Technology Options for 400G Implementation

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Working Group: Joint Carrier and Physical and Link Layer Working Groups

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ABSTRACT: This contribution presents the 400G White Paper document.

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List of Acronyms

ACO Analog Coherent Optics
ADC Analog-to-Digital Converter
AGC Automatic Gain Control
ASE Amplified Spontaneous Emission
ASIC Application-Specific Integrated Circuit
AWGN Additive White Gaussian
BER Bit Error Rate
CapEX Capital Expenditures
CD Chromatic Dispersion
CDC Colorless Directionless Contentionless
CFP 100G Form Factor Pluggable
CMOS Complementary Metal-Oxide Semiconductor
DAC Digital-to-Analog Converter
DBP Digital Back-Propagation
DCF Dispersion Compensating Fiber
DCM Dispersion Compensation Module
DD-LMS Decision-Directed Least Mean Squared
DFB Distributed-Feedback
DGD Differential Group Delay
DRA Distributed Raman Amplifier
DSF Dispersion Shifted Fiber
DSP Digital Signal Processing
DWDM Dense Wavelength-Division Multiplexing
ECL External Cavity Laser
EDFA Erbium-Doped Fiber Amplifier
ENOB Effective Number of Bits
FCRT Fixed-Code-Rate Transceiver
FEC Forward Error Correction
FIR Finite Impulse Response
FWM Four-Wave Mixing
GFF Gain Flattened Filter
GN Gaussian-Noise
GVD Group Velocity Dispersion
HD-FEC Hard-Decision FEC
HW Hardware
ICR Integrated Coherent Receiver
ISI Inter-Symbol Interference
ITLA Integrable Tunable Laser Assembly
LH Long-Haul
LO Local Oscillator
MMF Multimode Fiber
MIMO Multiple Input Multiple Output
MZM Mach-Zehnder Modulator

MQAM M-ary Quadrature Amplitude Modulation
NCG Net Coding Gain
NF Noise Figure
NLSE Nonlinear Schrödinger Equation
OEO Optical-Electro-Optical
OFDM Orthogonal Frequency Division Multiplexing
OpEX Operational Expenditures
OSNR Optical Signal-to-Noise Ratio
OTN Optical Transport Network
OTU Optical Transport Unit
PBC Polarization Beam Combiner
PBS Polarization Beam Splitter
PD Photo Detector
PDM Polarization-Division Multiplexing
PMD Polarization Mode Dispersion
PMQ integrated Polarization Multiplexed Quadrature modulated transmitter
PSD Power Spectral Density
QAM Quadrature Amplitude Modulation
QPSK Quadrature Phase Shift Keying
RF Radio Frequency
ROADM Reconfigurable Optical Add/Drop Multiplexer
SBS Stimulated Brillouin Scattering
SDN Software Defined Network
SDO Software Defined Optics
SD-FEC Soft-Decision FEC
SE Spectral Efficiency
SH Short-Haul
SSMF Standard Single-Mode Fiber
SNR Signal-to-Noise Ratio
SPM Self-Phase Modulation
SRS Stimulated Raman Scattering
SSFM Split-Step Fourier Method
TR Timing Recovery
TIA Transimpedance Amplifier
ULH Ultra-Long-Haul
WDM Wavelength-Division Multiplexing
WSS Wavelength Selective Switching
XPM Cross-Phase Modulation

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1 Project Summary

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2 Motivation or Executive Summary

Network carriers continue to face the bandwidth and capacity demand in metro, regional, and long-haul networks as the traffic grows at around 2 dB per year driven by more and more video streaming and proliferation of cloud computing, data centers, social media, and mobile data delivery. Currently, the widely deployed 100-Gb/s long-haul optical systems are all based on polarization division multiplexed quadrature phase-shift keying (PDM-QPSK) modulation format associated with coherent detection and digital signal processing (DSP). The achieved spectral efficiency (SE) is 2 bit/s/Hz over conventional 50-GHz optical grid and thus the system capacity has been increased to around 10 Tb/s in the C-band optical fiber transmission window. The corresponding standardization processes of client side 100GE, transport layer Optical Transport Unit 4 (OTU4), and the key electro-mechanical aspects have been completed by international standard organizations of IEEE/ITU-T/OIF to realize end-to-end system connection and interoperability networking.

Optical transport of per-channel bit rate beyond 100 Gb/s is now under active R&D to sustain the traffic growth, improve spectral efficiency, and lower cost per bit in fiber transmission. In that respect, 400-Gb/s data rate per channel emerged as a natural and promising step as a result of the consideration on both the evolution of datacom and transport interface speed and the implementation complexity. There exist different dimensions to scale the channel capacity to 400G, such as baud rate increase, higher-level quadrature amplitude modulation (QAM) modulation formats, or super-channel with advanced spectral shaping and multiplexing technologies.

Unlike 100G system with a commonly adopted solution, 400G is in active development based on multiple options in terms of different optical signal-to-noise ratio (OSNR) receiver sensitivity, implementation penalty and fiber transmission impairment penalty. As the whole industry moves forward for 400G-transmission speed, it is crucial to have standardized organizations working together, as was achieved with 100G optical interfaces.

Recognizing the industry's demand, the OIF authorized the joint PLL WG and Carrier WG to investigate 400G with a key objective of developing a white paper on potential enabling technologies for optical transport applications.

3 Introduction

The Physical Link Layer Working Group and The Carrier Working Group have jointly started a project on 400G White Paper. The expected output of this project is summarized as follows:

- This project will develop a white paper.
- This white paper will provide an overview of the current architectures and technologies for 400G transport solutions.
- Summary of 400G transport system characteristics.
- An attempt to rank these solutions according to the application area, e.g. short-haul (SH), metropolitan, long-haul (LH) and ultra-long-haul (ULH).

4 Carriers view on 400G transmission systems

4.1 Context

The success story of coherent 100G PDM-QPSK has begun in 2010 by the first industrial deployments of 100G wavelength-division multiplexing (WDM) systems for long-haul applications. This technology breakout has allowed keeping the existing infrastructure constituted of erbium-doped fiber amplifier (EDFA), G.652 fiber and 50 GHz dense WDM (DWDM) fixed grid while maintaining globally transmission reaches and increasing spectral efficiency tenfold when compared to 10G WDM systems. The coherent 100G PDM-QPSK systems tolerate at least 30 ps of polarization mode dispersion (PMD), about 50 000 ps/nm of chromatic dispersion (CD) and can cover about 2000-2500 km over G.652 fiber with dispersion compensating fiber (DCF)-free engineering and purely EDFA amplification thanks to coherent detection, digital signal processing/equalization at the receiver side and soft-decision forward error correction (SD-FEC).

The 100G implementation in long-haul WDM transmission was coupled with a concomitant availability of 100 GbE client physical interface standardized by IEEE 802.3 in 2010. Next step for higher bit rate in WDM transmission passes through the use of 400G but one has to keep in mind that 400G client interfaces are far from industrial availability. In parallel, 400GbE task force has just been launched by IEEE 802.3 in March 2014 for a standard approval expected by 2017.

4.2 Constraints & Challenges for 400G

Due to physical limits and network applications considered in term of reach, the quadrupling of spectral efficiency is not reachable for 400G when compared to 100G PDM-QPSK (2 bit/s/Hz). To significantly increase spectral efficiency above 2 bit/s/Hz, the use of 2^N-QAM (N>2, where N is the constellation order) is necessary. Nyquist filtering (or spectral shaping) implemented at the transmitter side may also help to improve spectral efficiency. But reduced transmission reach is unavoidable because these high-order QAMs require higher OSNR, they are more sensitive to laser phase noise (ex: 16QAM is 4-fold more sensitive than QPSK) and to fiber non-linear effects, in particular to non-linear phase noise. Another point to be considered is the tolerance of modulation format to cascading of reconfigurable optical add/drop multiplexers (ROADMs). The higher the order of QAM, the lower is the tolerance to narrow optical filtering. For instance, 16QAM will be less robust than QPSK to narrow optical filters.

As a consequence of these various constraints, equipment suppliers seem today to converge towards super-channels constituted of 2 sub-carriers carrying each 200G PDM-16QAM in 75 GHz bandwidth, corresponding to a spectral efficiency of 5.33 bit/s/Hz. The 2x200G PDM-16QAM requires when compared to 100G PDM-QPSK 7 dB higher OSNR, which corresponds more or less to a reduction by a factor of 5 of the maximum transmission distance of 2x200G PDM-16QAM when compared to 100G PDM-QPSK. Table 1 below summarizes the main features of the solutions proposed today by equipment suppliers to reach the data-rate of 400G per channel.

We observe that we cannot increase simultaneously the spectral efficiency and the maximum transmission distance of the WDM systems. Consequently, a trade-off has to be met between the order of QAM modulation, the symbol rate, and the spectral occupancy. However, 32 Gbaud seems to be the best trade-off to increase the spectral efficiency without stressing too much electronics (digital to analog converter (DAC) / analog to digital converter (ADC) / radio frequency (RF) drivers) and transmission performance.

Modulation	QPSK	16QAM	16QAM	8QAM	QPSK	QPSK
Overall Data Rate (Gb/s)	100	400	400	400	400	400
Symbol Rate (Gbaud) with FEC	32	32	64	43	64	32
Number of sub-channels	1	2	1	2	2	4
Nyquist filtering	No	Yes	Yes	Yes	Yes	Yes
Data rate per sub-channel (Gb/s)	100	200	400	200	200	100
Channel occupancy (GHz)	50	75	75	100	150	150
SE (bit/s/Hz)	2	5.33	5.33	4	2.66	2.66
Required OSNR at BER=10^{-2}	12.5	19.5	22.5	18.5	13.4	12.5
Maximum transmission reach* (km)	~2000	~400	~200	~500	~600	~2000
HW implementation penalty		++	+++	+++	++	+

Table 1 Constraints and challenges for 400G WDM.
Note: G.652 fiber, EDFA only, constant NLE with respect to 100G QPSK.

From a general point of view, the following remarks can be done:

- In terms of hardware (HW) implementation penalty:
  - High symbol rate stresses DAC/ADC in terms of bandwidth.
  - High-order QAM stresses DAC/ADC in terms of effective number of bits (ENOB).
- In terms of transmission performance:
  - High-order QAM requires more OSNR at the receiver side, which drastically reduce the transmission reach.
  - High-order QAM is significantly more sensitive to accumulation of linear (laser) & nonlinear (fiber) phase noise.
  - High symbol rate relaxes the sensitivity to fiber nonlinearities.

4.3 Long-Haul requirements for 400G

The minimum required transmission reach for 400G has to be above 1000 km and ideally ~2000 km as for 100G. Over DCF-free G.652 fiber transmission line using purely EDFA amplification, coherent 2x200G PDM-16QAM systems with Nyquist filtering (spectral occupancy = 75 GHz, SE ~ 5.3 bit/s/Hz) may have as low as 400 km reach, which is clearly insufficient for LH application requirements.

Using hybrid 3-pumps Raman/EDFA amplifiers with noise figure (NF) ~ 0 dB[1] saves ~ 5 dB of OSNR margins and increases maximum transmission reach in the range of [1200-1300] km for the same modulation format, which allows to cover a large range of applications. Otherwise, 400G could be obtained thanks to coherent 4x100G PDM-QPSK technique with maximum transmission reach around 2000 km. As already explained, this improvement of transmission reach is obtained at the expense of the spectral efficiency, which is weak in this case, i.e. 2.66 bit/s/Hz @ 400G against 2 bit/s/Hz @ 100G.

