been introduced [8], [9], offering an alternative to OFDM with tradeoffs in SE, DSP complexity, optoelectronic (O/E) hardware complexity, and subcarrier access possibilities [1]. From a networking point of view, the introduction of Tb/s-class superchannels has led to a rethinking of the spectral bandwidth allocation in optical fibers. While most current systems operate on a rigid 50-GHz WDM channel grid, Tb superchannels benefit from so-called "flexible grid" WDM systems that allow for more efficient utilization of the optical spectrum (see, e.g., ITU-T G.694.1, "Spectral Grids for WDM Applications: DWDM Frequency Grid").

The key benefits of superchannels in WDM systems are as follows:

1) the ability to meet the demand of high-speed serial interface rates, which increases faster than the speed provided by O/E converters, electro-optic (E/O) converters, DACs, and ADCs
2) higher SE in WDM transmission, by reducing the percentage of wasted optical spectrum between individual channels
3) increased efficiency in DSP
4) better leverage of photonic integrated circuits and ASICs



[FIG1] A schematic of a typical optical network.



[FIG2] The evolution of commercial optical communications ASICs.

5) native support of software-defined optical transmission, enabled by DSP at both the transmitter and receiver, to improve system throughput and flexibility.

OVERVIEW OF SUPERCHANNEL ARCHITECTURES

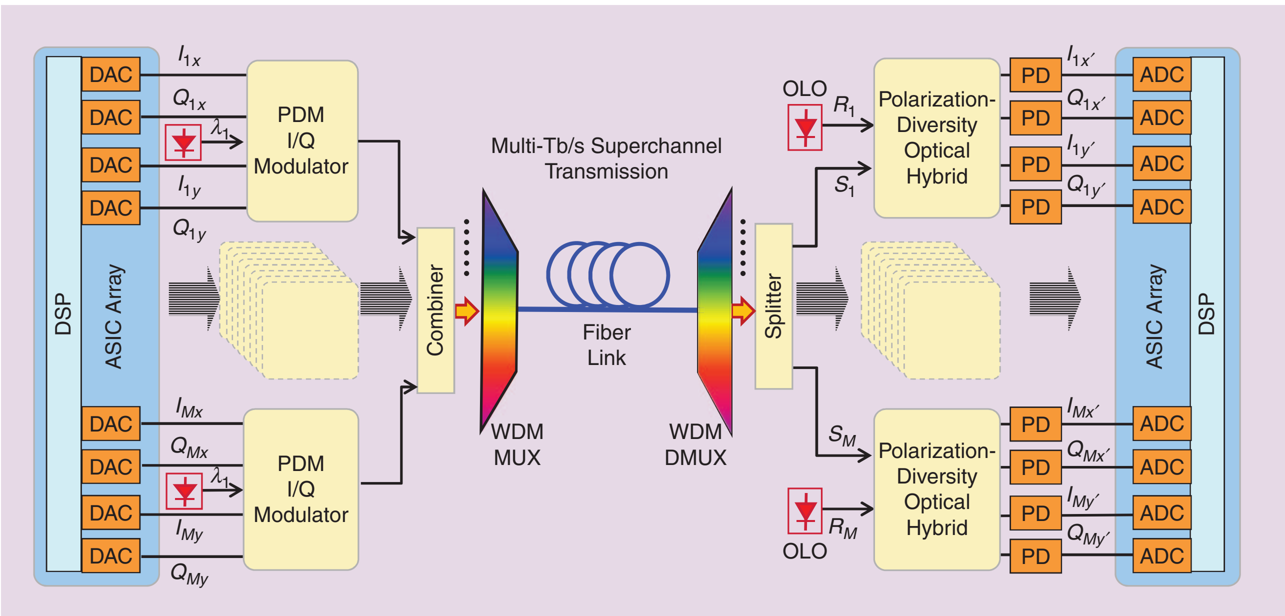
Figure 3 shows the schematic of a superchannel transponder embedded in a WDM optical network. The full optical field information of an optical signal can be decomposed into four orthogonal real-valued components, particularly the inphase (I) and quadrature (Q) components of the two orthogonal polarization states (x and y) supported by a single-mode optical fiber. At the transmitter, a polarization-division multiplexed (PDM) I/Q modulator is commonly used to imprint these four high-speed electrical waveforms onto an optical carrier, emerging from a semiconductor laser oscillating at 193 THz and stabilized to within about ± 1 GHz. At the receiver, a polarization-diversity 90° hybrid and an optical local oscillator laser (OLO) are used to decompose the received signal into four orthogonal components, which can then be detected by four photo-detectors (PDs) and processed in a digital signal processor to recover the original signal. To avoid the bandwidth bottleneck of electronic and O/E components in the transmitter and receiver, optical parallelism is utilized to generate and detect a superchannel, whose aggregate bandwidth by definition exceeds that of the individual transponder components.

