Technical Publication

Enabling Single-carrier Spectral Efficient 400Gbps Transmission

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Abstract

This article discusses the enabling building blocks for commercial deployment of 400Gbps DWDM systems over standard fiber infrastructure with EDFA amplification using single-carrier DP-32QAM and dual-carrier DP-8QAM for metro, regional and long-haul optical transport systems.

Inphi Corp in collaboration with NeoPhotonics

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Introduction

Network operators always face ever-increasing needs for capacity and bandwidth in their metro, regional and long-haul optical transport systems due to the demands of high-speed data services, internet video services, data centers and higher broadband residential connections. Until recently, the long-haul 10G DWDM market has been saturated since the first deployment of 100G from 2010, meaning there is no more 10G to replace. The expansion of 100G into new markets has been catalyst for huge growth of coherent 100G, resulting in over 50% ramp-up year-over-year throughout 2020 [1]. In order to offer additional network capacity, improved spectral efficiency, and lower cost per bit, the optical networking industry has been developing next-gen 400G coherent technologies for the last 3-4 years, and many field trials have been reported so far for commercial deployments [2].

The current 100Gbps "standard" optical bandwidth is represented by 32GBaud from components' level, thanks to the standardized modulation scheme known as DP-QPSK (dual polarized quadrature phase shift keying, aka 4QAM) modulation format [3] associated with coherent detection and digital signal processing (DSP). The spectral efficiency for 100Gbps is 2bit/s/Hz at the conventional ITU-T 50GHz grid spacing. Historically to increase the optical channel rates by a proportional improvement of the spectral efficiency decreases the cost per transmitted bit. To follow this path, 400Gbps signaling is expected to use the higher order QAM formats, but at the expense of greatly reduced transmission reaches [4].

To improve the distance of higher order QAM while simultaneously maintaining the spectral efficiency, the increase of component baud rates become necessary. With advancement in electro-optic and DSP components using higher component rates up to 45Gbaud, or even 64GBaud has been proved to be a feasible 400Gbps technology and will be soon commercially available industrywide as shown in Figure 1. The quadrupling of spectral efficiency is achievable for 400Gbps as high as 8bit/s/Hz.

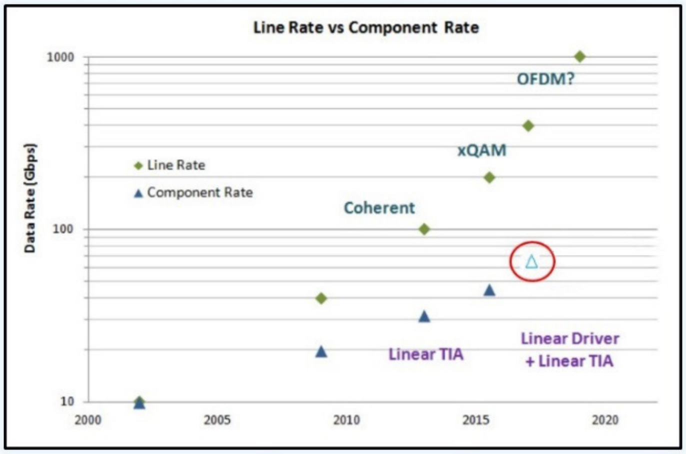


Figure 1 – Optical channel rates vs. component baud rates for 100Gb/s and 400Gb/s systems

Careful spectral pulse shaping is required to place 400Gbps signals on the conventional 50GHz or 75GHz channel grid. When comparing to 100Gb/s in 50GHz, each fiber can have 3-4 times more capacity while still using a single set of tunable laser, modulator and receiver devices. Its benefit is cost-effective as it allows to increase the network capacity through leveraging the existing ITU-T grid based infrastructure for a smooth upgrade from 100G to 400Gbps per channel, thus has many advantages in term of network management as well.