It can be also noticed that multi-band orthogonal frequency-division multiplexing (MB-OFDM) could be used either with 16-QAM, 8-QAM or QPSK and could relax significantly the pressure put on DAC/ADC (bandwidth and sampling speed) without any performance degradation with respect to Nyquist-WDM approach. Nevertheless, from a networking perspective, it seems that 4x100G transmission solutions offers a higher flexibility than the 2x200G or 1x400G transport solutions, in particular in terms of protection/restoration or more generally in terms of rerouting[2].

Another important point is that a new Flexgrid defined in ITU-T G.694.1 recommendation, based on 12.5 GHz spectral granularity, has been proposed recently. It specifies the following frequency slots for different bit rates as shown in Figure 1:

  - 100G PDM-QPSK @ 32 Gbaud can be put in 37.5 GHz spectral slot.
  - 2x200G PDM-16QAM @ 32 Gbaud can be put in 75 GHz spectral slot.

- Optical switching of 37.5 GHz or 75 GHz spectral slots is not possible without inferring significant filtering penalties in ROADM cascade.
- Theoretical 25% gain in capacity allowed by flexgrid is partially lost by the requirement to insert guard-band between the 37.5 GHz or 75 GHz spectral slots.

[1] Finisar, Hybrid Raman/EDFA data sheet available at https://www.finisar.com/optical-amplifiers/foa-r9300th-hbr3c-aa001.
[2] See reference [Pincemin 14] for more information.

- Keeping the 50-GHz ITU-T grid for 400G seems pragmatic, while waiting for ROADMs able to manage effectively the 37.5 GHz spectral slot.

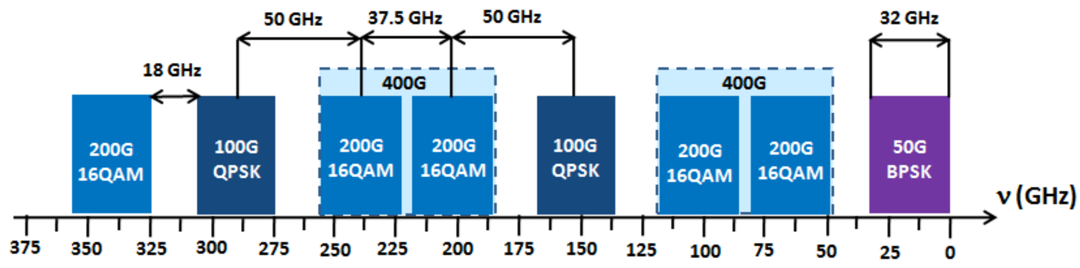

Figure 1 New Flexgrid defined in ITU-T G.694.1 recommendation.

4.4 Networking requirements for 400G

WDM systems were traditionally deployed in operator's networks by using terminal multiplexers placed at both ends of an optical line in a point-to-point (Pt2Pt) architecture. This type of architecture definitively lacks on flexibility of wavelength routing. Thanks to wavelength selective switch (WSS) integrated into ROADMs, a true photonic-layer networking is achievable at a reasonable cost. Thus, ROADMs have improved the manageability of wavelengths as add/drop, bypass and switching of an optical channel can be performed at each node of a network. Multi-degree ROADM, have allowed the photonic networks to evolve from Pt2Pt or ring architecture to a fully meshed network topology. Therefore, ROADM-based transmission network has been widely adopted by carriers and there is now a clear desire from carriers to take benefit of the flexibility brought by meshed network. Adoption of 400G should not compromise on this aspect and should even be an enabler for more flexibility.

Some of the requirements for 400G networking are given hereafter:

- Being able to resize the transport capacity between two nodes at the edges of the network depending on the real data rate demand will help operators to save bandwidth on intermediate segments of the meshed network when possible. Reuse of the saved capacity allows either accepting more services on the same infrastructure or allowing capacity for dynamic services.

- Being able to switch photonic channel all along its road and potentially re-optimize on the fly the route of a channel will allow operators either reorganizing easily the traffic matrix especially after some period of network usage (e.g. rerouting) or helping in reducing the critical impact of planned maintenance operations (reduce the emergency of interventions or avoid costly non-working hours operations).

- All the same, this would also give the possibility to differentiate optical services by introducing different SLA and by providing diverse types of channel recovery (optical 1+1, photonic restoration…) in a network where channels with different data rate and maximum reach coexist.

4.5 Metro requirements for 400G

For metro applications, the transmission reaches have to be above 50 km for metro/access and below 1000 km for metro/regional applications. Due to the high levels of PMD affecting parts the fiber infrastructure used in metropolitan transport networks, PMD robustness could be at least 25-30 ps. Furthermore, 400G has to be sufficiently resistant to narrow optical filtering resulting from a ROADM cascade, because it can go through up to ~10 ROADMs.

Cost, footprint reduction and power consumption are key parameters. 2x200G PDM-16QAM with its maximum transmission reach of 400 km partially meets metro requirements. For extending transmission reach up to requirements of metro/regional (~1000 km), may be required to improve optical amplification

- 100G "low-cost" & "energy-efficient" coherent PDM-QPSK pluggable interfaces are promised to a big success in metro context, and will not be replaced soon …(*"OIF Carrier WG Requirements for Intermediate Reach 100G DWDM for Metro Type Applications" (March 2014)*)

4.6 Conclusion

- Although some industrial systems begin to appear especially with 2x200G PDM-16QAM modulation format, 400G WDM technology is still in development.
- It has to be taken care to the risk to reproduce at 400G the "modulation format soup" which has "killed" 40G data-rate.
- Today, there is a need for 400G solutions to fully satisfy the requirements for LH or Metro applications in terms of:
    - Transmission reach versus spectral efficiency.
    - Flexgrid (ROADM cascade with 37.5 GHz / 75 GHz granularity).
- Hybrid Raman/EDFA amplification with improved noise figure could be the solution to the transmission reach/spectral efficiency trade-off.
- A new generation of ROADM able to manage really the 37.5 GHz spectral granularity has to emerge to make the "flexibility" concept true.
- On the other hand, 400G client interface standardization is also far to be achieved and it is unclear today what technique will be chosen.

5 Basics Concepts on 400G WDM Transmission

5.1 Coherent Systems

The path towards optical 400G is a bit more technologically challenging when compared to optical 100G as different applications may rely on different implementations [Reis 14]. Fortunately, the coherent transceiver concept design is very likely to be based on the implementation depicted in Figure 2. Similarly as the ongoing work carried out by OIF in analog coherent optics (ACO) module for CFP2[3], the transceiver in Figure 2 can be divided into two sub-modules. The first one is the integrated polarization multiplexed quadrature (PMQ) modulated transmitter and the second one is the integrated coherent receiver (ICR). Both analog transmitter and receiver modules are designed to support arbitrary optical signal generation and coherent reception. Here, three degrees of freedom can be exploited in the same transceiver implementation to cover different application needs: (i) frequency- or wavelength-division multiplexing is used to generate single channel or multi-channel transmission; (ii) the electro-optical front-end supports advanced modulation formats, such as QPSK, 8QAM, 16QAM, or 64QAM; (iii) the electronic components in the analog front-end (linear drivers, transimpedance amplifiers, digital-to-analog and analog-to-digital converters) support symbol rates as high as 64 Gbaud, so that symbol rates and modulation formats can be set to achieve line rates of 100 Gb/s (QPSK), 200 Gb/s (8QAM/16QAM) and 400 Gb/s (16QAM/64QAM). One important aspect regarding the transceiver in Figure 2 is that the electro-optical components may be re-used to achieve variable capacity and spectral efficiency given that the signal processing in the transmitter and receiver sides are reconfigured. Obviously, as the modulation level and symbol rate increase, the requirements in terms of bandwidth, resolution and amplification gain become more stringent. However, with optimized digital signal processing functionalities in the transmitter and receiver sides, these physical requirements in the transmitter-receiver chain can be relaxed.

- Polarization multiplexed quadrature optical transmitter

The transmitter concept in Figure 2 is used to generate a PDM optical signal for any modulation formats and symbol rate limited to the electronics present in the transmitter side. The four components of the digital signal conveying the transmitted information (in phase (I) and quadrature (Q) components for X and Y polarizations) are converted to the electrical domain via high-speed DACs. Current DAC technologies are capable of providing 64-80 GSa/s (8 bits resolution) with analog bandwidth around 20 GHz, sufficient to generate 32 Gbaud and beyond RF signals with the appropriate pre-equalization scheme. These signals are amplified by high-bandwidth linear drivers to adjust the voltage levels to the desired operating point and to drive a dual-polarization IQ modulator (IQM) that modulates the optical carrier generated from an external

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[3] CFP2 Analog Coherent Optics Transceiver Modules – oif.2013.130, http://www.oiforum.com/private/oif-current-project-status/

cavity laser (ECL) source. One important parameter is the laser linewidth which has to be limited to 100 kHz for high-order constellations, e.g. 64QAM. After the two signal polarization tributaries are combined by a polarization beam combiner (PBC), the PDM optical signal is amplified and/or filtered to achieve the target launch power and spectral occupation prior to transmission.

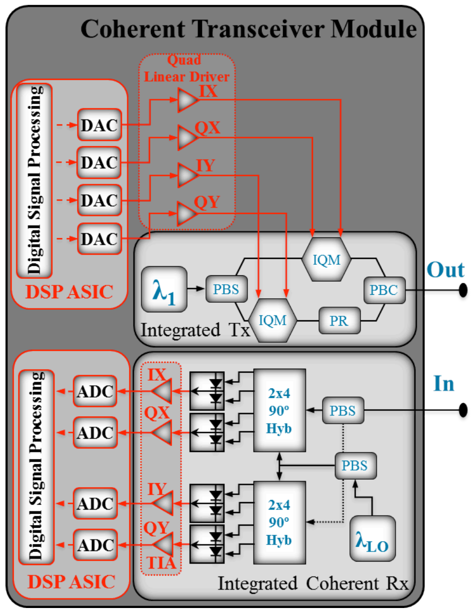

Figure 2 Coherent transceiver concept design for PDM systems with an integrated transmitter and coherent receiver. λ: laser source; IQM: in-phase quadrature modulator; PBS: polarization beam splitter; PBC: polarization beam combiner; PR: Polarization Rotator; LO: local oscillator.

- Integrated coherent optical receiver

After the optical signal travels through the optical network, a polarization/phase-diversity coherent optical receiver is used for linear detection. First, the PDM signal is split into two orthogonal polarizations via a polarization beam splitter (PBS). These optical signals are mixed with a free-running local oscillator (100 kHz – ECL) by a 2x4 90º optical hybrid. For each polarization, a pair of balanced photo-detectors (PD) is used to convert the optical signals to electrical domain. These RF signals are then amplified by transimpedance amplifiers (TIA), so that the high-speed ADCs are able to convert them to the digital domain. Important receiver parameters are the bandwidth of the photo-detectors (e.g., 30 GHz); imbalance due to imperfections of the optical hybrids' components, bandwidth (e.g. >20 GHz) and gain of the TIAs; tunability (e.g. over the entire C band), linewidth (e.g. ~100 kHz) and power of the local oscillator (e.g. ~18 dBm); and bandwidth (e.g. >25 GHz), effective number of bits (e.g. >7 bits of resolution) and speed of the ADCs (64-80 GSa/s). Although analog front-end components are the most critical, especially for broad bandwidth signals with advanced modulation formats, the subsequent digital processing may relax some of the system physical requirements.