It is evident from Figure 3 that the generation and detection of superchannels can greatly benefit from large-scale integration of both optical and electronic components, leading to potential savings in cost, size, and power. With all the constituents of a superchannel being available at the transmitter and at the receiver, joint DSP may be leveraged to improve the transmission performance and/or to reduce DSP complexity, as will be discussed in more depth later.

THE KEY ENABLING ELEMENTS FOR THE RECENT INTERFACE SPEED AND FIBER CAPACITY EXPANSION IN OPTICAL NETWORKS ARE HIGH-SPEED OPTICAL WDM TRANSCEIVERS BASED ON COHERENT DETECTION AND ADVANCED DSP.

SUPERCHANNEL CLASSIFICATION

Table 1 summarizes various superchannel demonstrations reported recently. Key performance indicators include intrachannel SE (ISE) and the ISE-distance product (ISEDP). Using OFDM-based seamless multiplexing, Chandrasekhar et al. demonstrated the transmission of a 1.2-Tb/s superchannel, consisting of 24 polarization division-multiplexed (PDM) quadrature phase-shift keying (QPSK) signals, over 7,200 km of ultra-large area fiber (ULAF) [3]. With the use of 16-QAM, Huang et al. demonstrated the transmission of a 1.5-Tb/s superchannel over 1,200 km of standard single-mode fiber (SSMF) [5]. With the use of reduced-guard-interval (RGI) OFDM, which essentially performs full chromatic dispersion compensation prior to OFDM processing and hence allows reduction of the guard-interval to accommodate mostly transmission effects with much shorter channel memory, Liu et al. demonstrated the transmission of a 485-Gb/s superchannel over an ISEDP as high as 30,000 km·b/s/Hz [10]. To avoid the use of accurately frequency-locked optical carriers, a small frequency guard-band between adjacent carriers within a superchannel can be used to allow one to trade a small fraction (e.g., <10%) of the link capacity for



[FIG3] An illustration of a superchannel transponder embedded in a WDM system.

[TABLE 1] RECENT Tb/s SUPERCHANNEL DEMONSTRATIONS.

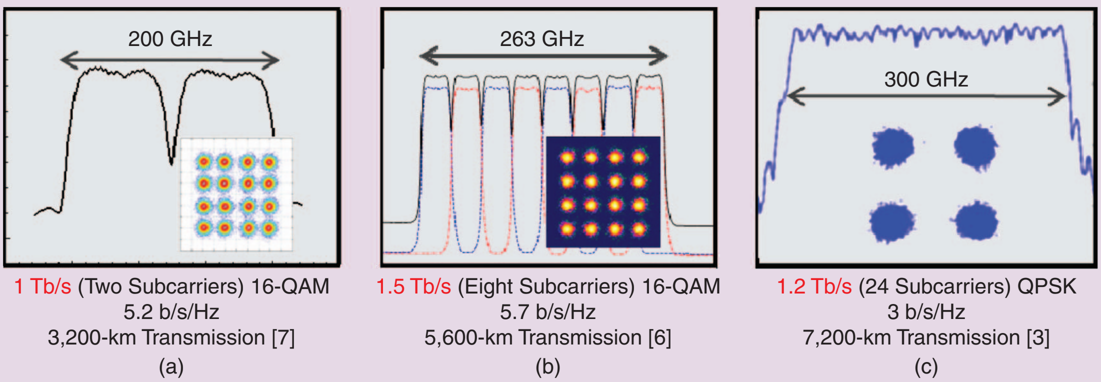
MODULATION FORMAT	SUPERCHANNEL DATA RATE	COMPOSITION	ISE (b/s/Hz)	REACH (km)	ISEDP (km × b/s/Hz)
SEAMLESS CO-OFDM (WITH FREQUENCY-LOCKED OPTICAL CARRIERS)					
PDM-QPSK [3]	1,200 Gb/s	24 × 50 Gb/s	3.74	7,200	26,928
PDM-16 QAM [5]	1,500 Gb/s	15 × 100 Gb/s	7.00	1,200	8,400
RGI-OFDM 16 QAM [10]	485 Gb/s	10 × 48.5 Gb/s	6.20	4,800	29,760
GUARD-BANDED CO-OFDM (WITH FREQUENCY-UNLOCKED CARRIERS)					
OFDM 16 QAM [6]	1,864 Gb/s	8 × 233 Gb/s	5.75	5,600	32,000
QUASI-NYQUIST–WDM (WITH FREQUENCY-UNLOCKED CARRIERS AND DIGITAL SPECTRAL SHAPING)					
PDM-32-64 QAM [11]	504 Gb/s	5 × 100.8 Gb/s	8.00	1,200	9,600
QUASI-NYQUIST–WDM (WITH FREQUENCY-UNLOCKED CARRIERS AND OPTICAL SPECTRAL SHAPING)					
PDM-16 QAM [7]	1,280 Gb/s	2× 640 Gb/s	5.00	3,200	16,000