The industry is starting to resolve these 400G transmission problems and develop key 400G optical components needed to implement and deploy 400G in real-world networks. The OIF has initiated the work to standardize new high-bandwidth electro-optical modulators and intradyne coherent receivers (ICRs), intended for 400G/1T coherent applications. Meanwhile IEEE P802.3bs Task Force has been chartered to develop the 400G Ethernet interface specifications, to be completed by end 2017 [5]. 400G is expected to be the next standard interface of choice going forward.

Status of 32Gbaud based 100G

The initial 100G deployment is based entirely upon 28 to 32G baud rates depending on the FEC overhead ranging from 7% to 20% with either hard-decision or LDPC based soft decision implementations [6]. With the introduction of 100G DP-QPSK modulation, it allows four bits of data to be encoded and sent as one optical symbol, i.e. the 25 Gbaud as opposed to 100 Gbps. Such application of lower bandwidth components reduces the system cost, and at the same time a number of optical propagation impairments become easier to compensate.

50GHz-spaced 100Gbps transport systems are basically enabled by the use of coherent detection and receiver-sided DSP. As shown in the Figure 2 (left), four data streams in the transmitter are formed from conventional serializer (or MUX) function, each consists of standard NRZ logic signal. Then four limiting drivers convert low level logic signals to amplitude levels required by the modulators. In the receiver side, the four logic signal with distortion are recovered after a number of passive optical components that form a demodulator, followed by four balanced photodetectors and linear transimpedance (TIA) amplifiers. The detected analog electrical signals are then digitized by 4 analog-to-digital converters (ADC), before sent to be processed by DSP unit. DSP allow optical impairments, such as CD and PMD, to be compensated electronically. DSP algorithms stays at the heart of the secret sauce of most 100G optical system vendors.

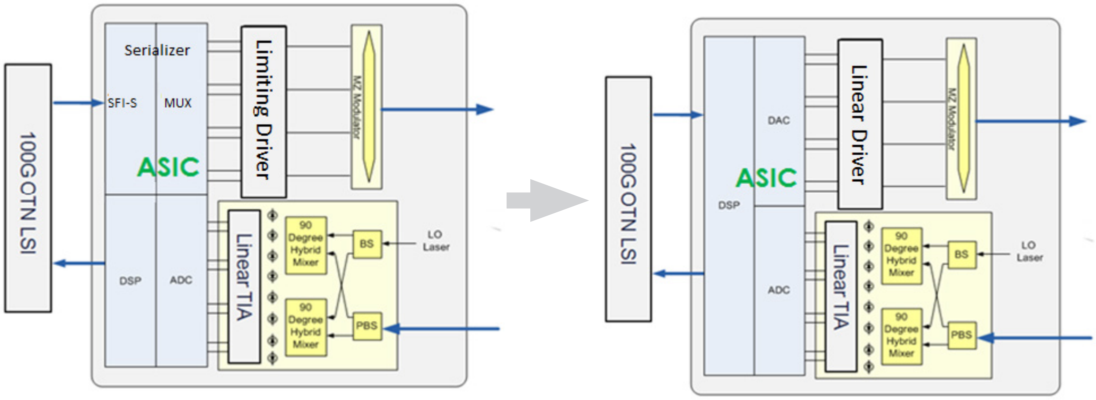


Figure 2 – Typical block diagram of a DP-QPSK (left) and DP-xQAM (right) for a transition to a flexible transceiver format. For simplicity, only key enabling components are shown.

A new breakthrough initially for 40G and soon after for 100G long-haul transmission happened with the introduction of DSP in the transmit side by deploying the DAC to replace the conventional serializer devices. As shown in Figure 2 (right), in addition to the DAC, the switch from limiting to linear driver is necessary in this transition. This allows the generation of higherorder QAM beyond QPSK (4QAM) in the search for higher spectral efficiency over 2bit/s/Hz by 100G. Taking advantage of the 32Gbaud linear components, DP-16QAM has been successfully deployed for doubling the capacity to 200Gbps in additional to DP-QPSK, so enable the rate adjustable (flexible or configurable) transceiver without increasing the transceiver cost.