5.2 Digital Signal Processing

Coherent detection and DSP were the key enabling technologies in the development of 100G optical transmission systems. 400G systems will continue this trend with DSP playing even more ubiquitous role at both transmitter and receiver. Although the specific algorithms for each process block are typically different because there are various realizations of the same process block in the implementation level, the generic functions in the structural level or function abstractions are similar for all major commercial products. As shown in Figure 3, transmitter DSP functions include symbol mapping and signal timing deskew adjustment, optional dispersion and nonlinearity pre-compensation, and software-programmable capability of supporting multiple modulation formats and encoding schemes. Transmitter DSP also allows compensating nonlinearities

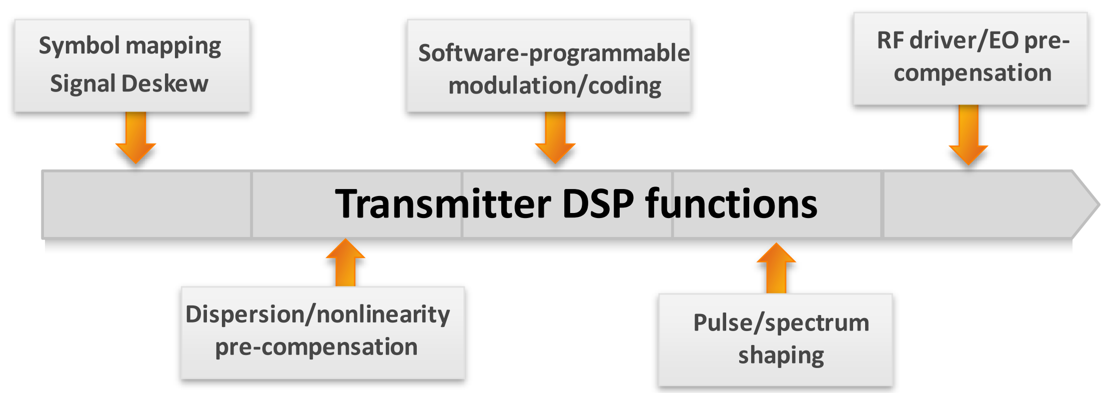

Figure 3 Transmitter-side DSP functions.

induced by the electrical driver and the optical modulator. Another benefit is to perform pulse shaping and thus engineering the signal spectrum as required in Nyquist WDM super-channels discussed later. In the case of electrical OFDM, DSP is used for computing the inverse fast Fourier transform (IFFT). Transmitter-side DSP enables more flexibility not only in channel impairment pre-compensation point of view but also in software configuration for flexible optical networks as the authors discuss in [Reis 14].

As far as the receiver is concerned, the major advantage of receiver-side DSP stems from the ability to arbitrarily manipulate the electrical field after ADC enabling sampled signals in the digital domain. As shown in Figure 3, the fundamental DSP functionality in a digital coherent receiver can be illustrated by the following flow of steps from structural level and algorithmic level of details. Firstly, the four digitized signals (i.e. in-phase (I) and quadrature (Q) components for X and Y polarization) after an ADC are passed through the block for the compensation of front-end imperfection equalization. The imperfections may include timing skew between the four channels due to the difference in both optical and electrical path lengths within the coherent receiver. Other types of front-end imperfections may include different output power for four channel components and quadrature imbalance, as the optical hybrid may not be exactly 90 degree. Secondly, the static and dynamic channel transmission impairments are compensated through digital filters, in particular, CD and PMD, respectively. Based on different time scales of the dynamics of these impairments, the static equalization for CD compensation is performed firstly because of its independence of state of polarization (SOP) and modulation format and the impact on the subsequent blocks before the CD estimation is needed to achieve the accurate compensation. Then, the clock recovery for symbol synchronization can be processed to track the timing information of incoming samples. Note that it is possible to perform joint process between the blocks of clock recovery and polarization demultiplexing or achieving the symbol synchronization after

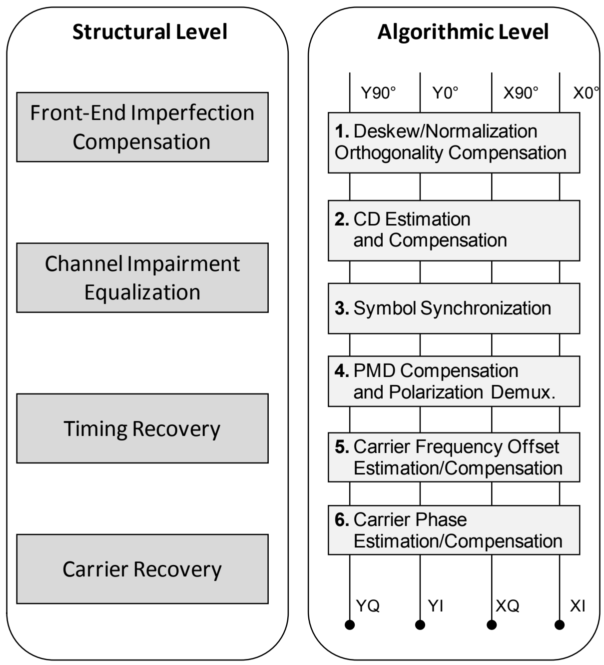

Figure 4 DSP flow in a digital coherent optical receiver.

equalized all channel impairments. A fast adaptive equalization is carried out jointly for two polarizations through a butterfly structure and the stochastic gradient algorithms. Then, the frequency offset between the source laser and the LO laser is estimated and removed to prevent the constellation rotation at the intradyne frequency. Finally, the carrier phase noise is estimated and removed from the modulated signal, which is then followed by symbol estimation and hard or soft-decision FEC for channel decoding.

The constellation evolutions in Figure 5 show three examples of the received signal with the modulation formats QPSK, 8QAM and 16QAM after linear transmission over uncompensated standard single-mode fibers (SSMF) using only EDFAs. The results are based on 32 Gbaud symbol rate. It is also noted that the impairments considered are due to both frequency offset of 0.1 GHz between 100-kHz linewidth Tx and LO lasers and 20000 ps/nm accumulated CD.

It is also important to mention that for a particular digital coherent receiver, the ordering of DSP flow may differ slightly from those detailed in Figure 4 because different design implementations may be either based on feed-forward or feedback processing. Additionally, it is possible to perform joint processing such as clock recovery and polarization demultiplexing as mentioned earlier. Furthermore, the same functions may rely on the use of training sequence (data-aided) or be performed totally blind.

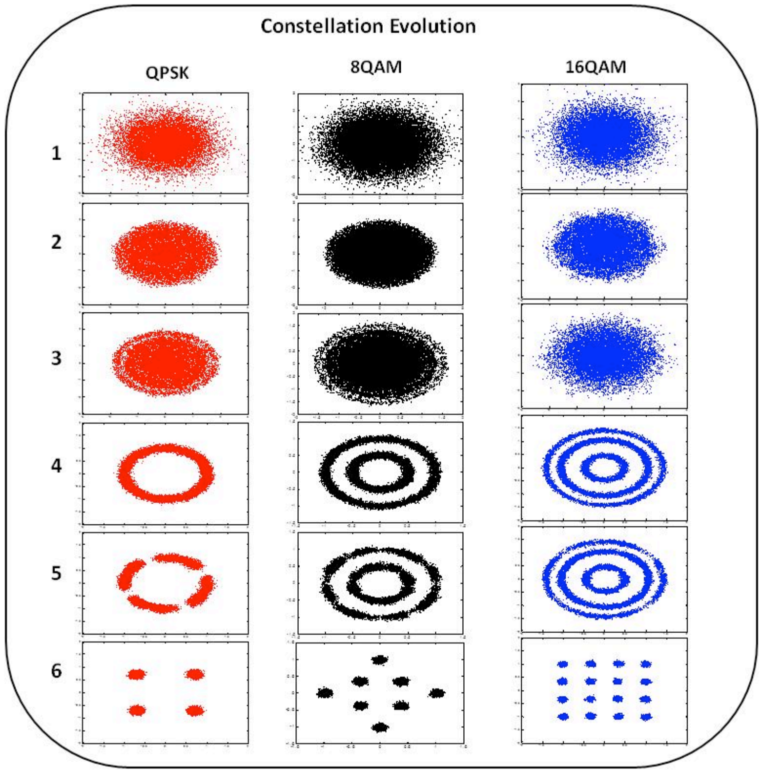

Figure 5 Constellation evolutions for QPSK/8QAM/16QAM signals in a digital optical coherent receiver.

5.3 Optical Channel Multiplexing

Frequency-division multiplexing (FDM) is a key enabling technology to generate optical super-channels in frequency grids below 150 GHz in high-capacity WDM networks employing 400 Gb/s coherent transceivers. In order to enhance spectral efficiency, two technological options have been used recently, Nyquist WDM and OFDM. Nyquist WDM is a super-channel technology that shapes the wavelength spectrum of each sub-channel close or even smaller than its symbol rate (Nyquist bandwidth) by filtering the optical pulses (*sinc* pulses) either in the optical domain (e.g. via WSS) or in the digital domain (e.g. via DAC). When generated in the digital domain, it has the advantaged of shaping the signal bandwidth very closely to the Nyquist limit (symbol rate). The most used pulse shaping is the raised cosine filter, which is implemented in the DSP ASIC using finite impulse response (FIR) digital filters. With a few filter coefficients (or filter taps), one can achieve very small roll-off factors. As the filter size increases, the Nyquist-shaped signal converges more efficiently to a rectangular spectrum bounded by the symbol rate [Schmogrow 12]. Another important point is that it is possible to further squeeze the sub-channel bandwidth below the Nyquist limit such that the interchannel spacing is below the symbol rate. This technology is referred as faster-than Nyquist or super-Nyquist [Wang 15], [JZhang 14].

In OFDM, the *sinc*-shaped subcarriers are orthogonally multiplexed and can also be viewed as super-channel technology when several OFDM bands (or sub-channels as in Nyquist WDM) are frequency multiplexed, i.e. Multi-Band OFDM (MB-OFDM) [Pincemin 14]. Coherent Optical OFDM (CO-OFDM) [Shieh 10] is a terminology used when the subcarriers are generated in the optical domain. Similarly as the Nyquist-shaped signal, the OFDM signal spectrum approaches a rectangle by increasing the number of subcarriers for a fixed symbol rate.

In the WDM view point, nearly rectangular spectra are desirable so that the inter-channel guard-band is reduced, which improves the overall spectral efficiency without introducing inter-channel (or carrier) interference (ICI). Figure 6 illustrates the main differences between Nyquist WDM and MB-OFDM in a WDM scenario.

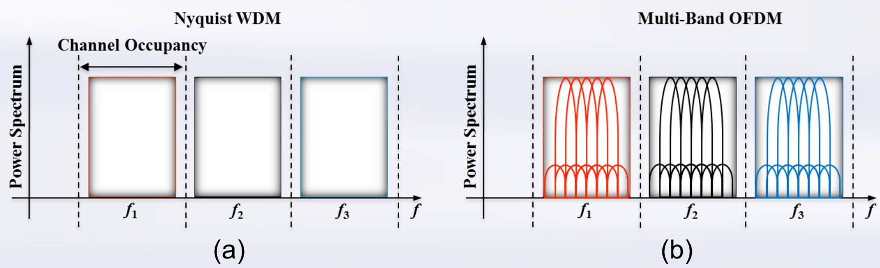

Figure 6: Optical channel multiplexing for spectrally-efficient WDM networks. (a) Nyquist WDM. (b) Multi-Band OFDM.