simplicity, scalability, and performance. With the use of this "guard-banded OFDM," Liu et al. showed the transmission of a 1.5-Tb/s superchannel, consisting of eight PDM-OFDM 16-QAM signals, over 5,600 km of ULAF, achieving a record ISEDP of over 32,000 km·b/s/Hz for Tb/s-class superchannel transmission with more than 5 b/s/Hz net SE [6]. Using Nyquist–WDM and hybrid 32-QAM and 64-QAM, Zhou et al. demonstrated the transmission of five 400-Gb/s superchannels on a 50-GHz grid over 1,200-km ULAF with a WDM SE as high as 8 b/s/Hz [11]. With the use of 80-Gbaud modulation and detection, Raybon et al. demonstrated the transmission of a 1-Tb/s superchannel using only two optical carriers and two pairs of transmitter/receiver front ends [7]. There, close-to-Nyquist spectral shaping was achieved by optical filters instead of digital pulse shaping. Figure 4 shows spectra of representative Tb-class superchannels, where the tradeoff between the number and modulation rate of the subcarriers becomes evident.

OVERVIEW OF DSP BUILDING BLOCKS

With access to the full optical field information at both the transmitter and receiver, modern coherent optical communications has benefited from many powerful DSP techniques originally developed for wireless communications. However, data rates in optical communications are usually several orders of magnitude higher than in wireless communications, necessitating efficient DSP techniques tailored specifically to optical communications, indeed reflecting a statement by Haykin [12], "Signal processing is at its best when it successfully combines the unique ability of mathematics to generalize with both the insight and prior information gained from the underlying physics of the problem at hand." For optical communications in single-mode fiber, channel equalization can be efficiently realized by separating slowly varying transmission effects such as chromatic dispersion (CD) from rapidly varying effects such as polarization rotations and polarization-mode dispersion (PMD).

Figure 5(a) schematically shows a superchannel transmitter DSP architecture. Key signal processing steps include forward error correction (FEC) encoding, constellation mapping (MAP), fiber nonlinearity compensation (NLC), up-sampling (UpS), electronic dispersion precompensation (EDC), Nyquist prefiltering, and equalization of a nonideal transmitter frequency response through a static transmitter equalizer (SEQ). The four resulting electrical signals representing I and Q components of the baseband signal in both x and y polarization are then modulated onto a high-frequency carrier, generated by a reasonably



[FIG4] (a)–(c) Representative Tb-class superchannel spectra. Insets: representative recovered signal constellations.