Higher-order QAMs significantly increase the capacity and spectral efficiency in a cost-effective manner by leveraging the DSP in both the receiver and transmitter, but require much higher OSNR tolerance, which translates to a much shorter distance. As a rule of thumb, a 3dB higher in OSNR requirement indicates halving the transmission distance. For example, the 200G 16QAM requires 7dB higher OSNR at given baud rate when compared against 100G DP-QPSK, which corresponds to a reduction of maximum transmit reach by a factor of 5. Besides 16QAM is more sensitive to laser phase noise and various nonlinearity effects. In practice, the required OSNR will grow much faster with further increasing the constellation size due to various implementation imperfections such as limited ENOB of ADC/DAC, limited laser linewidth, receiver noise and DSP processing limitations [7].

Hence, further to quadruple the capacity with 256QAM at the given baud rate on supporting single carrier 400G is unlikely to happen in the near future. An increase of symbol baud rate beyond 32Gbaud is unavoidable for reaching 400G in light of the trade-off between the order of QAM modulation and symbol baud rate. Figure 3 shows the estimated OSNR requirements with BER threshold in theory for various baud rates of ≥32Gbaud, typical implementation penalty for 32Gbaud in reality could be less than 2dB, and may grow much faster when going further up with increasing constellation size. Penalty for higher baud rates and constellations is usually much higher than theoretical predictions.

Figure 3 –
The estimated BER performance versus OSNR (in theory) for various baud rates of ≥32Gbaud

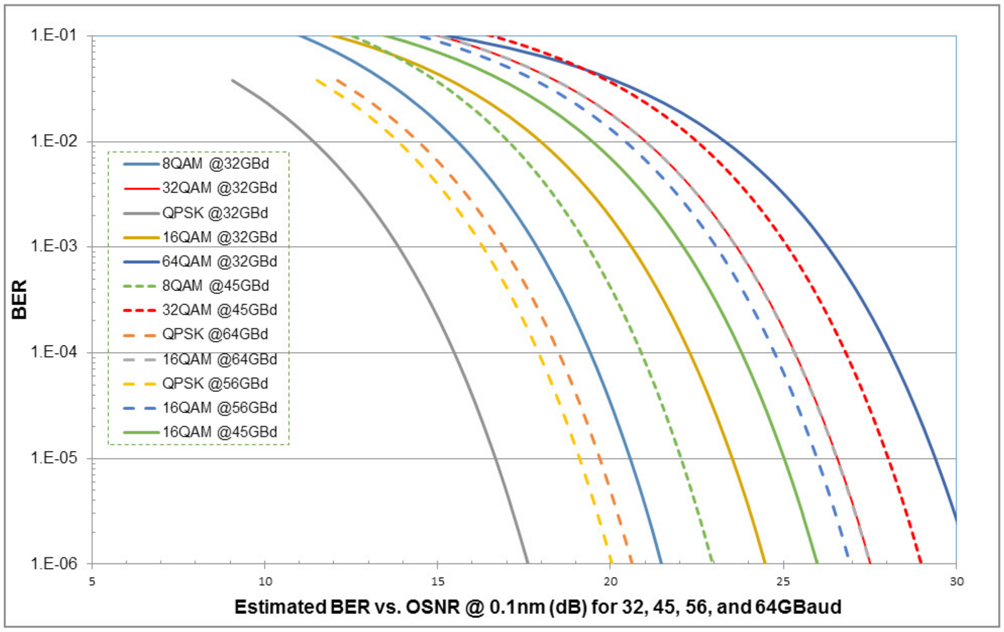


Table 1 lists the details of theoretical OSNRs required for different modulation formats under various BER thresholds. It is shown that the sweet spot for a near term path to support 400Gbps on a single carrier is at ~45Gbaud with 32QAM for a spectral efficiency close to 8b/s/Hz. This represents a rise of the baud rate by a modest 40% (or could be lower depending on FEC overhead) as compared to the 32GBaud used by QPSK. 32QAM could be especially useful for metro and regional distances which are limited to a few hundred km. Meanwhile, 8QAM running at 45GBaud for 400G on two carriers requires 1dB lower OSNR than 16QAM at 32GBaud, so could cover the meaningful distance of over a thousand km suitable for longhaul requirements.