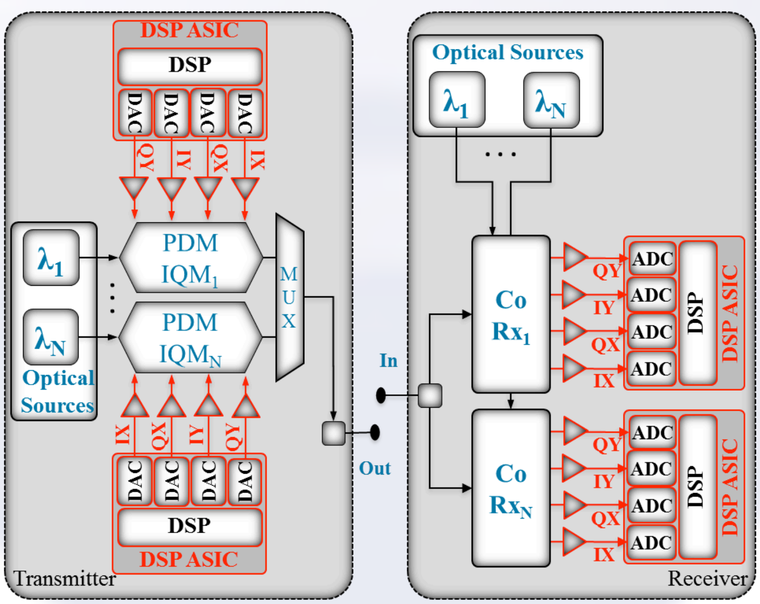

Figure 7: Conceptual structure of a super-channel transceiver. CO Rx: Coherent Receiver; PDM-IQM: Polarization-Division Multiplexing IQ Modulator.

Figure 7 illustrates an exemplary transceiver for generating and receiving an optical super-channel with two sub-channels. In this example, the sub-channel has the option to be generated either in (i) the optical or in (ii) the digital (electrical) domain. In the optical domain (i), the optical sources (or carriers) are modulated in a PDM IQ modulator (PDM-IQM) with the RF signals from the DSP application-specific integrated circuit (ASIC). These optical sources can be from free-running lasers as long as the frequency drifting does not introduce overlap between the modulated sub-channels. Otherwise, locked optical sources (synchronized) may be used to avoid ICI if the super-channel has very tight requirements regarding frequency grid. This approach has the advantage of relaxing the RF analog requirement since the front-end bandwidth is limited by the sub-channel bandwidth. The second option is when the super-channel is generated entirely in (ii) the digital domain, which eliminates any need for optical synchronization between the sub-channels. Instead, one can implement the multiplexed sub-channels or the MB-OFDM signal in the DSP ASIC so that they modulate only one optical source. The disadvantage of this method is that it pushes the RF analog components to the bandwidth of the optical super-channel.

The OFDM signal can be generated also in the DSP ASIC, as the DSP functions shown in Figure 8. At the transmitter, data are first parallelized and conveniently mapped into the complex symbols. Then, a training sequence (TS) is inserted for channel monitoring [Fabrega 13]. Next, the resulting symbols are OFDM modulated, typically using the IFFT algorithm. Subsequently, the cyclic prefix (CP) is inserted and the obtained OFDM symbols are serialized and converted to the analog domain via DACs. After coherent detection at the receiver, the DSP ASIC reverses the steps in the DSP transmitter for demodulating of the OFDM signal, i.e. parallel to serial, CP extraction, FFT, training sequence TS based equalization, on the TS and symbol demapping.

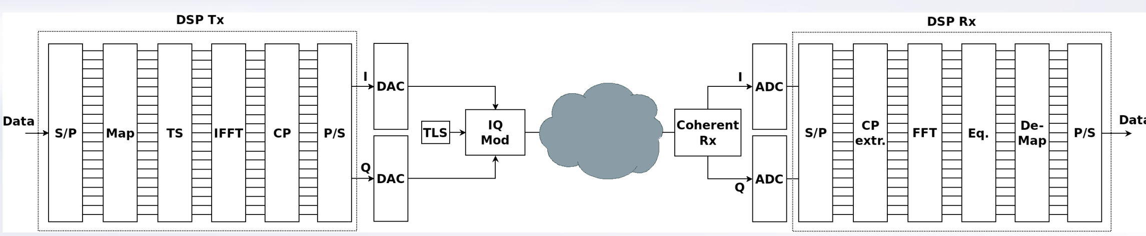

Figure 8: Generic scheme for the generation and detection of OFDM signals. The DSP functions include serial/parallel (S/P) and parallel/serial (P/S) conversion, symbol mapping and demapping, cyclic prefix (CP) insertion and extraction, training sequence (TS) insertion, and equalization.

5.4 Optical Path

The need is arising to transmit ever-higher bit rate data streams over long distances optically. However, it will become increasingly difficult to achieve higher spectral efficiency and to reduce the marginal cost-per-bit of transport in the future. The use of multiple optical carriers, near Nyquist channel spacing, as detailed in the previous section, is attractive because of the reuse of 100 Gb/s technologies at symbol rates of 32 Gbaud and below. This approach maximizes the optical reach but is limited in spectral efficiency improvement and requires that a flexgrid ROADM infrastructure be in place. However, in the longer term, this approach does not effectively utilize the transmission capacity of the optical fiber, because either the spectral efficiency or link reach are limited. These shortcomings will lead to more rapid fiber exhaust as traffic continues to grow. As optical fiber overbuilds or new routes are considered, it is sensible to evaluate the capacity benefits of improving on the basic ITU-T G.652 optical fiber.

Another straightforward way of increasing the spectral efficiency is to use a higher-order transmission modulation format than QPSK. However, other formats (such as 16QAM) have denser constellations, requiring higher OSNR for a given link reach. This requirement is such that links of this type are limited to ~600 km in reach when using standard G.652 fiber with EDFA amplification. To improve the reach, either higher transmission power or lower noise amplifier is required. Current understanding of coherent links (without dispersion compensation) reveals that the optical noise consists of two parts: an amplified spontaneous emission (ASE) noise from the EDFA sites and a nonlinear noise due to the fiber nonlinearities acting on the transmitted signals. Because the nonlinear noise scales with the cube of the channel launch power, it quickly becomes the dominant impairment.

Two optical fiber developments are underway to reduce the noise problem. These are fibers with lower optical attenuation, and fibers with larger effective mode field area. The first type requires lesser amplifier gain at the end of each span (thereby lesser ASE noise) and the second lowers the optical power density (mW/μm^2) so that the nonlinear noise is reduced. Fibers are now commercially available with 1550 nm attenuation near to 0.162 dB/km or effective areas of up to 125 μm^2 (terrestrial) and 150 μm^2 (submarine). A third technology that is relevant to the noise problem is Raman amplification. There is increasing acceptance today of hybrid amplification schemes involving both Raman and EDFA in the case of spans with higher than expected loss. In addition to being a broadband, wavelength addressable amplification technique, Raman also provides a lower noise figure than EDFA when it is deployed in a distributed fashion (throughout the transmission fiber).

As an example, consider a dual wavelength 400 Gb/s PDM-16-QAM system (32 Gbaud, 75 GHz channel width). The use of a 125 μm^2 effective area fiber (as opposed to the typical 83 μm^2 of G.652.D) with hybrid Raman-EDFA amplification achieves 2000 km reach with 80 km span lengths. The use of a standard effective area ultra-low loss fiber (< 0.16 dB/km 1550 nm fiber attenuation) can achieve 1600 km reach. A fiber with combined high effective area and low loss is capable of reaching 2500 km. All-Raman amplification provides another 25% increase in reach. Thus, there are fiber cable and amplifier solutions, feasible today, which enable ultra long-haul distances at 400 Gb/s with spectral efficiencies > 5 bit/s/Hz.

These same technologies will be critical as demands are made for higher line rates and spectral efficiencies. For example, spatial multiplexing has yielded record spectral efficiencies in short lengths of few-mode (32 bit/s/Hz over 177 km) or multi-core optical fibers (91.4 bit/s/Hz over 52 km). Feasibility has been demonstrated for splicing and connectorizing these fibers as well as for few-mode or multi-core amplifiers. One of the primary challenges remaining is the added complexity of signal recovery (multiple input multiple output (MIMO) is usually required in the few-mode case) and integration of the transmission optics to reap the benefits of the smaller fiber footprint. Nonetheless, these are promising paths for future evolution of ultra-high speed transmission links.

5.5 Optical Network Subsystem Elements

Current optical subsystems network elements and networking trends has been driven by the new agile optical layer routing elements such as ROADMs that aim at the maximum network flexibility through colorless-directionless-contentionless (CDC) channels adding and dropping. Along with the deployment of coherent transceivers (100 Gb/s) and future deployments of channel data rates of 400 Gb/s, new optical amplifiers technologies require flattened spectral gain with enhanced noise figure performance to improve legacy systems OSNR and thus enabling the smooth upgrade from 100 Gb/s to 400 Gb/s channels in metropolitan, long and ultra-long haul optical networks.

5.5.1 Optical amplifier paradigm

For optical WDM systems with 100 Gb/s per channel, the main optical amplification technology used was EDFA with automatic gain control (AGC) and distributed Raman amplifier (DRA) with fixed pumping control. However, several topologies were used depending on the optical network span length and degree of freedom, as follow:

I. Fixed gain: Single stage EDFA with AGC and gain flattened filter (GFF) providing flat spectrum only for one setpoint gain (nominal gain) and noise figure around 5 dB.

II. Variable gain: Double stage EDFA with joint stages AGC, providing flat spectrum for any setpoint gain and noise figure between 6 to 9 dB (lower to higher gain).

When topology I or II does not attend to the OSNR requirement, these amplifiers could be assisted by 2-3 pump DRA with fixed pumping control, to reduce the effective noise figure by 1 dB and 2-5 dB for topology I and II, respectively.

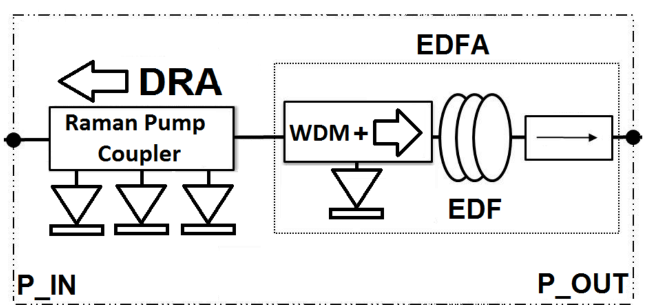

Figure 9 Structure of a hybrid optical amplifier (three pumps DRA and single stage EDFA).

However, the spectral gain flatness it is not guaranteed in this case for any topology.

Considering the data rate upgrade from 100 Gb/s to 400 Gb/s, a more stringent OSNR requirement is imposed in the system. One way to provide even lower levels of effective noise figure together with flattened spectral gain is through the use of a hybrid optical amplifier, as illustrated in Figure 9. The hybrid amplifier is composed by a three pump DRA and a single stage EDFA with a joint DRA/EDFA AGC based on DRA pump level control. This solution provides flattened spectral gain for different gain setpoints (due to the high saturation level compared to the EDFA) whereas the EDFA provides a fixed gain with high output power.