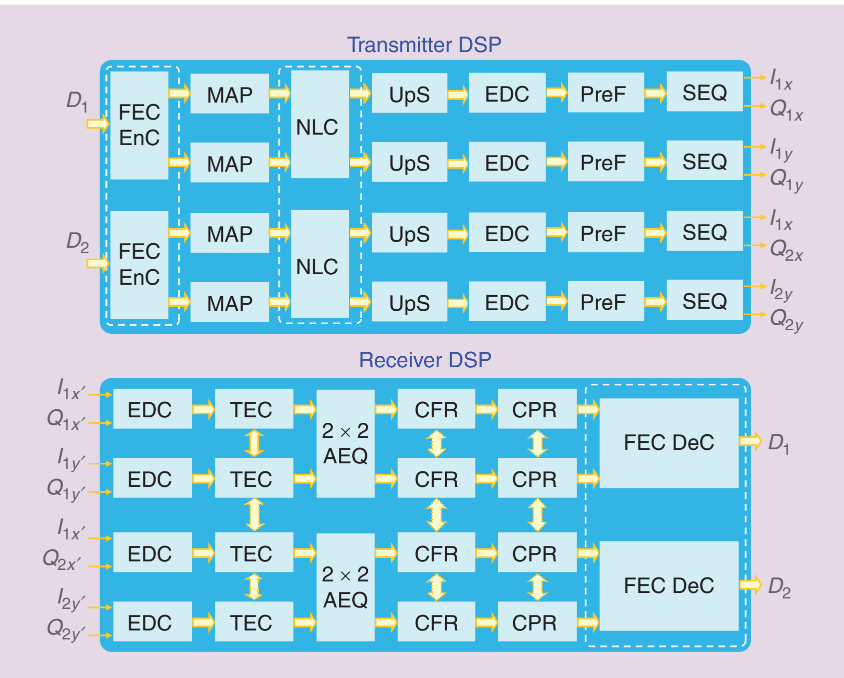
narrow-linewidth (~100-kHz) laser oscillating at around 193 THz. Note that some of the transmitter-side DSP modules shown in Figure 5, e.g., NLC and EDC, may bring valuable performance gains in long-haul optical transmission, but their DSP complexities need to be taken into consideration. In some cases, these modules can be made optionally available depending on the requirements on performance and power consumption.

Figure 5(b) shows the schematic architecture of a superchannel receiver DSP. After coherent O/E conversion, the DSP is presented with four electrical baseband signal representing I and Q components in x and y polarization. Key processing steps include EDC, timing error correction (TEC), adaptive 2×2 multiple-input-multiple-output (MIMO) equalization and polarization source separation compensating for polarization rotation and PMD, carrier frequency recovery (CFR), carrier phase recovery (CPR), and FEC decoding based on both soft decision (SD) and/or hard decision (HD). (Reviews of these techniques are given, e.g., in [1] and [13].) Typically, transmitter-side DSP has the potential advantages of 1) absence of optical noise and 2) efficient implementation operating on one sample per symbol. On the other hand, receiver-side DSP has the potential advantage of being able to adaptively and quickly react to dynamic channel changes. Note in this context that receiver-to-transmitter feedback is often problematic in optical systems: For a 1,000-km link, signal round-trip times are on the order of 10 ms, whereas channel dynamics can be in the 10-kHz range or above, owing to acoustically and mechanically induced vibrations of transmission fiber segments. As optical channels are usually well defined (in terms their frequency response), blind channel equalization and phase recovery has been widely used in optical coherent detection [13]. For fast channel equalization and/or sophisticated modulation formats, training symbols (TSs) can be inserted in the data symbol stream to aid channel equalization [14]. To enable the efficient implementation of high-performance FEC codes, it is desirable to recover the phase of the modulated symbols (as opposed to just the differential phase between symbols), which can be readily realized by pilot-assisted phase estimation (PA-PE) [15]. For superchannel transmission, some of the processes such as FEC and NLC may be performed jointly over multiple signals within the superchannel to improve the overall superchannel performance. We will discuss some key signal processing modules essential to superchannel transmission in the following sections.

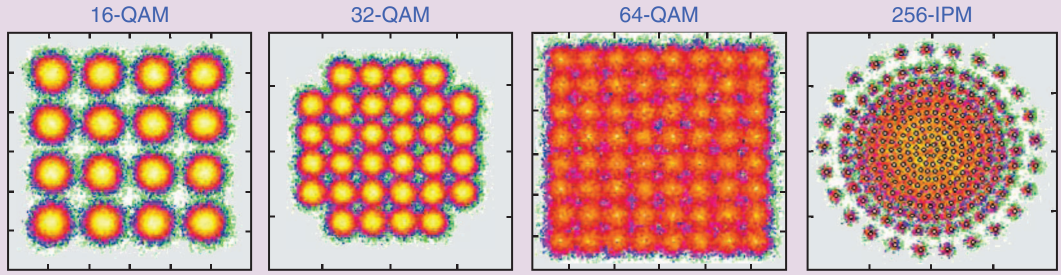
FOR SUPERCHANNEL TRANSMISSION, SOME OF THE PROCESSES SUCH AS FEC AND NLC MAY BE PERFORMED JOINTLY OVER MULTIPLE SIGNALS WITHIN THE SUPERCHANNEL TO IMPROVE THE OVERALL SUPERCHANNEL PERFORMANCE.