Table 1 –
OSNR requirements (theory) for 400G modulation format options

Net data rates per carrier (Gbps)	GBaud (max)	#Pol	Modulation formats	Grid (GHz)	Raw Channel rate(max) with FEC	SE (b/s/Hz)	OSNR @1E-3 (dB)	OSNR @ 1E-2 (dB)	#carriers needed for 400G
100	32	2	DP-QPSK	50	128	2	13.8	11.3	4
200	32	2	DP-16QAM	50	256	4	20.7	18.2	2
200	45	2	DP-8QAM	50	270	4	19.4	17.0	2
400	45	2	DP-32QAM	50	450	8	25.2	22.6	1
200	56	2	DP-QPSK	75*	224	4	16.2	13.7	2
400	56	2	DP-32QAM	75*	560	8	26.1	23.0	1
200	64	2	DP-QPSK	75*	256	4	16.9	14.5	2
400	64	2	DP-16QAM	75*	512	8	23.7	21.0	1

*So far only transmissions spaced by as narrow as ~75GHz for this baud rate have been demonstrated in lab.

Key enabling components for 400G platforms

Transmitting 400Gbps per-channel signal over long distance present significant challenges, and only recently the commercial deployment of 400G 32-QAM has become possible. Figure 4 shows a 400G DP-32QAM optics setup running at 45GBaud using commercial available components from off-the-shelf, which includes micro-ITLA narrow linewidth tunable lasers (μITLA), linear modulator drivers, I/Q modulators and coherent ICRs. Those are the key enabling components for implementing 400G DP-32QAM systems with flexible rate capability. 45Gbaud provides the intermediate step to increase baud rate by modest ~40% for the reason to reduce the system design complexity and cost.

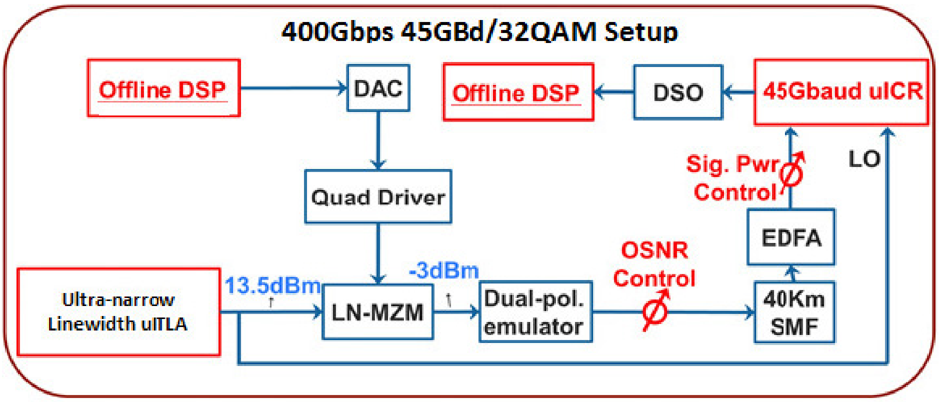


Figure 4 – 45Gbaud/DP-32QAM optics setup from OFC 2016 tradeshow (NeoPhotonics' demonstration)

μITLA

An μITLA incorporating a full-band tunable laser compliant with MSA provides the continuous wave light signal source at ITU grid, and also offers the reference local oscillators for the coherent ICR. The key parameters for μITLA are its high power level, narrow linewidth and frequency accuracy. Currently, the technology of choice for 400G is to integrate cooled External Cavity Laser (ECL) technology in a miniaturized package. The μITLA is one third as large with 25% less power consumption than a standard ITLA. The long cavity length of ECL gives a pure optical signal with the narrowest linewidth. In coherent 32QAM systems, any phase error in the signal and reference lasers, as represented by the laser's linewidth, will cause errors in the extracted phase information from the signal. Consequently, lasers with stable phase or, equivalently, a narrow linewidth become critical. The current state of the art in mass deployment is a laser power at approximately 14 to 15 dBm (32mW) (higher output power is preferred) and a linewidth of less than 300kHz (lower linewidth is preferred). Figure 5 shows a photo of μITLA unit from NeoPhotonics.