The hybrid amplifier (DRA/EDFA) with joint AGC could provide +/- 1 dB (with GFF) of gain flatness along a tenfold setpoint gain variation (10 dB) and effective noise figure level from -1 to 2 dB for metropolitan, long and ultra-long haul optical WDM networks.

5.5.2 ROADM paradigm

ROADMs have reconfiguration capabilities important in the agile network scenario, which allows part of the optical switching functionality to be managed by active optical devices through software-driven control and remote operability. In particular, due to the massive deployment of 50 GHz spacing Wavelength Selective Switches (WSSs) ROADMs in metropolitan optical networks, it may be required that one 400 Gb/s solution fits in 50 GHz grid preferably for distances up to 1000 km, e.g. 3 sub-carriers of 14 Gbaud – PDM-64QAM. Therefore, the already deployed 50 GHz infrastructure would be reused. On the other hand, other applications such as long and ultra-long haul WDM optical networks (>1000 km of fiber) can potentially allow the upgrade of fixed WSS module by a newly flexgrid modules with 12.5 or 6.25 GHz granularities. This is due to the fact that most of the 400G solutions would in theory fit in 75 GHz (e.g. 3 sub-channels of 21 Gbaud – PDM-16QAM) and 150 GHz for more relaxed modulation formats (4 sub-carriers of 32 Gbaud – PDM-QPSK) to achieve transmission distances of ~ 5000 km.

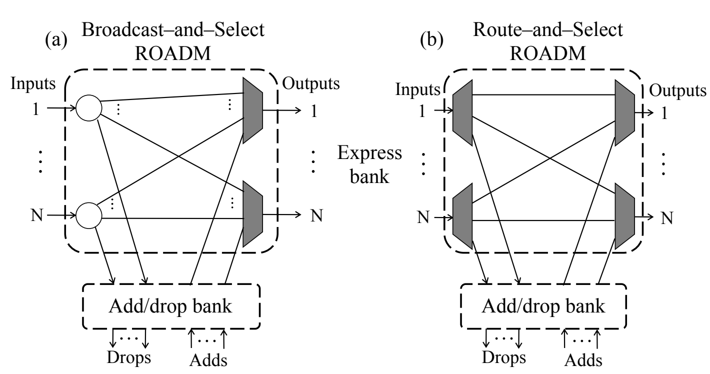

Figure 10 (a) Broadcast-and-Select and (b) Route-and-Select ROADMs.

As far as the ROADM is concerned, its architecture can be decomposed into two banks: the express bank and the add/drop bank. The express bank interconnects input and output ports whereas the add/drop bank inserts and derive the optical channels.

Figure 10(a) shows the classical Broadcast-and-Select architecture (BS-ROADM) with N splitters connected in a full mesh to N WSSs to pass the desired lightpaths at each output (low cost ROADM solution). The losses introduced by the broadcast splitters in the BS-ROADM increase linearly with N splitter ports. On the other hand, Figure 10(b) shows a Route-and-Select (RS-ROADM) architecture of degree N composed of N twin WSS modules. Lower and non-scalable losses are guaranteed when compared to the BS-ROADM at the price of increased cost especially for lower than 8 degrees ROADMs).

ROADM architectures notably evolved in recent years with different add/drop bank proposals that offer the so called colorless, directionless, and contentionless capabilities: colorless means that add/drop ports are not associated to a specific wavelength; directionless implies that add/drop ports are not associated to a specific ROADM input or output port; and contentionless means that the same color can be used without contention by up to N different ports of the same add/drop directionless structure each port being routed on different directions, and N corresponding to number of directions of the ROADM. Indeed, the design of the add/drop bank to provide CDC capabilities is subject of various studies and it still represents a technical challenge in the R&D community. However, considering that the main elements that compose the add/drop banks are lossy elements such as multiplexers/WSS switches (D, CD add/drop), multi-cast switches (CDC add/drop) and embedded EDFAs, it is valid to evaluate the impact of add/drop plus line ROADM noise figure over the transmitted 400 Gb/s channels and along with the fiber spans in order to sustain the required OSNR for 400 Gb/s WDM systems.

5.6 Software Defined Optics

Given the increasingly heterogeneous and dynamic traffic environment in current optical transport networks, such as connection lengths and hold times or different bandwidth requests and flexible grid [Ma 14], software defined optics (SDO), or reconfigurable and programmable optical transceivers, is regarded as

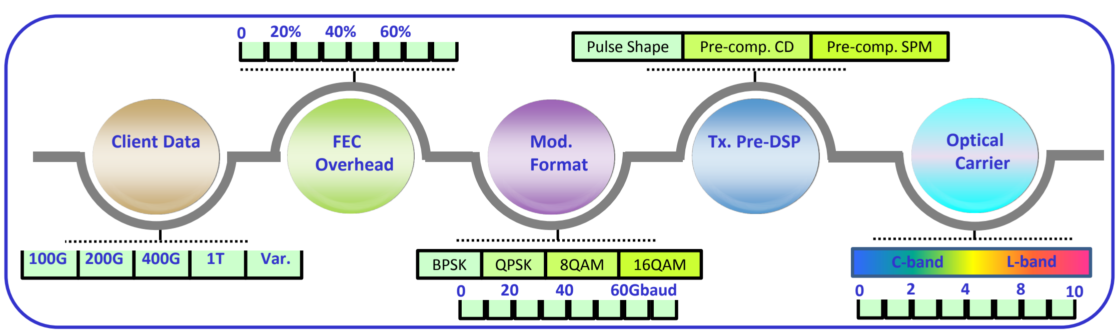

Figure 11 Software defined optics for flexible 400G optical transceivers.

one of the most effective approaches to deliver the best tradeoff between optical reach and spectral efficiency or the system capacity [Oliveira 14]. Using SDO technology, the same transceiver can operate in metro, long-haul and ultra-long-haul links with optimal performance and high power efficiency and also it can flexibly support the link adaptation through adjustment of transmission parameters as in software defined networks (SDN)[4]. Figure 11 illustrates the whole concept pictures for the SDO. At transmitter side, SDO may support variable client services. It can have different overhead coding scheme, configurable modulation formats and the corresponding transmitter side DSP, and also have different number of optical subcarriers [Aoki 14]. At the receiver side, a universal DSP is needed for supporting different modulation formats and FEC coding schemes [Isautier 14]. In terms of ASIC design and implementation, optimization is required between performance and power consumption. The current implementations in the optical industry have demonstrated partial programmable capabilities in terms of modulation format (BPSK/QPSK/8QAM/16QAM), symbol rate, and FEC overhead adaptation.

[4] For more information on SDN work by OIF, visit http://www.oiforum.com/private/oif-current-project-status/ SDN for Transport Document – oif2013.193

6 List of potential 400G transmission solutions and their characteristic parameters

6.1 State of the Art on Optical 400G Transmission

Practically all recently reported experiments of 400G transmission over metro, LH, and ULH distances rely on coherent reception with polarization diversity, to reduce the symbol rate and relax the bandwidth requirements on the different system components. Those reports can be classified into single-carrier and multiple-carrier solutions, where in the later case, usually two subcarriers are employed. To increase spectral efficiency, the proposed transmission schemes use high order modulation formats and low carrier spacing. The performance degradation due to the bandwidth and resolution limitations of the optical and electronic components are compensated by sophisticated signal processing techniques, e.g. advanced pulse shaping, high net coding gain FEC schemes, maximum likelihood detection, and use of high performance network components such as Raman amplifiers, ultra large area optical fibers, etc. This Section describes some research works on 400G recently reported and listed in Table 2. Table 2 summarizes the parameters (transceiver characteristics, modulation, rate and sub-channel counts) used in the reported works and the achieved SE and transmission distance. The performance results in terms of transmission reach, SE or any other figure of merit may change from work to another as different technologies (DSP, fiber, DAC/ADC, amplification etc) were used in the experiments. Another option for comparison is the required OSNR, whenever available, that should be listed along with the BER threshold. For more information on required OSNR, refer to Table 3 in sub-section 7.1 that lists theoretical OSNRs for different modulation formats and BER threshold.

In [Buchali 14], the authors reported a single carrier 400 Gb/s transmission over

Conference	Paper	Modulation	Symbol Rate Gbaud	Transceiver	#Carriers	SE bit/s/Hz	Distance km
OFC 2014	M2A1	64QAM	42.66	DAC 1.5 Sa/Sym	1	8	300
	Th3E4	16QAM	56	Fixed LUT + MAP	1	4	1200
	Th5B3	QPSK	110	ETDM	1	4	3600
	Tu2B1	16QAM	32	64 GSa/s DAC	2	4	1504
	Th4F3	16QAM	32	64 GSa/s DAC	2	5.44	630
	W1A3	8QAM	43	Nyquist+NL comp.	2	4.54	6787
	Th4F6	8QAM	40	64 GSa/s DAC	2	4	2250
ECOC 2014	PD.4.2	16QAM	64	88 GSa/s DAC	1	6	6600
	P.5.17	16QAM	40	64 GSa/s DAC	2	4	2150
JLT 2014	No. 4	16QAM	32	64 GSa/s DAC	2	6	9200
OFC 2015	W3E1	16QAM	32	2x200G / 50 GHz	2	4	550
	W3E2	QPSK	60	72 GSa/s DAC	2	4	6577
	W3E3	16QAM	32	2x200G/37.5 GHz	2	5.33	1000

Table 2 400G transmission experiments reported recently.

300 km of ultra large area fiber (ULAF) using PDM-64QAM modulation format at 42.66 Gbaud, to fit within the 50 GHz standard ITU-T grid, achieving net spectral efficiency of 8 bit/s/Hz. At the transmitter, DAC-based Nyquist pulse shaping was employed at a reduced oversampling rate of 1.5 samples per symbol, together with an additional pre-emphasis to compensate for the transmitter frequency slope. The authors also used a 24% overhead FEC code, so that the pre-FEC BER threshold is 4.5×10^{-2}.

Another example of a single carrier 400G system was reported in [Rezania 14], where the authors achieved 1200 km transmission using PDM-16QAM modulation format at 56 Gbaud with a 7% FEC overhead (SE = 4 bit/s/Hz). The bandwidth-related signal distortion due to the high symbol rate of the scheme was compensated by the use of an advanced maximum a posteriori (MAP) detection, previously established, training-based lookup table (LUT), to reduce the computational complexity. An important characteristic of this scheme is a raised cosine pulse shaping by a programmable optical filter at the transmitter.

Finally, an ultra-high symbol rate 110-Gbaud QPSK transmission over 3600 km of ULAF was reported in [JZhang1 14]. The authors used electronically time-division-multiplexing (ETDM) for signal generation, and an ultra-high rate 160 GSa/s 65-GHz bandwidth real-time oscilloscope. Additionally, a hybrid EDFA–Raman amplification scheme and a maximum likelihood Viterbi symbol decoding were employed, along with the super-Nyquist signal filtering, yielding net spectral efficiency of 4 bit/s/Hz.

Regarding the multicarrier approach, two PDM-16QAM, dual carrier experiments were reported in [Xia 14] and [Huang 14]. Both methods used 32 Gbaud signals and a 64 GSa/s DAC for the generation of the modulator driving RF signals. The first work reported a transmission over 1504 km of an aged fiber (field trial), with distributed Raman amplification. The carrier spacing was 50 GHz, so that a 400 GHz signal occupied a spectral portion of 100 GHz, yielding net spectral efficiency of 4 bit/s/Hz. Additionally, a high coding gain 25.5% FEC scheme was used. In the second work the transmission was performed over 630 km, with span-length greater than 200 km and Raman amplification. As in the previous case, a 25.5% overhead was considered for FEC. Here, Nyquist pulse shaping was used, yielding total signal spectrum of 75 GHz, and a spectral efficiency of 5.44 bit/s/Hz.