SPECTRAL SHAPING FOR NYQUIST-WDM SUPERCHANNELS

To enable the spectrally efficient construction of a superchannel, spectral shaping is needed at the transmitter to band-limit the optical spectrum of each superchannel subcarrier to be equal to or slightly higher than the modulation symbol rate. This is done by prefiltering the spectrum of a single-carrier signal by using a root raised cosine filter (RRC) with a given roll-off factor. Usually, a roll-off factor of about 0.1 is implementable at reasonable complexity and with negligible performance loss. Figure 4(b) shows the measured optical spectrum of a 1.5-Tb/s guard-banded OFDM superchannel [6]. It consists of eight spectrally shaped signals, closely packed at a net SE of 5.75 b/s/Hz using individual lasers without mutual frequency locking. The transmitter-side signal processing can also be used to mitigate the bandwidth limitation from DAC, modulator, modulator driver, and optical add/drop multiplexers (ROADMs), optical filtering elements used to optically route wavelength channels across a mesh network; c.f. Figure 1. The transmitter-side equalizer is usually implemented as a relatively static equalizer.



[FIG5] A schematic architecture of a transceiver DSP for a superchannel having two optical carriers.



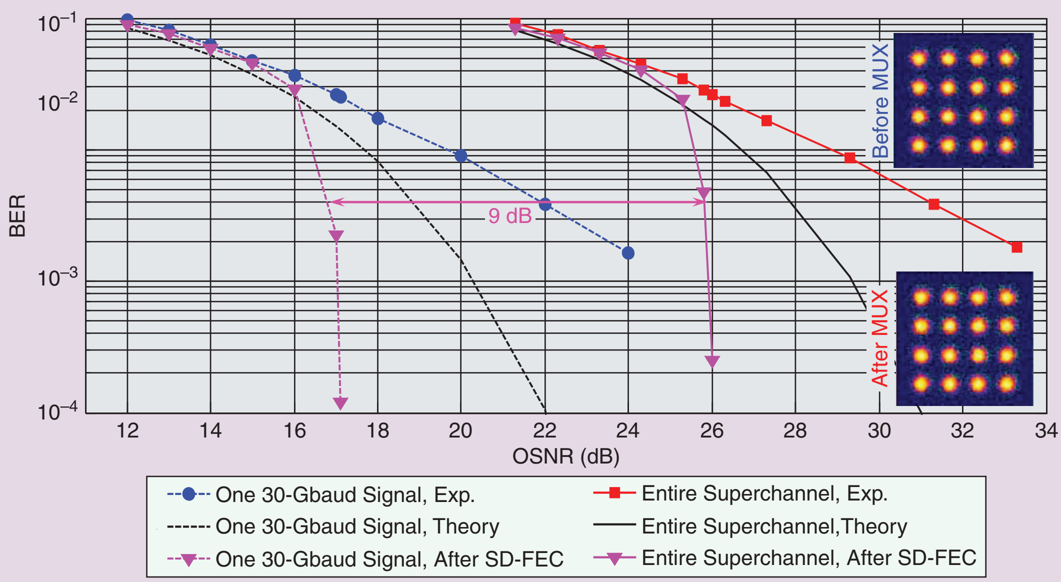
[FIG6] **Measured Tb/s-class signal constellations generated by software-defined transmitters.**

SOFTWARE-DEFINED MODULATION

With transmitter-site DSP and collaborative receiver-side DSP, the modulation format can be software defined to enable the optimization of system performance depending on the link conditions. Figure 6 shows some exemplary signal constellations generated in Tb/s-class superchannels by software-defined transmitters. In addition to conventional square QAM, advanced modulation formats such as iterative polar modulation (IPM) [16] and four-dimensional (4-D) modulation formats [17], [18] that jointly utilize the four orthogonal dimensions (two polarizations and two quadratures) can be realized. With optimized 4-D constellation shaping, the signal's tolerance to both linear noise and nonlinear fiber transmission impairments can be improved.