Figure 5 – High power and narrow line-width μITLA in a miniaturized package (NeoPhotonics)

IQ modulators

IQ optical modulator converts the electrical RF data into optical data stream, is a critical part of transmitter architecture for coherent application. The key modulator parameters for coherent 32QAM systems are the drive voltage required to induce a π phase shift ($V\pi$), linearity, extinction ratio (ER), and modulation bandwidth.

The LiNbO3 IQ modulators are widely used in today's 100G deployments and are the primary choice for 400G, but other technologies based on InP and Silicon Photonics have shown the advantages in enabling the low driving voltage and high bandwidth in smaller package [9].

Figure 6 –
45G LiNbO3 based I/Q modulators with singled-end RF drive. Courtesy FOC

Linear drivers

The key parameters for linear modulator driver are wide bandwidth, low power dissipation and excellent linearity, which support the implementation of higher order QAMs at baud rates of over 45 Gbaud. It's very critical to have the linear driver match the modulator for optimum performance. Any impedance mismatch between the modulator and driver leads to excessive jitter due to multiple reflections. Driver swing voltage is optimized based on modulator characteristics such as size, bandwidth, insertion loss and material properties. Nowadays the modulators show reduced swing requirements below 5Vpp for LiNbO3 based IQ modulators.

Figure 7 –
Quad 45Gbaud linear modulator driver with differential input and single-ended output

Figure 7 shows a quad channel linear modulator driver in a surface mount (SMT) package from Inphi Corporation with 45 GBaud capable to support 32QAM applications. This driver delivers an adjustable output swing of up to 5Vpp single-endedly and is well matched the I/Q modulator. Its high gain allows the driver to accept a differential input as low as 200mVppd from the DAC while delivering an output swing of 5Vpp single-ended.

ICRs

The ICRs combine polarization beam splitting optics for the signal and local oscillator inputs, two matched optical 90° hybrids with monolithically integrated balanced photodetectors, and four linear transimpedance amplifiers (TIAs) with differential outputs in a compact surface-mount package. They provide the advanced demodulation to analyze the state-of-polarization and optical phase of phase-modulated QAM signals relative to an externally-supplied optical reference local oscillator source.

The ICRs enables the recovery of the phase-polarization constellation of QAM format signals. Then the phase channels are converted into electrical signals by four pairs of balanced photodetectors that are monolithically integrated with the optical 90° hybrids, and subsequently amplified by linear TIAs. The TIAs feature integrated peak detectors and support both manual and automatic gain control.

The key parameters for ICR are high responsivity, high CMRR and excellent linearity in addition to the high bandwidth. Figure 8 depicts the 45GBaud balanced ICR receiver.

Figure 8 – The 45GBaud balanced ICR receiver

400G Experimental demonstration

The 400G DP-32QAM optics block diagrams are depicted in Fig.4. A live demonstration of its operation was presented at the OFC 2016 tradeshow as shown in Figure 9. In the transmitter configuration, a single laser source at 50GHz ITU grid wavelength of C-band is modulated by 72GS/s high speed DAC together with single-drive IQ modulator to produce 45GBaud Nyquist shaped 32QAM signal. In this case, a multilevel electrical RF driving signal was applied for each quadrature arm. The PRBS order of $2^{15}-1$ was encoded into 32QAM symbols. The pre-equalization was estimated offline and carried out in frequency domain to compensate for the non-ideal response in the transmitter chain consisting of the DAC, linear driver and IQ modulator. The polarization multiplexing is performed by dividing and recombining the signal with optical delay line after the IQ modulator, well before reaching polarization beam combiner. This emulated dual polarization (DP-) 32QAM signal was used to generate raw 450Gb/s data rate.