The dual-carrier systems that employed PDM-8QAM modulation format were reported in [SZhang 14] W1A.3 and [JZhang2 14]. In the first experiment, the authors employed digital Nyquist pulse shaping at 43 Gbaud, transmitting the signal over 6787 km at 121.2 km span-length with EDFA only-based amplification. The spans consisted of hybrid ultra-low loss and large core fibers. In addition to the standard chain of digital signal processing, authors used digital non-linear compensation. The experiment accounted for a 25.5% FEC overhead, yielding net spectral efficiency of 4.54 bit/s/Hz. In the second experiment, the authors used a slightly lower symbol rate, 40 Gbaud driving signal, proposing an advanced pre-equalization method for the mitigation of

DAC bandwidth limitation related impairments. Here, the transmission was performed over 2550 km of a standard single-mode fiber with EDFA-only amplification. The per channel spectral occupation of 100 GHz yielded net spectral efficiency of 4 bit/s/Hz.

More recent works focused on exploiting the technological limits regarding transmission performance [Cai 14], transmitter and receiver DSP subsystems [Rios-Muller 14] and optimized FEC schemes [Rahman 14]. In addition, 400G field trials using commercially available 100G/200G transponders have been reported in real-time transmissions such as in [Loussouarn 15] and in [Lavigne 15] and using 60 Gbaud transceivers [Wang 15].

6.2 Short Haul

Along with the development history of optical transmission, single carrier solution is the first option comes to mind for the 400 Gb/s optical transmission on line-side, neglecting the realization problem. Comparing with multi-carrier solution, it provides the benefit of simple structure, easy wavelength allocation and network management, smaller size, lower power dissipation, and lower cost.

The main problem with single carrier 400 Gb/s is the high electrical bandwidth requirements. For 50 GHz grid and 100 GHz grid channel spacing, PDM-64QAM and PDM-16QAM are the candidates for single carrier 400G, requiring around 42.7 Gbaud and 64 Gbaud, respectively, considering 20% SD-FEC. The commercial electro-optical components in the market mainly support 28 Gbaud to 32 Gbaud. Technically, the electro-optical components can reach the bandwidth to support up to 64 Gbaud. Considering 0.6 times symbol rate, electro-optical components with 40 GHz bandwidth is technically feasible, such as drivers, Mach-Zehnder modulators (MZM) and photodiodes (PD).

The DAC/ADC is the main obstacle as it is a great challenge to achieve enough bandwidth as well as ENOB for multi-level modulation. The bandwidth requirement for DAC would be a bit not that critical since pre-distortion can compensate some hardware impairment. However, the ADC is the real challenge. The ASIC design is also very difficult. Considering 8-bits quantization, the throughput would reach 4 Tb/s, in real time. Large-scale parallel process and fine clock control is required.

For such high symbol rate and high modulation order system, SD-FEC with high overhead is recommended for the error floor would be high, considering the bandwidth limitation and the high ENOB requirement. Below, it is discussed the single-carrier solution based on PDM-64QAM. In Section 6.3.2, it is discussed a bit further the option based on PDM-16QAM, which is also a potential candidate for metropolitan network applications

6.2.1 1x400G PDM-64QAM

With 0.1 roll-off Nyquist filter, 42.7 Gbaud PDM-64QAM can fit in 50 GHz channel spacing grid. The spectral efficiency is 8 bit/s/Hz after removing the SD-FEC overhead, with the total capacity of 32 Tb/s in C band without extension. The electrical bandwidth requirement is around 21.3 GHz. Most of current opto-electrical components can support such a system. The critical point is the ENOB and bandwidth required in the DAC/ADC. The DAC/ADC ENOB is very critical since 64QAM will have 1 dB OSNR penalty when the ENOB reduce from 8 bit to 6 bit, while current ADC/DAC can only reach about 6 bit on chip, not to mention the loss of resolution for pre-distortion.

6.3 Metropolitan

The analysis of the optical fibers Metropolitan Network scenario reveals some main characteristics of this type of network. It may be characterized as a kind of network made of several hundreds of kilometers fiber spans, generally covering distances from 100 km to 700 km. They usually support and serve large and concentrated metropolitan areas, linking cities and neighbor states, in order to work as a bridge or intermediary path between access and long-haul networks. Nowadays, this type of network exhibits a highly diverse traffic data flow, such as SONET-like channels coexisting with gigabit Ethernet channels. Therefore, they exhibit a large amount of fixed or reconfigurable optical add-and-drop multiplexers (OADM or ROADM), which are responsible for route the travelling channels. However, the traffic in these networks usually is DWDM, in which channels travel very close spaced from each other. Moreover, the acting of more than one ROADM over the transmitted channel causes to it a spectral narrowing, leading to inter-symbol interference impairments that penalizes the channel performance. Therefore, in order to successfully transmit a channel through a metropolitan network, it must obey as far as possible at least the features listed above:

- Compact spectral occupancy, aiming to reduce the neighbor channels crosstalk;
- Robustness to ROADM, targeting to minimize the penalty induced by their presence and acting;
- Spectral granularity, in other words, the channel potential to be split in many subcarriers that will be routed through the network;
- Respect some standards, such as ITU-T G.694.1, which defines the spectral grids for DWDM applications.

In the specific case of a 400 Gb/s channel transmission in metropolitan networks, the state-of-the-art researches point towards the optimization of the C-band occupancy, increase of the spectral efficiency and compensation of the spectral narrowing effects induced by the ROADMs. Also, most of the recent researches propose multicarrier channels and ITU-T channel occupancy grids of 75 GHz and 50 GHz, while some wage on single carrier channels with high symbol rates and a 50 GHz occupancy grid. The characteristics of these 400 Gb/s transceiver are, among others, the presence of digital Nyquist filtering with low roll-off (around 0.01), DAC employment, frequency-shifter for multicarrier generation, high order modulation formats such as 32QAM and 64QAM, low symbol rates for multicarrier channels and high symbol rates for single carrier ones, optical pre-filtering employment for ROADM effects pre-compensation, DSP at the receiver that is able to process Nyquist pulse demodulation. Some architecture proposals are presented in the following sections.

6.3.1 2x200G PDM-16QAM

A promising architecture for 400G transceivers for metropolitan applications is depicted in Figure 12. In order to increase system capacity together with the line rate, digital filtering at the transmitter side is enabled by high-speed DACs. This architecture employs 2 sub-channels at 200 Gb/s each, with PDM-16QAM modulation at 32 Gbaud, and Nyquist channel spacing (32 GHz). Linear drivers are required for amplification of high-speed multilevel electrical signals. At the receiver side, parallel reception of both wavelengths is performed by using two coherent receiver architectures. Wavelength selection is performed by tuning an ITLA in order to recover a specific carrier. At the transmitter side, two high-speed DACs are employed. Minimum requirements for the DACs are: sampling rate of 64 GSa/s, bandwidth of 16 GHz, and ENOB of 6 bits. High bandwidth linear drivers are also required to maintain signal waveform. At the receiver side, parallel reception and joint DSP is performed to recover both wavelengths. Requirements for the ADC are: bandwidth higher than 16 GHz, sampling rate of 64 GSa/s, and ENOB of 6 bits. In comparison with current 100G coherent transceivers, this architecture employs the double of components. Photonic integration is required for optical parallelization at the transmitter and receiver. Power consumption and costs could be reduced with the evolution in integrated photonics and CMOS technology.

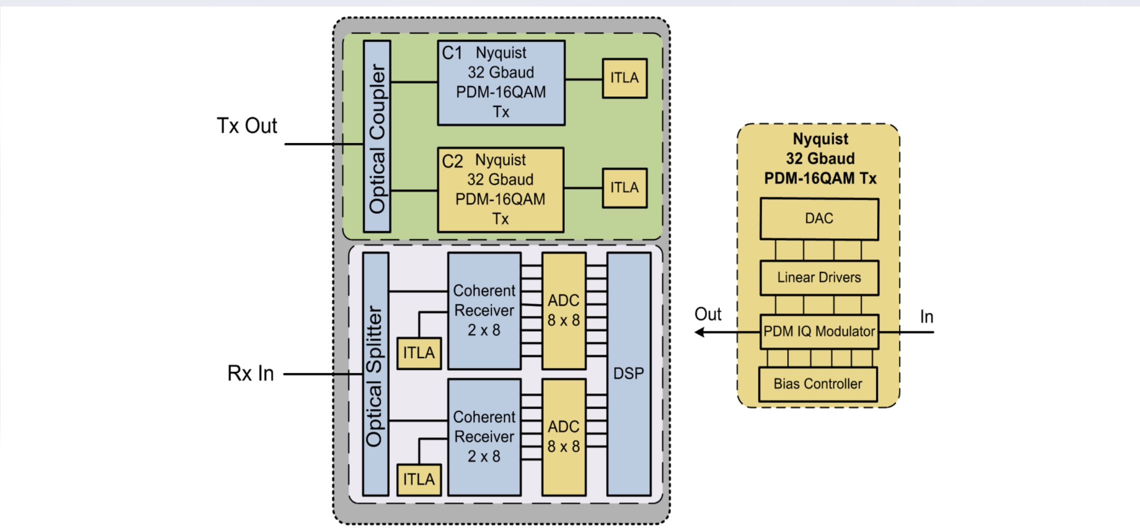

Figure 12 Transceiver architecture for metropolitan application 2x200G PDM-16QAM.

6.3.2 1x400G PDM-16QAM

Reusing the classical simple transponder structure, single carrier 400G PDM-16QAM is with the potential of smaller size and lower cost. 1x400G 64 Gbaud PDM-16QAM with 20% SD-FEC can fit in 100 GHz or 75 GHz channel spacing, corresponding to classical ITU-T grid or flexible grid, respectively. Thus, the spectral efficiency can reach 4 or 5.33 bit/s/Hz, with the total capacity of 16 Tb/s or 21 Tb/s considering C band with 32 nm bandwidth. With Nyquist digital filter, the bandwidth requirement can be reduced to about 32 GHz. Considering the current commercial components, one critical step is to realize the high speed DAC/ADC that can support such a symbol rate come to real.

Another way is to use faster-than-Nyquist (FTN) filtering, to squeeze the bandwidth further, with medium penalty. Systematically, 1x400G PDM-16QAM has the potential not only for metropolitan application but also for short-reach application as it brings all the benefit of smaller size, lower cost and easier network management.

6.3.3 3x133G PDM-64QAM

This architecture focuses on a high spectral efficiency of 8 bit/s/Hz, allowing the 400G super-channel fitting in a 50 GHz grid. The implementation uses three Nyquist shaped sub-channels (0.1 roll-off) employing 14 Gbaud PDM-64QAM spaced by 16 GHz. The super-channel configuration compatible with SD-FEC occupies around 46 GHz, which ideally fits in a 50 GHz grid. The main advantaged of this configuration is that the reduced symbol rate relaxes the analog front-end specifications (e.g. ENOB) and the required OSNR per sub-channel, i.e. around 18.5 dB at typical SD-FEC threshold (theory). Considering 2.5 dB implementation penalty, typical transmission distances beyond 600 km are expected in a 50 GHz WDM metropolitan network.