ADVANCED CODING

FEC is a powerful technique to improve transmission performance. Since soft information is available within a coherent DSP ASIC, an SD FEC can be readily implemented [19]. In a recent experiment [6], a low-density parity check (LDPC) code with a rate of 0.864 (16% coding overhead) was implemented for the inner SD-FEC, and a rate 0.935 (7% coding overhead) HD FEC code was assumed as the outer code to achieve the typical optical networking requirement of post-FEC bit-error ratios (BERs) on the order of 10^{-15}. Figure 7 shows the back-to-back BER performance of the 1.5-Tb/s superchannel based on offline digital signal processing. Remarkably, there is essentially no extra penalty due to guard-banded multiplexing (MUX), thanks to the well-confined optical spectrum of the OFDM signals making up the superchannel. For a typical 7%-overhead outer HD-FEC, the correction threshold is about 4×10^{-3} for a final BER of $< 10^{-15}$. For the output BER of the SD-FEC decoder to be below the correction threshold, the input BER of the SD-FEC needs to be $< 2.7 \times 10^{-2}$ when 15 decoder iterations are used. (Note that optical systems experiments rarely implement actual FEC but rather use the pre-FEC BER to assess transmission



[FIG7] **The measured back-to-back BER performance of the 1.5-Tb/s superchannel before and after the SD-FEC decoding. Insets: recovered subcarrier constellations before and after the guard-banded multiplexing (after [6]).**

quality, which implicitly assumes sufficient scrambling to ensure the statistical independence of errors, and in the case of SD-FEC also assumes additive white Gaussian noise. Since either premise may be violated under nonlinear optical transmission conditions, advanced experiments implement at least the inner SD-FEC decoder.) Figure 8 shows the measured BER (based on offline signal processing) of all eight 30-Gbaud PDM-OFDM-16QAM signals that make up the 1.5-Tb/s superchannel after 5,600-km transmission at a superchannel launch power (P_{in}) of 9 dBm. The BER after SD-FEC is below the outer HD-FEC threshold for each of the eight subcarriers.

More recently, a coded 231.5-Gb/s RGI-CO-OFDM signal, with constellation shaping through 256-IPM subcarrier modulation, was transmitted over a distance of 800 km in ULAF, achieving an ISE as high as 11.15 b/s/Hz [14]. This study shows the promise of combining coding with modulation and nonlinear compensation to achieve substantially higher optical transmission performance than using coding alone. With iterative decoding based on a maximum a posteriori decoder and a LDPC FEC, 30.58-Tb/s transmission over 7,230 km at an SE of 6.1 b/s/Hz has recently been demonstrated, achieving a record capacity-distance product of 221 Pb/s·km for a submarine transmission link [18].

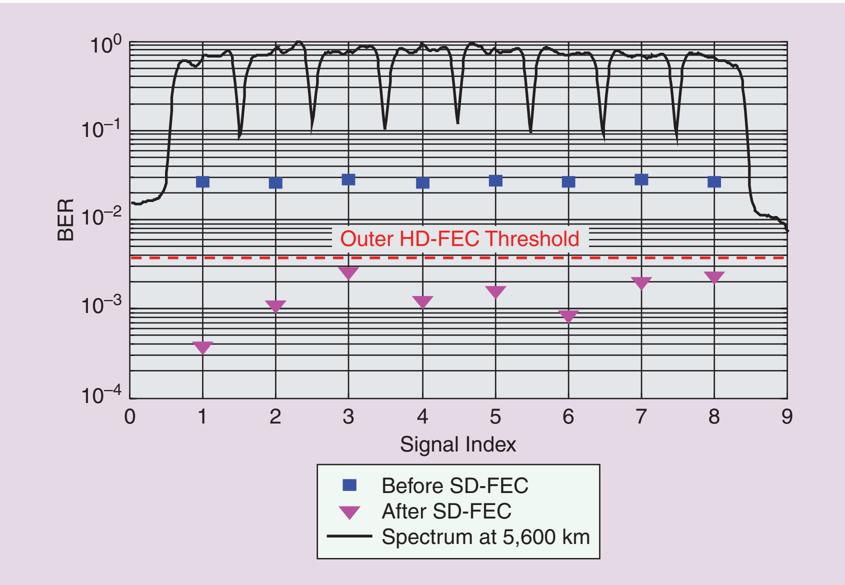
JOINT PROCESSING OF SUPERCHANNEL CONSTITUENTS

As the constituents of a superchannel share the same optical transmission path, they experience some common transmission properties. Hence, the monitoring of some transmission properties of the superchannel can be simplified by monitoring only one of the constituents, or more accurate measurements can be obtained by averaging certain channel estimates across superchannel constituents. For example, if the source lasers of the superchannel constituents are frequency-locked, as in the case of CO-OFDM, the frequency estimation of a superchannel can be simplified. As the signal fields of all constituents are available at the receiver, joint DSP can be applied to mitigate certain impairments, such as coherent crosstalk between adjacent signals [20].