At the receiver, the incoming signal was down-converted into baseband by the coherent ICR through beating with reference local oscillator, using the same laser source with a narrow linewidth of 50kHz as the transmitter side. The intradyned signals were sampled and digitized using a 4-channel real-time sampling oscilloscope at sampling sate of 80GSa/s with a 33-GHz single-side analog electrical bandwidth. The captured data were processed off-line using a laptop by standard DSP algorithm to recover the signals. For this experiment, errors were counted based on a total of about 1×10^{6} bits.

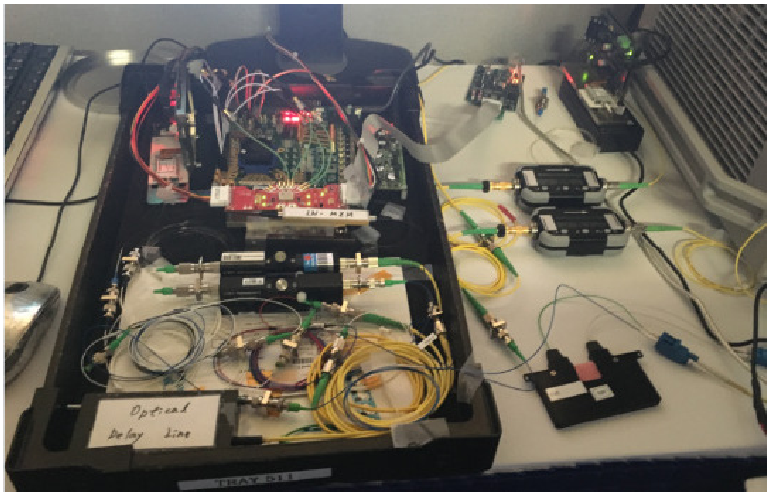


Figure 9 – 45Gbaud/DP-32QAM optics demonstration from OFC 2016 tradeshow (only transmitter part is shown) (NeoPhotonics demonstration)

For the first experiment, Figure 10 shows the measured 32QAM constellation diagrams at 34dB OSNR and -10dBm received signal power. As comparison, the 8QAM and 16QAM constellations are also shown.

Figure 10 – Constellation diagrams for 8/16/32QAM at 45GBaud. Inset shows the XI eye for 32QAM. (NeoPhotonics demonstration)

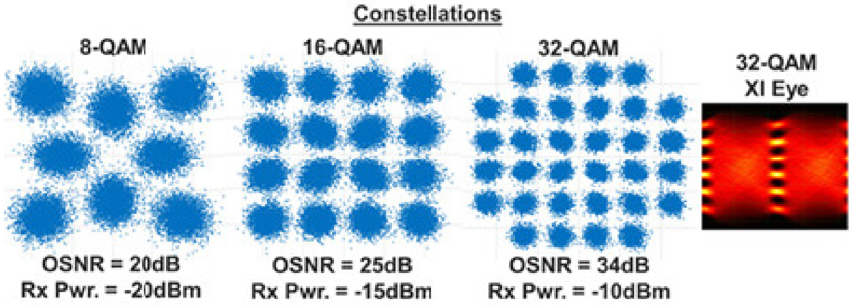
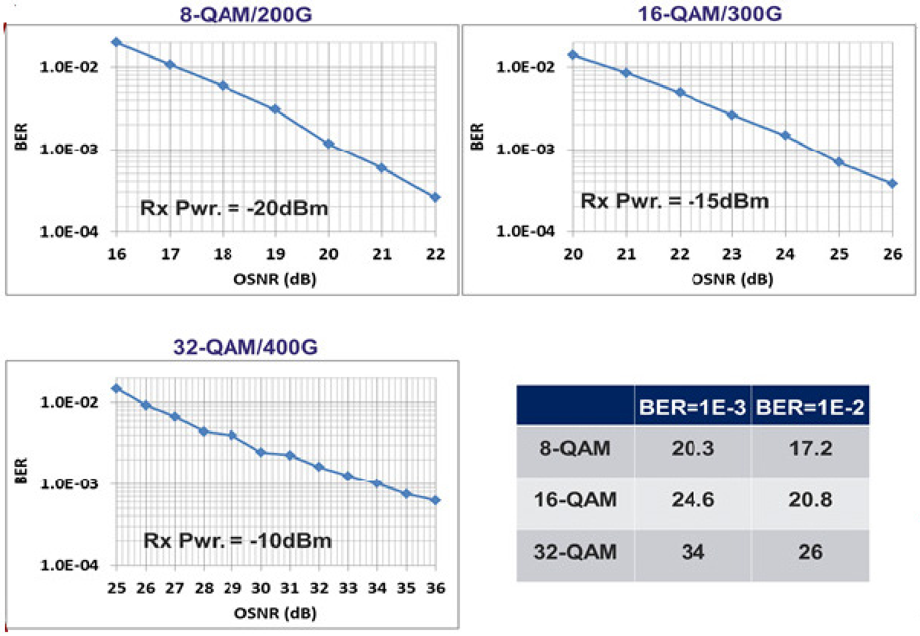