6.3.4 Multi-Band OFDM

As briefly discussed in subsection 5.3, MB-OFDM has the advantage of using very low symbol rates per sub-band when compared to higher symbol rate optical super-channels (i.e. 32 Gbaud). The main idea is to use several lower speed OFDM signals (e.g. 50 Gb/s) multiplexed in several frequency slots to achieved high line rates, e.g. 100 Gb/s, 200 Gb/s or 400 Gb/s. Figure 13 illustrates the frequency allocation for a MB-OFDM signal with five OFDM sub-bands equally spaced. Typical MB-OFDM experimental demonstrations have reported 4 sub-bands spaced by 10 GHz, each carrying 8 Gbaud OFDM signals, with distances around 1000 km [Pincemin 14]. With QPSK, the net bit rate is 25 Gb/s (excluding typical OFDM and FEC overheads) whereas the net bit rate may be increased to 50 Gb/s per sub-band when using 16QAM (200 Gb/s MB-OFDM). With this configuration, 400 Gb/s MB-OFDM would require 8 sub-bands with 16QAM or 16 sub-bands with QPSK. Besides the bandwidth

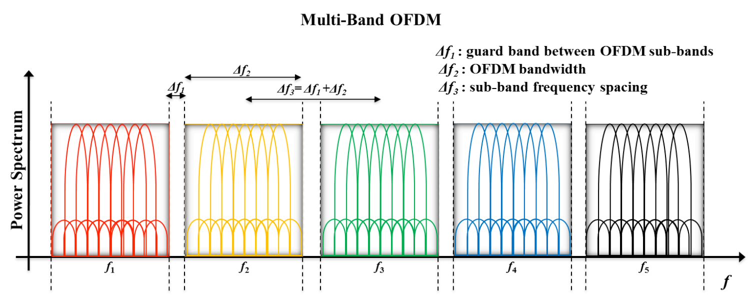

Figure 13 Multi-band OFDM spectral allocation highlighting the guard band (Δf_1), bandwidth (Δf_2) and frequency spacing (Δf_3) between the OFDM sub-bands.

flexibility, this approach has the advantage of requiring lower speed optic-electronics in the transceiver when optical generation and reception are performed in a sub-band by sub-band basis. Photonic integration is key as the number of optic-electronic devices (drivers, modulators, coherent receivers, TIA, DAC/ADC etc) in the transceiver scales with the number of sub-bands.

6.4 Long-Haul

Long-haul networks capacity was boosted by the emergence of coherent 100 Gb/s DWDM transmission technology, increasing by ten times total capacity. The OIF standard for long-haul transceivers defined PDM-QPSK as coherent modulation format for 100 Gb/s channels that accounts for a net spectral efficiency of 2 bit/s/Hz. For the next generation of coherent transmission systems for long-haul applications, high order modulation formats are needed to increase SE on optical coherent transmission systems. However, as the constellations size becomes larger, also OSNR requirement turns to be higher. In addition, fiber channel nonlinear behavior can lead to strong impairments on signal integrity. Due to these issues, it is very challenging to employ M-QAM constellations with $M \geq 32$ in order to obtain suitable performance for long haul distance applications. The state of the art on long-haul transmission systems indicates that today's available technology only shows reasonable results by the use of PDM-16QAM as largest constellation size and Nyquist filtering to demonstrate long-haul transmission reach with $SE \approx 6.0$ bit/s/Hz as maximum spectral efficiency achievable on a real link.

6.4.1 2x200G PDM-QPSK

A possible architecture for 400G transceivers for long-haul applications is depicted in Figure 14. In order to increase system capacity together with the line rate, higher baud rate with lower modulation order would be considered. This architecture employs 2 wavelengths at 200 Gb/s each, with DP-QPSK modulation at 64 Gbaud, and Nyquist channel spacing (75 GHz). Linear drivers are required for amplification of high-speed multilevel electrical signals.

At the receiver side, parallel reception of both wavelengths is performed by using two coherent receiver architectures. Wavelength selection is performed by tuning an integrable tunable laser assembly (ITLA) in order to recover a specific carrier.

At the transmitter side, two high-speed DACs are employed. Minimum requirements for the DACs are: sampling rate of 90 GSa/s, bandwidth of 20 GHz, and ENOB of 5 bits. High bandwidth linear drivers are also required to maintain signal waveform.

At the receiver side, parallel reception and joint DSP is performed to recover both wavelengths. Requirements for the ADC are: bandwidth higher than 20 GHz, sampling rate of 90 GSa/s, and ENOB of 5 bits.

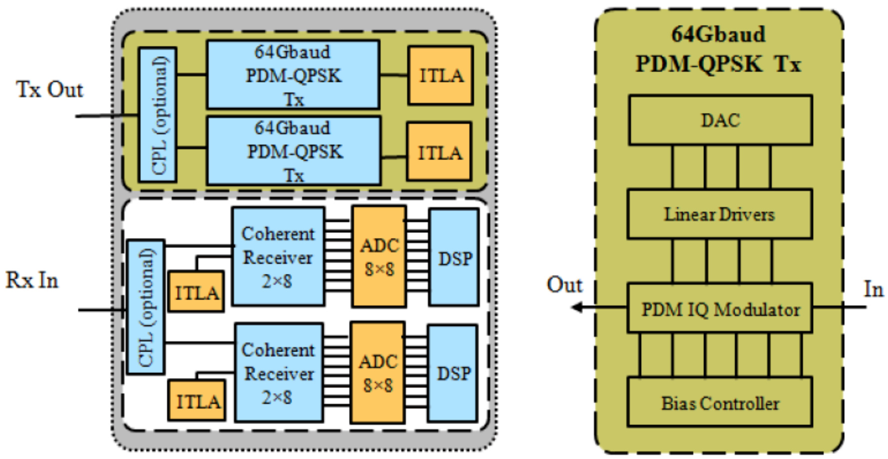

Figure 14 Transceiver architecture for metropolitan application 2x200G PDM-QPSK.

In comparison with current 100G coherent transceivers, this architecture employs the double of components. Photonic integration is required for optical parallelization at the transmitter and receiver. Power consumption and costs could be reduced with the evolution in integrated photonics and CMOS technology.

6.4.2 4x100G PDM-QPSK

An example of 400G transceiver architecture for long-haul applications is depicted in Figure 15. This architecture employs 4 wavelengths at 100 Gb/s each, with PDM-QPSK modulation at 28 Gbaud, and sub-Nyquist channel spacing (25 GHz). In order to increase spectral efficiency, the 100 Gb/s wavelengths are densely packed in frequency domain by employing tight optical filtering in the individual carriers and then combining them into a multicarrier 400G signal. Optical filtering at the transmitted is performed to reduce crosstalk penalties. Multiple carriers may be obtained by using an optical comb generator. This transceiver enables 400G transmission at 100 GHz channel grid with 4 bit/s/Hz

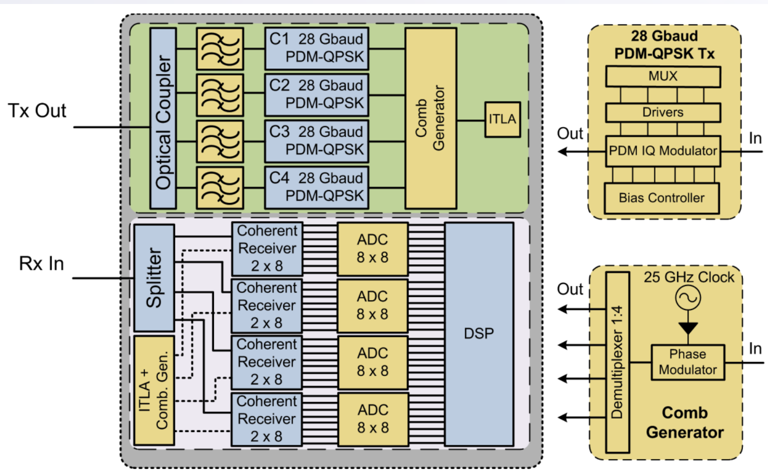

Figure 15 Transceiver architecture for 400G long-haul applications based on 4x100G PDM-QPSK.

spectral efficiency.

At the receiver side, parallel reception of the four wavelengths is performed by using four coherent receiver architectures, using an optical comb generator to obtain the local oscillators. In comparison with current 100G coherent receivers, the DSP also performs ISI cancellation caused by the tight optical filtering at the transmitter. Joint DSP can also be used to compensate for the residual crosstalk due to the non-ideal optical filtering.

In this approach, four parallel 100G transceivers are needed to obtain the 400G multicarrier signal. Optical comb generators are needed to provide the transmitter light sources and the receiver local oscillators. Also, special DSP for ISI cancellation and crosstalk mitigation are required at the receiver. Those requirements, combined with lower cost and lower power consumption in comparison with current 100G transceivers could be enabled by evolution in both integrated photonics and CMOS technology.

6.4.3 4x100G PDM-16QAM

Assuming this state of the art technique to project 400 Gb/s long-haul transceivers, we have the modular architecture showed in Figure 16. This approach is based on a multi-carrier transmitter. At the transmitter side, four carriers with 16 GHz of frequency spacing are modulated with PDM-16QAM at 16 Gbaud and Nyquist pulse shaping. Each 400G channel will occupy around 64 GHz. A set of coherent hybrid receivers and ADCs compose the receiver side. Here, it is considered that ADCs have enough bandwidth and ENOB to acquire two neighbor carriers simultaneously, and mean that only two ITLAs need to be used as LO. DSP block can functions that allow channel linear and non-linear joint equalization.

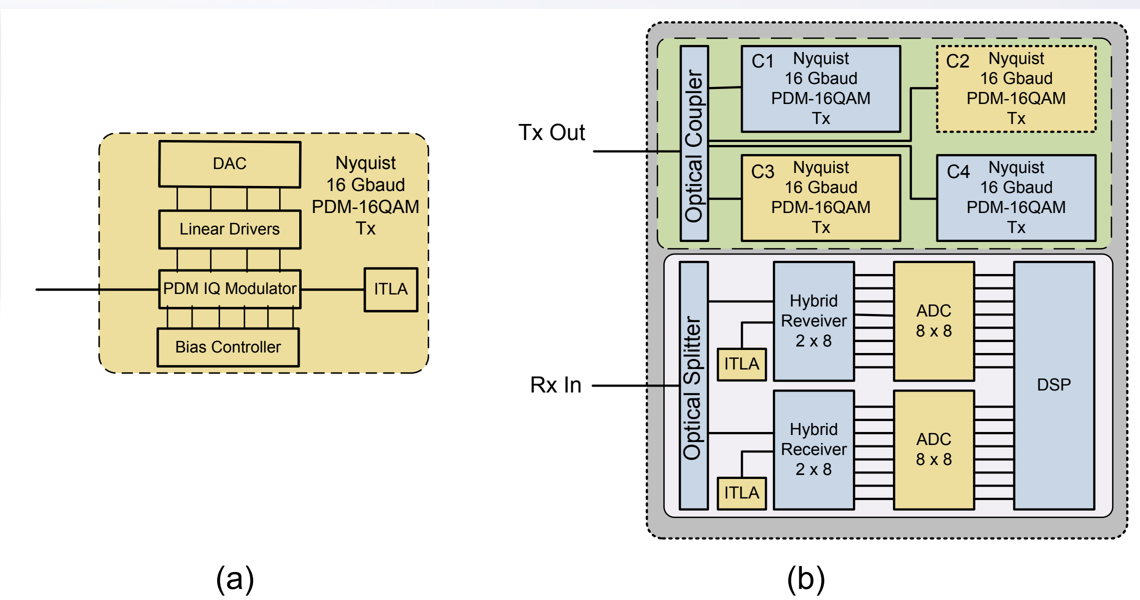

Figure 16 Long-haul 400 Gb/s transceiver architecture. (a) One sub-channel transmitter block; (b) Transceiver complete module based on 4x100G PDM-16QAM.