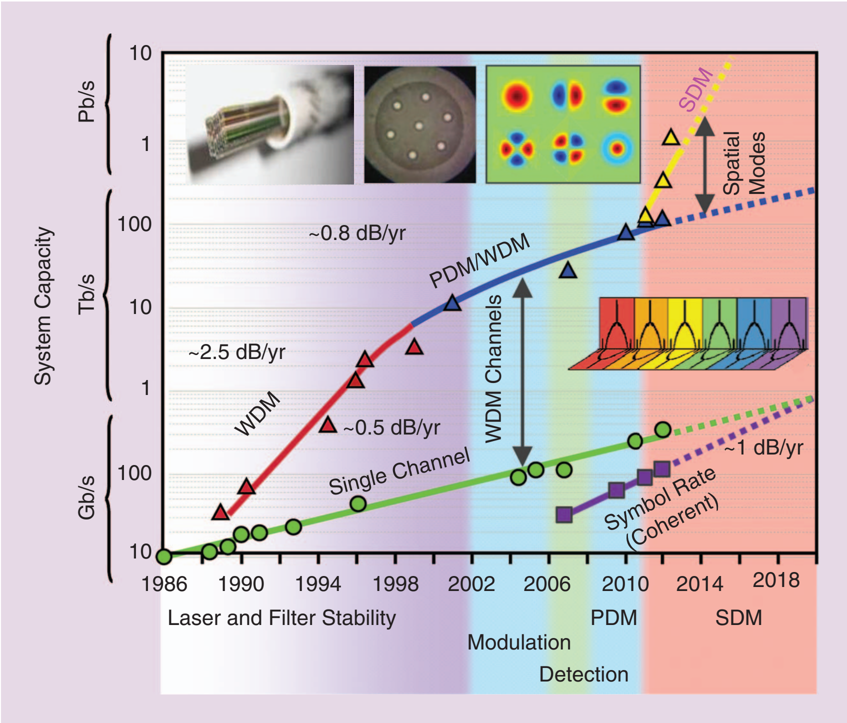
FIBER NONLINEARITY IS A MAJOR TRANSMISSION IMPAIRMENT IN OPTICAL FIBER COMMUNICATIONS.

Fiber nonlinearity is a major transmission impairment in optical fiber communications. In contrast to static nonlinearities encountered in some radio-frequency systems, fiber transmission suffers from the interplay of power-dependent phase and amplitude distortions within and across WDM channels, coupled with chromatic dispersion that induces correlation across many, sometimes even hundreds of symbols. Mathematically, fiber transmission in two polarizations is described by the coupled nonlinear Schrödinger equation (NLS). Digital backpropagation (DBP) as a means to numerically invert the NLS at the receiver [21], [22] has been introduced to mitigate signal-to-signal nonlinear interactions such as self-phase modulation (SPM) and cross-phase modulation (XPM). With the availability of the signal fields of all the constituents of a superchannel, joint DBP can be applied to mitigate both SPM and XPM impairments. XPM compensation using DBP via the coupled nonlinear Schrödinger equation has been experimentally demonstrated [22]. It was found that as XPM is phase-insensitive, the phase-locking among the interacting signals is not needed for XPM compensation. The DSP complexity of DBP based fiber nonlinearity compensation is much higher than that of a conventional coherent receiver. This calls for DSP-efficient fiber nonlinearity compensation schemes. Recently, novel fiber nonlinearity mitigation schemes based on the Volterra series [23] and phase-conjugated twin waves [24] have been introduced.

For DSP-efficient dispersion compensation of superchannels, subband equalizers [25] and filter-bank-based digital subbanding [26] have been proposed. In these approaches, a superchannel is divided into multiple subbands, which are individually dispersion-compensated to achieve higher DSP efficiency and easier parallelization. As briefly mentioned earlier, joint FEC using all the superchannel constituents may provide additional performance improvements. In [27], a coherent modem is implemented by coding across two PDM-QPSK channels spaced at 200 GHz and is found to reduce the transmission penalty due to PMD and polarization-dependent loss as compared to that without joint FEC processing. In a recent WDM transmission experiment,



[FIG8] The measured BER of all the constituents making up the superchannel after 5,600-km transmission (after [6]).



[FIG9] The evolution of optical transmission system capacity. Experimentally achieved single-channel bit rates are also shown. The possible future evolution of SDM is also shown (after [1]).

short-wavelength channels are worse performing that long-wavelength channels, and joint FEC processing using a long-wavelength channel and a short-wavelength channel has also been found to be beneficial [18].