Figure 11 shows the measured BER for various OSNR values at specific received powers for DP-32QAM in comparison with DP-8/16QAM. The OSNR values at 0.1nm resolution bandwidth are controlled precisely by optical noise loading. The implementation penalty at 10^{-2} BER is calculated to be 0.2/1.2/3.4 dB for 8/16/32QAM. Those values are increased at the BER threshold of 10^{-3} to 0.8/2.3/8.7dB which is understandable as discussed previously.

Figure 11 – Measured BER vs. OSNR performance for DP-4/16/32QAM at 45GBaud. (NeoPhotonics demonstration)



	BER=1E-3	BER=1E-2
8-QAM	20.3	17.2
16-QAM	24.6	20.8
32-QAM	34	26

Conclusion

The industry is quickly moving beyond current "standard" optical bandwidth, which is represented by 32GBaud. With the joint effort, we have demonstrated at OFC 16 tradeshow a near term path to 400G on a single carrier based on DP-32QAM running at 45GBaud. With advancement in electro-optic and DSP components using higher symbol rate transmission, up to 64GBaud has been proved to be feasible and will be commercially available soon. These new high optical bandwidth technologies will significantly decrease the number of components inside the modules and systems, moderately increase spectral efficiency by maintaining the existing ITU grid DWDM fiber infrastructure and meaningfully reduce module sizes, power consumption and costs.

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Sources

[1] A. Schmitt; "Metro DCI – What's Next?" at the annual OSA Executive Forum before OFC 2016, March 2016.

[2] Optical Internetworking Forum (OIF), "Technology options for 400G implementations", July 2015.

[3] Optical Internetworking Forum (OIF), "100G Ultra Long Haul DWDM Framework Document", November 2010.

[4] X. Zhou: "High spectral efficiency 400G transmission", ZTE Communications, Vol.10, No.1 pp.3-9, March 2012.

[5] IEEE P802.3bs Task Force, http://www.ieee802.org/3/bs/index.html

[6] F. Chang, K Onohara, and T. Mizuochi; "Forward error correction for 100 G transport networks"; IEEE Communications Magazine, Vol. 48, Iss#3, pp. S48 - S55, March 2010.

[7] Geyer et al; "Practical implementation of higher order modulation beyond 16-QAM"; OFC15, Th1B.1, March 2015.

[8] R. Rios-Muller et al.; "Optimized spectrally efficient transceiver for 400-Gb/s single carrier transport"; presented at the Eur. Conf. Optical Communications, Cannes, France, Paper PD.4.2, September, 2014.

[9] G. Wang; "Optical IQ modulators for coherent 100G and beyond"; Lightwave Journal Vol.32, Iss#2, March 2015.