The biggest challenges to implement this transceiver architecture are related with devices integration and power consumption. Transmitter card needs a very delicate integration of high speed DACs, linear drivers, modulators, ITLAs and additional control circuits. The receiver side structure will depend on ADC available bandwidths and ENOBs, since it will define the number of devices needed to convert all 400 Gb/s channel carriers from baseband spectrum to digital domain. Techniques for efficient fiber non-linear impairments compensation are also expected to be part of DSP routines.

6.5 Ultra-Long-Haul

As ultra-long-haul links, both terrestrial and submarine, usually have distances way beyond 2000 km, the 400G super-channels will most likely to be based on lower order constellations such as QPSK or eventually 8QAM. Spectral occupancy can be relaxed in order to meet the OSNR requirements for very long distances. Terrestrial links may have the presence of a few ROADMs whereas in submarine links these subsystem elements are most likely to be absent. Optical amplification, either based on EDFA, all Raman, or hybrid EDFA plus Raman, is key in order to allow using the entire available optical spectrum (S, C and L bands). The 150-GHz grid is one option for allocating 400G super-channels in very high capacity WDM links for ultra-long haul applications. Below, two technological options are discussed.

6.5.1 4x100G PDM-QPSK

The four sub-channels of 32 Gbaud – PDM–QPSK with Nyquist filtering occupies much lesser than 150 GHz and has the advantage of reusing all the along coherent optics and ASIC present in already deployed 100G modules. Moreover, commercially available 100G modules already operate with very low OSNR around 11.5 dB at SD-FEC limit, which is only 1 dB worse than theory. This low OSNR requirement makes the 4x100G-PDM-QPSK an important candidate for ultra-long-haul applications with distances beyond 2000 km. More details on the analog coherent optics implementation can be found on subsection 6.4.2. It is important to mention that sub-channel spacing is increased to around 35 GHz that is sufficient for 32 Gbaud with Nyquist filtering.

6.5.2 3x133G PDM-16QAM

This solution is based on 3 sub-channels, each operating at 21 Gbaud with PDM-16QAM spaced by 23 GHz. It has the advantage of operating in a lower symbol rate per sub-channel that reduces both the required OSNR and the analog specifications (bandwidth and ENOB) when compared to the 32 Gbaud case. For instance, the required OSNR at SD-FEC limit is around 14.5 dB with analog bandwidth around 11 GHz with 6 bits of ENOB. With total spectral occupancy around 67 GHz using Nyquist filtering, this solution has the potential to be compatible with 75 GHz flexgrid and the potential to reach transmission distance above 5000 km in ultra-long-haul links using pure silica low-loss and large-area fibers.

6.5.3 2x200G PDM-8QAM

Compared to the 4x100G-QPSK solution, the solution based on 2x42 Gbaud – PDM-8QAM has the advantage of decreasing the spectral occupancy to below 100 GHz using Nyquist filtering. Therefore, the spectral efficiency is increased from 2.66 bit/s/Hz to nearly 4 bit/s/Hz using 8QAM solution instead of QPSK solution. This comes at price of an OSNR requirement around 15 dB. On the other hand, recent reported works have demonstrated this technological option with distance beyond 5000 km that is certainly attractive for ultra-long haul applications. Although the symbol rate is around 42 Gbaud, the analog coherent optics may be very similar to the 2x200G-16QAM solution. The analog coherent optics for generating and receiving one sub-channel may have around 20 GHz with 20 GHz – DACs/ADCs with 5 bits ENOB.

7 Comparison of 400G transmission technologies

This section summarizes the 400G implementation options taking into account modulation formats, spectral efficiency, OSNR and network application.

7.1 System parameters for all modulation formats

Table 3 summarizes the OSNR requirements for different modulation format options for 400G super-channels, i.e. QPSK, 8QAM, 16QAM and 64QAM. Based on their implementation parameters such as net bit rate (Gb/s), symbol rate (Gbaud), pulse shaping (non-return to zero (NRZ) or Nyquist), optical bandwidth occupancy (BW, in GHz), frequency grid, spectral efficiency (SE), one can obtain the required OSNR either at BER=10^{-3} (corresponding to typical 7% hard-decision FEC) or at BER=10^{-2} (corresponding to typical 20% soft-decision FEC). For more details about FEC implementation schemes, refer to OIF FEC 100G white paper[5] and the newly started FlexEthernet projects[6]. As an example, PDM-QPSK can offer net bit rate of 100 Gb/s (28 Gbaud) with 12 dB OSNR at HD-FEC limit. If one application requires achieving lower OSNR, higher BER threshold (10^{-2}) can be achieved with 20% SD-FEC. On the other hand, to avoid decreasing the 100 Gb/s net bit rate, the symbol rate has to be increased from 28 Gbaud to 32 Gbaud in order to transport the higher FEC overhead, i.e. 20%. The 100 Gb/s – PDM – QPSK can be achieved with 10.4 dB OSNR. The same analysis can be applied to the other modulation formats where the OSNR numbers are

Modulation Format	Net Bit Rate (Gb/s)	Symbol Rate (Gbaud)	Shaping	BW (GHz)	Grid (GHz)	SE (bit/s/Hz)	OSNR BER=10^{-3}	OSNR BER=10^{-2}
PDM-QPSK	100	28	NRZ	56	50	2	**12**	9.8
	100	32	Nyquist	35	50	2	12.6	**10.4**
	200	56	NRZ	112	100	2	**15**	12.8
	200	64	Nyquist	70	75	2.66	15.6	**13.4**
PDM-8QAM	100	18.7	NRZ	37.3	50	2	**13.8**	11.4
	100	21.3	Nyquist	23.4	25	4	14.3	**12**
	200	37.3	NRZ	74.6	100	2	**16.8**	14.4
	200	42.7	Nyquist	47	50	4	17.4	**15**
PDM-16QAM	100	16	Nyquist	17.6	25	4	16.2	**13.8**
	200	32	Nyquist	35.2	50	4	19.2	**16.8**
	400	64	Nyquist	70.4	75	5.33	22.2	**19.8**
PDM-64QAM	200	21.3	Nyquist	23.4	25	8	23.4	**20.8**
	400	42.7	Nyquist	47	50	8	26.4	**23.8**

Table 3 OSNR requirements (theory) for 400G modulation format options. Achievable OSNR without decreasing net bit rate is highlighted in bold text. Typical implementation penalty is around 2 dB.

[5] OIF-FEC-100G-01.0 – 100G Forward Error Correction White Paper
[6] FlexEthernet Project Start Proposal, oif.2015.039, http://www.oiforum.com/private/oif-current-project-status/

highlighted in bold to represent that these OSNRs can be achieved without decreasing the net bit rate.

7.2 Comparison and preference listing of technologies

Table 4 compares the implementation options versus different 400G applications depicted in first column. The 400G application is sub-divided into short-haul (SH), Metropolitan (Metro), Long-Haul (LH) and Ultra Long-Haul (ULH). SH applications target very high spectral efficiency, e.g. single carrier in 50 GHz with distances of at least 100 km. Metro applications target at least 1000 km with the presence of ROADMs with fixed grid (100 GHz) and or newly flexgrids (75 GHz). For LH application, the presence of ROADMs is optional but with distances close to 2000 km. ULH applications should be compatible with distances beyond 2000 km. From the second to the sixth column, implementation options are given based on Section 6. The seventh column highlights the maximum transmission reach, either reported in research works or discussed within the OIF 400G white paper framework, with similar modulation options per each application. It is worth emphasizing that the reported distances in the seventh column may not reflect exactly the modulation options discussed in previous sections as they may use different technologies such as DSP, fiber, amplification, optical filtering, and DAC/ADC specs etc to attain a certain distance. In addition, the analog specifications are given in both in fifth (DAC

	Modulation	Symbol Rate (Gbaud)	#sub-channels	DAC Options[1]	ADC Options[1]	State of the art Distance (km)[2]
SH (~100 km, 50 GHz)	64QAM	42.7	1	1x4 80 GSa/s, 6.5 bits, 25 GHz[3]	1x4 80 GSa/s, 6.5 bits, 25 GHz[3]	300[Buchali 14]
	16QAM	64	1	1x4 88 GSa/s, 16 GHz[Rios-Muller 14]	1x4 90 GSa/s, 25 GHz[Rios-Muller 14]	6600[Rios-Muller 14]
Metro (<1000 km, 75/100 GHz, 10x ROADM)	16QAM	32	2	2x4 64 GSa/s, 16 GHz[4]	2x4 80 GSa/s, 33 GHz[4]	1800[4]
	16QAM	64	1	1x4 88 GSa/s, 16 GHz[Rios-Muller 14]	1x4 80 GSa/s, 33 GHz[Rios-Muller 14]	6600[Rios-Muller 14]
	64QAM	14.2	3	3x4 32 GSa/s, 6.5 bits, 10 GHz[5]	3x4 32 GSa/s, 6.5 bits, 10 GHz[5]	600[5]
	MB-OFDM (16QAM)	8	8	8x4 12 GSa/s, 10 GHz[Pincemin 14]	8x4 50 GSa/s, 5 GHz[Pincemin 14]	1000[Pincemin 14]
LH (~2000 km, optional ROADM)	QPSK	64	2	2x4 90 GSa/s, 5 bits, 20 GHz[6]	2x4 90 GSa/s, 5 bits, 20 GHz[6]	6577[Wang 15]
	QPSK	32	4	4x4 64 GSa/s, 14 GHz[7]	4x4 80 GSa/s, 33 GHz[7]	2975[7]
	16QAM	16	4	4x4 32 GSa/s, 5 bits, 10 GHz[3]	2x4 64 GSa/s, 5 bits, 17 GHz[3]	630[3]
ULH (>2000 km)	QPSK	32	4	4x4 64 GSa/s, 14 GHz[7]	4x4 80 GSa/s, 33 GHz[7]	2975[7]
	8QAM	42.7	2	2x4 64 GSa/s, 16 GHz[4]	2x4 80 GSa/s, 33 GHz[4]	6787[SZhang 14]
	16QAM	21	3	3x4 40 GSa/s, 6 bits, 11 GHz[5]	3x4 40 GSa/s, 6 bits, 11 GHz[5]	5000[5]

Table 4 Potential 400G architectures in the state of the art.

[1]DAC and ADC characteristics taken either from Section 6 or from the state of the art.
[2]Distances reported either in the state of the art or from OIF contributions.
[3]OIF2014.030.00, [4]OIF2015.030.01, [5]OIF2015.100.00, [6]OIF2015.037.01, [7]OIF2014.031.00

options) and the sixth (ADC options) column wherein ***n*x4** (where ***n*** is the number of sub-channels) represents two pairs of DAC/ADC per sub-channel, i.e. in-phase, quadrature, polarization X and polarization Y tributaries.

8 Summary

This white paper reported technological options for optical 400G superchannels and how they comply with future high-capacity WDM networks. System parameters and network requirements driven by telecom carriers, network infrastructure vendors and R&D works were addressed as optical 400G is the next technological upgrade to support the bandwidth demands in optical networks.

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