FUTURE OUTLOOK

As today's WDM communication technology has already taken advantage of all degrees of freedom of a lightwave in a single-mode fiber, particularly frequency, polarization, amplitude, and phase, further multiplicative growth has to explore new degrees of freedom. Space-division multiplexing (SDM) is expected to further scale network capacities, using parallel strands of single-mode fiber, uncoupled or coupled cores of multicore fiber, or even individual modes of a few-mode fiber [28]. Figure 9 illustrates the capacity growth trend of optical fiber communication systems [1]. In SDM systems that induce coupling between the spatial modes, multiple-input, multiple-output (MIMO) DSP has been demonstrated to undo the mode coupling and enable penalty-free mode multiplexing [28].

Similar to the case of superchannel transmission, joint DSP can also be applied in the case of SDM transmission to efficiently compensate for transmission impairments that are common to the spatial modes involved. Joint DSP for CFR in such spatial superchannel transmission has recently been experimentally demonstrated [29].

DSP WILL CONTINUE TO PLAY A KEY ROLE IN THE FUTURE EVOLUTION OF OPTICAL NETWORKS TO SUPPORT THE EVER-INCREASING DEMAND FOR INTERNET TRAFFIC AND CLOUD COMPUTING.

One important goal of optical fiber communications is to support the communication capacity growth in a sustainable fashion, which means continuously lowering the cost per information bit. In addition to improving transmission capacity and/or performance for a given set of hardware components, this can be achieved by using advanced DSP to compensate for the shortcomings of lower-cost and highly integrated O/E components. For example, compact all-InP integrated laser and modulator assemblies and silicon photonics-based devices, when complemented with advanced DSP, are promising candidates to reduce the cost, size, and power consumption of future optical transport systems [30].

CONCLUSIONS

DSP has played an important role in supporting the recent capacity expansion of optical core networks based on coherent modulation and detection. To enable sustainable capacity growth, the cost per information bit needs to continuously decrease. Superchannels, with their improved system SE and their natural compatibility with large-scale integration, are expected to be well suited to meet this demand. DSP may see more emerging applications in superchannel transmission and in relaxing the physical requirements on optical components, and continue to play a key role in the future evolution of optical networks to support the ever-increasing demand for Internet traffic and cloud computing.

AUTHORS

Xiang Liu (xiang.liu@alcatel-lucent.com) is a distinguished member of technical staff at Bell Labs, Alcatel-Lucent. He received his Ph.D. degree in applied physics from Cornell University in 2000. Since joining Bell Labs, he has been working on high-speed optical communication technologies including advanced modulation formats, digital coherent detection, and fiber nonlinear impairment mitigation. He was recognized as a core member of the "100 Gb/s Coherent (Long Haul–High Capacity WDM Interface) Team" that received the 2010 Bell Labs President's Award. He has authored/coauthored over 250 journal and conference papers and holds 51 U.S. patents. He is a fellow of the Optical Society of America and an associated editor of *Optics Express*.

S. Chandrasekhar (sc@alcatel-lucent.com) is a distinguished member of technical staff at Bell Labs, Alcatel-Lucent. He received the Ph.D. degree in physics from the University of Bombay, India, in 1985, and joined Bell Labs, New Jersey in

1986. He was recognized as a member of the "100 Gb/s Coherent (Long Haul–High Capacity WDM Interface) Team" that received the 2010 Bell Labs President's Award. His current interests include coherent optical transmission for high SE transport and networking beyond 100 Gb/s. He is a Fellow of the IEEE and the OSA. He received the IEEE LEOS Engineering Achievement Award in 2000 and the Optical Society of America Engineering Excellence Award in 2004 for his contributions to optoelectronic integrated circuits and WDM systems.

Peter J. Winzer (peter.winzer@alcatel-lucent.com) heads the Optical Transmission Systems and Networks Research Department at Bell Labs, Alcatel-Lucent. He received his Ph.D. degree in electrical engineering from the Vienna University of Technology, Austria, and joined Bell Labs in 2000, focusing on hardware and architectural aspects of fiber optic transmission systems and networks. He has published over 300 journal and conference papers, holds over 30 U.S. patents, and is actively involved in technical and organizational tasks with the IEEE and the Optical Society of America, currently serving as editor-in-chief of *Journal of Lightwave Technology*. He is a distinguished member of technical staff at Bell Labs and a Fellow of the IEEE and the Optical Society of America.

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